100 Years of the International Union of Radio Science

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Front Cover Photograph : The Founding Fathers on 6 April 1914.

Rear Cover Photograph: CSIRO's Australia Telescope Compact Array, Narrabri. Image: CSIRO/A. Cherney.

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Foreword

In 1919, shortly after the end of World War I, a small number of countries created the International Research Council and, with it, four scientific Unions, of which one was the Union Internationale de Radiotélégraphie Scientifique. The first General Assembly was held in 1922, and in 1928 the Union changed its name to the Union Radioscientifique Internationale (URSI) or the International Union of Radio Science.

Since then URSI has grown from its original three members to over forty members and its areas of research have substantially evolved. However, a constant through the last century has been the dual strands of scientific research using radio techniques, and applied research to support the ever-growing application of electromagnetic waves and signals. Sometimes one has been in the ascendancy in URSI, sometimes the other. It seems very likely that this duality will continue into the second century, albeit with different emphases as topics wax and wane.

This centennial publication presents an eclectic compendium of articles from twenty Member Committees and all ten Commissions, plus one overview historical article. Each article has a different emphasis, with some focused on individuals and others on particular topics. Together we hope they provide a valuable historical narrative and much interesting reading.

20 June 2021

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The History of URSI to 1940

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1. Origins of URSI: Before 1914

In the last decade of the 19th century communications "without wires" developed rapidly. Ranges were initially very modest, but Marconi managed to increase them progressively, reaching 110 km over water in 1899. Finally, in 1901 he created a radio link across the Atlantic Ocean, from Cornwall in the UK to Newfoundland in Canada.

Radio communications from ship to shore had started in 1898 and 1899, and from 1900 onwards ships were progressively equipped with wireless facilities. The new technology fired the interest of the industrialized world and the use of radio spread explosively. By 1904 daily news bulletins were provided to Cunard line passengers by means of signals picked up from shore stations which successively came within radio range during the transoceanic journey. Radio communications were also involved in the drama of the Titanic, which struck an iceberg just before midnight on April 14, 1912, during its maiden voyage. A small passenger ship, the California, which was in the vicinity, had noticed the presence of an icefield in the evening and sought to warn the Titanic by radio. The Titanic's operator, Phillips, was busy exchanging messages with Cape Cod at the time and told Evans, the California's radio-telegraphist, to leave him alone, upon which Evans went to sleep. After the collision, around midnight, the Titanic started transmitting distress signals. These were eventually picked up by the Carpathia, which was, unfortunately, five hours sailing away, and did not reach the Titanic until daybreak. Several vessels were close by, but were not equipped with wireless and, therefore, could not be alerted.

From 1900 onward, there was fierce competition for domination of the radiocommunication market. Several systems were soon available. For example, by 1905 there existed the de Forest company, the Telefunken company (advised by Wien, later involved in the birth of URSI) and the Marconi company (advised by Edison and Pupin). Marconi tried to create a

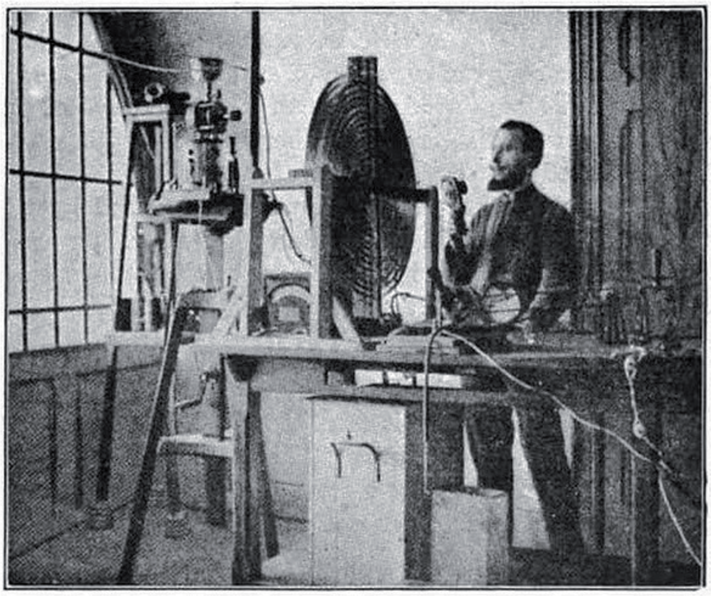

Figure 1. The radio station of Robert Goldschmidt in Laken.

de facto monopoly by restricting the traffic within his own system to reception and transmission from his own equipment and distress signals from differently equipped ships would, therefore, have remained undetected. To remedy this chaotic situation a series of administrative conferences were organized with the first held in Berlin in 1903. These conferences made recommendations on such matters as the allocation of frequencies, the form of signals from radio beacons and the transmission of weather reports and time data. These were inter-governmental meetings and only around 1913 did the need for scientific cooperation become apparent.

Some of the early development work on radio communications, including in his own private laboratory, was carried out under the patronage of the King Albert I of Belgium, who was interested at an early stage in the technology of wireless telecommunications. The central location for the radio projects was in the Villa Lacoste, near Brussels, in the grounds of the summer palace of Laken. A training school for operators, workshops and a research laboratory were set up at this location and Dr. Robert Goldschmidt was selected to take the leading role in these projects (Figure 1).

King Albert created a School for Wireless Telegraphy in the gardens, which also hosted a powerful 300 kW transmitter. As a consequence of the increasing interest in the test broadcasts from Laken a concert was broadcast on Saturday, March 28, 1914 at 5 pm, in which live speech and gramophone records were played. This was the very first European radio broadcast. Later that evening, at 8:30 pm, a special concert was broadcast for the Belgian royal family, who listened to the concert through a crystal receiver. Queen Elisabeth, a great music lover, was very interested and the concert was dedicated to her. Until July of that year, when the First World War broke out, broadcasts were arranged from Laken on a regular basis.

2. Early Scientific Cooperation: 1913

Goldschmidt was intrigued by the “fading” which disturbed the operation of his radio links and he soon concluded that international cooperation was essential for the investigation of the phenomenon. At the Paris “Conférence Internationale de l’Heure” in 1912 he decided to create, together with his German colleague Schmidt, a central research organization. A first meeting took place on October 13, 1913 in the gardens of the Royal Palace of Laken, near the centre of Brussels. The “Commission Provisoire Internationale de Télégraphie Sans Fil (Wireless Telegraphy) Scientifique” was created by nine participants, who represented seven countries.

A second meeting, attended by sixteen participants was held from April 6 to 8, in 1914. The participants decided to drop the “provisoire” (provisional) from the title of the Commission. Three Member Committees were formed, respectively in France, the United Kingdom and Belgium, and a first program of research was agreed upon. These activities were reported in the first (and only) bulletin of the Commission. A translation from French of a few pages of this first Bulletin are reproduced below since it gives an interesting glimpse into the goals and statutes of that time which closely foreshadow URSI as we know it a century later. The research projects, on the other hand, illustrate the tremendous evolution radio science has undergone over this period.

BULLETIN
DE LA
Commission Internationale
DE
Télégraphie Sans Fil Scientifique
T. S. F. S.

Under the Honorary Presidency of His Majesty the King of the Belgians

SUMMARY OF NUMBER 1. - MAY-JUNE 1914

ORIGINS AND GOAL OF THE INTERNATIONAL COMMISSION

Research on the laws of the propagation of electromagnetic waves requires the collaboration of a large number of observers placed at often very distant points.

Personal initiatives had hitherto been often hindered by the difficulty of assuring the permanent concurrence of powerful stations.

At the International Conference of the Hour, held in Paris in October 1912, Prof. Schmidt, from Halle, and Dr. Robert B. Goldschmidt, from Brussels, laid the foundations of a central body to co-ordinate efforts and increase the means of action in order to perform:

- *research on the propagation of electric waves;*
- *radiotelegraph measurements;*
- *and in a general way the study of the problems which are attached to it.*

Mr Goldschmidt put at the disposal of this body his powerful station and its laboratories in Laeken, Brussels. It also allocated a grant of 50,000 francs to cover the preliminary costs of experience and organization.

Thanks to the activity of Prof. Schmidt and Dr. Goldschmidt, the support of a certain number of scientific personalities was obtained, and a preparatory meeting, held in Brussels on October 13th, 1913, included the following names:

Prof. ABRAHAM, from Paris.
Prof. BENNDORF, from Graz.
W. DUDDELL, from London
Commander FERRIÉ, from Paris.
Dr. R.-B. GOLDSCHMIDT, from Brussels.
Prof. SCHMIDT, from Halle.
Prof. VANNI, from Rome.
Prof. WIEN, from Jena.
Prof. WULF, from Valkenburg.

A temporary office was formed:

Mr. DUDDELL, President.
Mr Wien, Vice-President.
Mr R. GOLDSCHMIDT, Secretary General.

Draft statutes were drawn up and the Commission agreed on a preliminary work plan:

- *determination of the means to ensure the constancy of emissions from the Laeken station and setting the means in order to assure this constancy;*
- *relative measurements of the variations of the signals in the different receiving stations from one day to the next, variations corresponding to the modifications of the wavelength and of the different characteristics of the emission of the Laken station;*
- *comparison of the intensity of the signals received in the different directions and at different distances from the transmitting station;*
- *simultaneous measurements of atmospheric disturbances in the various stations.*

Work was actively pursued and the Commission reconvened on April 6, 1914, to determine the organization's final form, to discuss the preliminary results achieved, and to outline the plan for future work. The statutes for the commission that were adopted contain the outlines of a structure that to a large extent is still present in URSI 100 years later.

STATUTS DE LA COMMISSION INTERNATIONALE DE T. S. F. S.

I. In Brussels an International Commission of T. S. F. S. was created for the purpose of doing research on the propagation of electric waves; measurements of radiotelegraphy and, in general, the study of the scientific problems relating to T. S. F.

II. The International Commission is composed of a delegation from each of the acceding countries, where a National Committee will have been formed, if possible with the support of the Government. This National Committee chooses its president and regulates his work freely. Each of the delegations referred to above includes the chairman of the National Committee and other members appointed by this Committee. The President alone has the right to vote and, in his absence, he appoints his replacement.

III. The Bureau of the International Commission includes: the President, the Vice-President, the Secretary General. The members of the Bureau are elected by the Commission and remain in office until the end of the next meeting of the Commission. The President can only be elected twice in succession and remains in office for at least one year. The Secretary General can be re-elected indefinitely. The headquarters of the General Secretariat is in Brussels. The official language of the International Commission is the French language. All freedom is left to the members to use the language that suits them for communications and discussions. The Commission should meet as much as possible and at least once a year. The date of each meeting shall be fixed by the Bureau after consulting the Chairmen of the National Committees.

IV. National Committees are free to publish, under their own responsibility and at their expense, the results of their tests undertaken under the auspices of the International Commission. The International Commission chooses among the works undertaken by itself and between the works communicated to it by the National Committees, those which it deems useful to publish on its behalf. The National Committees undertake to send as soon as possible the results of the measurements made in their countries. The publications of the International Commission are made at its expense.

V. The International Commission has a subsidy of 50,000 francs, granted by Mr. Goldschmidt, and possibly contributions from the National Committees. These resources should not, as far as possible, be allocated to the costs incurred by the work of the National Committees. If a change in the Statutes is requested, the Secretary General shall notify the Presidents of the National Committees at least four weeks before the date of the meeting at which the proposal is to be discussed. The vote on a modification of the statutes can be acquired only by a majority reaching two thirds of the represented countries.

Figure 2 depicts a drawing of the antenna with a pylon of 333 m constructed in Laken in 1914 and used for the experiments performed by the scientists of the International Commission of T. S. F. S. The planned efforts collapsed when World War I started, barely four months later, at which time international cooperation was necessarily discontinued. Fearing that the transmitting installation would fall into hostile hands, King Albert I of Belgium ordered the complete destruction of the Laken radio station in August 1914. The photograph of the founding fathers (Figure 3) reproduced from the Bulletin includes General Ferrié (first President of the future URSI), Schmidt, Wien (expert from Telefunken), Duddell (an early developer of HF alternators) and Goldschmidt.

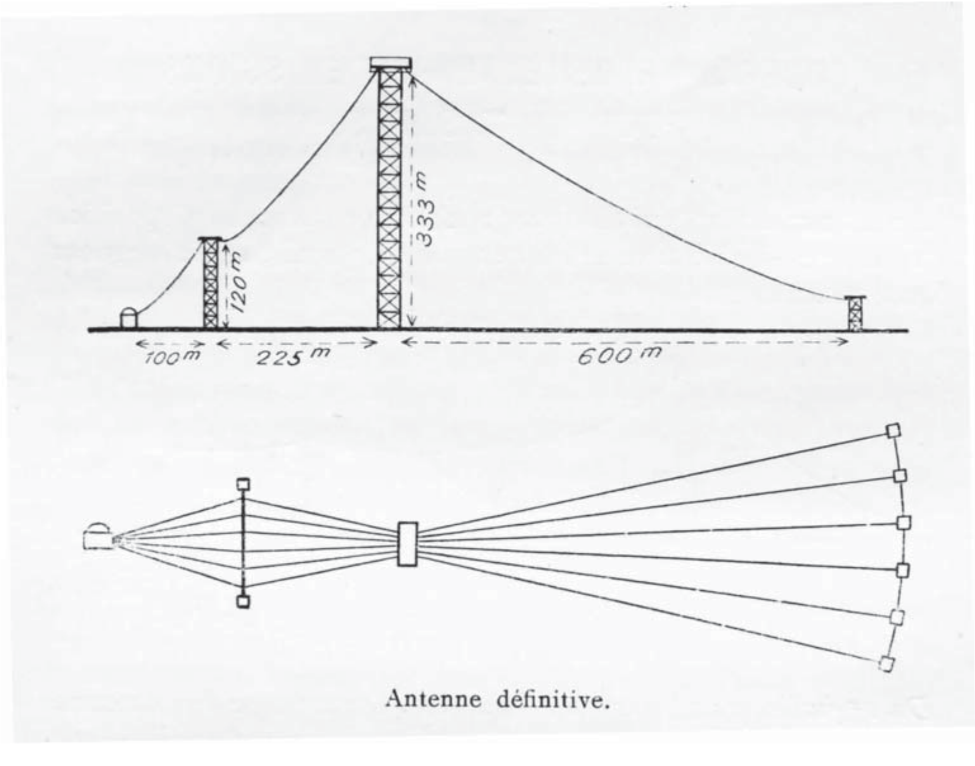

Figure 2. Antenna constructed in Laken.

Figure 3. Founding Fathers on April 6th, 1914 (from left to right in the picture) Marchant, Drumaux, Father Wulf, Ferrié, Duddell, Schmidt (above), Abraham, Wien, Eccles, Father Lucas, Benndorf, Lutze, Vollmer, Robert Goldschmidt, Braillard.

3. Founding of URSI: 1919

By 1919, alternators supplying continuous waves and the development of electronic tubes (valves) had completely revolutionised the transmission and reception of radio signals. Radio-telephony, unreliable before the war, had become practical.

Mass production of radio valves started during the war and, once the problem of producing an adequate vacuum in them had been solved by highly efficient pumps, they gave superb service. Just what mass production did achieve in the years of 1914-1918 can be seen from the figures of one French firm, Société Française Radio-Electrique; it had produced for the allied armies during those four years, 63 fixed radio stations, 300 ship stations, 18,000 aircraft stations and 12,500 mobile stations.

World War I generated a strong desire, in many countries, to abandon the disastrous nationalistic policies of the past, and to emphasize international cooperation, in particular in the various fields of science. This new attitude resulted in the creation of the “International Research Council”, the predecessor of what was later known as ICSU. The Council was founded in Brussels in 1919 in the beautiful building of the Academy and under the honorary chairmanship of King Albert I. The proceedings of the founding meeting of the Research Council were published a few years later.

It was brought to the attention of the founders that an international research organisation had existed in radio science since 1913. Thus, was born the “Union Internationale de Radiotélégraphie Scientifique”, one of the four scientific unions created at the time, together with those of chemistry, astronomy and geophysics. Radio was actually a rather restricted discipline, as compared with the other three, and attempts were made in later years to absorb URSI into physics or another discipline. These attempts failed, partly because radio is a very multidisciplinary science - with connections to astronomy, geophysics, and even biology - but also because of the ever-growing importance of radio communications in the world. The stated objective of the International Union of Scientific Radio Telegraphy was *to promote scientific studies of radiotelegraphy and to encourage research requiring international cooperation in this field*.

The various Unions showed, from the start, a common pattern of activity, that at the time were summarized as:

- *to promote the study of problems relating to their respective disciplines;*
- *to initiate, facilitate and co-ordinate research into, and investigation of problems which require international co-operation, and*
- *to provide for discussion, comparison and publication.*

A Union is maintained by the voluntary, part time work of a small group of active scientists, who in most cases serve only for a limited number of years. The Secretary General conducts the correspondence; he usually draws on the resources of his own research institution, supplemented by subventions from Union funds to cover expenses for secretariat assistance. It is significant that the Unions can draw directly on the knowledge and enthusiasm of active scientists, that the administration is small and flexible, but that the possibility (and need) for coping with a large, daily flow of correspondence or inquiries is limited.

The activities of the Unions are directed towards organizing meetings of various kinds and maintaining limited publication services, often in association with professional publishing firms. It is clear that the Unions, born from Academies, operated in the spirit of these. They are, in a way, International Academies devoted to well defined disciplines. The Unions are mostly interested in fundamental problems.

It is remarkable that 100 years later the above principles still govern the functioning of URSI. The Unions were clearly meant to be non-governmental organizations, and URSI, did not and does not duplicate the efforts of the International Telecommunications Union (ITU), which sets rules and codes of operation recognized by governments.

4. URSI from 1919 to 1940

From 1919 onward, URSI progressively acquired its present form and the leadership through this period can be seen in the Appendix. The main topics of discussion at the successive General Assemblies give an idea of the evolution of radio science over the years. During the successive Assemblies new problems develop; others have an ephemeral interest and disappear. This is often revealed in the changing names of the various Commissions.

In 1922 the first General Assembly was held in Brussels. In addition to the founding Member Committees of Belgium, France and the UK, Member Committees from the U.S.A., Australia, Spain, Italy, Japan and the Netherlands were formally admitted to the Union. General G. Ferrié (Figure 4) from France was elected as President of the Union and Dr. R.B. Goldschmidt (Figure 5) from Belgium was elected as Secretary General. This first General Assembly marked the start of Commissions dedicated to research in particular subfields of radio science (Table 1).

In October 1927 the General Assembly was held in Washington DC, USA, in conjunction with the International Radio Conference, the first after WWI, and was attended by delegates from 80 countries. The Washington DC Conference might be called the first of the truly modern telecommunication conferences. In addition to the 80 countries which were represented, there were 64 private companies, broadcasting organisations, and other international bodies which were interested in radio but which attended in a non-voting capacity.

Mr. Herbert Hoover, Secretary of Commerce of the United States, who was later to become US President, was elected Chairman of the Conference. At the suggestion of his delegation a new rule of procedure was adopted. *"French is the official language of the Conference. Nevertheless, since the presiding administration so requested, and as an exceptional measure, English may be used. Delegations are recommended to use this privilege with discretion."* This was indeed a revolutionary step. French, the ancient language of diplomacy, had always been the official language of the International Telegraph Union and of the Radiotelegraph Conference.

At the 1927 General Assembly in Washington DC participants included Appleton, Smith-Rose, Dellinger, Mesny, Van der Pol, Koga and Yagi. Much attention was devoted to propagation problems, however, there were also talks on quartz oscillators and international comparison of frequency standards. Notably, Yagi described his famous antenna.

Immediately after the war knowledge of radio propagation was poor and almost all of the experts tried to explain an astonishing range of radio wave propagation phenomena by radiation along the surface of the earth. There were, however, observations which could not be reconciled with the concept of only groundwave, and it became obvious that there must be a reflecting layer in the upper atmosphere to guide the radio waves around the curvature of the Earth as hypothesised by Heaviside in 1902 and independently by Kennelly. (Note that the existence of a conducting layer at greater heights

Figure 4. General G. Ferrié.

Figure 5. Dr. R.B. Goldschmidt.

had been assumed by geophysicists even prior to the advent of radio in order to explain variations in the geomagnetic field.) In retrospect, it is rather astonishing that it took 25 years for the reflecting layer to be generally accepted. There were several phenomena that pointed very strongly to more than one path of propagation, for example the fading of radio waves, which was dependent on the wavelength and the point of observation; the fact that the field strength did not fall off monotonically with distance, but showed maxima and minima with increasing distance; the variations of field strength from day to night; and the occurrence of deviations in direction-finding systems during the night.

L. W. Austin, Chair of the Commission on Radio Wave Propagation presented a report to the General Assembly of the Union in Washington DC. Most of the report was devoted to experimental results, but it is interesting to quote the questions put by Austin at the end of his report:

- *Does transmission from east to west differ from that from west to east, as indicated by the results of the Marconi expedition?*
- *Is there a limit in wavelength beyond which transmission over land is practically identical with transmission over water?*
- *Does the over water transmission in certain parts of the world differ materially from that in other parts?*
- *Is there a difference in transmission along and across the earth's magnetic field?*
- *What are the causes of the ionisation of the reflecting layer?*
- *Do the waves above a certain frequency fail to return to the surface of the earth?*
- *There also remains the question of the amount of correlation between radio transmission, solar activity, and variations in the earth's magnetic field; and how this may differ at various wavelengths and in various portions of the earth.*

For many years, only the radio scientist with radio probing devices could provide observational data on these regions of the upper atmosphere. Until the advent of the artificial satellite, URSI meetings were the principal forum for discussions on the characteristics of the earth's ionized environment. The purely geophysical aspects of these regions are now recognised as being more appropriate to the American and European Geophysical Unions and other bodies, but URSI still maintains a lively interest in them, and URSI took the initiative which led to the formation of several Inter-Union Working Groups which deal with questions of concern to other Unions.

In view of later discussions on the reorganization of URSI (at the General Assemblies in Warsaw 1972, and Lima 1975), and the problem of finding a proper balance between radio science and geophysics in URSI, it should be noted that in the twenties the situation was different. It was radio science and radio methods which gave a new impetus to the study of the atmosphere, especially the ionosphere, and provided new instrumentations and new theories.

At the 1928 Assembly, held in Brussels, the word "telegraphy" disappeared from the Union's title, which became "Union Radioscientifique Internationale". Radioscientifique was a neologism, which apparently was accepted with mixed feelings by the French delegates. As shown by the papers presented at the 1928 General Assembly, research on the reflecting layer was pursued by most Member Committees. (The word ionosphere would only be commonly used more commonly a few years later.) Other papers discuss negative resistance, the development of directive antennas, and the tremendous development of decametric waves.

Towards the end of the third decade, in September 1929, the first Plenary Assembly of the International Radio Consultative Committee (CCIR), set up at the Washington DC Convention of 1927, was convened at The Hague. General Ferrié, the URSI President and Goldschmidt, the Secretary General attended this meeting.

Jansky's discovery of radio emission from cosmic origin was still 2 years away when General Ferrié made his visionary remarks during this first CCIR meeting:
" ... Does it not lead to a broadening of our mental horizons, thanks to the waves which extend over the whole earth, reach the highest layers of the atmosphere, and according to certain theories about the delayed echoes observed in recent years, may perhaps even penetrate into interplanetary space?"

From the very outset, the CCIR enjoyed the support of the International Union of Radio Science (URSI), as a scientific body highly qualified in radio matters. The following has been said of the collaboration between the two bodies: *"Close co-operation between the CCIR and URSI is both desirable and inevitable, particularly since some of the researchers working in URSI's area of activity are also engaged in CCIR studies"*. Indeed, between their meetings in Brussels in 1927 and in Copenhagen in 1931, the Commissions of URSI devoted much attention to the theory of wave propagation in the upper atmosphere, interference measurement and the non-linear vibration theory, which subsequently proved to be very important for stabilizing transmitters and for frequency standards.

Although URSI and its Commissions are concerned first of all with the basic scientific aspects of radiocommunications, it would be quite wrong to assume that the typical radio scientist spends all his/her time in an ivory tower, and thinks of nothing else but fundamental research problems. There is clearly a need for good contacts between the research scientist and the communications engineer and this was appreciated many years ago by people like Balthasar van der Pol, J.R. Dellinger, and Bernard Decaux. These three scientists were all very active in URSI as Chairmen of Commissions and they all later occupied important positions in the International Radio Consultative Committee, one of the technical advisory organs of the International Telecommunication Union.

In 1931 the General Assembly was held in Copenhagen, Denmark. It was the last General Assembly with General G. Ferrié as URSI President.

The International Research Council, the original parent body of the Unions, was created in the post-war atmosphere of the year 1919 and tended, therefore, to be influenced by political considerations. It excluded from its membership the Central Powers in Europe, which included Austria and Germany. In later years, the Unions objected to the resulting restrictions in their membership, since these deprived the Unions of contacts with scientists in non-member countries where important research work was in progress. It was largely as a result of pressure from the Unions that the International Research Council was dissolved in 1931. It was replaced by the International Council of Scientific Unions, membership of which is open to any country in the world, irrespective of political considerations.

In 1931 the name "ionosphere", proposed by Watson-Watt (the man behind the radar defences of the United Kingdom in 1939), appeared with increasing frequency in the discussions of the Commission on Atmospherics. In the 1931 Assembly the problems regarding the ionosphere expanded and became better defined. Researchers were already talking about the F layer and the relationships between solar activity, magnetism and propagation. The Assembly ratified the creation of the URSIgrammes, which had internationally reported solar data and geophysics since 1928 and whose name was proposed by General Ferrié in 1930. Quartz clocks had appeared and international frequency comparisons took place between 1928 and 1931.

At the 1934 General Assembly, held in London, UK, Sir Edward Appleton, became URSI President and remained so until 1952 (Figures 6 and 7). The ionosphere was still in the spotlight at the 1934 Assembly and the terms that concern it were defined. A new phenomenon became apparent when the powerful radio broadcasting station of Luxembourg was put into operation. This "Luxembourg effect" included "wave interaction" about which URSI organized systematic observation campaigns. It was also at the 1934 Assembly that Jansky's observations on "extra-terrestrial noise" were described. The Assembly resolved to continue this research and it was the precursor of the future Radio Astronomy Commission.

Figure 6. Participants at the 1934 General Assembly in London.
Back Row: Mr. G.H. Rayner, Miss A.S. Robertson, Mrs. C.L. Fortescue, Mrs. A.B. Wood, Dr. A.B. Wood, Prof. Dr. J. Koga, M. Pierre Baudoux, Dr. G. Fanselau, Prof. H. Yagi, Mr. S. Okamoto, Mr. J.E.D. Vigoureux, Dr. R.L. Smith-Rose, Mr. L.H. Bainbridge-Bell, Mr. R.H. Barfield, Dr. A.G. Jensen, Mr. R.A. Heising, Mr. L.A. Briggs, Dr. F.W.G. White, Lt.-Col. Algeri Marino, Mr. J.A. Ratcliffe, Mr. S. Namba, Lt. Habert, Prof. C. Manneback, M. Bureau.
Second Row: Miss D.J. Lipscombe, Miss L. Ingram, Miss D.H. Mercer, Miss H.J. Brooker, Miss E.M. Steedman, Mrs. J.H. Dellinger, Signora Marino, Mrs. E.H. Rayner, Mme. Mesny, Mde. Jouaust, Mde. R. Mesny, Dr. Mary Taylor, Col. Luigi Sacco, Dr. D. La Cour, Mrs. Hackett, Dr. Hafstad, Mrs. Hafstad, Com. Carlo Matteini, Mr. J.F. Herd, Mr. T.L. Eckersley, Mr. S. Gejer, Mr. R. Naismith.
Front row: Dr. E.H. Rayner, Mr. R.A. Watson Watt, Mrs. R.A. Watson Watt, Dr. J. Lugeon, Prof. H. Norinder, Mde. S. Dorsimont, Capt. S. Dorsimont, Monsieur R. Mesny, Dr. R.B. Goldschmidt, Dr. W.H. Eccles, Prof. E.V. Appleton, Dr. B. Van der Pol, Dr. J.H. Dellinger, Dr. K.W. Wagner, Mde. D. La Cour, Mde. G.J. Elias, Monsieur Jouaust, Prof. G.J. Elias, Dr. Tullio Gorio.

The last General Assembly of the thirties was held in 1938 first in Venice and then in Rome. At the Assembly of 1938 a number of scientific problems appeared that would be further researched after the World War II. This included ionospheric tides and sudden ionospheric disturbances for which the URSI organized international observations. For the first time the propagation of very low frequency waves in the troposphere and in the stratosphere were discussed. In 1935,

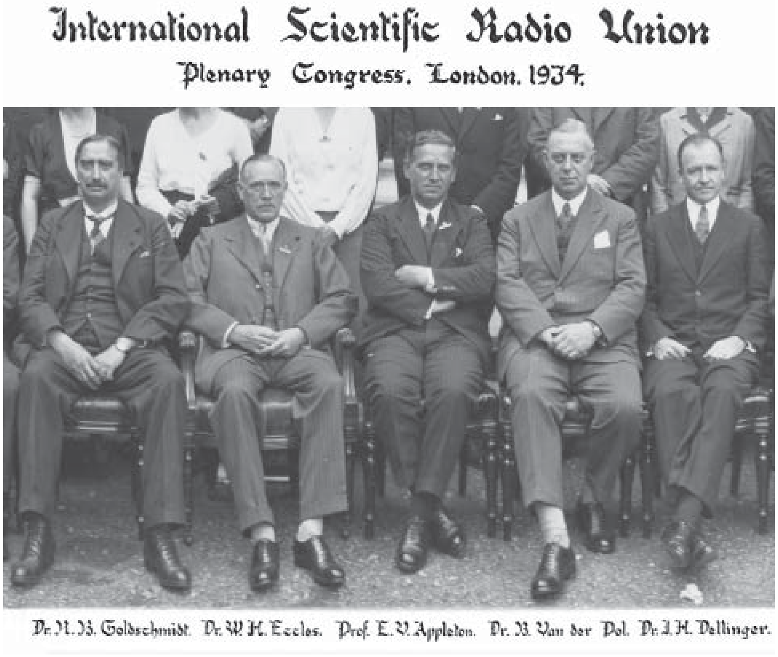

Figure 7. Dr. Goldschmidt, Dr. Eccles, Prof. Appleton, Dr. Van der Pol, and Dr. Dellinger at the 1934 London General Assembly.

after the death of Goldschmidt, Philippson had taken over as Secretary General. For the first time in 1938, a German National Committee took part in the General Assembly. The latter was seriously disturbed by the Germany-Czechoslovak crisis, which was to lead, several days later, to the Munich Agreement. Thus, many of the delegates, who had important official positions in their countries, had to leave the meeting prematurely. The remaining delegates chose Paris for the 1940 venue of the Assembly. Subsequent events delayed that optimistic choice until 1946.

5. Some Personal Concluding Remarks

The story of URSI is a history of organisational change, global technology research and rapid developments and the story of individuals.

The first post war General Assembly was held in Paris at the Sorbonne in September 1946 with Sir Edward Appleton as President. URSI was penniless, but with new life and renewed hope and it embarked on its post war programme of reconstruction and reorganisation. The six years of war had stimulated great advances in the application of radio waves; indeed, there can be little doubt that radio had played a key role in the fortunes of the war itself. Furthermore, the world community of radio scientists had been greatly enlarged and URSI had to adapt itself to the new situation with appropriate organisational changes. For example, in the years before the war, URSI held just six Assemblies, some of which were quite small gatherings of a few dozen scientists, whereas in the post war period the Union has held 26 General Assemblies. Most of these have been attended by at least an order of magnitude more delegates.

The activities of the Union since 1945 have also been colored by the rapid development of radio technologies. Radar, the transistor, microelectronics, microwave techniques, space research, satellite communication, the maser, the laser, the computer, fibre optics - to mention just a few new fields - have all contributed to the radio and electronic revolution. The history of radio science within URSI closely parallels the subject development in the world at large.

Those who have been associated with the affairs of URSI for a long period of years will know that at meetings of the Board of Officers, the Council and the Commissions, much time has been spent on recurrent debates of the same time-honored problems. These have included, discussions on issues such as: what form should Commission meetings and General Assemblies take? Should Commissions spend technical sessions reviewing progress over the previous three years or should they concentrate on new results? What publications, if any, should URSI undertake? What is the optimum size and duration of General Assemblies? What constraints, if any, should be placed on attendance at Assemblies? What efforts should we make to get young scientists to URSI. Should URSI introduce individual membership? How can URSI cooperate more effectively with ITU?

This last question is closely linked to the debate that was going on for most of the twentieth century. In 1919, the mission of URSI was to foster the scientific study of radiotelegraphy and more specifically those issues that required international cooperation. Over the following century the scientific domains encompassed by URSI have extended to all of radio science, ranging from the transmission of information by means of electromagnetic waves to the measurement of a wide range of geophysical, astronomical and even biological data by detecting the electromagnetic emission properties or by means of remote sensing. This has, for example, made it possible to gain a profound understanding of the ionosphere, the magnetosphere and for radio astronomy to discover many aspects of our universe and its origins. Scientists involved with URSI have played an important part in many of these research topics.

In the post war period the question whether URSI should choose to emphasize the research related to geophysics or instead revert to its original aims of advancing telecommunications science and technology was often debated. In the sixties and seventies, a split threatened between the telecommunication scientists (often close to engineering technology and industry) and the radio geophysicists and radio astronomers. The latter were strengthened by the remarkable scientific discoveries brought about by the advent of the space age.

At the General Assemblies of Warsaw (1972) and Lima (1975) the Board and Council succeeded in broadening the mission of URSI so as to encompass all science related to radio. It is interesting to quote Dr. Minis, the URSI Secretary General at the Lima General Assembly: *"The difficulty with this procedure is that there are people concerned with telecommunications science, who feel that URSI has drifted too far away from this subject in the past quarter century. If, in 1975, the URSI Council merely decides to apply the principles described in this document to the existing Commission structure, these people will be unlikely to believe that URSI seriously intends to reidentify itself with telecommunications science"*. After reviewing the then Commission structure of URSI, Mr Kirby, then Director of CCIR (now part of ITU), expressed the view that *"URSI does not attempt to meet a broad need for communication science and technology, nor does* *it appear to be so inclined. If the URSI Council decides that the time has come for the Union to concentrate its attention once again on telecommunications science, then it must take clear cut action on the reorganization of the Commissions".*

The end of the 20th century and the beginning of the 21st saw the emergence of a trillion-dollar ICT industry. Semiconductor industries, computer hardware and software companies, mobile communication companies and Internet companies became dominant in society in general and in technological research in particular. Notwithstanding this, URSI, in line with its affiliation with the national academies, chose to concentrate on curiosity driven, predominantly university led, research.

Major successes for URSI at the end of its first century of existence are, undoubtedly, the Young Scientist program, the Student Paper Competition and other similar initiatives. Supporting the students and early career radio scientists, adopting a broad scientific scope as defined by the terms of reference of the Commissions and being open to any interested scientist without reference to nationality or border, should allow URSI to prosper further in its second century of existence.

Appendix

The following tables contain a chronological overview of the Member Committees, the Scientific Commissions, the Presidents, the Secretary Generals, the General Assemblies and the Honorary Presidents. The Union has from time to time designated Honorary Presidents. They hold this dignity for life.

Table 1. New URSI Member Committees from 1919 to 1938

Belgium, France and UK	1919
USA, Australia, Spain, Italy, Japan and the Netherlands	1922
Portugal and Norway	1927
South Africa, Denmark and Switzerland	1928
Sweden and New Zealand	1931
Morocco	1934
Germany	1938

Table 2 URSI Commissions from 1922 to 1940

I	Measurements and standardization	1922
II	Radiowave propagation	1922
III	Atmospherics	1922
IV	Cooperation with amateurs	1922-46
V	Radiophysics	1928

Table 3. The Presidents of URSI from 1913 to 1952

W. Duddell, United Kingdom T.S.F.S	1913
General G. Ferrié, France	1919-1932
Dr. L.W. Austin, USA	1932
Prof. A.E. Kennelly, USA	1932-1934
Dr. E.V. Appleton, United Kingdom	1934-1952

Table 4. Secretary Generals from 1913-1939

Dr. R.B. Goldschmidt T.S.F.S.	1913
Dr. R.B. Goldschmidt	1919-1935
Prof. M. Philippson	1935-1939

Table 5. General Assemblies from 1914 to 1938

Brussels (Belgium)	1914
Brussels (Belgium)	1922
Washington, D.C. (U.S.A.)	1927
Brussels (Belgium)	1928
Copenhagen (Denmark)	1931
London (U.K.)	1934
Venice and Rome (Italy)	1938

Table 6. Honorary Presidents from 1914 to 1939

H.M. King Albert, Belgium	1914-1934
Dr. W.E. Eccles, United Kingdom	1934-1966
Dr. A.E. Kennelly, USA	1934-1939

URSI
MEMBER
COMMITTEES

Radio Astronomy in Australia: Impact and the Growth of Community

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1. Introduction

In 1946 researchers in Australia were the first to use an interferometer to study the sun. Today the country has world-class radio telescopes and is preparing to host the low-frequency antennas of the international Square Kilometre Array. The years between have seen the Australian radio-astronomy community grow and Australians have significant impact. Developments fall roughly into three phases, defined by changes in instrumentation.

2. Foundational Years: 1946-1961

During the Second World War, radar operators in both the UK and New Zealand saw sporadic bursts of radio emission from the sun. Immediately after the war, researchers in Australia and the UK began investigating this solar emission – and then, for good measure, the cosmic radio waves detected by Karl Jansky in 1932. In the first decade of these investigations Australians used, and in some instances created, several types of radio telescope, and notched up important firsts in interferometry and studies of the sun. By the late 1950s Australians had produced far more papers in radio astronomy than any other group in the world [1]. Many authors have explored this early period in detail. Sullivan [1, 2] gives a relatively brief treatment; Goss et al. [3] cover it at length.

A single government institution drove the Australian research. This was the Radiophysics Laboratory of the Council for Scientific and Industrial Research (CSIR; from 1949, CSIRO, the Commonwealth Scientific and Industrial Research Organisation). Radiophysics was established in 1939 to work on radar defences for Australia. Its staff was drawn largely from the radio ionospheric community built up in the 1930s at the Universities of Sydney and Melbourne and in the research lab of Amalgamated Wireless (Australasia) Ltd [4]. By the war's end Radiophysics, then housed at the University of Sydney, had more than 300 staff, a well-equipped workshop, and a large stock of radio equipment, both its own and some salvaged from US and British forces. The laboratory's leader, Edward ("Taffy") Bowen, was in good standing with the CSIR Executive. In 1945 Bowen drew up a list of nine research areas Radiophysics could pursue in peacetime, "non- thunderstorm" (i.e. cosmic) radio noise among them. By 1949 the radio-noise investigators numbered about 20 (later growing to 30). They were the laboratory's biggest research group and published the largest share of its papers [1].

Australian universities of the day could not match this effort. Government funds for university scientific research were a thirtieth those for CSIR [1]. Universities offered almost no postgraduate studies. The first Australian PhD was awarded in 1948, by the University of Melbourne [5]. Australians went abroad for their advanced training.

Radiophysics's scientific leader, Joseph L. Pawsey, had followed that path. After taking a degree in physics at the University of Melbourne he had completed a thesis on ionospheric physics under J.A. Ratcliffe at Cambridge – an important connection for the development of Australian radio astronomy. Pawsey worked in the UK on early television systems then joined Radiophysics in 1940. Already expert with antennas and transmission lines, by the war's end he had gained skills with receivers, radar systems and atmospheric propagation and experience in managing a research group.

Pawsey made the first documented use of the term "radio astronomy" to describe the new field, in a letter dated 14 January 1948 [6]. Martin Ryle at Cambridge also used the term in April that year: he and Pawsey had probably discussed it

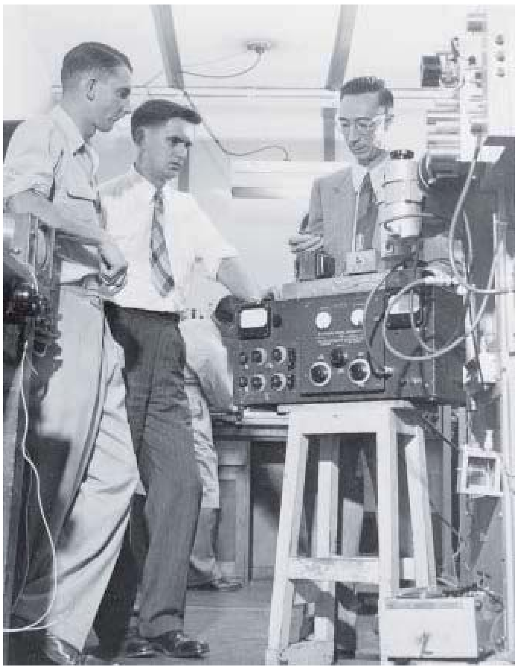

Figure 1a. Radiophysics researchers John Bolton, Gordon Stanley, and Joseph Pawsey (credit: CSIRO Radiophysics Image Archive B11833-6).

Figure 1b. One of radiophysics most important early field stations, the Dover Heights radar station, looking north towards Sydney Heads (credit: CSIRO Radiophysics Image Archive B81-1).

when they met earlier that month. Both URSI and the International Astronomical Union (IAU) needed a name for the new subdiscipline, URSI for its Commission J, and the previous "cosmic noise" or "radio noise" was considered unsuitable. Pawsey was very active in both URSI and the IAU – he was president of IAU Commission 40 (Radio Astronomy) from 1952 to 1958 – and he promoted the use of the term "radio astronomy" to build a connection with the rest of astronomy.

Pawsey's management style played a big role in the success of the Radiophysics astronomy group. He followed the philosophy of CSIR's Chief Executive Officer, David Rivett: get the best people possible, give them resources and let them run free. Members of the radio astronomy group worked alone or in small numbers at field stations in and around Sydney, linked only by Pawsey, who advised and encouraged each small unit (Figs 1a and 1b). However, there were also practical reasons for this way of working. Christiansen [7] notes that the number of field stations was partly the result of the taking over of a number of former radar sites, but it continued because maintenance work and observations at the same site by different groups produced mutual electrical interference.

With this freedom to experiment the researchers developed significant new instruments. In 1961 Pawsey [8] highlighted four:

- the Mills Cross at Radiophysics's Fleurs field station west of Sydney (Fig. 2a). This consist of two intersecting lines of dipoles, each about 450 m long, running north-south and east-west. It produced a pencil beam 49 arcminutes wide – excellent for the time – without the need for digital computers to do the Fourier synthesis [9, 10]
- the Christiansen Cross (Chris Cross), also at Fleurs (Fig. 2b). This combined design features of Christiansen's earlier grating array [11] and the Mills Cross to generate a grid of pencil beams for imaging the sun [12]
- a 48-channel receiver at the Murraybank field station north of Sydney, used for a detailed survey of neutral (un-ionized) hydrogen gas over the whole southern sky (Fig. 2c) [13]
- a swept-frequency receiver and interferometer at Dapto south of Sydney, used to study the spectra and location of radio bursts from the sun (Fig. 2d) [14].

With these instruments and others, Radiophysics researchers achieved notable results including:

- first use of an interferometer in radio astronomy (by Pawsey and Payne-Scott, January 1946) first published description of how Fourier synthesis could be used to make radio images [15] first Earth-rotation 2D aperture-synthesis image – an image of the quiet sun [16]
- first direct evidence of a link between compact solar radio bursts and sunspots [15] identification of different types of solar radio bursts ([17] and subsequent work)
- early identification of three discrete radio sources ("radio stars"), one with a supernova remnant in our Galaxy and two with extragalactic nebulae [18]

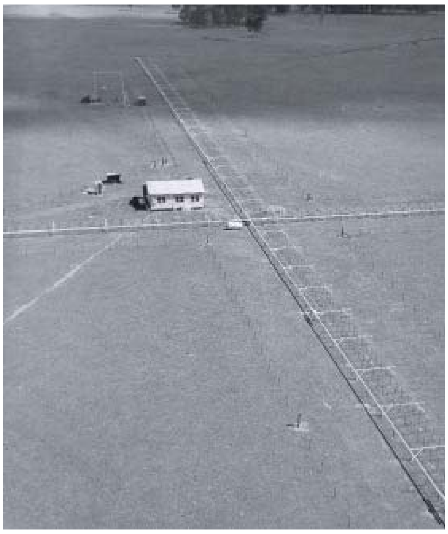

Figure 2a. The Mills Cross at Fleurs field station (credit: CSIRO Radiophysics Image Archive R3476-1).

Figure 2b. The Christiansen Cross (Chris Cross) at Fleurs (credit: CSIRO Radio- physics Image Archive R5804-6).

Figure 2c. Richard McGee working on the antenna at the Murraybank field station used for hydrogen-line observations (credit: CSIRO Radiophysics Image Archive R5695-8p).

Figure 2d. Antennas of the solar interferometer at Dapto (credit: CSIRO Radio- physics Image Archive 2888-1).

- detection and cataloguing of large numbers of discrete cosmic radio sources, in projects led (separately) by John Bolton and Bernard Mills. From 1954 to 1957, Mills and his colleagues Bruce Slee and Eric Hill used the Mills Cross to record more than 2,000 sources of discrete radio emission, creating the (Mills, Slee and Hill) MSH catalogue [19-21]. MSH conflicted with Cambridge University’s 2C catalogue, leading to a controversy that took years to resolve [22]
- maps of the neutral hydrogen gas in our Galaxy. These, combined with a northern sky survey, showed conclusively our Galaxy has spiral arms [23].

By the 1950s Australia was a world leader in radio astronomy. This was a major reason why URSI held its tenth General Assembly in Australia in 1952 (the first time this meeting took place outside Europe or the USA). However, the country’s expertise was essentially confined to one group, Radiophysics. A few other local investigators had tried their hand at radio astronomy. Researchers at the University of Western Australia in Perth observed the sun in 1946-48. Clay Allen at the Commonwealth Observatory at Mt Stromlo near Canberra (in 1946) and Gordon Newstead at the University of Tasmania (in 1952) observed the sun and cosmic sources respectively, using equipment lent by Radiophysics. From 1954, Graeme “Bill” Ellis of the Ionospheric Prediction Service made low-frequency observations in Tasmania, initially

Figure 3. Edward "Taffy" Bowen with the newly completed Parkes radio telescope (source: CSIRO Radiophysics Image Archive B15850-2).

with US radio astronomy pioneer Grote Reber. Ellis moved interstate for a few years and returned in 1960, having been appointed Professor of Physics at the University of Tasmania. There he set up a research group focused on low-frequency radio astronomy [24, 25].

However, in the 1950s Australia could hardly be said to have a radio astronomy community. In fact, Radiophysics leader Bowen was not looking to have rivals. When in 1951 the Mt Stromlo observatory's director announced plans to build up a radio astronomy group, CSIRO management had this initiative squashed [26]. However, without radio astronomers in universities there was no way to systematically transfer knowledge to students. This situation changed with the coming of CSIRO's 64-m Parkes radio telescope.

In the late 1940s, Radiophysics learned of the University of Manchester's plans to build a large, fully steerable reflector. This would take shape as the 76-m Lovell Telescope, opened at Jodrell Bank Observatory in 1957. Bowen began to champion the building of another large dish. Such an instrument, he argued, would provide greater sensitivity, greater resolution, and the ability to operate over a wide range of frequencies. The funding was found, thanks to Bowen's contacts in the USA, and the site chosen – a shallow valley near the town of Parkes, a five-hour drive west of Sydney. Construction began in 1959. Robertson [26] gives a detailed history of the Parkes telescope (Fig. 3) from its conception through to operation.

The Parkes telescope created new scientific opportunities although it ended Radiophysics's work in high-resolution, low-frequency astronomy, and led key staff to leave. By 1959 it was clear Parkes would absorb most of Radiophysics's radio-astronomy resources. Two proposed instruments – a larger Mills Cross and a radioheliograph for studying the sun– were competing for the rest. Asked to vote, the astronomy group backed the radioheliograph. Mills, who had lobbied for the larger Cross, moved to the University of Sydney in 1960 and took up a professorship in the School of Physics. Wilbur ("Chris") Christiansen followed soon after, becoming the university's Professor of Electrical Engineering. Pawsey was offered the Directorship of the National Radio Astronomy Observatory in the USA but died in 1962 before he could take it up. There were other departures too, Mills's and Christiansen's being the most significant for the growth of radio astronomy in Australia.

2.1 Mills and Christiansen at the University of Sydney

Ensconced at the University of Sydney, Mills built his dream instrument: the Molonglo Cross, located 35 km from Canberra. The Cross had two 1600-m arms, running north-south and east-west. It operated at 408 MHz and had a beamwidth of 2.8 arcminutes. The Cross was used to survey the southern sky, generating a catalogue of more than 12,000 radio sources; determine an absolute scale for flux density at 408 MHz, adopted worldwide; and discover more than 150 pulsars (including the Vela pulsar), over half the total then known. McAdam [27] describes the building of the Cross (Fig. 4) and its research program.

During 1978-81 Mills mothballed the Cross's north-south arm and converted the east-west one to a radio synthesis array, the Molonglo Observatory Synthesis Telescope (MOST). Operating at 843 MHz, MOST

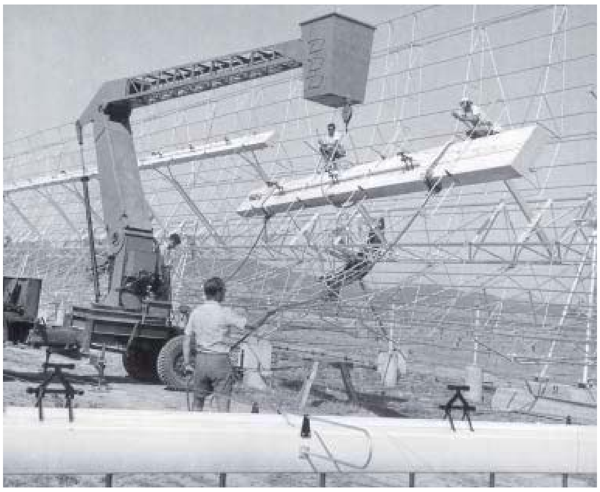

Figure 4. Lifting the feed on the east-west arm into position during the building of the Molonglo Cross in 1965 (credit: The University of Sydney).

made deep imaging surveys of the southern sky, notably the Sydney University Molonglo Sky Survey (SUMSS) and complementary surveys of the Galactic Plane [28, 29]. SUMSS's sensitivity and resolution equaled the NRAO VLA Sky Survey (NVSS) for the northern sky, and it became a standard reference. MOST also observed Supernova 1987A, the brightest supernova seen since telescopes were invented: it detected both the prompt radio emission from the explosion in 1987 and the radio source that emerged from the explosion site in 1990 [30, 31].

In 2014-15 the radio-astronomy group at Swinburne University of Technology, led by Matthew Bailes, upgraded MOST and brought it into the "big data" era [32]. Swinburne staff and students now use the telescope to find and study pulsars and the mysterious, fleeting signals called Fast Radio Bursts (FRB).

Christiansen regained control of the Chris Cross in 1963 when CSIRO transferred the Fleurs field station and most of its telescopes to the University of Sydney. Over the next two decades university staff and students converted this telescope into a synthesis instrument, the Fleurs Synthesis Telescope (FST). During the 1970s and '80s it was used to study individual radio sources, particularly large radio galaxies, supernova remnants and emission nebulae [33]. In its final form the FST consisted of the Chris Cross and six 13.7-m antennas. It had a resolving power of 20 arcseconds, making it the highest-resolution radio telescope in the southern hemisphere until the Australia Telescope began operating in the late 1980s [34].

These university telescopes were training grounds for students and so helped grow the radio astronomy community. Their alumni include Anthony Beasley, present director of the US National Radio Astronomy Observatory; John O'Sullivan, Terence Percival and Graham Daniels, members of the CSIRO team that developed technology forming part of the 802.11 Wi-Fi standard; David Skellern, who co-founded Radiata to commercialize wireless LAN research; and Robert (Bob) Frater, who drove the Australia Telescope project in the 1980s.

2.2 The Parkes Radio Telescope

With the opening of the Parkes telescope in 1961 Australia gained a world-class instrument. The telescope's design innovations included its structure (which keeps the dish a fairly constant shape even as it tilts) and its pointing system (a "master equatorial" – small optical telescope – to which the radio dish is slaved by a servo system). Parkes preceded the 64-m (later 70-m) antennas of NASA's Deep Space Network (DSN) and a NASA-funded design study of Parkes led to some of the telescope's features, such as the drive and control systems, being incorporated into the DSN antennas [3].

CSIRO had set out Parkes's likely science program in 1955 [35]. Studies of the 21-cm hydrogen line – first detected in 1951 – were thought the most important. The telescope was also forecast to study discrete sources of small angular size ("radio stars") and the sun, and precisely measure distances to the sun, Moon and planets using radar. By 1960, polarisation measurements were also thought likely to be important because polarized emission was detected in the Crab nebula (a supernova remnant) in 1957.

Once at work, Parkes did not stick entirely to the script. It did no significant solar work and did not measure distances to the planets. However, a lot of the telescope's time early on was given to cataloguing discrete radio sources so they could be matched with optical counterparts. Hydrogen-line observations were immensely important, from the telescope's first days to the present. And in 1962 Parkes's observations of Centaurus A polarisation at two wavelengths led to the (serendipitous) discovery of the phenomenon of Faraday rotation. As Pawsey realized, this gave "the first real chance of measuring magnetic fields in interstellar space" [3].

As astronomy advanced Parkes was also used for studies its designers had never dreamed of. The number of radio spectral lines expanded, allowing Parkes to identify molecules in space, study new kinds of objects such as cosmic masers, and map the Galaxy through radio recombination lines from regions of ionized hydrogen. In 1963 researchers used Parkes to determine the position of a radio source, 3C 273, by lunar occultation. The position was accurate to within an arcsecond – the best determination of a radio source position made at that time [36]. This allowed 3C 273 to be identified with an optical source with strange spectral lines. When US astronomer Maarten Schmidt realized these lines were those of hydrogen, hugely redshifted, it was clear 3C 273 must be both extremely distant and 100 times more luminous than any known galaxy. 3C 273 was the first object to be identified as a quasar – a type of source whose power could only be generated by a black hole.

The Parkes telescope has distinguished itself above all in studying pulsars, which were unknown when it was built. It has found more than half of the ~2600 pulsars currently known, including the first (and so far, only) double-pulsar system, PSR J0737−3039. It also times a set of super-fast millisecond pulsars, the Parkes Pulsar Timing Array, with a view to detecting low-frequency gravitational waves.

Figure 5a. The corrugated, hybrid-mode feedhorn used on the Parkes telescope in 1969 to receive signals of the Apollo 11 moonwalk (credit: CSIRO Radiophysics Image Archive B9245-2).

Figure 5b. The Parkes control room during the Apollo 11 moonwalk, with John Shimmins, Edward Bowen (front), and other CSIRO and NASApersonnel watching the vision as it was received (credit: CSIRO Radiophysics Image Archive 9190).

In 2007 Parkes's pursuit of pulsars led to the discovery of another phenomenon. Astronomer Duncan Lorimer was searching recorded Parkes data for overlooked pulsars when he found a powerful spike of radio waves lasting just a few milliseconds. This was the first recognized Fast Radio Burst (FRB). Many more were recorded since; Parkes found a large fraction of the early ones, thanks to its multibeam receiver. Astronomers have established FRBs come from distant galaxies, although their cause is still unknown.

Parkes was also used to track spacecraft on 13 occasions to date, mostly for NASA but also for ESA's Giotto mission to Halley's comet. In this regard, its best-known role is receiving the television pictures of the first moonwalk in 1969 (Figs 5a and 5b). The telescope captured these signals with a CSIRO-designed, high-efficiency dual-hybrid-mode feed, a refinement of the corrugated, hybrid-mode feed CSIRO had developed – specifically for Parkes – in 1968 [37]. Corrugated horns were developed independently, and around the same time, by Minnett and Thomas in Australia, and Kay and Simmons in the USA [38]. Developed largely for radio telescopes, the technology was rapidly applied to Earth-station antennas.

By becoming a hub for research, Parkes helped expand the radio astronomy community. Although the telescope was run for CSIRO staff, collaboration with outside users was encouraged and students could use it for their thesis work. This included Australian students, as Australian postgraduate training had expanded after the war. The telescope's first director, John Bolton, took up his role in 1960, after spending five years at Caltech overseeing the design and construction of the Owens Valley Interferometer. He was a scientist of international repute and three of his graduate students – Ken Kellermann, Ron Ekers and Jasper Wall – became directors of observatories.

Parkes's performance was continually increased by a series of upgrades to its surface, receivers, backend signal processing, and pointing and control systems. Probably the most significant instrument, which extended the telescope's capabilities, was a 13-beam receiver installed in 1997. This receiver increased the telescope's instantaneous field of view 13-fold and made possible a ground-breaking survey of the southern sky for neutral hydrogen (essentially a blind survey for galaxies in the local universe [39]), the discovery of fast radio bursts, and a major survey for pulsars. CSIRO subsequently built similar multibeam instruments for the Arecibo and Jodrell Bank observatories and for China's FAST (Five-hundred-meter Aperture Spherical Telescope). The most recent enhancement to Parkes is an ultra-wideband receiver covering 0.7 GHz to 4.2 GHz, installed on the telescope in 2018 [40].

2.3 CSIRO Radioheliograph

Radiophysics's second major instrument of the 1960s was its radioheliograph. This was located near Narrabri in northwest New South Wales, where a large area of flat land was available. Opened in 1968, it consisted of 96 parabolic reflectors, each 13.7-m in diameter, arranged in a circle 3 km across; the 96 signals were combined to form a comb of 48 pencil beams in a north-south line [41]. Observations were made initially at 80 MHz (1 m wavelength) then later at 160 MHz.

Figure 6. Australia's Prime Minister, Robert (Bob) Hawke, opening the Australia Telescope on 2 September 1988 (credit: CSIRO Radiophysics Image Archive N15191-11).

The radioheliograph produced frames once a second, generating unique "radio movies" that allowed the various types of solar bursts to be studied in detail. In the late 1960s and early '70s it was a world-leading instrument: in 1969 URSI bestowed its highest award, the Balthasar van der Pol Gold Medal, on the radioheliograph's creator, Paul Wild [42]. By the 1980s the radioheliograph had fulfilled its mission. It was closed in 1984, ending Australia's role in solar radio astronomy.

3. The Australia Telescope and the ATNF

Despite Parkes's productivity, by the 1970s Australia was no longer at the forefront of cosmic radio astronomy as it lacked a major radio synthesis instrument such as Westerbork in the Netherlands (operational 1968) or the Very Large Array in the US (constructed 1975-80). Over 1975-79 a working group drawn from Radiophysics, the Australian National University and the University of Sydney developed a proposal for an Australian Synthesis Telescope (AST), a set of dishes to be located at the Parkes observatory. However, by 1980 this project looked unlikely to get off the ground.

In 1981 Radiophysics gained a new leader, Robert H. Frater. Frater had worked on the electronic design of the Molonglo Cross for his PhD and became Associate Professor of Electrical Engineering at the University of Sydney. He thought the AST proposal lacked ambition and pushed for a bolder plan. Six moveable antennas on railtrack would be located at the radioheliograph site near Narrabri while a seventh would be built near the town of Coonabarabran, 120 km south. Frater committed to the Australian Government that 80 per cent of the project's funding would be spent in Australia and the telescope would be opened in 1988, Australia's bicentennial year. Government approved the project in 1983 and work began.

The telescope, now called the Australia Telescope, was the largest project CSIRO had ever undertaken. It came in on time and on budget (Fig. 6). The antenna designs were developed in partnership with industry, which later adapted them for commercial Australian-built satellite Earth stations. A study by the Australian Bureau of Industry Economics [43] found the overall benefit-to-cost ratio of CSIRO's antenna research was 2:1.

The six 22-m Culgoora antennas (the Australia Telescope Compact Array, ATCA) were designed to be as versatile as possible, with high resolving power, a spectral-line capability, wide bandwidth, and the ability to measure polarisation accurately [44]. Although they were originally equipped to operate at centimetre wavelengths (the 1.5, 2.3, 5.0 and 8.6-GHz bands) they were also designed to handle higher frequencies, and later acquired receivers for the 16-25 GHz, 30-50 GHz and 85-105 GHz bands. Later upgrades combined the 1.5- and 2.3-GHz bands combined into a single band covering 1.1-3.1 GHz, and the 5.0- and 8.6-GHz bands combined into a 4-12 GHz band. In 1998 a short north-south rail track was added to the existing east-west track. This allowed millimetre-wave observations to be completed at high elevations, where these short wavelengths are least absorbed by the atmosphere.

In ATCA's first year its international users came from just 10 institutions. Within six years they were coming from more than 110. An independent analysis in 2008 ranked the telescope's impact just behind the larger US Very Large Array [45]. Its most influential papers are those from the 1990s describing mosaicked images of neutral hydrogen in the Large and Small Magellanic Clouds, at the time the most detailed images of atomic gas in any external galaxy. Other notable science from ATCA includes:

- observations that provided the first link between a supernova (SN1998bw) and a gamma-ray burst
- an unprecedented time sequence of observations of SN1987A from 1991 to the present day, and the first measurements of polarisation within the radio remnant
- the AT20G survey, which to date is the only large area 20-GHz survey of the sky
- follow-up of the gravitational wave event created by merging neutron stars in 2017 – the most highly cited paper using ATCA data.

The seventh, standalone antenna of the Australia Telescope is located at the Mopra Observatory 120 km south of ATCA. A 2006 upgrade gave the Mopra telescope four overlapping frequency sub-bands, each with a bandwidth of 2.2 GHz, providing a total of 8.3 GHz of continuous bandwidth. Mopra was originally used for very-long-baseline interferometry and single-dish observations at centimetre wavelengths; in recent years its focus was surveys of various molecular species along the Galactic plane. Since 2012 CSIRO has managed the Mopra telescope under contract for university consortia.

In 1989 a new institution, the Australia Telescope National Facility (ATNF), came into being to operate all of CSIRO's radio telescopes. Observing time was made freely available to all researchers who submitted competitive observing proposals. This gave Australian researchers access to world-class facilities that were beyond the means of any local university. The ATNF now also handles proposals for service observations on antennas at the Canberra Deep Space Communication Complex, part of NASA's Deep Space Network: although dedicated to spacecraft tracking, they can be used for some astronomy.

3.1 Radio Astronomy at the University of Tasmania

As already mentioned, the University of Tasmania initially focused on low-frequency radio astronomy (Fig. 7a) [46]. The discovery of pulsars in the late '60s prompted a move to higher frequencies. Today the University's main observatory houses two dishes, 14 m and 26 m in diameter (Fig. 7b). The smaller dish monitors the well-known Vela pulsar for glitches – sudden changes in the pulsar's rotation period gave clues to its internal structure – while larger one is used mostly for very long baseline interferometry, plus some studies of pulsars and cosmic masers. The university also owns a 30-m dish at Ceduna, South Australia, which adds a useful east-west baseline to the Australian array for Very Long Baseline Interferometry.

Figure 7a. The poles of the Llanherne Low Frequency Array near Hobart, Tasmania, operating at frequencies between 2 MHz and 35 MHz. This was one of the University of Tasmania's major low-frequency instruments. It was used from 1972 to the early 1980s to record decametric bursts from Jupiter and to map the radio sky at low frequencies [46] (credit: the estate of Grote Reber)

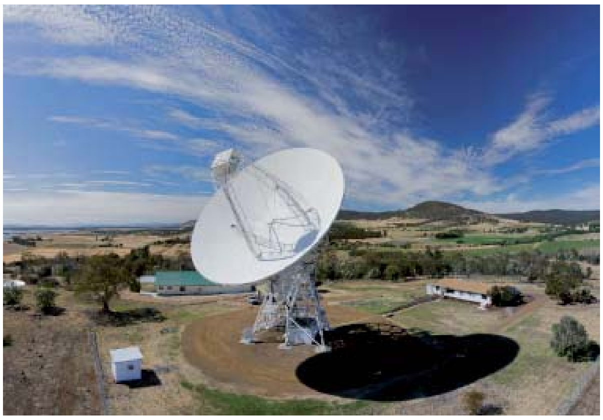

Figure 7b. The University of Tasmania's 26-m antenna at Mount Pleasant Observatory (credit: Jim Lovell).

3.2 Very Long Baseline Interferometry (VLBI)

US and Canadian institutions pioneered Very Long Baseline Interferometry (VLBI) – interferometry with widely separated antennas – in the 1960s. Australia made its first successful international VLBI experiment in April 1969, when the Parkes telescope was linked to an antenna in California's Owens Valley [47]. Just a few months later, VLBI observations using DSN antennas in Australia and California gave the first evidence of a radio source apparently expanding at a speed faster than light [48] – a phenomenon, later seen in many extragalactic sources, caused by the source's orientation. Routine Australian VLBI started in the 1980s with the development of a network called SHEVE, the Southern Hemisphere VLBI Experiment [49].

By the mid-1990s SHEVE had evolved into today's Australian Long Baseline Array (LBA). This network routinely uses the ATCA, Mopra, Parkes, Hobart and Ceduna antennas; on occasion it may also incorporate antennas from the Canberra Deep Space Communication Complex, the Australian SKA Pathfinder in Western Australia, the 26-m antenna at Hartebeesthoek in South Africa, the 12-m antenna at Warkworth in New Zealand, and other antennas of the University of Tasmania mainly used for geodesy. LBA data was originally recorded on tape (the Canadian S2 system) and then on disk. Some of the LBA antennas were used for e-VLBI – streaming data over high-speed fibre networks and correlating it in real time. Edwards and Phillips [50] describe the LBA and its operations.

Australia has made successful international VLBI observations over baselines to Antarctica, China, Europe, India, Japan, Korea, South Africa and the USA – Alaska, California and Hawaiʻi [51].

Australia also took part in the first space VLBI experiment, made in 1986 between NASA's TDRSS-E satellite and antennas in Australia and Japan. Australia has since contributed co-observing radio telescopes for two space VLBI missions, Japan's VSOP (VLBI Space Observatory Programme) and Russia's RadioAstron, and also designed and built a 1.6-GHz receiver that flew on RadioAstron.

4. The Square Kilometre Array (SKA) and Australian Precursors

4.1 Australia and the SKA

In the 1980s astronomers from several countries began to discuss building an extremely large, international radio telescope to study the early universe. Their original aim was to detect the faint, redshifted hydrogen-line signals from distant galaxies.

In 1997 Australia was one of six countries that agreed to cooperate to develop technology for the telescope, now with a broader set of science goals and called the Square Kilometre Array (SKA). In the same year CSIRO began searching for areas in Australia where the telescope could be sited. By 2007 it had chosen a superbly radio-quiet location in Western Australia and began to transform it into the Murchison Radio-astronomy Observatory (MRO), building there a SKA "precursor" telescope, the Australian SKA Pathfinder (ASKAP). ASKAP was soon joined by a second precursor, the Murchison Widefield Array (MWA).

In the past decade, Australia was active in eight of the 11 international consortia designing SKA systems. In 2019 Australia was one of seven countries that signed the treaty establishing the SKA Observatory as an intergovernmental organisation.

The MRO will host the SKA's array of low-frequency antennas, SKA-Low. Construction is expected to start in 2021. This prospect, plus the building of the SKA precursor telescopes at the MRO, has expanded the radio astronomy community in Western Australia. The Perth-based International Centre for Radio Astronomy Research (ICRAR) was created in 2009, drawing together researchers from the University of Western Australia and Curtin University: it is now the largest radio astronomy group in the country. The ATNF also has a growing presence in Western Australia.

4.2 The Australian SKA Pathfinder

The Australian SKA Pathfinder (ASKAP) is a radio interferometer: a set of thirty-six 12-m dishes (Fig. 8a) [52]. It is designed as a fast, mid-frequency survey instrument and its first years of full operation will be spent on large survey projects aimed at understanding the formation and evolution of galaxies, cosmic magnetic fields, the interstellar medium,

Figure 8a. Antennas of the Australian SKA Pathfinder (ASKAP) at CSIRO's Murchison Radio-astronomy Observatory (MRO) in Western Australia (credit: CSIRO).

Figure 8b. A phased-array feed on an the ASKAP antenna (credit: CSIRO).

and transient radio phenomena. These projects, being carried out by large international teams, will exploit ASKAP's key characteristics: sensitivity, wide bandwidth, and wide field of view. Pilot observations have begun.

ASKAP's key technology is its phased-array feeds (PAFs), designed and built by CSIRO (Fig. 8b). These replace the feedhorns traditionally used in radio telescopes. A PAF is a close-packed array of simple receptors, located in the antenna's focal plane. The voltages from the receptors are combined to form multiple beams on the sky pointing in different directions. This is computationally intensive, but allows the direction of the beams to be controlled by varying the weighting of different PAF elements, so beams can be shaped to meet a project's specific needs. PAFs also give a large instantaneous field of view (for ASKAP, 30 square degrees) and a wide bandwidth (for ASKAP, currently 288 MHz).

In addition to the usual two axes of rotation, altitude and azimuth, ASKAP has a third one that allows the PAF to be kept in the same orientation with respect to the sky while the telescope tracks. This "roll" axis suppresses imaging artefacts and makes image processing less complex than it would be if the PAF's orientation changed. It also allows polarisation measurements to be calibrated extremely well.

ASKAP's 36 antennas generate up to 9 TB of data an hour. The data are processed and the data products stored at the Pawsey Supercomputing Centre (named after Joseph Pawsey, founder of Australian radio astronomy) in Perth, Western Australia.

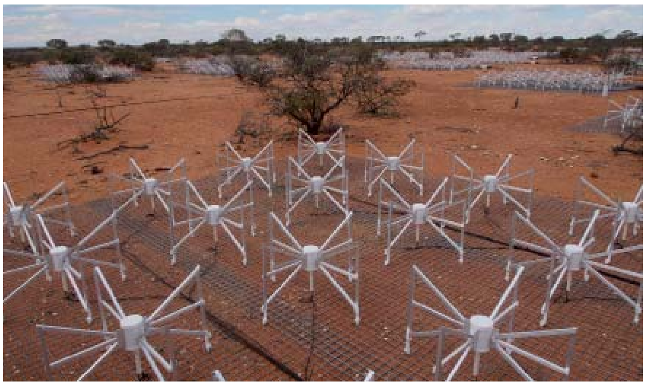

Figure 9a. The Murchison Widefield Array (MWA) (credit: ICRAR/Curtin University).

Figure 9b. Installing antennas of the Aperture Array Verification System, a testbed for SKA-Low, at the MWA site (credit: ICRAR/Curtin University).

ASKAP's power is illustrated by its work on fast radio bursts (FRBs) – cosmic radio bursts of unknown origin lasting for just milliseconds, first found with the Parkes telescope. From January 2017 ASKAP was used to search for FRBs in a unique "fly's eye" observing mode. Within a year it detected 20, almost doubling the number known at the time. In 2018 ASKAP became the first telescope to measure accurate positions for non-repeating FRBs and so determine their host galaxies.

ASKAP has recently made a rapid radio-continuum survey of the sky from the south celestial pole to a declination of +40°, over frequencies from 744 MHz to 1032 MHz. Although intended mainly for calibrating future deep surveys, the survey images are already significantly deeper and of higher angular resolution than those of the existing radio surveys at this frequency, and include full polarisation information.

4.3 The Murchison Widefield Array

The Murchison Widefield Array (MWA) at the MRO consists of 4096 dual-polarisation dipole antennas optimized for frequencies from 70 MHz to 300 MHz [53]. The dipoles are arranged in 4 x 4 arrays called tiles (Fig. 9a). Most tiles lie in a core region about 1.5 km across while some sit up to 6 km away to give higher angular resolution. The MWA was completed in its initial form of 128 tiles in 2013 then expanded to 256 tiles in 2016. The telescope was developed by an international collaboration and is managed (as a national facility) by the Curtin Institute of Radio Astronomy at Curtin University in Perth, Western Australia.

Like ASKAP, the MWA is an official SKA precursor – a demonstrator for SKA science and technology, located at one of the SKA's two sites. The MRO will host SKA-Low, the SKA's low-frequency antennas. The MWA has already contributed to SKA-Low's operations by measuring the local radio-frequency interference and ionospheric conditions, and helping to characterize the Aperture Array Verification System (AAVS), the testbed for SKA-Low antennas (Fig. 9b).

To date much of the MWA's observing time was used for projects – on systematics, foreground sources, and calibration procedures – to support the detection of the redshifted 21-cm hydrogen signal from the epoch of reionisation, when the first stars formed and ionized most of the universe's hydrogen gas. To characterize foregrounds, the MWA has carried out the GaLactic and Extragalactic All-sky Murchison Widefield Array (GLEAM) survey, covering declinations south of +30° and Galactic latitudes outside 10° of the Galactic plane. The GLEAM catalogue [54] contains more than 307,000 radio sources, each with flux density measurements at 20 frequencies within 72-231 MHz.

The MWA had an immediate impact even during commissioning observations in 2013. While using the telescope for her Honours thesis, a University of Sydney student, Shyeh Tjing (Cleo) Loi, found large, tubular ducts of plasma in the ionosphere aligned with the Earth's magnetic field. Loi used the MWA to make the first detailed images of these ducts, deduced their heights and sizes, and imaged their motion in real time [55]. This work gained worldwide attention and showed the MWA to be a superb instrument for studying the ionosphere.

5. Conclusion

Seven decades ago, a relatively small and isolated group of Australian researchers became pioneers of radio astronomy. Today, institutions such as the ATNF, the Universities of Sydney, Tasmania and Western Australia, Curtin University and Swinburne University of Technology have sizeable groups of radio astronomers and the community is actively involved in international projects. With the advent of global facilities such as the SKA, and the inevitable decrease in funding for smaller facilities, the Australian radio-astronomy community will need to deepen this international engagement. Its continuing success will rest on being involved in Australian-hosted international facilities, doing multiwavelength science, and maintaining a world-class ability to design and build instruments.

6. Acknowledgments

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100 Years Of Radio Science Acivities In Belgium

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1. Introduction

Belgium has a very special position in the history and the development of radio science by virtue of the early initiatives and support of both King Leopold II (1835-1909) and then King Albert I (1875-1934). Radio science quickly developed as both a scholarly research topic and as the provider of a practical technique to communicate with, and manage, the Belgium Congo colony in Africa. This, in turn, led to the initiation of what was to become the International Union of Radio Science (URSI), with the Secretariat located in Belgium. This article describes many of those early national and international initiatives and then traces the progress and development of Belgian URSI through to today.

The events that brought URSI into existence in Belgium are summarized in Section 1, with two subsections, one for the events in Belgium before URSI was founded and the other addressing the formal founding of URSI. Section 2 is devoted to a description of Belgian activities in radio science, largely in chronological order. The figures and references are, by necessity, limited.

2. The Founding of URSI in Belgium

2.1 Wireless in Belgium at the Start of the 20th Century

Prior to the 20th century many of the foundations of radio science were in place. Lodge had demonstrated radiation from waveguides, Rayleigh had published solutions for Maxwell’s equations describing the modes that can propagate in rectangular and circular waveguides, Bose had developed a semiconductor detector at 60 GHz, and the future was ready for Hertzian radio links with paraboloidal antennas.

Belgium took its own important part in the development of radio at the start of the 20th century [1-7]. In 1884, Leopold II, King of the Belgians, purchased an enormous territory in Central Africa and became responsible for its future. This territory became the Belgian Congo in October 1908, Zaïre after its independence in 1960 and is now the République Démocratique du Congo.

Before the introduction of radio, communications between Belgium and the Congo, and within the Congo, were unreliable (because of the very short lifetime of telegraph cables in equatorial regions and the necessity of using foreign submarine cables). Consequently, in 1907 Leopold II invited the Marconi Company to demonstrate the capabilities of wireless telegraphy by installing equipment in the grounds of the Royal Castle in Laeken, near Brussels and also at a site near the end of river Congo. Unfortunately, these first results were poor because of the heavy attenuation and the prohibitive levels of atmospheric noise.

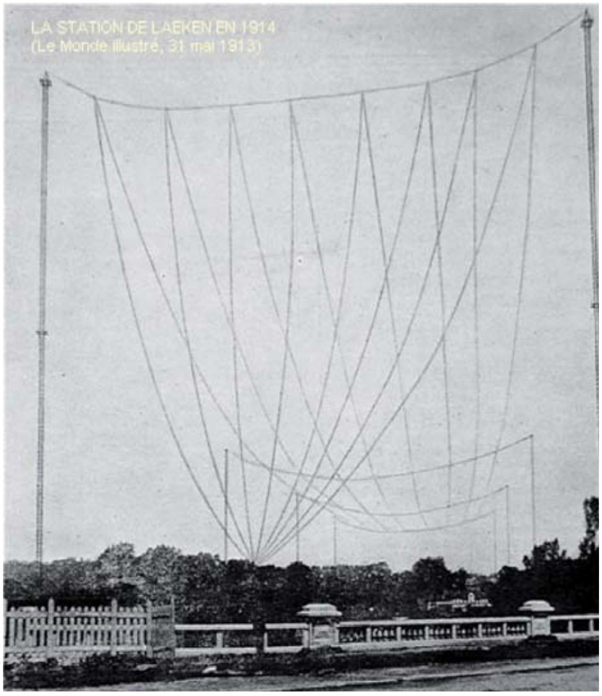

Figure 1. The station in Laeken 1914 (Le Monde Illustré, 31 May 1913) [4].

Technological advances however led the new King, Albert I, to replace wired telegraphy by wireless telegraphy to and within the Congo in 1910. This he did despite government opposition, bearing the cost himself. It is astonishing to observe that only two years later, in 1912 twelve 5kW transmitting and receiving stations had been designed and manufactured in Belgium, transported by ship from Belgium to Congo and installed along the river Congo at intervals of 250 to 500 km from Boma to Lubumbashi [1]. These provided reliable radiotelegraphy links over distances of more than 2,500 km. The final installation of this network was supervised by A. Wibier, a lieutenant in the Belgian army.

In all of this the King was supported by R. Goldschmidt and M. Philippson, who had themselves experimented with wireless telephony between the Court Hall in Brussels and receivers borne by balloons 50 to 100 km away, near the cities of Namur and Liège [4].

Goldschmidt was a banker, but was interested in physics and engineering and had a number of inventions of his own. This multi-talented man was able to supervise the engineering and was also able to supervise the logistics of transferring the equipment (motors, alternators, 100 m masts for the antennas etc) from Belgium to the Congo and make them operational. Probably unusually for the time, he also trusted African staff as both operators and as equipment engineers.

In Belgium, Goldschmidt founded a school of Wireless Telegraphy in the park of Laeken Castle with the purpose of developing equipment and for the education and training of the staff. It was here that he improved the 300 kW transmitter used on the Belgium-Congo path in 1913. At the time, this was one of the most powerful stations in the world and on 8 October 1913, Belgian newspapers announced that communication had been established with the city of Boma in Congo, at a distance of 6,300 km. To support this Goldschmidt installed in Laeken a 600 m long antenna, supported by four pairs of pylons, with one 120 m high and the other three 65 m high; this antenna had a resonant wavelength of 3,500 m or 85.7 kHz (Figure 1).

While King Albert I had a strong interest in science and engineering, his wife Queen Elizabeth was a distinguished violinist. She also had interest in technology and conversations between her husband Albert and Goldschmidt stimulated her interest in radio telegraphy. In 1913, the Queen decided that she wished to receive radio telegrams and to facilitate this Goldschmidt's colleague, Braillard, who had a significant role in the technology of the Belgium Congo nework, developed a small crystal set for the Queen using a galena crystal as a point-contact diode detector. Braillard also recorded a course for learning the Morse code which the Queen rapidly mastered [4].

The support from the Queen resulted in the first ever broadcast concert which took place from Laeken Castle, Brussels on 28 March 1914, after tests in 1913. The programme was the following (originally in French [4]); note that item 7 is missing:

Figure 2. The second meeting of the Commission Provisoire Internationale de Télégraphie Sans Fil Scientifique, Brussels, 6–8 April 1914. In the picture from left to right: Marchant (UK), Father Wulf (the Netherlands), Drumaux (Belgium), Ferrié (France), Duddell (UK, President), Schmidt (Germany), Abraham (France), Wien (Germany), Eccles (UK), Father Lucas (Belgium), Benndorf (Austria), Lutze (Belgium), Vollmer (Germany), Goldschmidt (Belgium) and Braillard (Belgium) [3].

1. Recondita armonia, air de Cavaradossi dans Tosca, Puccini (ténor)
2. La donna è mobile, air du duc, dans Rigoletto, G. Verdi (ténor)
3. Puppchen du bist mein Augenstern, dans Puppchen, J. Gilbert, xylophone, solo (phono)
4. Le Cor, A. Flégier (baryton)
5. Vision fugitive, air de Hérode, dans Hérodiade, J. Massenet (baryton)
6. Enchantement du Vendredi-Saint dans Parsifal, R. Wagner (phono)
8. Où peut-on être mieux qu'au sein de sa famille, Grétry (orchestre)
9. Fantaisie n° 3 pour piano, P. Benoit
10. La Brabançonne, F. Van Campenhout (orchestre)
11. La Marseillaise (orchestre).

In 1912, the school in Laeken was extremely active and very well equipped, with A. Wibier, now a Captain in the Belgian Army, as Director General. The school had an active staff of about ~100 persons coming from Belgian universities, industry, and administration. Training was theoretical, technical, and practical. The students had to go through the machine-shop, laboratory, and the design office. Proficiency in Morse code was of course required with practice extending into the night [4].

By this time a number of countries were exploring radio telegraphy and in Paris in October 1912 at the Conférence Internationale de l'Heure, K Schmidt and R. Goldschmidt proposed the creation an international body, to organize research on electromagnetic wave propagation, to make measurements on radiotelegraphy and to investigate more generally the problems these raised. This proposal was very well received by European experts especially when they heard that Goldschmidt was offering the stations and laboratories in Laeken as well as a sum of 50,000 Belgian Francs (BF) (~€ 400,000 in 2020).

On 13 October 1913, a meeting was held in Brussels where the Commission Provisoire Internationale de Télégraphie Scientifique Sans Fil was founded. There were nine participants representing seven countries: Austria, Belgium, England,

NUMÉRO 1 MAI-JUIN 1914

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T. S. F. S.

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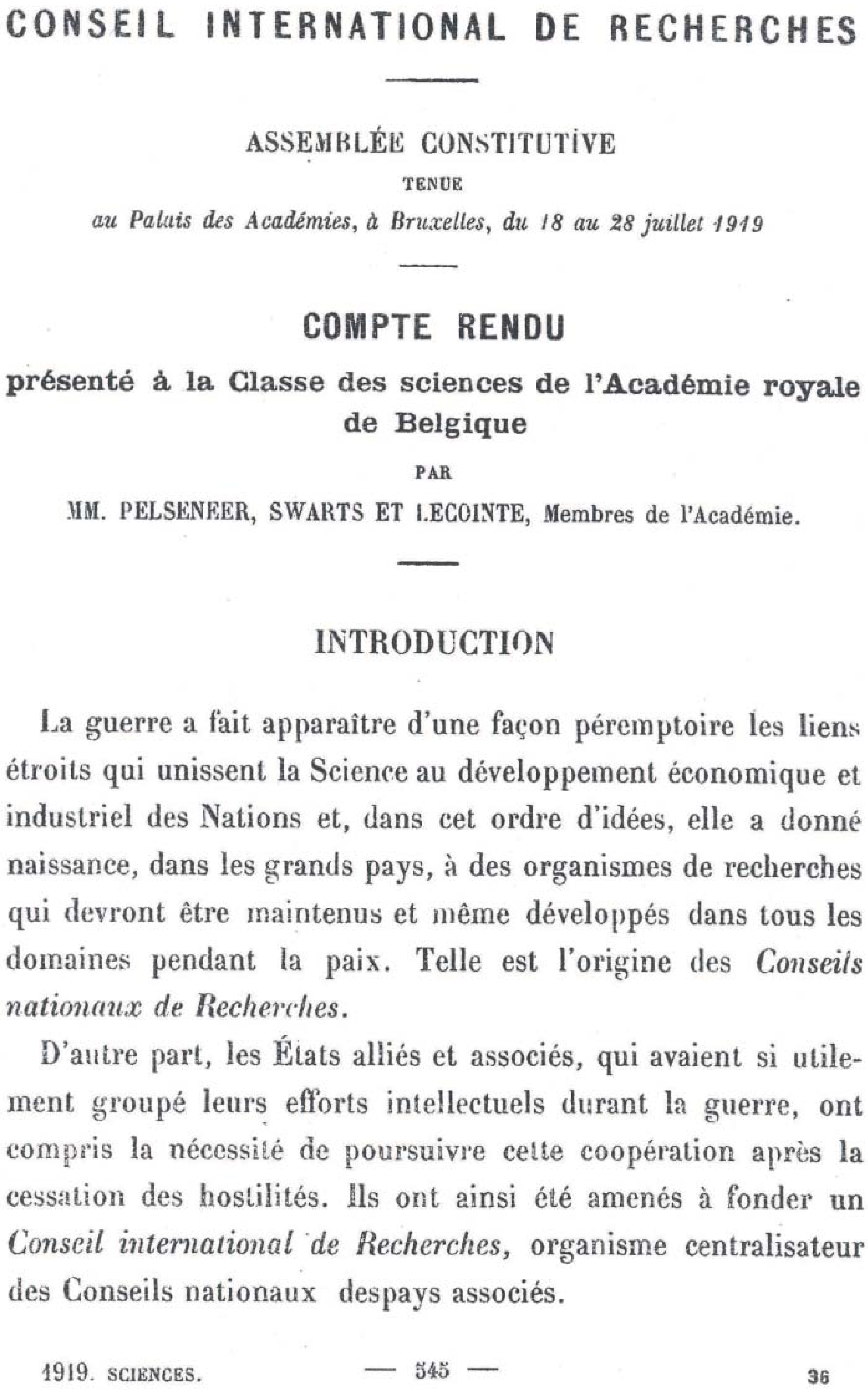
Figure 3. The single issue of the Bulletin de la Commission Internationale de Télégraphie Sans Fil T.S.F.S. [1].



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TENUE
au Palais des Académies, à Bruxelles, du 18 au 28 juillet 1919

COMPTE RENDU

présenté à la Classe des sciences de l'Académie royale de Belgique

PAR
MM. PELSENEER, SWARTS ET LECOINTE, Membres de l'Académie.

INTRODUCTION

La guerre a fait apparaître d'une façon péremptoire les liens étroits qui unissent la Science au développement économique et industriel des Nations et, dans cet ordre d'idées, elle a donné naissance, dans les grands pays, à des organismes de recherches qui devront être maintenus et même développés dans tous les domaines pendant la paix. Telle est l'origine des *Conseils nationaux de Recherches*.

D'autre part, les États alliés et associés, qui avaient si utilement groupé leurs efforts intellectuels durant la guerre, ont compris la nécessité de poursuivre cette coopération après la cessation des hostilités. Ils ont ainsi été amenés à fonder un *Conseil international de Recherches*, organisme centralisateur des Conseils nationaux despays associés.

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Figure 4. The proceedings of the Founding Meeting of the International Research Council [3].

France, Germany, Italy, and the Netherlands. They elected R. Goldschmidt as Secretary of the Commission and expressed the wish to have, as soon as possible, national committees so that an international Commission might be set up on the basis of representation of state members. A further meeting was held in Brussels in April 1914, with sixteen participants who set up an evaluation programme on the measurements made in Laeken (Figure 2). Worth noticing in the picture are General Ferrié and Goldschmidt who later became the first URSI President (1919-1932) and Secretary General (1919-1935), respectively.

By April 1914 three national committees from Belgium, England, and France had been founded, with the Austrian committee founded a little later in 1914. On this basis, the participants decided to drop "provisoire" from the title of the Commission and King Albert I accepted to become Président d'Honneur of the Commission. The minutes for this meeting were recorded as a bulletin of the Commission Internationale de T.S.F.S. (Figure 3). Unfortunately, the war started in August 1914 and the Laeken station was destroyed upon the order of the King before Belgium was invaded.

2.2 The Formal Founding of URSI

The experience of World War I generated a strong desire to abandon the disastrous nationalistic policies of the past in favour of international cooperation, in particular in the various fields of science [3]. This new attitude resulted in the creation of the Conseil International de Recherches that was initiated in July 1918 and founded in July 1919 in Brussels, under the honorary chairmanship of King Albert I. The Conseil is the predecessor of the International Council of Scientific Unions (ICSU) which merged in 2018 with the International Social Science Council (ISSC) to become the International Science Council (ISC).

The international cooperation proposed by Goldschmidt and Schmidt in 1912 was still relevant, but new ways of working had to be developed. A. Wibier - once again - who had become a member of the Belgian National Committee recalled that a Commission de Télégraphie Sans Fil Scientifique had existed since 1913, that it had investigated radio before the war and that it still had available a sum of 40,000 BF. He proposed to transform the Commission to an association linked with the Conseil International de Recherches.

The former Commission was, therefore, incorporated in the Conseil and reborn as Union Internationale de Radiotélégraphie Scientifique (URSI), one of the four scientific unions created at that time, alongside those of chemistry, astronomy and geophysics. Radio was actually rather restricted in scope compared to the other three and attempts were made over the years to absorb URSI into physics or another discipline. These attempts failed, partly because radio is a highly multidisciplinary science, which reaches into astronomy, geophysics, and now biology, and also because of the rapidly increasing importance of radio communications in the modern world. The proceedings of the founding meeting of the Research Council were published a few years later (Figure 4). From 1919 on, URSI gradually acquired its present form but that is the story of URSI and not of radio science activities in Belgium.

The Secretariat of URSI has been located in Belgium throughout its existence with a number of distinguished Belgian scientists serving as Secretary General, including: R.B. Goldschmidt (1919-1935), M. Philippson (1935-1939), C. Manneback (1939-1946), A. Dorsimont (1946-1948), E. Herbays (1948-1968), P. Hontoy (1978-1979), J. Van Bladel (1979-1993), P. Lagasse (1993-2017), and now P. Van Daele, (2017-).

3. Past and Present Scientific URSI Activities in Belgium

3.1 The Twentieth Century

Much of the early development of wireless in Belgium sought to support the Belgian Army during World War I. Wireless communication proved to be much more efficient than wired communication when the army was on the move. At the King's request, the military command designated A. Wibier as the Technical Director responsible for organizing the military wireless network. His duties included, among others, increasing the number of mobile radios, establishing radio links between the various military components and founding a central station for the Belgian military radio in Calais, France, which was operational by 1915. In 1916 the Belgian Army had eighty-seven operating radio sets and nine on reserve while at the end of the war in 1918 it had about six hundred radio transmitters-receivers serviced by fifteen hundred radio-telegraphists. Wibier combined this task with the supervision of radiotelegraphy in the Congo until 1920 [6].

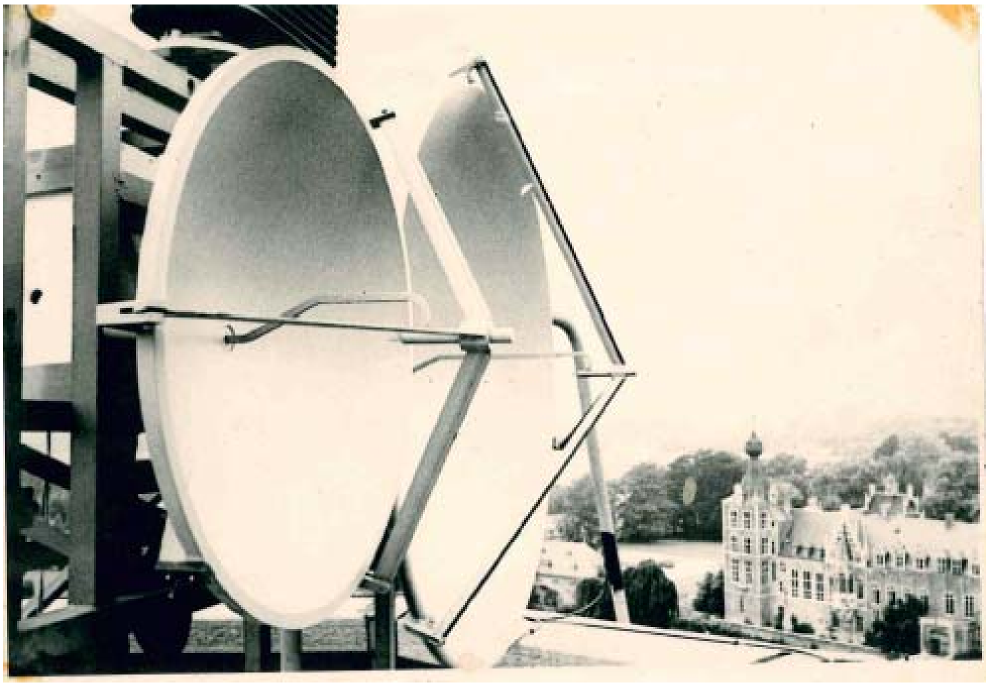


Figure 5. Two horizontal links at 11.6 and 35 GHz, respectively, Heverlee, Belgium, 1971 [9].

A laboratory for radio-electricity was founded in 1925 at the Université Libre de Bruxelles (ULB). It was here that R. Goldschmidt had been a student, obtaining a PhD in chemistry. From the 1930s, the radio-electricity laboratory was led by E. Divoire, during which time he founded the Revue HF: Belgium Journal on Electronics and Telecommunications. He also supervised the thesis on antennas of P. Baudoux, who later became a professor in electromagnetics. P. Hontoy succeeded E. Divoire as Director of the laboratory.

A similar laboratory was created around 1948 at the Royal Military School, now Royal Military Academy (RMA), by A. Dorsimont, another pioneer in radio transmission. His teaching incorporated information theory and cybernetics. In the 1950's, he even developed information theory about nerve signal transmission in the human body. His successor in 1966 was J. Charles, who had a strong interest in circuit theory and vacuum tubes electronics and who was President of the Belgian National Committee of URSI.

Back from the US with a PhD obtained at M.I.T., E. Gillon ran a booth at the Universal Exhibition, Brussels in 1935, offering radio experiments to the public. He became a senior professor of Electrical Engineering at the Université Catholique de Louvain (UCL) at the end of the 1940's.

Three national institutions lie in close proximity in Brussels: the Royal Observatory (ROB), the Royal Meteorological Institute (RMI) and the Royal Institute for Space Aeronomy (BISA). The first two were initiated in the 1820's by A. Quetelet, a Belgian statistician. The third was founded in the middle of the 20th century. All three have been involved in radio science activities. L. Bossy (RMI and UCL) was involved with ionospheric investigations for many years and was Chair of the Belgian URSI Committee at the time of the 60th anniversary of URSI in 1979.

The last part of the 20th Century saw two giants contributing to radio science in Belgium in their respective field: V. Belevitch, part-time professor at UCL, and J. Van Bladel, professor at Universiteit Gent (UG), respectively. They both published copiously and with significant books and papers, which won each of them an undisputed international reputation.

V. Belevitch was born in Finland and moved to Belgium at the age of four. After graduating at UCL, he joined the Bell Telephone Manufacturing Company (BTMC), Belgium. There, W. Cauer introduced him to circuit theory and filter design. Subsequently, he became Head of the Transmission Laboratory at BTMC, intensively cooperated in the design of an early electronic computer, became Director of the Belgian Computing Centre and then founded in 1963 the Laboratoire de Recherche MBLE (Philips).

Sponsored by C. Manneback, Belevitch wrote a doctoral dissertation at UCL in 1945, in which he introduced a revolutionary concept which he called the "repartition matrix" and which later became the scattering matrix, still used today by every microwave engineer. It is interesting to observe that the same concept was developed simultaneously but independently by H. Carlin at Brooklyn Polytechnic, US. Belevitch made significant contributions to the mathematical foundations of circuit theory, with contributions to filter theory, the theory of coupled lines, and non-linear circuit theory as well. He also made major contributions to the fields of information and system theory, the design of electronic computers, mathematics and linguistics. He received a number of honours for his scientific achievements. Among his numerous publications, there should be a special mention for his book on circuit theory [8].

After graduation in Belgium, at ULB, J. Van Bladel obtained a PhD in the US. He was then appointed professor at the University of Wisconsin-Madison, and Washington University, St. Louis. He remained in the US for more than 10 years returning to Belgium in 1964 to start the Laboratory of Electromagnetics and Acoustics at the University of Gent. The Laboratory was later renamed the Department of Information Technology but still includes research activities on electromagnetics.

J. Van Bladel was eminent in electromagnetic theory and applications, relating the latest theories and formulations to today's technologies. He served URSI for many years and has been an inspiration for many. He was interested in almost any question related to electromagnetic theory and in particular small-hole coupling. He was also interested in the relationship between relativity and engineering. He wrote a book on this subject where he showed that a correct solution for a number of engineering problems requires the use of relativistic principles. The book is accessible to space engineers, nuclear engineers and more generally, applied physicists. He received a number of honours for his scientific achievements. Among his numerous publications, there should be a special mention for his book on electromagnetic fields [9].

After two years in the US working on radio-astronomy, A. Vander Vorst founded the Microwave Laboratory (MWL) at UCL in 1966, from which a number of doctoral theses were developed by F. Gardiol, R. Govaerts, A. Laloux, C. Eugène, G. Brussaard, D. Vanhoenacker, I. Huynen, J.-P. Raskin, J. Teng, B. Stockbroeckx, C. Oestges, Dirk Adang, and others. The research activities first investigated miscellaneous propagating structures including loaded waveguides in one, two, and three dimensions; strip lines, microstrips and fin lines; p-i-n transmission lines and opto-effects at frequencies up to 100 GHz [10].

After 1970, research at MWL moved to tropospheric propagation at frequencies up to 300 GHz [11]. Studies included two horizontal links at 11.6 and 35 GHz from 1970, (Figure 5); Belgian participation in the ESA Orbital Test Satellite (OTS); a related transmitting-receiving television station and two receiving stations; Belgian participation (with D. Vanhoenacker-Janvier) in the ESA Olympus experiment and the related design of two receiving stations operating at 12.5, 20, and 30 GHz; fast measurements every 34 ms investigating scintillation effects [12]; site-shielding, in particular by a knife-edge obstacle with measurements up to 94 GHz; bit-error rate prediction of tropospheric communications links and linearly tapered slot antennas including the Vivaldi antenna.

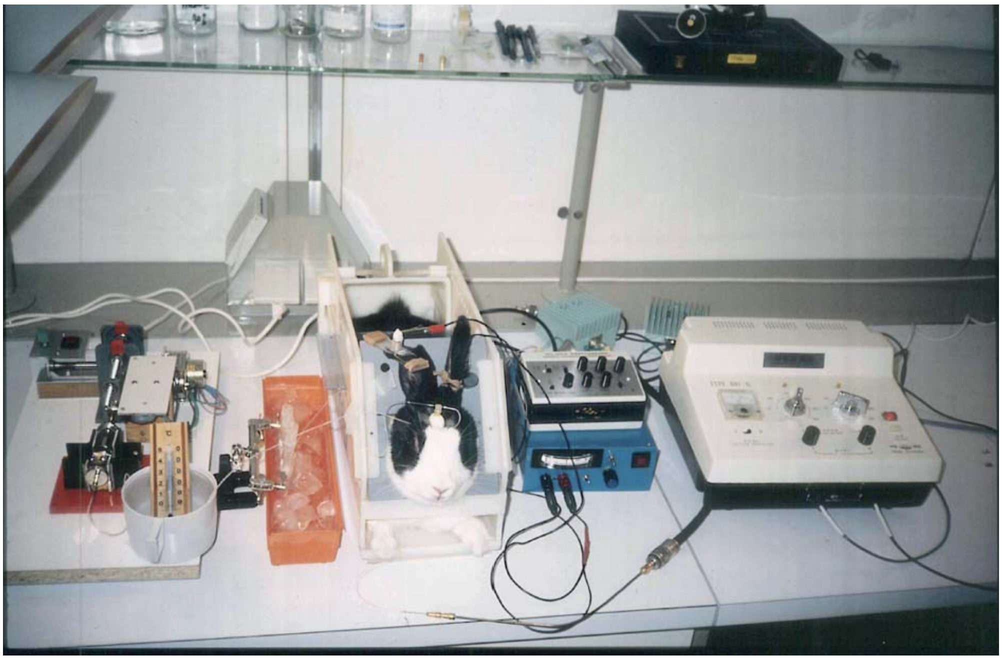


Figure 6. Measuring the pain threshold on a rabbit as a function of antalgic microwave acupuncture [11].

Figure 7. Well-being for a happy rat… [12].

Microwave biological effects were investigated extensively at MWL from 1978 onward. A patented and commercialized system for protecting open-air surgeries from bacteria was developed between 1978 and 1980 using microwave heating to kill the bacteria. The effects of RF on animals were investigated on two occasions. Research on rabbits occurred between 1987 and 1994 by J. Teng who developed a microwave acupuncture method to stimulate the nervous system, then a pain measurement method to measure its reduction using acupuncture. The composition of the cervical liquid near the center of pain was observed to vary. A microwave micro-antenna was also inserted in close proximity to the spinal cord to check if this could induce a non-thermal effect, but with negative results (Figure 6) [13]. D Adang carried out research on rats between the years 2000 and 2009 D (Figure 7). Three groups of 31 rats plus a further control group of 31 rats, were exposed to microwaves for 21 months. Fifteen blood parameters were measured six times on the 124 rats. A variety of results were observed. These included modifications of the blood composition as well increased mortality in the exposed rats [14]. Additional public concern and questions about microwave hazards led to a book on RF/Microwave interactions with biological tissues in 2006 [15].

P. Delogne was appointed at UCL in 1971. He first joined the activities of the Microwave Laboratory in tropospheric propagation [16] while further developing his expertise in regard to propagation in tunnels and underground radio systems, including subways [17]. He showed that the leaky feeder radiation at higher frequencies was due to the random diffraction on the feeder leakage fields by the wall irregularities.

With his two main collaborators, B. Macq and L. Vandendorpe, Delogne then moved into the general area of digital signal processing for data compression, and especially image compression in the context of digital television. In 1988, they filed for a patent for a method in which data related to the image are read in successive blocks, then subjected to orthogonal transformation. B. Macq developed his doctoral thesis on perceptual coding for digital TV with P. Delogne as the supervisor. They developed picture coding for videotelephony, television and high-definition television [18]. In

Figure 8. A variety of target vehicles [20].

Figure 9. The Interpoint 55 Braille Printer.

1993, signal processing activities started for wireless communications systems, in particular with industrial cooperation in support of Terrestrial Trunked Radio (TETRA). This was followed by research activities (transmission and reception) related to Digital Subscriber Line (DSL) and in particular Very High Bitrate Digital Subscriber Line (VDSL) transmission systems (high rate on wire pairs) [19]. Image processing is still investigated at UCL.

3.2 The Twenty-First Century

In April 2004, E. Schweicher (RMA) organized, together with D. Bohan (US Army) and D. Clement (Germany), a cooperative demonstration (with thirteen participating nations) in Zutendaal, Belgium, and in Ft. Belvoir, US a demonstration showing that modern multispectral camouflage is effective in reducing the signature of targets (Figure 8) [20].

A very efficient system for printing Braille was developed by G. François, Katholieke Universiteit Leuven (KUL), with 2.000 pages printed per hour of both graphs and text (Figure 9). The printers were sold in a number of countries over most continents (2008) by the company, Interpoint.

Figure 10. The SPADE telescope at Humain observatory.

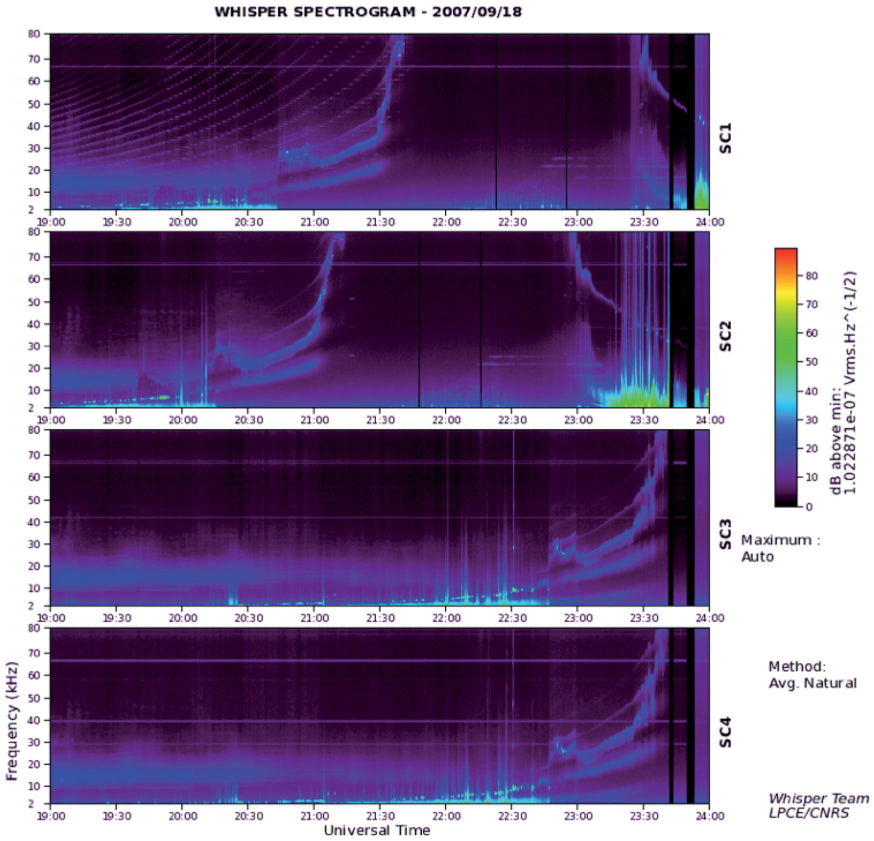


Figure 11. Time-frequency electric field spectrograms measured by WHISPER, Cluster spacecraft, September 2007; the plasmapause position corresponds to the sharp increase of the electron plasma frequency (blue line) directly related to the electron density [22].

ROB operate a radio astronomy station in Humain with a long history. A solar radio-interferometer was built there by Raymond Coutrez and Roger Gonze. Coutrez later became a professor at ULB and was President of the URSI National Committee after J. Charles, while Gonze became Head of the Solar Physics Department at ROB. Since 2008, with C. Marqué leading work on solar radio telescopes, there has been a revival of activities related to radio physics within the framework of the Solar Terrestrial Centre of Excellence. This is a common research effort of ROB, RMI, and BISA. ROB has developed solar radio instruments to monitor eruptions on the sun. One of these is part of an international network of observatories and the other two have been developed inhouse using software defined radio (SDR) techniques. They provide radio spectra of the sun between 45 MHz and 1500 MHz using a 6-m parabolic telescope. ROB has also developed an SDR based solar flux monitoring system (SAFIRE) operating between 1 and 5 GHz using a refurbished 4-m telescope dish from a decommissioned solar interferometer and also a small phased array spectrograph (SPADE) in the band 20-80 MHz. The latter consists of eight antennas, that will monitor shock waves in the solar corona (Figure 10).

Belgium has a long experience in radio observations for space weather applications, especially concerning the effects of the ionosphere. BISA has expertise in the plasmasphere, the extension of the ionosphere at low and middle latitudes. Pioneer studies of J. Lemaire and K. Gringauz [21] were continued with the development of a three-dimensional dynamic model of the plasmasphere-ionosphere system (V. Pierrard, BISA and UCL) (Figure 11) [22]. Plasmasphere observations with radio waves are mainly based on the instrument WHISPER on board the four Cluster satellites that measure the in-situ plasma frequency in the range 2-80 kHz [23]. Very low frequency (VLF) antennas have been installed by BISA in Antarctica at the Belgian Princess Elisabeth station and in Belgium at Humain.

Natural whistler-mode radio waves were measured at the Belgian Princess Elizabeth station in Antarctica between 2015-2016 using crossed magnetic coil antennas (F. Darrouzet, BISA) (Figure 12). Whistler signals occur at frequencies between 5 and 20 kHz depending on the magnetic latitude of the observations and are the dispersive signals from impulsive lightnings strikes whose energy has propagated along plasmaspheric geomagnetic field lines. The signals can be used to yield the electron density. Chorus waves were also detected, in the same frequency range. The system in Antarctica as well as one in Humain are part of the worldwide network, Automatic Whistler Detector and Analyzer (AWDA) [24]. The aim is to analyze such data in almost real-time.

Figure 12. The installation of an instrument measuring whistler waves at the Princess Elisabeth station in Antarctica [24].

Empirical relations between the plasmapause equatorial distance and a variety of geomagnetic and solar wind indices have been deduced. Different waves circulate inside and outside the plasmasphere and also along the plasmapause, so a model of the plasmasphere is useful to determine its influence on radiation belts dynamics. A new detector called the Energetic Particle Telescope was developed at BISA and launched on the PROBA-V satellite in 2013. These achievements complement other Belgian studies concerning radio waves in space plasmas, for example ionospheric observations made at RMI, solar and GPS observations made at ROB and Galileo developments at the *Université de Liège* (UL).

Textile antennas seek to provide wireless communication links between on-body nodes and a base station. Starting in the 2000's, the Electromagnetics group (EG) at UG has devoted extensive research efforts to wearable antenna design, resulting in a wide variety of robust textile antennas that exhibit efficient radiation characteristics under many adverse conditions such as antenna bending or moisture [25-26]. This is particularly important for low-weight, flexible, Smart Fabric and Interactive Textile (SFIT) electronic systems used in applications, such as space, aeronautical and terrestrial communications and include end-users such as rescue-workers, the military, and health professionals (Figure 13).

Specific innovations introduced by EG include: avoiding fragile interconnections and long transmission lines between antenna and transceiver by directly integrating the latter directly underneath the antenna; embedding the connectors and coating the antenna and ground planes using water-repellent layers that make the antenna washable; and avoiding stress in the antenna by making the antenna and interconnects stretchable. Another important market driven advance consists of improving their robustness and expanding their functionality by converting them into wireless textile nodes. High robustness is achieved by minimizing the lengths of all wired interconnections.

Fading and shadowing can dramatically reduce signal-to-noise ratio in mobile communications. In recent years, EG has extensively investigated the off-body communication channel in the 2.45 GHz industrial, scientific, and medical band

Figure 13. Wearable antennas for communication (left), localization (middle) and sensing (right).

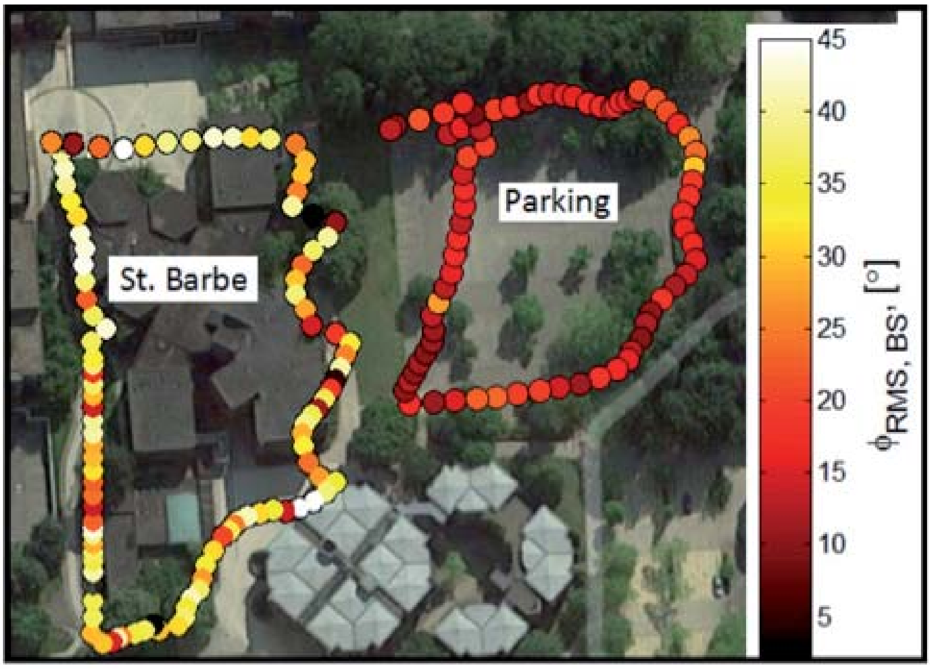


Figure 14. Base station azimuth-spread for two routes followed by a mobile terminal, average value of delay-spread (ns) [31].

between a command post and multiple/dual-polarized textile antennas integrated into the suit of a firefighter in an indoor environment. Spatial receive diversity gain, combined spatial/polarization receive diversity, and combined receive/transmit spatial/receive diversity gain were all characterized by transmitting actual data sequences by means of a Multiple Input/ Multiple Output (MIMO) wireless test bed [27].

In the 2000's the Radio Channel Team (RCT), led by C. Oestges, at UCL characterized space-time random fields for broadband wireless communication systems. Wireless channel characterization expertise has been developed for modelling new communication systems, e.g., for beyond 3G and 4G systems, as well as wireless sensor networks with a strong focus on experiments made possible by purchasing in 2009 a multi-antenna broadband channel sounder. It led to the investigation of the multiple dimensions of wireless channels: time, frequency, space, and polarization [28]. RCT explored various aspects of MIMO channels, especially dual-polarized MIMO as well as a better understanding of MIMO at large, dealing in particular with radio time-reversal [29]. They also developed a ray-tracing tool [30], including dense multipath components, in combination with alternative numerical methods for modelling complex structures.

A model was developed for vehicle-to-vehicle channels as well as for the tropospheric depolarisation in the 20-50 GHz band for both satellite systems and high-altitude platforms. Regarding body-centric channels, both empirical and analytical (electromagnetic) models were developed in the contexts of MIMO-Ultra-Wideband (UWB) and of dynamic propagation as well as a prototype for a wireless Electroencephalogram (EEG) using 20 nodes, which was validated by medical practitioners. Large-scale parameters, such as shadow fading, delay and angular spreads, have been evaluated in urban microcells at 3.8 GHz in the city of Louvain-la-Neuve, Belgium (Figure 14) [31].

The Antenna and Radiation Group (ARG), KUL, led by G. Vandenbosch, developed several innovative concepts. Due to the increasing demand for multi-functional, multi-band, consumer-centric wireless technology, textile antennas have been receiving a growing attention. In wearable applications, flat surfaces cannot be guaranteed (Figure 15). Thus, an important antenna requirement is its ability to work with good robustness against environmental, positional and location changes when being worn [32]. ARG developed the first fully fabric based slotted Planar Inverted-F Antenna (PIFA). It also developed the first microstrip technology based UWB wearable antenna, which is effectively shielded from the human body by the full ground, greatly reducing the degrading effect of the body. Several multifunctional textile antennas based on artificial materials have also been developed [33].

ARG has also been active in the field of beam steered antenna architectures. Whereas they started with the development of the first system based on analogue baseband phase shifters, nowadays they aim at much more flexible digital systems [34]. Since beam steering is one of the new key technologies in 5G, this research is very timely. It has led to cooperation with the Technische Universiteit Eindhoven, in the Netherlands, and Chalmers University, Sweden, within the so-called SILIKA project (http://silika-project.eu/).

Figure 15. The MyHeart instrumented shirt [32].

ARG is also active in the application of Computational Electromagnetics (CEM) in the field of nanostructures. CEM is the technology modeling the interaction of electromagnetic (EM) waves with physical objects and their surroundings. This technology has been demonstrated to be a key element in the design of modern antennas, and waveguiding/shaping devices, etc. It has played a pivotal role in forging modern communication systems, and, therefore, was, is and will greatly impact peoples' daily life. However, despite all of these successes, very recent experiments on the interaction of light (EM waves at optical frequencies) with deep-nanoscale metallic structures suggest the need of a paradigm shift in the classic CEM algorithms, where a more refined material model is required. As a very first step in this direction, ARG combine the dynamics of classical EM waves with the semi-classical hydrodynamic motion of free electrons in metals. The problem is formulated in the framework of boundary integral equations and subsequently solved by the method of moments algorithm. This research seeks to bridge the computational gap between the classical macroscopic world and the quantum mechanical microscopic world and provide an essential tool for chemists and physicists to understand new physics in the nanoscale world [35].

The WAVES group at UG, led by W. Joseph and L. Martens, Department of Information Technology, assessed the in-situ exposure of the general public to fields from Long Term Evolution (LTE) cellular base stations. They developed procedures for measuring in the vicinity of Global System for Mobile Communications (GSM), of Universal Mobile

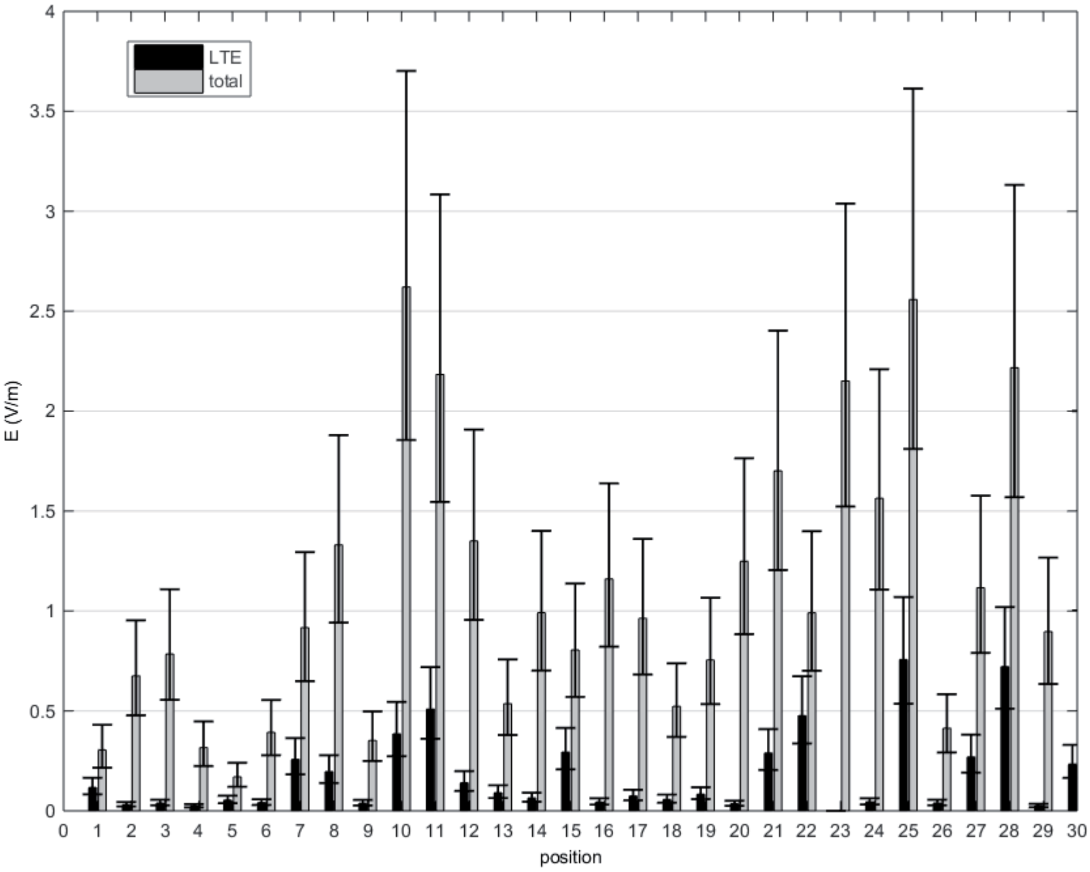
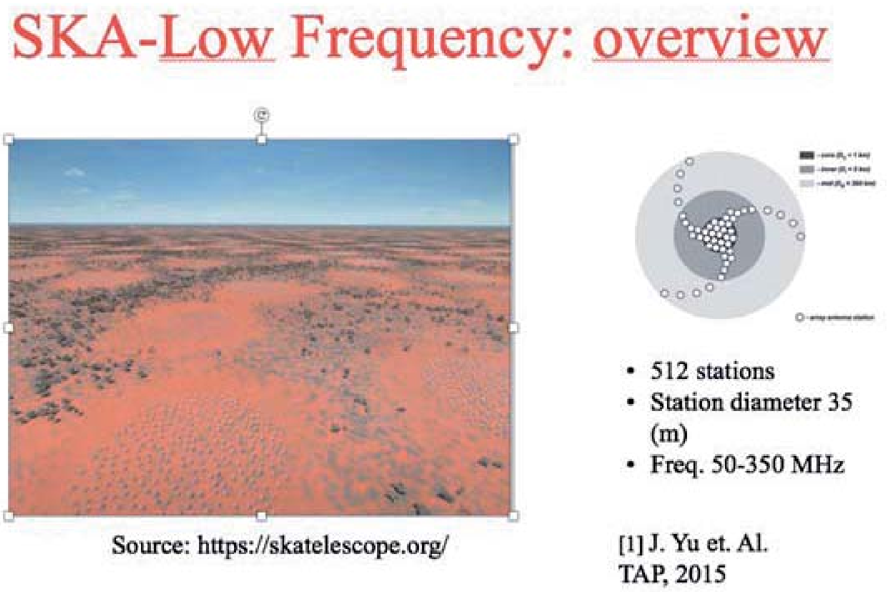


Figure 16. The electric-field strength (V/m) in Stockholm for LTE and the different RF signals for the different locations



SKA-Low Frequency: overview

- 512 stations
- Station diameter 35 (m)
- Freq. 50-350 MHz

Source: https://skatelescope.org/

[1] J. Yu et. Al.
TAP, 2015

Figure 17. The low-frequency implementation of the Square Kilometre Array (SKA) made of 512 stations, comprising each 256 antennas [39].

Telecommunications System (UMTS), and Worldwide Interoperability for Microwave Access (WiMAX) base stations, respectively [36-38]. A standard exists for measuring field strength related to human exposure near base stations but assessment of exposure to electromagnetic fields of emerging wireless systems such as LTE was missing, which stimulated the activity of the group. They investigated a commercial LTE network deployed in Stockholm, with channels at 2660 MHz and a bandwidth of 10 MHz and at 2630 MHz with a bandwidth of 20 MHz, respectively. Field measurements were performed in the band 80 MHz - 6 GHz with a narrowband spectrum analyser at twenty-seven outdoor and three indoor locations, randomly spread over the city.

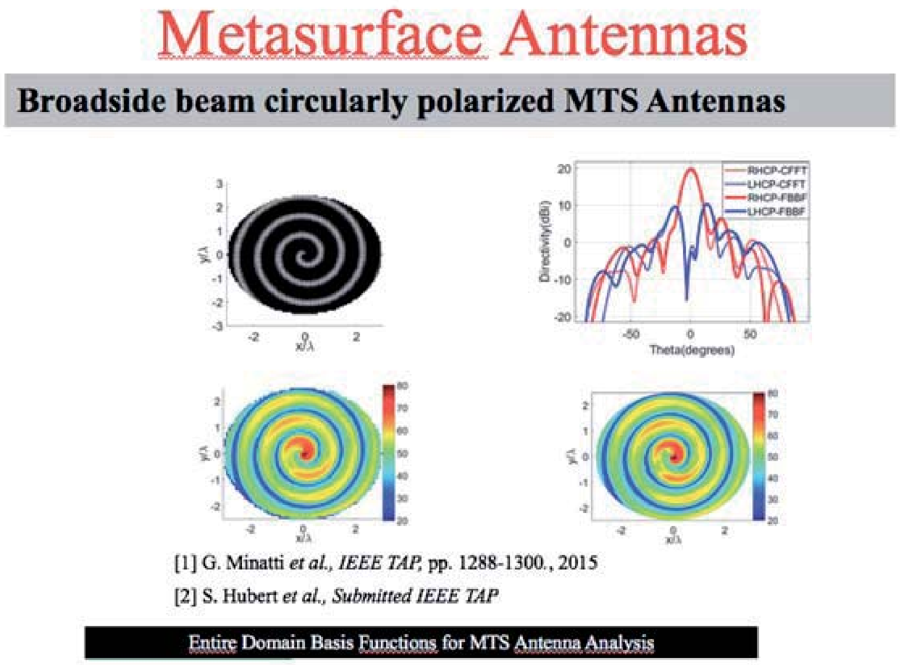
Current wireless RF sources mainly operate in the frequency range of 80 MHz up to 6 GHz. The narrowband measurements were performed during the daytime on weekdays. Exposure to amplitude modulation signals below 10 MHz was not considered as this concerns different biological effects. Considering that all the parameters, and certainly not the sweep time, are almost never discussed in literature, the team at UG showed that it is important to specify these and obtained the following settings that they considered as optimal to perform exposure assessment of LTE: root-mean-square detector, resolution bandwidth 1 MHz, sweep time 20 s, and a frequency span of 50 MHz.

Among other information, Figure 16 lists for all present RF signals, the variation of the electric-field strength (V/m) for the 30 random locations. Total exposures at all locations are between 0.2 and 2.6 V/m, LTE exposure levels up to 0.8 V/m were measured, and the average contribution of the LTE signal to the total RF exposure equals 4 %. The group concluded that RF exposure in Stockholm is dominated by GSM and UMTS-HSPA. LTE is present everywhere in the city but the contribution to the total exposure is limited to about 4 % on average.

An Antenna Group (AG), led by C. Craeye, started its activities at UCL around 2002, designing antennas and arrays for applications in radio-astronomy, radar, medical imaging, radio frequency identification (RFID), sensing and tracking, ultra-wideband positioning and communications, together with localisation of people and cell-phones in disaster situations like avalanches, fire and earthquake conditions. Fast techniques have also been developed for the design of large arrays devoted to space-based synthetic aperture radar (SAR).

The research activities of AG have focused on antenna arrays and metamaterials, both from the numerical and design perspective, in particular in support of the Square Kilometer Array (SKA) [39]. This is an international radio-telescope with a sensitivity one to two orders of magnitude better than that of most currently existing telescopes. Its low-frequency 50-350 MHz implementation (led by University of Cambridge, UK) will consist of 512 stations, each comprising 256 antennas (Figure 17).

AG have also developed metasurface (MTS) antennas (Figure 18). These correspond to a new type of radiating structure, in which a surface wave trapped in a dielectric slab is transformed into a leaky wave. This is done via space-domain modulation using surface patterning which is very dense compared to the wavelength. The group developed a quasi-direct and accurate technique for ascertaining the patterning, without the need for an optimizer, despite the fact



Metasurface Antennas

Broadside beam circularly polarized MTS Antennas

[1] G. Minatti *et al.*, *IEEE TAP*, pp. 1288-1300., 2015

[2] S. Hubert *et al.*, *Submitted IEEE TAP*

Entire Domain Basis Functions for MTS Antenna Analysis

Figure 18. Broadside beam circularly polarized metasurface (MTS) antennas [40].

that about 20,000 parameters had to be determined [40]. This was achieved by adapting integral-equation methods using expansions of the full-domain basis functions, such that the surface impedance offered by the patterning becomes the unknown instead of the currents.

4. Conclusions

Belgium played an important role in the early development of radio science and in the birth of URSI. This led to it becoming the home of URSI for this, its first 100-years. All but one of the General Secretaries has been a Belgian.

Through those 100-years Belgium has also provided technological and scientific leadership in the field of radio science. Many Belgian radio scientists have been identified above, including two giants in the field, V. Belevitch (circuit theory) and J. Van Bladel (electromagnetic fields). Belgian scientists and engineers have been active in all of the URSI Commissions and are destined to continue with innovative and transformative developments for the foreseeable future.

5. Acknowledgements

This paper could not have been written without contributions from: Christophe Craeye, Fabien Darrouzet, Guido François, Wout Joseph, Christophe Marqué, Claude Oestges, Viviane Pierrard, Hendrik Rogier, Emile Schweicher, Peter Van Daele, Jean-Louis Van Eck, Guy Vandenbosch and Claude Vloeberghs.

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URSI in Canada: A Retrospective

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1. Introduction

Canada has a long history of innovation and invention in telecommunications. Key contributions were made in the late 1800s and early 1900s by pioneers such as Alexander Graham Bell (telephone,1876, photophone, 1880), Reginald Fessenden (first wireless voice transmission, 1900), Guglielmo Marconi (first trans-Atlantic wireless transmission, 1901) and innovative companies such as Marconi Wireless Telegraph Company (first commercial radio broadcast, radio station XWA in Montreal, in 1919) and Rogers Vacuum Tube Company (first practical mains-powered radio using specially designed vacuum tubes, 1924). In 1903, the Canadian Army became the first military organization in the British Empire to organize a dedicated Signal Corps. During the First World War, wireless communications played a particularly critical role in naval operations.

The early history of radio communications in Canada (1900-1950), including both development and deployment of the technology is well documented by S. A. Babaian [1]. Commercial and regulatory activity in the Canadian telecommunications sector from the late 1800's to the late 1980's is well described by R. E. Babe [2]. The visual, material and spatial presence of radio as it reshaped Canadian society in the second quarter of the twentieth century is well explained by M. Windover and A. F. MacLennan [3]. During the inter-war period, Canadian radio science activities were influenced heavily by the British model, which is described in detail by A. Anduaga [4] and W. E. K. Middleton [5].

During the Second World War, military needs and priorities led to dramatic growth in Canadian activity in the development of both radar and radiocommunication equipment and the study of radio wave propagation, as described in detail by W. E. K. Middleton [6], D. Avery [7], and D. Zimmerman [8]. The great successes of the war years were based, in large part, on international cooperation and it seemed certain that post-war success would be equally dependent on such cooperation. Joining the International Union of Radio Science (URSI) became a natural next step for Canada as the federal government took steps to build upon this newly developed national capacity.

Although Canadian efforts during the war years was well documented, the equally fascinating story of how this national capacity developed in the post-war years is not as well-known and has only recently begun to be considered by historians, e.g., [9, 10]. The remainder of this chapter is organized as follows: Section II presents a brief history of Canadian participation in URSI, including development of the Canadian National Committee, Canadian participation in URSI International, URSI Meetings and Symposia in Canada, and Canadian Recipients of URSI senior awards. Section III presents a brief glimpse of the manner in which the Canadian government laboratories engaged in radio research evolved during the period immediately after Canada joined URSI. Section IV surveys some of the Canadian museums and archives are helping to preserve the documents and artifacts relevant to the history of Radio Science in Canada.

2. A Brief History of Canadian Participation in URSI

2.1. Development of the Canadian National Committee

During the first half of the twentieth century, both the Institute of Radio Engineers (IRE), formed in 1912 in New York City, and the International Union of Radio Science (URSI), formed in Brussels in 1919, sought to provide a forum and mechanism for sharing recent developments and encouraging innovation and international cooperation in wireless technology. Reports from the post-war-II era demonstrate the good rapport and strong cooperation between the two organizations [11]. A key difference between the two was the nature of their membership. Any individual engaged in the profession could join IRE but only Member Committees established in a territory by its Academy of Sciences or Research Council, or by a similar institution or association of institutions could join URSI.

The difference between IRE and URSI was critical given the increasingly important role played by government research laboratories during the post-war era and increasing interest in international joint ventures in science and technology. The opportunity for Canada to join URSI in the post-war era came at a critical time in the development of radio science in Canada. By 1949, B. G. Ballard, then Officer-in-Charge of the combined Electrical Engineering and the Radio Sections, was so impressed with the manner in which post-war scientific activities were progressing that he pressed for a formal Canadian National Committee to apply for membership in URSI. By 1950, with many National Research Council (NRC) radio researchers no longer involved in defence work, an Associate Committee on Radio Science was formed to consider this possibility [12, 13].

On 21 September 1951, the Associate Committee on Radio Science became the Canadian Committee for URSI under the chairmanship of D. W. R. McKinley, then Associate Director of the Radio and Electrical Engineering Division (REED) of NRC, J. C. M. Scott of the Canadian Radio Wave Propagation Committee (CRWPC) as secretary, and R. E. Williamson, Professor of Astronomy at the University of Toronto, as Chairman of Commission 5 on Radio Astronomy. In 1952, Canada finally became a member of URSI, relatively late compared to the United States (1921) and our sister commonwealth countries Australia (1922) and New Zealand (1931), but just in time to participate in preparations for the International Geophysical Year (IGY) in 1957-58, the coming of age of radio astronomy, and the advent of space exploration.

From 1952 to 1973, the Canadian National Committee (CNC) of URSI served in a dual role as a government advisory committee and as an URSI member committee with NRC serving as the adhering member. It originally consisted of six senior scientists and engineers from government laboratories and departments concerned with radio science and its applications, and five radio physicists, an electrical engineer and a radio astronomer from academia. By 1968, the size of the committee had grown to 23 members from government, academia and industry. An important achievement of the committee in this period was bringing the URSI General Assembly to Ottawa in 1969. In 1973, the NRC Bureau of International Relations (now simply NRC International Relations) was formed, which became the administrative body that oversees all Canadian member committees of the international scientific unions. CNC-URSI's government advisory role ended and the Canadian National Committee of URSI assumed its present form.

The Canadian National Committee of URSI currently consists of the CNC Chair, a Past Chair, a Secretary and a Canadian representative to each of the URSI Scientific Commissions. A single person serves as representative to both Commission G, Ionospheric Radio and Propagation, and Commission H, Waves in Plasmas. Commission representatives are appointed for three-year terms with due regard for geographical and institutional representation. A list of the CNC-URSI chairs and secretaries since 1952 is given in Table 1.

2.2. Canadian Participation in URSI International

After Canada joined URSI, Canadian radio scientists in both academia and government quickly became involved in URSI affairs. In 1952, G. A. Woonton of McGill University became Chairman of Commission VII on Radio Electronics and later became a Vice President of URSI (1957-63). Woonton also organized the 1952 McGill Symposium on Microwave Optics, the forerunner of the Triennial Commission B Symposia on Electromagnetic Wave Theory. The third such meeting was held in 1959, organized by G. Sinclair of the University of Toronto, who became Chairman of Commission VI, Radio Waves and Circuits, in 1957. Two early committee members were B. G. Ballard and J. H. Chapman. Ballard was later appointed President of the National Research Council of Canada while Chapman went on to lead the development of Alouette I, Canada's first satellite, and became the first winner of the John Howard Dellinger Gold Medal.

Table 1. CNC-URSI Chairs and Secretaries

CNC-URSI Chairs		CNC-URSI Secretaries	
1951-57	D. W. R. McKinley	1951-54	J. C. Scott
1957-61	J. S. Marshal	1955-58	Ann Marshall
1961-65	J. T. Henderson	1958-61	D. W. McKinley
1965-68	R. S. Rettie	1961-63	P. M. Millman
1968-71	M. P. Bachynski	1966-68	J. H. Chapman
1971-74	R. E. Barrington	1968-73	J. L. Locke
1974-80	F. J. Osborne	1973-80	J. Y. Wong
1980-86	E. V. Jull	1980-86	L. H. Doherty
1986-93	P. H. Wittke	1986-93	R. F. Clark
1993-99	G. Y. Delisle	1993-96	R. H. Hayward
1999-2008	Y. M. Antar	1996-97	K. F. Tapping
2008-17	F. S. Prato	1997-2011	J. P. Vallée
2017-20	D. G. Michelson	2011	A. D. Gray

Since the 1990's, Canada has seen its greatest participation in URSI at the international level. E. V. Jull of the University of British Columbia served as a Vice-President from 1987-1992 and then served as President from 1993-96. M. A. Stuchly of the University of Victoria served as a Vice-President from 1996-99, P. H. Wittke of Queen's University served as a Vice-President from 2000-05, and Y. M. M. Antar of the Royal Military College of Canada served as a Vice-President from 2008-11 and then again from 2014-17.

Commission A, Electromagnetic Metrology, was chaired by J. Vanier of the NRC from 1990-93, Commission C, Radiocommunication Systems and Signal Processing, was chaired by P. H. Wittke of Queen's University from 1993-96, Commission H was chaired by H. G. James of the Communications Research Centre from 1999-2002 and Commission K, Electromagnetics in Biology and Medicine, was chaired by M. A. Stuchly of the University of Victoria from 1991-93 and by F. S. Prato from Lawson Imaging Research Institute from 2005-08.

2.3. URSI Meetings and Symposia in Canada

Canada has hosted many URSI meetings and symposia since it joined the Union. The U.S. and Canadian National Committees have long cooperated closely and held joint URSI meetings in Ottawa in 1953, 1962, 1967 and 2007. The next such joint meeting is planned for 2021. Canada hosted the URSI General Assembly (later renamed the URSI General Assembly and Scientific Symposium to reflect an updated format) in Ottawa in 1969, in Toronto in 2000 and in Montreal in 2017. Canada also hosted the triennial Commission B Electromagnetic Theory Symposium, in Victoria, BC in 2001.

The IEEE International Symposium on Antennas and Propagation/North American Radio Science Meeting was hosted by Canada many times. It was held in Quebec City, in 1980, under the leadership of J. A. Cummins and G. Y. Delisle of Laval University; in Vancouver, in 1985, under the leadership of K. S. McCormick of NRC and E. V. Jull of the University of British Columbia; in London, Ontario, in 1991, under the leadership of A. R. Webster of the University of Western Ontario; in 1997, in Quebec City, under the leadership of G. Y. Delisle of Laval University and S. J. Kubina of Concordia University; in 2010, in Toronto, under the leadership of G. Eleftheriades of the University of Toronto; and in 2015, in Vancouver, under the leadership of D. G. Michelson of the University of British Columbia, L. Shafai of the University of Manitoba, and R. Vaughan of Simon Fraser University. The IEEE AP-S/URSI meeting will next be held in Montreal in 2020 under the leadership of A. Kishk of Concordia University, L. Shafai of the University of Manitoba, D. G. Michelson of the University of British Columbia and Y. M. M. Antar of the Royal Military College of Canada.

2.4. Canadian URSI Award Recipients

Since Canada became a member of the Union, several Canadians were recognized with URSI Senior Awards (Figures 1-4).

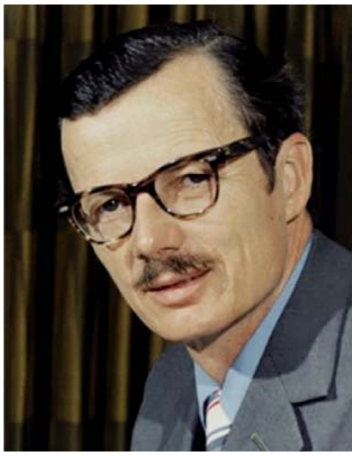

Figure 1. In 1966, the John Howard Dellinger Medal was awarded to John H. Chapman of the Defence Telecommunications Research Establishment (Canada) for contributions to "Radio wave propagation and the Alouette I topside ionosphere sounder."

Figure 2. In 1984, the Balthasar Van der Pol Gold Medal was awarded to Gerald W. Farnell of McGill University (Canada) "for work in physical electronics, in particular on microwave lenses, spin phonon interactions in solids, microwave acoustics, and acoustic microscopy."

Figure 3. In 2002, the Booker Gold Medal was awarded to Simon Haykin of McMaster University (Canada) "for significant and fundamental contributions to adaptive signal processing and neural networks, and their applications to radar and digital communications, the characterizations of which are dominated by nonstationary physical phenomena."

Figure 4. In 2017, the Booker Gold Medal was awarded to Lot Shafai of the University of Manitoba (Canada) "for outstanding contributions to antenna miniaturization by electromagnetics and numerical techniques, small satellite terminals, planar antennas, invention of virtual reflectors, low loss engineered conductors and dielectric film components and antennas."

3. Canadian Radio Science in the URSI Era

3.1. The National Research Council

The decision to petition for Canadian membership in URSI was a direct result of the significant effort Canada had devoted to radio science during the Second World War and the realization that Canada had an important role to play as a global contributor to the field in the post war era. While the massive war-time effort was well documented, historians have only recently begun to explore the post-war years. In this section, the manner in which government laboratories reorganized following the war and influenced subsequent events are briefly reviewed.

Figure 5. The DRTE Radio Physics Laboratory near Dow's Lake in Ottawa in January 1950.

The fifteen years between NRC's decision to form an Associate Committee for Radio Research (essentially an advisory committee whose members provide their time and services at no charge) and the end of the Second World War witnessed phenomenal growth and accomplishment. By the early 1940's, the number of people in the Radio Section surpassed the number of people in the rest of the Division of Physics. While NRC researchers contributed many advances in radio and radar technology, they performed an equally important role in coordinating the efforts of academia, industry, and the armed services; acting as a point of contact for international cooperation; and preparing the next generation of radio professionals who would in turn help Canada become a global player in radio astronomy, radar, and telecommunications [5-8].

As the number of NRC researchers engaged in radio research increased during the Second World War, it became necessary to reorganize several times. The Radio Section became a semi-separate branch and, in 1946, the Radio Section and the Electrical Engineering Section were amalgamated to form the Electrical Engineering and Radio Branch of the Division of Physics. In 1948, they were separated from the Division of Physics to form the Radio and Electrical Engineering Division (REED), also referred to in some places as the Division on Radio and Electrical Engineering, under future NRC vice-president B. G. Ballard. Plans to move from their facilities on Sussex Drive, John Street and the Metcalfe Road Field Station to a new building (M-50) at the NRC's Montreal Road facility were finally realized in 1954 [14].

NRC's efforts in Radar, Antennas, Direction Finding, and Electronic Tube development during the war was remarkable and they elected to continue these efforts in the post-war era. REED agreed to continue their support for the armed services and devote approximately 20 percent of its efforts to defence work, but retained the option of accepting or rejecting any project. During the Korean War (1950-53), however, this fraction rose to as much as 50 percent. The Division used this expertise to contribute to the rapidly growing fields of radar meteorology, radar astronomy, and particularly radio astronomy, where Canada made key contributions in the next several decades, including: the collection of long-term solar-flux measurements; the first demonstration of Very Long Baseline Interferometry in 1967; and the development of what became the Canada-France-Hawaii telescope in the late 1960's and early 1970's. In 1975, NRC formed the Herzberg Institute of Astrophysics (NRC-HIA) to oversee and support this work. The group, now known as the Herzberg Astronomy and Astrophysics Research Centre, appoints members of CNC-URSI and provides support for its activities. However, in 1986, in response to a government-wide austerity initiative, REED was dissolved.

3.2. The Defence Research Board and the Defence Research Telecommunications Establishment

During the latter years of the Second World War, and for a short time afterwards, the Canadian Radio Wave Propagation Committee (CRWPC), which included members from the Canadian military, the Canadian Broadcasting Corporation, the Department of Transport (DOT), and the NRC, and representatives of allied nations, oversaw ionospheric research. A network of field stations was established by Operational Intelligence Centre/6 (OIC/6), of the Royal Canadian Navy (RCN),

Figure 6. The new DRTE Radio Physics Laboratory at Shirleys Bay in Ottawa in February 1953.

Figure 7. The opening of new Radio Physics Lab at Shirleys Bay by the DND Deputy Minister, Col C. M. Drury (second from the left) with J. C. W. (Jim) Scott, Dr. O. M. Solandt and F. T. (Frank) Davies.

and its Radio Propagation Lab (RPL). In 1945, the RCN asked NRC to take over RPL's ionospheric network, but NRC declined. DOT agreed to man the network if OIC/6 continued responsibility for equipment, training and use of the data. This arrangement continued until RPL was transferred to the newly formed Defence Research Board (DRB) in 1947 [15, 16].

When RPL was first formed, it was housed in Naval Headquarters in Ottawa. In 1947, this unit moved to a building provided by the Navy on the Prescott Highway near Dow's Lake, just outside Ottawa. The construction of an additional building to house scientific staff permitted the concentration of all RPL staff at the Prescott Highway site in 1949. The site is shown in Figure 5. The laboratory expanded in terms of both staff and commitments, until the need for additional accommodation had become urgent. In 1951, RPL (renamed the Radio Physics Laboratory) amalgamated with the Defence

Research Electronics Laboratory (DREL), a small establishment working on communications equipment problems, to become the Defence Research Telecommunications Establishment (DRTE). At this time, RPL's work was conducted by six sections: Atmospheric Physics, Radio Prediction, VLF, Ionospheric, Microwave Propagation and Theoretical Studies. The Electronics Laboratory had five sections: Transistors, Radio Warfare (also known as Electronic Warfare), Components, Navigation, and Radar. 1n 1952, a large new facility was constructed at Shirleys Bay, several kilometres west of Ottawa, where there was space for large antenna installations and where there was relatively little radio interference from the city. The building is shown in Figure 6 and the opening ceremony is shown in Figure 7.

Quite separately, DRB created the Electronics Laboratory (EL) in January 1950. EL began in three small rooms in what was then the Army's Canadian Signals Research and Development Establishment (CSRDE) in the NRC engineering area east of Ottawa. The unit was later located into an RCAF (Royal Canadian Air Force) H-hut in the Rockcliffe RCAF housing area. In 1951, EL moved into a new, much larger building adjoining the Army's CSRDE, and F. T. Davies was appointed Superintendent of EL as well as RPL. In 1961, DRB released the EL facilities to NRC, and extended the RPL/CL building at Shirleys Bay to include an EL Wing, naming the considerable laboratory and field area the Defence Research Telecommunications Establishment (DRTE). EL was officially opened on 10 July 1961 by Dr. H. H. Zimmerman, Chairman of the DRB.

From the earliest days, the link between DRTE and the NRC Division of Radio and Electrical Engineering was close and always mutually cooperative. For several years, DRTE's activities were dominated by the design and construction of several scientific satellites, beginning with Alouette 1 in 1958. In the late 1960's, the Chapman Report recommended Canada should focus its efforts on satellite communications and influenced the federal government's 1969 decision to establish Telesat Canada and transfer regulatory responsibility for the radio spectrum from the Department of Transport to a new Department of Communications (DOC). The government assigned the DRTE staff, buildings, resources and programs provided direct support to the military to a new entity called Defence Research Establishment Ottawa (DREO), later renamed Defence Research and Development Canada (DRDC) - Ottawa. Responsibility for the existing Alouette-ISIS program passed to DOC and the DRTE teams focused on basic research were transferred to DOC under the name Communications Research Centre (CRC).

While their new mandate focused on civil communication, CRC continued to provide support to DND and DREO through a cooperative agreement, and to operate a portion of DND's technical program. The DRB itself was dissolved in 1977. Due in large part to their role as the research branch of the Department of Communications (absorbed into the Department of Industry, Science and Technology in 1993, which was renamed Industry Canada in 1995 and renamed Industry, Science and Economic Development Canada in 2015), CRC has used the International Telecommunications Union and its Study Groups rather than URSI as its primary forum for international cooperation and contribution.

4. Canadian Museums with Radio Science Collections

Museums and Archives are important but perhaps underappreciated repositories of documents and artifacts relevant to the history of Radio Science in Canada. This final section introduces seven museums and historic sites from across Canada that preserve both artifacts and sites associated with some key milestones in Canadian radio science. CNC-URSI will develop a more complete directory of such museums and historic sites for the benefit of radio science researchers, engineering professionals, and the public. The possibility of CNC-URSI endorsing museums that meet a set of requirements, and allowing them to display signage to that effect, and taking steps to link historians and policy analysts to science and engineering researchers, is also being considered.

4.1. Admiralty House Communications Museum – St. John's, Newfoundland

H.M. Wireless Station Mount Pearl was constructed by the Marconi Telegraph Company for the Royal Navy just outside St. John's, Newfoundland in 1915. One of thirteen identical wireless stations built across the globe in that era, it is the only one remaining. It is located 14 km south-west of the Signal Hill National Historic Site where Marconi received the first trans-Atlantic wireless transmission in 1901.

The Museum's collection includes both general history of the area and wireless technology associated with the station. One wireless exhibit is dedicated to H.M. Wireless Station Mount Pearl and its role in fleet communications, intercepting German naval transmissions, tracking icebergs, and listening for ships in distress. Another wireless exhibit is called Telegraph Alley and features the development of modern wireless communications and the contributions of Samuel

Figure 8. The main building of the Admiralty House Communications Museum.

Morse, Guglielmo Marconi, Reginald Fessenden, and others. The main building of the Admiralty House Communications Museum is depicted in Figure 8. Further details concerning the museum can be found at http://admiraltymuseum.ca.

4.2. Musée des ondes Emile Berliner – Montreal, Quebec

The Musée des ondes Emile Berliner honours the contributions of an important pioneer in the development of audio technology. The museum's collection, housed in the old RCA building in St. Henri (Montreal, Quebec), has expanded greatly during the past twenty-five years and now consists of more than 30 000 audio reproduction and recording devices, radios, televisions, and architectural acoustical plans.

The year 2019-2020 is particularly noteworthy as it marks the 100th anniversary of broadcasting in Canada. In December 1919, radio station XWA was the first to conduct experimental broadcasting from its William Street studio in Montreal. The Musée and the Société Québécoise de Collectionneurs de Radios Anciens (SQCRA) have joined their efforts along with other groups in the Montreal area to highlight this anniversary. The centennial event logo is shown in Figure 9. Further details concerning the museum can be found at https://moeb.ca/.

Figure 9. The logo of the Centennial of Broadcasting in Canada.

4.3. Military Communications and Electronics Museum – Kingston, Ontario

The Military Communications and Electronics Museum is located at Canadian Forces Base, Kingston. It features the troops, the times and the technologies used in Canadian military communications and electronics.

The history of Canadian military signals dates from 1903, when the militia-based Canadian Signal Corps was established as the first military unit dedicated to communications in the British Empire. The exhibits are arranged chronologically from that time, through World War I and II, the Korean War and various NATO and United Nations peacekeeping missions. The museum also

Figure 10. A wireless exhibit at the Military Communications and Electronics Museum.

features a complete, working amateur radio station as a gateway in the Canadian Forces Affiliate Radio System (CFARS). A wireless exhibit at the museum is depicted in Figure 10. Further details concerning the museum can be found at http://www.candemuseum.org/.

4.4. Canada Science and Technology Museum/Canadian Aviation and Space Museum – Ottawa, Ontario

The Canada Science and Technology Museum (CSTM) and the Canadian Aviation and Space Museum (CASM) in Ottawa, Ontario, are two of the three museums that comprise the Canada Science and Technology Museums Corporation.

The CSTM and CASM both hold important collections concerning early work in telecommunications conducted by the Defence Telecommunications Research Establishment including the sounding rocket experiments conducted at Fort Churchill, Manitoba, and the Alouette-ISIS and Hermes satellite programs. An engineering model of the Alouette satellite on display in the Canadian Aviation and Space Museum is shown in Figure 11. Further details concerning the museums can be found at https://ingeniumcanada.org/.

Figure 11. An engineering model of the Alouette ionospheric topside sounding satellite.

Figure 12. A vintage radio exhibit at the Hammond Museum of Radio.

4.5. Hammond Museum of Radio – Guelph, Ontario

The Hammond Museum of Radio began when museum founder, Fred Hammond VE3HC, began collecting early radio and wireless equipment at the age of 16. The museum moved to its current location in Guelph, Ontario in 1999.

The Museum is now home to hundreds of receivers and transmitters dating from the spark era up to and including National's first solid state HRO500. It hosts one of the largest collections of Collins Radio equipment anywhere, including a rare but fully operational Collins 30K. Kept in pristine condition, the station frequently takes to the air with the same bold signal it produced the day it left the Collins factory. A vintage radio exhibit at the museum is depicted in Figure 12. Further details concerning the museum can be found at http://www.hammondmuseumofradio.org/.

Figure 13. A radar exhibit at the Canadian Forces Museum of Aerospace Defence.

Figure 14 - A broadcast studio exhibit at the SPARC Museum.

4.6. Canadian Forces Museum of Aerospace Defence

The Canadian Forces Museum of Aerospace Defence traces the evolution of aerospace defence through four eras: World War I, World War II, the Cold War, and the post Cold War. The Museum is located at 22 Wing/Canadian Forces Base North Bay near Jack Garland Airport.

A significant portion of the museum's collections are devoted to the development of the Pinetree Line, Mid-Canada Line and Distant Early Warning (DEW) Line air defence radars during the 1950's, and the three-storey Underground Complex (UGC) built 60 storeys beneath the surface at 22 Wing/Canadian Forces Base North Bay to house Canada's air defence headquarters, electronic warfare, and the growing importance of space defence. A radar exhibit at the museum is depicted in Figure 13. Further details concerning the museum can be found at https://www.aerospacedefence.ca.

4.7. SPARC Museum – Vancouver, BC

The SPARC museum is located on the Riverview Hospital grounds, near Vancouver, BC. Its extensive collection is divided into ten themes: Amateur, Bamfield, Broadcast, Broadcast Studio, Marine, Military, Museum Library, Shortwave and Commercial, Spark Era, and Television.

The amateur radio section features large tube equipment mostly from the 1930's through 1950's, vintage Collins A-line and E.F. Johnson radio equipment from the 1940's, and Collins S-Line equipment from the 1960's. The military section features transceivers manufactured in Canada for use in tanks on the Russian Front in WWII, racks of Canadian Navy radio equipment, and transmitters and receiver/direction-finding equipment from bombers. The museum pursues an active restoration program. A broadcast studio exhibit at the SPARC Museum is depicted in Figure 14. Further details concerning the museum can be found at https://sparcradio.ca.

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Radio Science in Czechia

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https://cz.ursi.org/
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1. Predecessors of Radio Science in Czechia

The early development of science, education, and industry in the geographical region of Czechia (the north-western part of the Austro-Hungarian Empire before 1918 and the western part of Czechoslovakia from 1918 until 1992) took place in parallel with similar developments in Europe. The first scientific societies were established in this region in 1784. At that time, Czechia was the most industrialized part of the Austro-Hungarian Empire. The most important higher education and scientific institutions were Charles University founded in 1348 [1], the Czech Technical University in Prague founded in 1707 [2], and Brno University of Technology founded in 1899 [3].

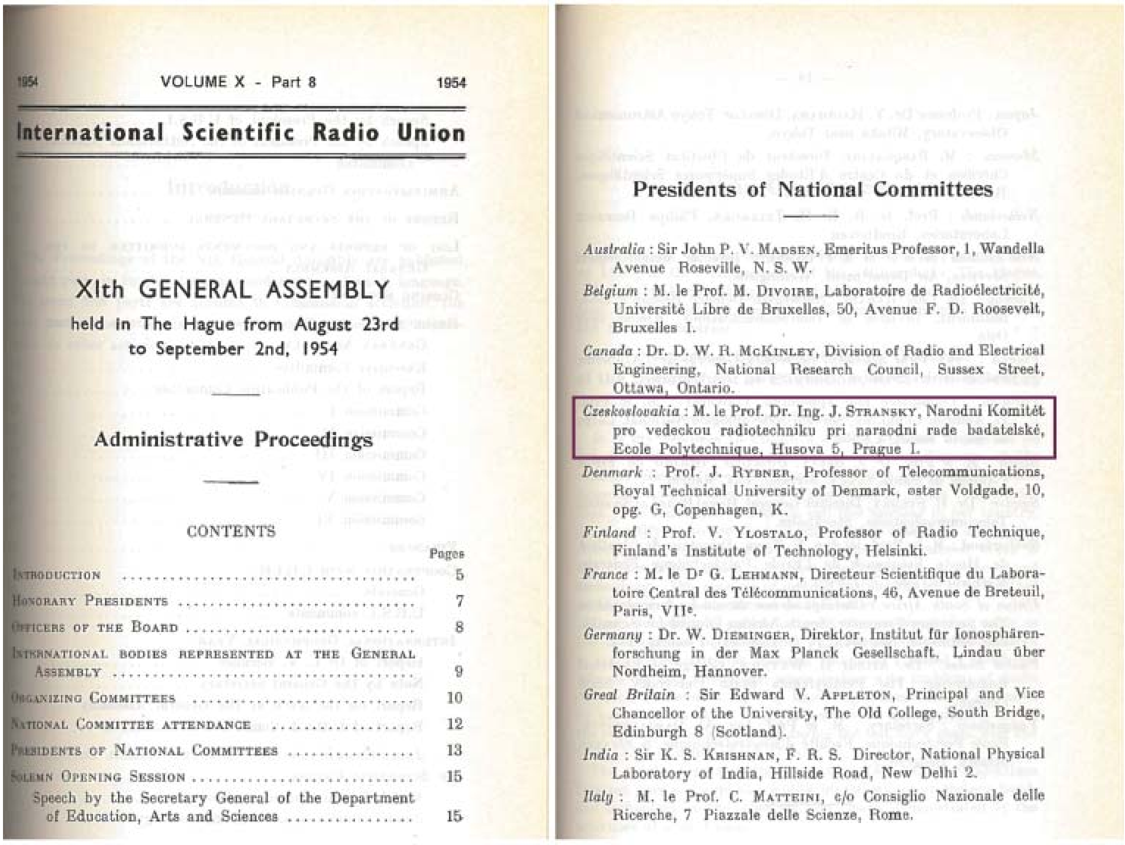
The very first Czech scientist interested in electricity was a catholic priest Prokop Diviš (1698-1765). In order to minimise the impact of thunderstorms and lightning in his parish, he erected in 1754 a 40 m high pole in Přímětice, on which he mounted several tin boxes and more than 400 metallic spikes. The pole was secured by conductive chains that grounded it and thus it became the first operational lightning rod in the region. Notably it was better grounded than Franklin's experimental lightning rods at that time. He published his findings in 1762 [4].

One of the first Czech pioneers in the field of radio engineering was Augustin Žáček (1886-1961). He published a number of articles in the journal, Časopis pro pěstování matematiky a fysiky. In his most important article [5] he described a new method for exciting very short electromagnetic (EM) waves by a magnetron. He also contributed significantly to the development of magnetron theory [6].

Another Czech scientist, explorer, and writer František Běhounek (1898-1971) was a scientific crew member, serving as an expert on cosmic rays, on the Norge (1926) and Italia (1928) airships. He flew as the first Czech over the North Pole in 1928 and he obtained important results from his measurements of electric conductivity of the atmosphere and ionic mobility from measurements on the Italia airship [7].

2. History of the Czechoslovak and Czech National Committee of URSI

After the foundation of an independent Czechoslovakia in 1918, the international relationships of its research institutions with the International Research Council (CIR) fell under the auspices of the Czechoslovak National Research Council (CNRC). This organization, Československá národní rada badatelská, was established in 1923 and became a regular member of CIR in 1925 when its statutes were accepted by the government. CNRC provided Czechoslovak research institutions with technical assistance in networking and establishing international scientific collaboration.



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International Scientific Radio Union

XIth GENERAL ASSEMBLY
held in The Hague from August 23rd
to September 2nd, 1954

Administrative Proceedings

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Presidents of National Committees

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Belgium : M. le Prof. M. DIVOIRE, Laboratoire de Radioélectricité, Université Libre de Bruxelles, 50, Avenue F. D. Roosevelt, Bruxelles 1.

Canada : Dr. D. W. R. MCKINLEY, Division of Radio and Electrical Engineering, National Research Council, Sussex Street, Ottawa, Ontario.

Czeskoslovakia : M. le Prof. Dr. Ing. J. STRANSKY, Narodni Komitét pro vedeckou radiotechniku pri naraodni rade badatelské, Ecole Polytechnique, Husova 5, Prague I.

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Finland : Prof. V. YLOSTALO, Professor of Radio Technique, Finland's Institute of Technology, Helsinki.

France : M. le D^{r} G. LEHMANN, Directeur Scientifique du Laboratoire Central des Télécommunications, 46, Avenue de Breteuil, Paris, VII^{e}.

Germany : Dr. W. DIEMINGER, Direktor, Institut für Ionosphärenforschung in der Max Planck Gesellschaft, Lindau über Nordheim, Hannover.

Great Britain : Sir Edward V. APPLETON, Principal and Vice Chancellor of the University, The Old College, South Bridge, Edinburgh 8 (Scotland).

India : Sir K. S. KRISHNAN, F. R. S. Director, National Physical Laboratory of India, Hillside Road, New Delhi 2.

Italy : M. le Prof. C. MATTEINI, c/o Consiglio Nazionale delle Ricerche, 7 Piazzale delle Scienze, Rome.

Figure 1. The first appearance of the Czechoslovak National Committee of URSI in the URSI archive.

During World War II, the activities of the Czechoslovak National Research Council stopped and after the war, the internal structure of CNRC was changed to accommodate an increasing number of scientific committees. The National Committee for Radio Science was among those newly established committees. CNRC became a member of URSI in 1948 and was later renamed the Czechoslovak National Committee of URSI.

In 1953 the newly established Czechoslovak Academy of Sciences took over responsibility for all national committees originally supported by CNRC, including the Czechoslovak National Committee of URSI. After January 1, 1993, when Czechoslovakia split into two independent states, Czechia and Slovakia, the Czechoslovak National Committee of URSI worked another seven years as a common member committee for both countries (Czech and Slovak National Committee of URSI). The two countries only set up independent member committees in 1999.

The Czech National Committee of URSI was supported by the Czech Academy of Sciences until the end of 2017 when the support was terminated due to changes in national legislation. These changes resulted from a ruling of the Czech Supreme Audit Office which banned the Czech Academy of Sciences from paying the yearly membership dues to URSI. Fortunately, the Institute of Atmospheric Physics of the Czech Academy of Sciences agreed to legally take over the agenda of the Czech National Committee of URSI. The Institute appointed a new committee, composed of active members of the former Czech National Committee of URSI, to represent the Czech radio science community at both national and international levels.

3. Presidents of the Czechoslovak and Czech National Committee of URSI

Prof. Dr. Ing. Josef Stránský was one of the founders of the Czechoslovak National Committee for Radioscience and served as its president for 35 years. The first appearance of the Czechoslovak National Committee (NC) of URSI in the URSI archives is documented in Figure 1. This shows, Josef Stránský among the other national committee presidents attending the XI General Assembly in Den Haag in 1954. Prof. Stránský (1900-1983) had finished his studies at the Czech Technical University in 1923, continuing at the École Supérieure de Electricité, section radio, in Paris, France. After graduation he worked in the technical department of the Post and Telegraph Directory in Prague, Czechoslovakia and also spent several years at the Western Electric Company and Bell Telephone Laboratories in the USA. He was appointed the first Professor of Radio Engineering at the Czech Technical University in 1937. He was an author of many monographs and textbooks on the principles of radio science and taught many future radio specialists who continued their careers in science and industry.

Josef Stránský was followed, as National Committee President by Prof. Václav Zima, at that time the Director of the Institute of Radio Engineering and Electronics of the Czechoslovak Academy of Sciences. He served as President of the Czech NC of URSI from 1984 to 1991. Prof. Zima was very active in preparations of the XXIIIrd URSI General Assembly which was held in the Czech capital Prague in 1990 and was hosted by the Czechoslovak NC of URSI.

Dr. Václav Čížek from the same institute (the current name of the institute is the Institute of Photonics and Electronics of the Czech Academy of Sciences) replaced Prof. Zima in 1991 and served as President up to 1999, when the common Czech and Slovak NC of URSI was split into two independent national committees.

The first President of the Czech NC of URSI was Dr. Vladimír Fiala from the Institute of Atmospheric Physics of the Czech Academy of Sciences (1999-2008), followed by Prof. Miloš Mazánek from the Czech Technical University (2008-2016). The current president of the Czech NC of URSI, Dr. Ivana Kolmašová from the Department of Space Physics of the Institute of Atmospheric Physics of the Czech Academy of Sciences, recently led the efforts to maintain the legal existence of the Czech NC of URSI. Members of the NC of URSI have represented Czechoslovakia and later Czechia as official members in individual commissions of URSI; many doing so for more than 20 years.

4. International Activities of the Czechoslovak and Czech National Committee of URSI

Several members of the Czechoslovak or Czech NC of URSI participated or participate in URSI activities at the international level. Prof. Václav Zima served as a Vice Chair and Chair of international Commission C from 1975 to 1980. Dr. Vladimír Fiala served as a Vice Chair and Chair of international Commission H from 1993 to 1999. Prof. Ondřej Santolík served as a Vice Chair and Chair of Commission H from 2006 to 2017. The international visibility of the Czech Commission H community has recently (2017) been strengthened by the election of Associate Prof. Dr. František Němec as an Early Career Representative of Commission H. In regard to Czech or Czechoslovak representation on the URSI board, Prof. Václav Zima was elected as the Vice-President of URSI for two triennia from 1984 to 1990 and Prof. Ondřej Santolík was elected Vice-President of URSI in 2017.

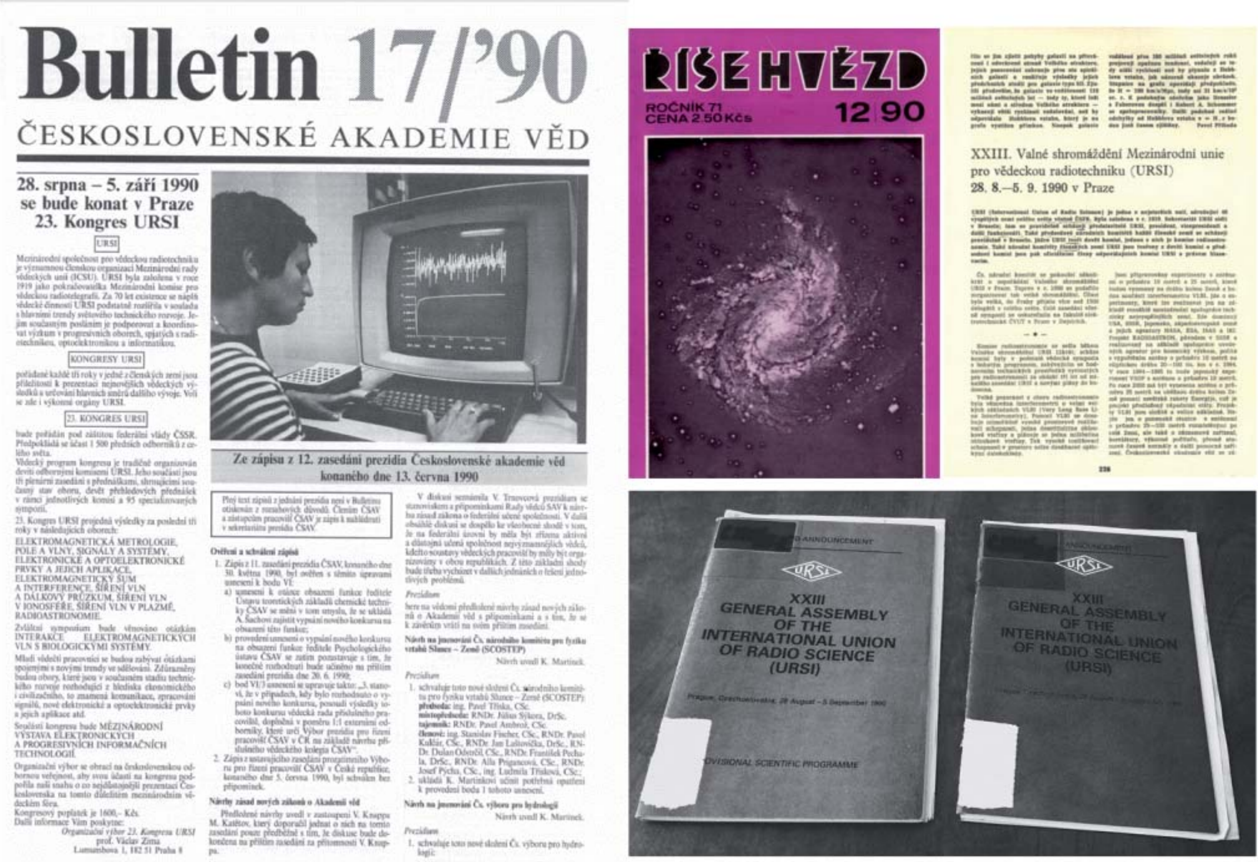
The XXIIIrd General Assembly of URSI was held in Prague, Czechoslovakia from August 28 to September 5, 1990 (Fig. 2). Prof. Václav Zima, President of the Czechoslovak NC of URSI and an URSI Vice-President chaired the Organizing Committee of this General Assembly. This successful meeting included 1176 contributions in the abstract book, more than any previous General Assembly of URSI at the time. Prague hosted more than 1500 radio scientists from different countries all over the world. For many Czechoslovak radio scientists this Assembly became the first opportunity to personally meet their foreign peers whose names they previously knew only from scientific papers.

5. Current Activities of the Czech National Committee of URSI

The Czech NC of URSI regularly provides technical sponsorship to conferences Radioelektronika and MAREV which are organized by Czech and Slovak technical universities. The Czech NC of URSI also supports many international conferences when held in Czechia, e.g., PIERS 2007 (Progress in Electromagnetic Research), ISMOT 2011 (International Symposium on Microwave and Optical Technology), EuCAP 2012 (European Conference on Antennas and Propagation), PIERS 2015 and EuMCE 2019 (European Microwave Conference in Central Europe).

It also supports other adhoc conferences, workshops and seminars which are related to the scientific topics of URSI commissions. The Czech NC of URSI supports the journal Radioengineering - Proceedings of Czech and Slovak Technical Universities, which publishes original scientific and engineering papers in wireless communication and the application of wireless technologies. Members of NC URSI have served on the editorial board of this journal.

Representatives of the Czech NC of URSI regularly attend the URSI flagship conferences, participate in meetings held during these conferences and inform the Czech radio science and radio engineering communities about the outcomes of these meetings. The NC of URSI also encourages national participation in URSI Young Scientist competitions at URSI flagship meetings.



Bulletin 17/'90

ČESKOSLOVENSKÉ AKADEMIE VĚD

28. srpna – 5. září 1990
se bude konat v Praze
23. Kongres URSI

URSI

KONGRESY URSI

23. KONGRES URSI

Ze zápisu z 12. zasedání prezidia Československé akademie věd
konaného dne 13. června 1990

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XXIII. Valné shromáždění Mezinárodní unie
pro vědeckou radiotechniku (URSI)
28. 8.—5. 9. 1990 v Praze

XXIII
GENERAL ASSEMBLY
OF THE
INTERNATIONAL UNION
OF RADIO SCIENCE
(URSI)

Figure 2. Announcements of the 23rd URSI General Assembly in Prague in the 1990: (l) From the bulletin of the Czechoslovak Academy of Sciences; (top right) From the popular astronomical magazine, *Realm of Stars*; (bottom right) The first and the second official announcement by the organizing committee (photos from the archive of the Institute of Photonics and Electronics of the Czech Academy of Sciences, which co-organized the XXIIIrd GA in Prague. At that time this institute was named, the Institute of Radio Engineering and Electronics of the Czechoslovak Academy of Sciences).

The Czech NC of URSI cooperates with the other NC of URSI. The members of the NC occasionally attend the conferences organized by the German, French or North American National Committees of URSI. The Czech NC also cooperates closely with the member committees from Austria, Poland, Hungary and Slovakia. In 2018, the Czech and Slovak National Committees of URSI organized a one-day Czech and Slovak National Radio Science Meeting in order to commemorate 70 years of URSI in Czechia and Slovakia. Representatives of the member committees of neighbouring European countries were invited. As a part of this meeting, the Czech NC arranged a student poster competition with the participation of fourteen students. The first, second, third prizes and two fourth prizes were respectively awarded to Barbora Bezděková from the Charles University (Fig. 3), Andrea Kolínská from the Czech Technical University, Jan Záhlava from the Charles University, Marek Novák from the Brno University of Technology, and Michaela Poplová from the Czech Technical University. International guests Prof. Frank Grohnwald from Germany, chair of international Commission E, Prof. Janos Lichtenberger, chair of the international Commission H and Prof. Piotr Słobodzian, Chair of Commission E of the Polish NC of URSI took part in the meeting and helped with the evaluation of student posters.

6. Czech Institutions Active in Radio Science

Nowadays radio science research is largely concentrated in several institutes of the Czech Academy of Sciences (Institute of Atmospheric Physics, Institute of Photonics and Electronics and Astronomical Institute), in Charles University in Prague (the Faculty of Mathematics and Physics), and in five technical universities in Prague, Brno, Liberec, Plzeň and Ostrava. Czech scientists and engineers participate in many international research programs and projects, which are related to the area of radio science. For example, Prague is now the administrative center of European Global Navigation Satellite System Agency (GSA).

Figure 3. The student poster competition organized during the Czech and Slovak National Radio Science Meeting – 70 years of URSI in Czechia and Slovakia (l-r): Ondřej Santolík (URSI Vice-President), Barbora Bezděková (winner of the competition), Ivana Kolmašová (President of the Czech NC of URSI), Vladimír Štofánik (President of the Slovak NC of URSI).

6.1 Czech Academy of Sciences, Institute of Atmospheric Physics (IAP)

IAP, established in 1964, is oriented toward basic research of the atmosphere, ionosphere and magnetosphere of the Earth, of the ionospheres and magnetospheres of planets of the Solar system, and of the solar wind. Two of the four departments of the institute (Department of Space Physics and Department of Ionosphere and Aeronomy) and one working group (Numerical Simulations of Heliospheric Plasmas) map well onto URSI, in the domains of space plasma physics and space weather. The remit includes design and development of scientific instruments, in situ experimental measurements, data analysis, theory, and numerical simulations. Researchers and technicians at IAP take advantage of a strong heritage originating from scientists and engineers from the team led by Dr. Pavel Tříska and Ing. Jaroslav Vojta who designed, built, and operated a series of five Magion spacecraft (1978-2002).

The Department of Space Physics [8] led by Prof. Ondřej Santolík is active in areas of research related to URSI Commission H (Waves in Plasma). The research consists of experimental studies of processes in heliospheric plasmas via analysis of data from spacecraft and ground observatories, large scale numerical simulations of space plasma processes, and the design and development of scientific instruments for future spacecraft missions. Nowadays the data analysis is largely focused on the study of waves and oscillations in various plasmas in the magnetosphere of the Earth, Jupiter, Saturn and in the solar wind.

The main field of interest of the Department of Ionosphere and Aeronomy, led by Dr. Jan Laštovička, is the physics of the ionosphere including the International Reference Ionosphere which is led by Dr. Vladimir Truhlik, forcing of the ionosphere by atmospheric waves and by space weather, and global changes in the upper atmosphere and ionosphere.

6.2 Czech Academy of Sciences, Institute of Photonics and Electronics (IPE)

IPE (formerly the Institute of Radio Engineering and Electronics) of the Czech Academy of Sciences has a long tradition in research related to several areas of URSI. Among many historical achievements, was the construction of the first maser in Czechoslovakia in 1963 (Dr. Jan Blabla and Dr. Viktor Trkal). Currently IPE carries out fundamental and applied research in photonics, optoelectronics and electronics. In these fields, IPE generates new knowledge and develops new technologies. In the field of photonics, the primary focus is the research and development of optical biosensors (Prof. Jiří Homola), high-power fiber lasers (Dr. Pavel Honzátko), generators of coherent radiation in the mid-infrared band, and special optical fibers (Dr. Vlastimil Matějec, Dr. Ivan Kašík, Prof. Jiří Čtyroký). In the field of optoelectronics, IPE investigates electrical and optical phenomena occurring on the surfaces and interfaces of nanomaterials. These phenomena are induced by photons, ions, electrons, and the adsorption of atoms and molecules, and are used for applications in sensing, light generation and advancement of analytical techniques (Dr. Jan Grym, Dr. Petar Gladkov, Dr. Karel Žďánský). In the field of electronics (with extensions to photonics), the main research activities of IPE are the study of electrodynamic properties of biological systems and the development of detection systems (Dr. Jiří Pokorný, Dr. Michal Cifra). In addition to these activities, IPE runs the Laboratory of the Czech Etalon of Time and Frequency (Dr. A. Kuna).

6.3 Czech Academy of Sciences, Astronomical Institute

Radio Astronomy Observations in Czechoslovakia started at the Ondřejov Observatory (nowadays part of the Astronomical Institute [9]) in 1955 with the acquisition of a 7.5m Würzburg Riese Radar, previously used by the German Luftwaffe during the World War II. The antenna was used for continuous measurements of the solar radio flux at 260, 536 and 808 MHz until 1994, when the main bearing broke down. Later the antenna was moved to the Military Museum. Nowadays the Institute operates a 3m dish for measuring the solar radio flux at 3 GHz, a 10m dish as part of a solar radio spectrograph at 0.8-2.0 GHz, and another 3m dish as part of the solar radio spectrograph at 2.0 - 5.0 GHz. All instruments are fully automated, acquiring data with 10 ms time resolution.

6.4 Charles University, Faculty of Mathematics and Physics, Department of Surface and Plasma Science

The scientific group at the Department of Surface and Plasma Science [10] (formerly the Department of High Frequencies and Vacuum Technics, later Department of Electronics and Vacuum Physics) has a long history in the development of spacecraft instruments, going back to the early 1970s (Prof. Zdeněk Němeček, Prof. Jana Šafránková). The instrument development was accompanied by the data analysis, and the space physics group was formed. Although the main scientific focus was originally on space plasma properties, there is a now a major focus on EM wave phenomena in space (Prof. Ondřej Santolík, Associate Prof. František Němec). Multicomponent wave measurements and detailed analyses of wave properties, propagation, and growth are used to understand the wave and particle dynamics in space, in particular in the Earth's inner magnetosphere.

6.5 Czech Technical University in Prague, Faculty of Electrical Engineering (Department of Electromagnetic Fields and the Department of Radio Engineering), and Faculty of Biomedical Engineering

The Faculty of Electrical Engineering [11] undertakes basic and applied research and the education of students within the scientific scope of URSI: Radio technology (receivers and transmitters), signal processing, electronics, physics, the theory of EM fields, antennas, radio wave propagation, radio frequency and microwave circuits and systems, radio frequency and microwave measurements, biological effects of EM fields, medical applications, beam and fiber optics, electromagnetic compatibility, 5G, navigation, etc. The research activities related to URSI are concentrated in the Department of Electromagnetic Fields and in the Department of Radio Engineering.

The Department of Electromagnetic Fields was founded in 1972 [12] and has had several important radio science scientists in its history, above all Prof. Václav Tysl, Prof. Jaroslav Vokurka, Prof. Jaroslav Prokop and Prof. Karel Novotny. In the period 1977-1992 this department was involved in Earth remote exploration (in cooperation with the Institute of Physics of the Czechoslovak Academy of Sciences). The project was related to participation in the INTERKOSMOS program. The research was focused on microclimate and millimeter radiometry and Earth imaging in these bands (Prof. Miloš Mazánek). The work was associated with the EM wave propagation program and grew into applications in radiometry for biomedical effects (Assoc. Prof. Přemek Hudec). In parallel there were other research projects, e.g. parametric amplifiers for low noise receivers and microstrip circuits (Prof. Ján Zehentner, Prof. Jan Macháč), measurement systems for centimetric and millimetric waves (Prof. Karel Hoffmann) and last, but not least since 1981 the development of hyperthermia technology and its clinical applications (Prof. Jan Vrba).

Nowadays there are, in this department, several research groups working in topics related to URSI activities, e.g., the theory of EM fields (Prof. Jan Macháč, Prof. Zbyněk Škvor), antennas and electromagnetic compatibility (EMC) (Prof. Miloš Mazánek, Assoc. Prof. Pavel Hazdra), radio wave propagation (Prof. Pavel Pechač), free space and fiber optics (Prof. Stanislav Zvánovec), microwave circuits, systems and measurement (Prof. Karel Hoffman, Assoc. Prof. Přemek Hudec), radio frequency identification (RFID) (Assoc. Prof. Milan Polívka), computational electromagnetics (Assoc. Prof. Lukáš Jelínek, Assoc. Prof. Miloslav Čapek) and biomedical applications of EM fields (Prof. Jan Vrba).

The Department of Radio Engineering [13] studies wireless analog and digital communication and multimedia technology. The Department has specialized laboratories for teaching and carrying out research on signal broadcasting, receiving and processing, audio-visual technology, radio-electronic measurements, RF circuit analysis and design, radar and satellite navigation, and space technologies. It cooperates with universities, scientific institutions and industry, mostly on research and development (R&D) projects and in teaching support. The Department of Radio Engineering has several research activities related to URSI fields of interest, e.g., 5G technologies and the applications of RF and multimedia internet of things (Assoc. Prof. Václav Žalud), the implementation of the European Galileo satellite positioning system in the Czech Republic (Prof. František Vejražka), the development of quality evaluation methods for calomel optical elements (Prof. Miloš Klíma), participation in the preparation of payloads for ESA space missions (Prof. Petr Páta) and analysis and optimization of RF circuits using computer-aided design (Assoc. Prof. Josef Dobeš).

The Faculty of Biomedical Engineering [14] undertakes basic and applied research and the education of students in biomedical engineering. Research groups with interests related to URSI include, the bio-electromagnetic team, from the Department of Biomedical Technology (Prof. Peter Kneppo) which is working on the use of microwave signals for medical diagnostics, e.g., cancer diagnostics and stroke recognition (Assoc. Prof. Jan Vrba jr.), metamaterial technology for cancer treatment (Assoc. Prof. David Vrba) and non-invasive temperature measurement (Dr. Ondřej Fišer jr.).

6.6 Brno University of Technology, Faculty of Electrical Engineering and Communication, Department of Radio Electronics (DREL)

The Department of Radio Electronics (DREL) [15] was established in 1959 and this year celebrates 60 years of teaching students in radio electronics and communications. It conducts R&D in future communication technologies. Former heads of the DREL were Prof. Jan Kalendovský (1959 - 1970), Prof. Kamil Vrba (1970 - 1981), Prof. Vladimír Mikula (1981 - 1990), Prof. Jiří Svačina (1991-2006) and Prof. Zbyněk Raida (2006-2013). Since 2013, the head of the DREL is Prof. Tomáš Kratochvíl. The main research activities of the DREL are radio and wireless communication systems (Prof. Roman Maršálek), mobile communications (Prof. Stanislav Hanus), traffic and vehicle-to-vehicle communications (Prof. Aleš Prokeš), applied EM including wearable antennas and electronics (Prof. Zbyněk Raida), satellite communications including communication transponders and their design for various space missions (Prof. Miroslav Kasal), hybrid radio and optical communication systems for free space optical links and networks (Prof. Otakar Wilfert), design of radio electronics and communication systems (Prof. Zdeněk Kolka) and digital video and audio broadcasting and coexistence of radio and wireless systems (Prof. Tomáš Kratochvíl). Each of these radio science research groups is led by a professor and includes master's students and doctoral students. In 2019, the DREL team consisted of 37 academicians, 20 Ph.D. students, and 8 technician assistants teaching and researching in 14 modern and well-equipped laboratories. In last ten years, 567 electrical engineers specialising in radio electronics and communications have successfully completed their master's degree studies at the DREL and almost all of them are working in the electronic and communication R&D field.

Since 2007 DREL has been the publisher of the Radioengineering Journal (ISSN 1210-2512), being the Proceedings of Czech and Slovak Technical Universities and URSI Committees. The journal is listed in Web of Science and Scopus.

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National Radio Science Committee of Egypt: History and Activities

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1. Establishment

The National Radio Science Committee (NRSC) of Egypt was established on the 29th February, 1976 as an affiliate of the Egyptian Academy of Science and Technology. It held its first meeting on the 15th May, 1976, and was presided over by the late Professor Abd-El-Samie Mostafa (IEEE Fellow and former Dean of Engineering at Alexandria University).

2. History

During the period 1976 until 1992, the Egyptian NRSC was chaired by the late Professor Abd-El-Samie Mostafa; from 1992 until 2005 it was chaired by Professor Ibrahim Salem (former Director of the Military Technical College); and from 2005 until 2018 it was chaired by Prof. Said El-Khamy (IEEE Fellow and former Head of the Electrical Engineering Dept. at Alexandria University). The current committee was formed by Decree 186 of year 2018, issued by the President of the Egyptian Academy of Scientific Research and Technology on the 17th October, 2018. Figure 1 shows the current members of the NRSC of Egypt:

Figure 1. Members of the Egyptian National Radio Science Committee as of 17 October 2018.

Dr. El-Sayed Saad
Professor Emeritus
Helwan University
NRSC Chair
Commission F
Representative.

Dr. Mahmoud EL-Hadidi
Professor Emeritus
Cairo University
NRSC Vice-Chair
Commission J
Representative.

Dr. Rowayda Sadek
Vice Dean
Beni-Suef University
NRSC Secretary
Commission A
Representative.

Dr. Ahmed Ibrahim
Associate Professor,
Minia University.

Dr. Hesham El-Badawy
Professor
National Telecommunication Institute
Commission E
Representative.

Dr. Hadia El-Hennawy,
Professor Emeritus
Ain Shams University
Commission B
Representative.

Dr. Said El-Khamy,
Professor Emeritus
Alexandria University
Commission C
Representative.

Dr. Ahmed Eltrass
Assistant Professor
Alexandria University.

Dr. Ahmed Heikal
Associate Professor,
Mansoura University.

Dr. Diaa Khalil
Professor and Vice Dean
Ain Shams University
Commission D
Representative.

Dr. Ahmed Madian
Associate Professor
Nile University.

Dr. Imbaby Mahmoud,
Professor
Egyptian Atomic Energy
Authority
Commission H

Dr. Hend Malhat
Associate Professor
Menoufia University
Commission G
Representative.

Dr. Khaled Shehata
Professor and Dean
AAST&MT
(Sheraton Branch).

Dr. Saber Zain-El-Din
Professor
Menoufia University
Commission K
Representative.

Figure 2. Sample pages of the reports published in the *Radio Science Bulletin* for the National Radio Science Conferences of Egypt.

Report on the 33rd National Radio Science Conference (NRSC 2016)

The 2016 33rd National Radio Science Conference (NRSC 2016) was held in Aswan, Egypt, February 23-25, 2016. It was jointly organized by the National Radio Science Committee (URSI-NRSC) of the Egyptian Academy of Scientific Research and Technology, and the Arab Academy for Science, Technology, and Maritime Transport (South Valley Branch, Egypt). For the first time in the history of the NRSC conference series, the venue for the event was located in Upper Egypt. The intention was to attract researchers, students, and academic staff from this remote part of the country to participate and attend this highly prestigious scientific gathering. To the pleasant surprise of the conference organizers, a good response of contributions was achieved, with a total of 105 technical papers and 16 graduation projects submitted. Following a rigorous refereeing process, whereby all papers were blindly evaluated by three independent reviewers, only 53 papers were selected for inclusion in the conference proceedings. All of the graduation projects were presented in the form of posters.

Figure 1. The formal opening ceremony of NRSC 2016. (r-l) Prof. El-Khamy, President of Egypt's NRSC; Prof. Ismail Abdel Ghafar, AASTMT President; H. E. Prof. Ashraf El-Shihy, Minister of Higher Education and Research; H. E. Governor of Aswan Providence; Prof. Mahmoud Sakr, President of the Academy of Scientific Research & Technology; and Prof. Hesham El-Badawy, General Secretary of NRSC.

The following are some of NRSC 2016 conference highlights.

The opening session was inaugurated by the Minister of Higher Education and Scientific Research, the Governor of Aswan Province, the President of the Egyptian Academy of Scientific Research and Technology, the President of the Arab Academy for Science, Technology, and Maritime Transport, as well by the Presidents of Aswan and Alexandria Universities, and Prof. Yahia Antar, Vice President of URSI. Figure 1 shows the formal opening ceremony.

Figure 2a. Honoring Egyptian radio science pioneers: Prof. Said El-Khamy (r) was honored by H. E. Minister of Higher Education and Scientific Research (l).

Figure 2b. Honoring Egyptian radio science pioneers: Prof. Othman Lotfy (r).

Figure 2c. Honoring Egyptian radio science pioneers: Prof. Lotfy Sakr (r).

Figure 2a. First page of the NRSC2016 Report (URL:http://www.ursi.org/content/RSB/RSB_356_2016_03.pdf)

Report on the Egyptian 34th National Radio Science Conference (NRSC2017)

The 2017 34th National Radio Science Conference (NRSC 2017) was held in Alexandria, Egypt, March 13-16, 2017. The conference was jointly organized by the National Radio Science Committee of the Egyptian Academy of Science and Scientific Research & Technology, and the Arab Academy for Science, Technology, and Maritime Transport (AASTMT) (main campus at Abo-Qir, Alexandria, Egypt). The following are some of the NRSC2017 conference highlights.

The opening session of NRSC2017 was held in the historical conference hall of the AASTMT main branch in Abo-Qir, Alexandria. The VIP guests included Prof. Mahmoud Sakr, President of Egypt's Academy of Scientific Research & Technology (ASRT), Gen. Magdy Mohamadeen, Assistant to the Minister of Military Production, and Prof. Ismail Abdel-Ghafar, President of AASTMT. A photo of the main desk during the formal opening is shown in Figure 1. Figure 2 shows some of the main speakers at the opening session.

During the formal opening ceremony, Prof. Hesham El-Badawy, General Secretary of NRSC, introduced the event (Figure2a). Prof. El-Khamy, Chair of NRSC2017, gave a briefing of the efforts that had been made during the whole past year to enable the conference in its distinguished form for the 34th time (Figure 2b). Prof. Ismail Abdel Ghafar, AASTMT President, provided a briefing on the efforts and facilities that had been presented by AASTMT to support the NRSC2017 (Figure 2c).

The President of ASRT praised the efforts of the National Radio Science Committee, NRSC, especially in maintaining the NRSC for 34 consecutive times in different universities and research institutes in Egypt. After his talk, Prof. Sakr was honored by the conference Chair and AASTMT Chair, as shown in Figure 3.

Following the tradition of the NRSC conference series, three pioneers of radio science in Egypt were honored, and their contributions to radio theory and practice were acknowledged. They were Prof. Nabil Eldaib (Figure 4a, Military Technical College), Prof. Onsy Abd Alim (Figure 4b, Alexandria University), and Prof. Ahmed Soliman (Figure 4c, Cairo University). In addition, for the first time in the NRSC conference series, one of the logistics and administration directors of radio science in Egypt, Mr. Emad Emam (Figure 4d), technical secretary of the Egyptian NRSC, was honored for his contributions to the support of the administration procedures for more than 20 years. Figure 5 is a photo of the honored radio-science pioneers with the organizing committee of NRSC2017 and VIP guests.

Figure 1. The formal opening ceremony of NRSC 2017. (l-r) Top row: Prof. El-Sayed Saad Conference Vice-Chair; Prof. Said El-Khamy, Conference Chair and President of Egypt's NRSC; Gen. Magdy Mohamadeen Assistant to the Minister of Military Production; Prof. Ismail Abdel Ghafar, AASTMT President; Prof. Mahmoud Sakr, President of ASRT; Prof. Allaa Abdel-Bary Vice President of AASTMT for Scientific Research; Prof. AttaAllah Hashad, Chairman of the Local Organization Committee. Front row: Prof. AbelMonem Abdel El-Bary, Local Committee member, and Prof. Khaled Shehata Conference Co-Chair.

Figure 2b. First page of the NRSC2017 Report (URL:http://www.ursi.org/content/RSB/RSB_361_2017_06.pdf)

35th National Radio Science Conference

The 2018 35th National Radio Science Conference (NRSC 2018) was held in Cairo, Egypt, March 20-22, 2018. The conference was jointly organized by the National Radio Science Committee of the Egyptian Academy of Science and Scientific Research & Technology and the Misr International University (MIU), Cairo, Egypt. The following are some of the NRSC2018 conference highlights.

The opening session of NRSC2018 was held in the main Hall of the Tolip Golden Plaza Hotel, Cairo. The VIP guests included Prof. Amro Farouk, Vice President of Egypt's Academy of Scientific Research & Technology (ASRT); Mr. Mohamed El-Rashidy, President of the Board of Trustees of MIU, the conference's honorary chair; and Prof. AbdelRazik Sebak from the University of Concordia, Canada. A photo of the main desk during the formal opening is shown in Figure 1.

Figure 2 shows some of the main speakers at the opening session. Prof. Hesham El-Badawy, General Secretary of NRSC, introduced the event (Figure 2a). Prof. El-Khamy, Chair of NRSC2017, gave a briefing on the efforts that had made done during the past year to enable the conference to be in its distinguished form for the 35th time (Figure 2b). Mr. Mohamed El-Rashidy, President of the Board of Trustees of MIU, gave a briefing on the efforts and facilities that were supplied by MIU to support the NRSC2018 (Figure 2c).

The Vice President of ASRT praised the efforts of the National Radio Science Committee, NRSC, especially in maintaining the NRSC for 35 consecutive times in different universities and research institutes in Egypt. After his talk, Prof. Amro Farouk was presented with an honor by the conference honorary chair, Mr. El-Rashidy, and the NRSC president, Prof. El-Khamy, as shown in Figure 3.

Figure 1. The formal opening ceremony of NRSC 2018: (r-l) Prof. El-Sayed Saad, conference Vice Chair; Prof. Hassan ElGhitany, conference Co-Chair and Dean of Engineering at MIU; Prof. Said El-Khamy, conference Chair and President of Egypt's NRSC; Prof. Amr Farouk, Vice President of ASRT; Mr. Mohamed El-Rashidy, President of the Board of Trustees of Misr International University (MIU).

Following the tradition of the NRSC conference series, four pioneers of radio science in Egypt were honored and their contributions to radio theory and practice were acknowledged. They were Prof. Hassan Elkamchouchi (Alexandria University), Prof. Salwa El-Ramly (Ain Shams University), Prof. El-Sayed Saad (Helwan University), and Prof. Dr. Hany Fikry (Ain Shams University). Figures 4a-4c show three of the radio science pioneers receiving their honors.

Figure 5 is a memorial photo of Egypt's National Radio Science Committee (NRSC) members with the local organizing committee from MIU and some of the VIP guests.

The conference attracted researchers, students, and academic staff from different universities and research

Figure 2. Opening ceremony speeches: (a) Prof. Hesham El-Badawy, General Secretary of NRSC; (b) Prof. Said El-Khamy; (c) Mr. Mohamed El-Rashidy.

Figure 2c. First page of the NRSC2018 Report (URL:http://www.ursi.org/content/RSB/RSB_364_2018_03.pdf)

Report on 2019 Egyptian National Radio Science Conference (NRSC2019)

1. Event Organizers

The National Radio Science Committee, an affiliate of the Academy of Scientific Research and Technology of Egypt (which acts as the national representative of URSI) organized its 36th annual national radio science conference in Port Said, Egypt, during the period of April 16-18, 2019. The co-organizer was the Arab Academy for Science and Technology (AAS&T), which is an affiliate of the Arab League, with six branches in Egypt, one branch in Syria, and another branch in UAE. The Institute of Electrical and Electronics Engineers (IEEE) acted as the technical cosponsor of the conference, following a tradition that is more than twenty years old.

2. Venue

Historically, the city of Port Said is known for the role it played during the Suez Crisis in 1956. Since then, many developments have taken place in this vibrant city. It recently has been selected by the Egyptian Government to be the role model for a number of its digital transformation projects, notably in the medical insurance sector. In addition, a number of "mega" projects have been implemented in Port Said, including the eastern extension of the Port Said seaport, and the digging of two new tunnels underneath the Suez Canal that span 3.92 km each. With these facts in mind, NRSC2019 was hosted in the city's new cultural center, thanks to a generous offer from the Governor of Port Said, General Adel El-Ghadban (Figure 1).

Figure 1. NRSC2019 was hosted in the Cultural Center of Port Said City.

3. Conference Highlights

3.1 Paper Statistics

NRSC conferences follow a tradition that has been established over the years. Prospective authors (national and international) were encouraged to submit their contributions to the conference portal. Submissions were solicited in two versions: a `.doc` version (containing details for the authors and their affiliation), and a `.pdf` version (without authors' names or their affiliation, for blind reviewing). Cross checking by an IEEE plagiarism checker was carried out to determine the eligibility of each submitted paper before evaluation. Three separate referees from institutions other than the affiliations of the submitting authors were selected and their evaluations, supported by any constructive remarks, were solicited. Subsequently, the Technical Program Committee reviewed the papers' evaluations and determined the candidate papers for presentation at the conference. Another cross checking for plagiarism was carried out before a candidate paper was finally accepted.

NRSC2019 received 109 papers, but only 51 were accepted for presentation, corresponding to an acceptance ratio of 46.78%. The accepted papers for NRSC2019 were distributed among the 10 URSI tracks as follows: Commission B (11 papers), Commission C (23 papers),

Figure 2. The NRSC2019 opening ceremony was attended by (l-r) Dr. Khaled Shehata (NRSC2019 co-Chair), Dr. Mostafa Saad (NRSC2019 Chair), Dr. Mahmoud Sakr (President of Academy of Scientific Research and Technology), General Adel El-Ghadban (Governor of Port Said), Dr. Alaa Abd-El-Bary (Vice-President of Arab Academy for Science and Technology), and Dr. Mahmoud El-Hadidi (NRSC2019 Vice Chair).

Figure 2d. First page of the NRSC2019 Report (URL:http://www.ursi.org/content/RSB/RSB_369_2019_06.pdf)

3. Activities

Over the past forty years, the Egyptian NRSC has served the Radio Science community in Egypt through a number of activities, including: its flagship annual conference, The National Radio Science Conference, and through a number of workshops that address the latest advances related to one of the ten URSI Commissions. In addition, it has encouraged several Egyptian researchers to participate as young scientists in the URSI meetings, and has also nominated several Egyptian scholars as candidates for a number of awards announced by URSI.

4. The National Radio Science Conference

This is an annual event, which started in 1984, and is, by far, the most visible activity of the Egyptian NRSC. The Egyptian scientific community considers it to be a highly respected research event and papers published in its proceedings receive the top grade when evaluated by the Staff Promotion Committees of the Supreme Council of Universities. The first 9 conferences were hosted in the Military Technical College (MTC). Starting from 1993, the conference was moved out of the MTC and National Universities and National Academic Institutes in Egypt were encouraged to participate in its organization and activities. Then, starting from 2009, Private Egyptian Universities participated in the conference organization and activities. Table 1 lists the history of the NRSC of Egypt, including conference number, conference year, organizing institute, and the names of Radio Science Pioneers who were honored during the activities of each event. Starting from the 33rd National Radio Science Conference (NRSC2016), highlights of this event are reported in the Radio Science Bulletin (See Figure 2).

5. Workshops on Special Topics

A number of events have been organized by the Egyptian NRSC (as the main sponsor) or by members of the Egyptian NRSC. Table 2 summarizes these events.

6. Young Scientists Participation in International Events

The Egyptian NRSC has encouraged a number of young scientists to participate in the URSI General Assembly (GASS) and the URSI Atlantic Radio Science Conference (AT-RASC). Table 3 lists the URSI event and those Egyptian scientists who received Young Scientist awards.

Table 3. The URSI meeting and Egyptian Young Scientists who received awards.

No.	Event	City, Country	Year	Name of Young Scientist(s)
1	GASS	Prague, Czechoslovakia	1990	Hany Assal
2	GASS	Kyoto, Japan	1993	Mahmoud Mohanna
3	GASS	Lille, France	1996	Diaa Khalil
4	GASS	Toronto, Canada	1999	Wafaa Kassem (C), Khaled Marzouk
5	GASS	Maastricht, the Netherlands	2002	Mostafa El-Khamy (C)
6	GASS	New Delhi, India	2005	M. Gad (C), N. Messiha
7	GASS	Chicago, USA	2008	Mohamed El-Dosoky (K), Amina El—Zein
8	GASS	Istanbul, Turkey	2011	Sherif Shakib (B), Noha El-Ganainy (C), Heba Shaban (K)
9	GASS	Beijing, China	2014	Hend Malhat (B), Sara Kamel (C)
10	AT-RASC	Gran Canaria, Spain	2015	Karim Moussa (C)
11	GASS	Montreal, Canada	2017	Hend Malhat (B)
12	AT-RASC	Gran Canaria, Spain	2018	Mohamed Abd-El-Azeem (G)

Table 1. A list of the Egyptian NRSC conferences, including conference number, conference year, co-organizing institute, location, and the names of the honored Radio Science Pioneers.

Number	Year	Co-Organizing Institute	Location	Honored Radio Science Pioneers
36	2019	AASTMT	Port Said	Abd-El-Halim Shousha Esmat Abd-El Fattah Fatma Abou-Shady
35	2018	MIU	Cairo	Hassan El-Kamshoushi Salwa El-Ramly Elsayed Saad Hany Fikri
34	2017	AASTMT	Alexandria	Nabil El-Deeb Onsy Abd-El-Aleem Ahmed Soliman
33	2016	AASTMT	Aswan	Said El-Khamy Osman Lotfy Lotfy Sakr
32	2015	MSA	Giza	Hamdy El-Mikati El-Sayed El-Badawy Adel El-Nadi
31	2014	Ain Shams Univ	Cairo	Kamal Awad-Allah Mahmoud Hanafy Emad Al-Husseiny
30	2013	NTI	Giza	Mamdouh Fouad El-Sayed Youssef Magdy Ibrahim
29	2012	Cairo Univ	Giza	Saad Eid Mohamed El-Saeed Magdy Fikri
28	2011	NTI	Cairo	Abd-El-Wahab Fayez Abd-El-Hady Ammar
27	2010	Menoufia Univ	Menouf	Abd-El-Salm Fathy Mohamed Saleh
26	2009	Future Univ	Cairo	Sayed El-Sherbini Tadrous Halim
25	2008	Tanta Univ	Tanta	Farid Badran Abd-El-Karim El-Wardany
24	2007	Ain Shams Univ	Cairo	Mohamed Adeeb El-Hilaly Eid
23	2006	Menoufia Univ	Menouf	Mahmoud Shabana
22	2005	AASTMT	Cairo	Fouad Sourial Mohamed Marzouk
21	2004	NTI	Cairo	Awad Saleh
20	2003	AEA	Cairo	Safwat Mahrous Abd-El-Moneim Bilal
19	2002	Alexandria Univ	Alexandria	El-Sayed Talkhan Ahmed Abou-El-Soud
18	2001	Mansoura Univ	Mansoura	Mohamed Abd-El-Aziz
17	2000	Menoufia Univ	Menouf	Ahmed Kamal
16	1999	Ain Shams Univ	Cairo	Ibrahim Salem
15	1998	Helwan Univ	Cairo	Mostafa El-Marashly
14	1997	Cairo Univ	Giza	Yehia El-Hakeem
13	1996	MTC	Cairo	
12	1995	Alexandria Univ	Alexandria	Ibrahim El-Abd
11	1994	MTC	Cairo	Saad-El-Din Youssef
10	1993	NTI	Cairo	Ibrahim Selim
9	1992	MTC	Cairo	Abd-El-Samie Mostafa
8	1991	MTC	Cairo	Hammam Mahmoud
7	1990	MTC	Cairo	Tradition for honoring Radio Science Pioneers was not established yet.
6	1989	MTC	Cairo	
5	1988	MTC	Cairo	
4	1987	MTC	Cairo	
3	1986	MTC	Cairo	
2	1985	MTC	Cairo	
1	1984	MTC	Cairo	

Abbreviations

AASTMT	Arab Academy for Science, Technology and Maritime Transport
AEA	Atomic Energy Authority
MIU	Misr International University
MSA	Modern university for Science and Arts
MTC	Military Technical College
NTI	National Telecommunications Institute

Table 2. Events organized by the Egyptian NRSC (as the main sponsor) or organized by members of the Egyptian NRSC.

No.	Workshop Title	Year	Location
1	Photonics and Electronics	1996	Laser Institute, Cairo University
2	Photonics and Electronics	1997	Laser Institute, Cairo University
3	Photonics and Electronics	1998	Laser Institute, Cairo University
4	Teaching Electronic Devices at Egyptian Engineering Faculties and Institutes	1998-11-05	Academy of Scientific Research and Technology
5	Teaching Photonics at Egyptian Engineering Faculties and Institutes	1999-05-18	Laser Institute, Cairo University
6	Teaching Photonics at Egyptian Engineering Faculties and Institutes	2000-10-24	Laser Institute, Cairo University
7	Teaching Electromagnetics at Egyptian Engineering Faculties & Institutes	2000-11-21	Academy of Scientific Research and Technology
8	Photonics and Its Applications	2002-01-05	Laser Institute, Cairo University
9	Advancement of Electronic Devices	2002-09-28	Faculty of Engineering, Ain Shams University
10	Photonics and Its Applications	2004-05-04	Academy of Scientific Research and Technology
11	1st URSI-Egypt Workshop on Signal Processing	2004-05-20	Arab Academy for Science, Technology, and Maritime Transport (Sheraton Branch)
12	1st URSI-Egypt Workshop in Communication Systems & Microwaves	2004-11-25	Faculty of Engineering, Ain Shams University
13	Advanced Photonics	2005-01-06	Laser Institute, Cairo University
14	2nd URSI-Egypt Workshop on Signal Processing	2006-01-17	National Telecommunication Institute
13	Mobile Communications	2006-06-15	Arab Academy for Science, Technology, and Maritime Transport (Sheraton Branch)

120 Years of Radio Science in Finland

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Abstract

Radio science has a long history in Finland. Starting with the wireless experiments and operations of A. S. Popov, 120 years ago, we present the developments of radio science, engineering, and public service activities during the past century. Particular attention is given to the founding of the Finnish Member Committee of URSI and the organization of the 1978 URSI General Assembly in Finland.

1. Prehistory of Radio Science in Finland

The existence and applications of radio science rest on the solid foundation of Maxwell's equations, formulated in the 1860's. The sesquicentennial of Maxwell's equations was celebrated some years ago, among other occasions during the URSI Atlantic Radio Science meeting, AT-RASC, in Gran Canaria, in 2015 [1]. Even with the theoretical understanding of electromagnetics and its laws, it took a rather long time before the existence of radio waves was experimentally demonstrated. This happened through the efforts of Heinrich Hertz, in 1886 - 1888, in Karlsruhe [2]. The work by Oliver Lodge and Édouard Branly, in developing the coherer for detection of radiating electromagnetic oscillations, was also essential in putting these radio waves into practical and scientific use.

The radio wave pioneer of telegraphic communications was Guglielmo Marconi. With clever use of spark transmitters, wire antennas, and coherers, he managed to transmit signals over a distance, behind hills, later over the Bristol Channel in England, and finally he managed to transmit signals cross the Atlantic Ocean. Another founding father of radio communication was Alexander Stepanovich Popov, a teacher at the Navy Torpedo School, Kronstadt, outside St. Petersburg, Russia. Simultaneously with Marconi, Popov demonstrated wireless transmission of information by radio waves. Popov was also interested in using his device for the detection of thunderstorms by receiving the radio noise emitted by lightning strikes [3].

Popov also managed to establish wireless communications between ships operating in the Gulf of Finland. By accident, the first use of radio for a marine rescue operation happened in the territory of Finland (at that time Finland was an autonomous Grand Duchy of the Russian Empire). This happened when the Russian battleship "General-Admiral Apraksin" ran aground, in 1899, on Hogland, an island in the Gulf of Finland. Popov's duty was to construct a wireless communication channel to Hogland. He erected a 70-meter tall antenna tower on the coast where the present-day city of Kotka is sited. This antenna link to the island 40 kilometers away helped to carry out the rescue operation to free "Apraksin" from the rocks [4].

Thanks to these efforts by A. S. Popov, radio science in Finland can now claim an age of 120 years.

2. Early 20th Century

After the dramatic years of the First World War, and the Russian revolution, Finland became an independent country at the end of 1917. The young nation started to develop its cultural, scientific, and economic activities. As a sign of commercial pursuits in electronics, companies like Helvar, Fenno-Radio, and Hellberg Oy, with a business focus on radio receivers and marine radio systems, were already founded by the 1920s and 1930s [5].

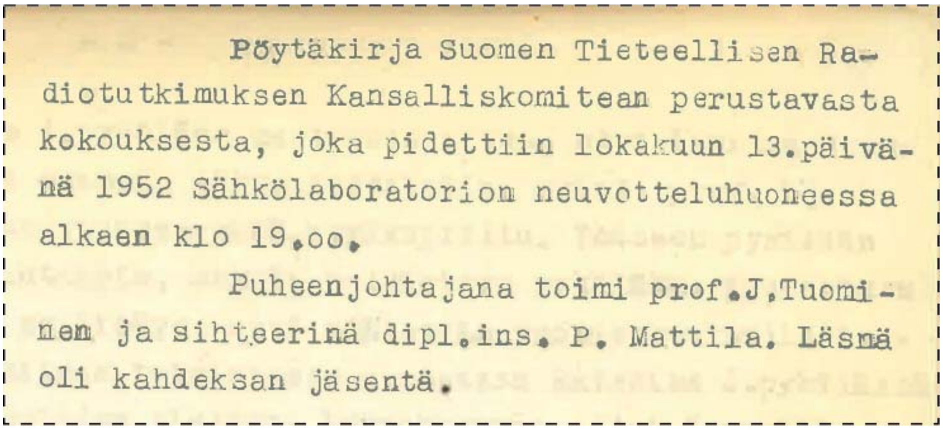
Initially, the legislation on communication of the young country, only government-controlled installations of wireless transmitters were allowed. In 1920, the radio traffic in Finland was run by six military-operated and seven land-to-ship radio stations [6]. Starting from 1921, amateur radio enthusiasts applied and were permitted to build and operate radio emitters. By 1925, 250 stations were in use. Serious radio broadcasting had its beginning in 1926, when the Finnish Broadcasting Corporation was founded (Oy Suomen Yleisradio; Ab Finlands Rundradio) [7]. A kind of culmination of this process was the construction of the great station of Lahti ("Lahden suurasema"), which, in 1928, was the most modern in Europe, with 150-meter-high towers, operating at AM-modulated low frequencies, with wavelengths between 1000 – 2000 m. Once the transmission power of the station was increased from 25 kW to 40 kW, Lahti became the strongest radio-broadcasting station in Europe!

Karl F. Lindman's (later professor in Åbo Academy University, in Turku) electromagnetics studies were revolutionary. In the early 1910s, he explored the effect of artificial chiral media on the propagation of microwave radiation. Chiral media are handed; that is, they are geometrically different from their mirror image. Lindman twisted small helices from copper into spiral form and immersed these into cotton balls in random orientation, thus synthesizing samples of chiral media. His measurements showed the rotation of the polarization plane of the propagating wave, an effect known for light waves in naturally chiral media, where it is called optical rotatory power [8, 9]. Through these efforts, Lindman can be said to be a forerunner of electromagnetic metamaterials studies [10].

The tiny northern village of Sodankylä is a central place for both past and present radio science of our country. This started with the First International Polar Year, 1882 - 1883, when research interest around the world focused on the geophysics of arctic regions. A modest station, built in the wilderness of Lapland (67° 24.4' N, 26° 35.6' E, north of the arctic circle), was capable of providing ample magnetic and meteorological data, some of which are still being analyzed [11]. Later, in 1913, the Finnish Academy of Sciences and Letters secured sufficient funds to establish the Sodankylä Geophysical Observatory for magnetic measurements. At the time it was the northernmost observatory of its kind in the world.

During the 1930s, the scientific impact of the Sodankylä Observatory increased as its research expanded more broadly into the domains of geophysics and with international co-operation with other Nordic countries. The director, Eyvind Sucksdorff, was especially known for his studies of geomagnetic micropulsations [12].

In Southern Finland, magnetic measurement had already started in 1844. Johan Jacob Nervander, the poet and physicist [13], started a series of extremely careful geomagnetic measurements of the Earth's local magnetic field in



Pöytäkirja Suomen Tieteellisen Radiotutkimuksen Kansalliskomitean perustavasta kokouksesta, joka pidettiin lokakuun 13.päivänä 1952 Sähkölaboratorion neuvotteluhuoneessa alkaen klo 19.oo.

Puheenjohtajana toimi prof.J.Tuominen ja sihteerinä dipl.ins. P. Mattila. Läsnä oli kahdeksan jäsentä.

Figure 1. An extract from the records of the first meeting of the Finnish Member Committee. Translation: "Protocol of the constitutive meeting of the Finnish National Committee for Scientific Radio Research, which was held on 13th of October 1952 at 7:00 p.m. in the meeting room of the Electrical Laboratory, Prof. J. Tuominen served as Chairman and Dipl.Eng. P. Mattila as Secretary. Eight participants were present."

Helsinki. Measurements, covering several decades in the 19th century, were comprehensive and unique, and are still being analyzed today [14]. However, magnetic disturbances, due to the introduction of electric streetcars at the end of the 19th century ended the accurate geomagnetic measurements, and a new magnetic observatory was built 50 km north of Helsinki, in Nurmijärvi. In addition to collecting vector magnetic data, ionospheric measurements started in the 1950s with an instrument that was designed in the Radio Laboratory of the State Technical Research Centre.

The first doctoral dissertation in the field of radio science and engineering in Finland was defended by Mr. Jouko Pohjanpalo in 1941. His thesis dealt with improving the efficiency of a modulated radio transmitter (in Finnish: "Eräs menetelmä moduloidun lähettimen hyötysuhteen parantamiseksi"). The next doctoral theses were by Pentti Mattila ("Detection of Weak Periodic Signals From Noise," 1955) and Martti Tiuri ("Investigations of Radio Reflections From Satellite-Produced Ion Trails Using 100 Mc CW Radar," 1960) [15].

3. Founding of the Finnish Member Committee of URSI

URSI was already more than 30 years old and consisted of 26 member committees ("national sections" [16]) before Finland took steps towards establishing formal ties with the union. The founding meeting of the Finnish national committee was held in Otaniemi, Espoo, on 13 October 1952 (Figure 1). The "Finnish National Committee for Scientific Radio Research" (Suomen tieteellisen radiotutkimuksen kansalliskomitea), in its statutes, included the following institutions as members:

- Finnish Academy of Sciences and Letters (Suomalainen Tiedeakatemia)
- Finnish Society of Sciences and Letters (Suomen Tiedeseura)
- Helsinki University of Technology (Teknillinen korkeakoulu, which in 2010 merged with two other universities to become Aalto University)
- State Technical Research Centre (Valtion Teknillinen Tutkimulaitos)
- Institute for Post and Telegraph (Posti- ja lennätinlaitos)
- Finnish Broadcasting Corporation (Yleisradio)
- Central Institute for Meteorology (Ilmatieteellinen Keskuslaitos)
- Finnish Maritime Administration (Merenkulkuhallitus)
- Finnish Defence Forces (Puolustuslaitos)
- Society of Radio Engineers (Radioinsinööriseura)

The first President of the Committee was Professor Viljo Ylöstalo. Diploma Engineer (later Dr.Tech.) Pentti Mattila was elected as Secretary. In addition to establishing the administrative and organizational structure, the Committee began to boost radio research in Finland, in particular by supporting ionospheric research projects. Indeed, by the International Geophysical Year 1957 - 1958, ionosonde measurements were performed at both the Nurmijärvi and Sodankylä observatories. Juhani Oksman (later Rector of Oulu University) contributed greatly to the instrumentation hardware.

The first yearly Member fee of the Finnish Member Committee to URSI Central was 450 Gold Francs, corresponding to 34 000 Finnish marks (FIM). The cost was covered by the Ministry of Education. In terms of the present (2019) currency, this corresponds to about 1100 €, which is close to the current Category 1 fee.

4. The First "Radio Days" in Finland, in 1953

The official records of the national committee show clearly that it was considered important to organize a national scientific meeting in the field of radio. The first "Radio Days" ("Radiopäivät") took place in Helsinki, 24-25 April 1953. The meeting program included 26 presentations and attracted over 200 participants. The registration fee, which included copies of the presentations, was 200 Finnish marks (about 6.5 € in today's currency).

The presentations covered a broad range of radio, scientific, and engineering topics from theoretical approaches to radars, antennas, and wave propagation to microwave instruments and radio electronics. The following sample of the meeting presentation titles provides a summary of the interests of the radio science community of Finland in the early 1950s.

- Elimination of the background noise when observing the radiowave emission of stars
- Radio heating in our industry
- Radio engineering in service of surveying science
- The operating distance of radar as a statistical problem
- Determination of the mirror surface of a radar antenna with point feed

- Propagation phenomena of very short and ultrashort radio waves
- Betatron—an electromagnetic accelerator
- Phase comparator
- Linear sweep generators
- A graphical method to determine the optimum noise figure of a microwave receiver
- Experiments with remote control
- Rationalization in use of the slide rule

As can be seen from this list, the scientific depth and range of topics were rather variable. The same can be said for the educational background of the speakers. The following titles are listed for them: Professor, Diploma Engineer, Engineer, Master, Bachelor of Philosophy, and Technician.

5. Finnish Participation in EISCAT

In 1958, William E. Gordon, URSI Honorary President from 1990 until his death in 2010, analyzed the possibility of measuring properties of the Earth's ionosphere and magnetosphere using a powerful radar [17]. Incoherent reflections from electrons in plasma, although weak, provide information about the electron density and temperature profiles. This provides considerably more detailed information about the ionosphere than the earlier methods using ionosondes and riometers. Gordon led the design team to construct the Arecibo Ionospheric Observatory in Puerto Rico, and became its first director in early the 1960s [18].

However, no incoherent radars existed in northern latitudes, close to the auroral zone. The first initiative for a Scandinavian ionospheric scattering facility was triggered, in 1969, by Bengt Hultqvist, head of the Kiruna Geophysical Observatory in Sweden, and also Chairman of URSI Commission G, 1978 - 80 [19, 20]. Following intense negotiations among the Nordic geophysicists and radio scientists, gradually bigger European countries were involved in the project, which came to be known by the name EISCAT (European Incoherent Scatter Scientific Association). The President of URSI, (later Sir) William John Granville Beynon, presided over the decisive meeting for EISCAT, in October 1973. Germany, France, and finally also the United Kingdom agreed to participate in the project, which from the Finnish perspective was not without political considerations [21]. The possible Soviet participation to EISCAT, which did not eventuate in the end, was a sensitive discussion topic during these years.

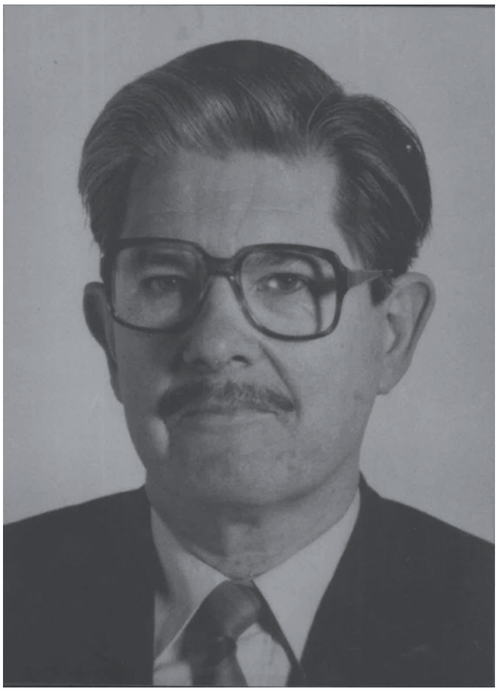


Figure 2. Professor Martti Tiuri (1925-2016), President of the Finnish Member Committee (1966-1990).

The final EISCAT agreement was signed in Paris, in January 1975. The EISCAT network consisted of three stations: Tromsø (Norway), Kiruna (Sweden), and Sodankylä (Finland). The facility was designed to operate on two frequency bands: the UHF system (931 MHz as center frequency) transmitted from Norway, with receivers in each of the three stations, thus forming a multi-static radar system. The second channel operated in VHF (224 MHz) and its transmitter and receiver were in Tromsø. Both systems had a peak power of the order of 1 MW to 2 MW [21]. With a push of the starting button in Kiruna, by the King of Sweden, His Majesty Carl XVI Gustaf, EISCAT operations started on 26 August 1981 [22].

Up to three quarters of the EISCAT installment costs were covered by Germany, France and UK, with the remaining quarter divided between Sweden, Norway, and Finland, in proportions 2:2:1 [23]. Despite the modest share of the Finnish financial input (5%), Finland is active in the scientific activities of EISCAT. Furthermore, the Finnish contribution was essential, in part owing to the extremely efficient signal processing algorithms developed in the Sodankylä Observatory and Oulu University. These make use of alternating and perfect radar codes in approaching the inverse problem of an inhomogeneous atmosphere [24].

Figure 3. (l-r) URSI President Jean Paul Voge, Secretary General of the Ministry of Education Jaakko Numminen, and Conference Chairman Martti Tiuri during the reception of the URSI General Assembly, 1978, in Helsinki.

6. 1978 General Assembly of URSI in Helsinki

The organization of the URSI General Assembly, in 1978, was a major historic undertaking for the Finnish radio scientists. During 1974, the Finnish committee analyzed the financial and technical possibilities for arranging such a large meeting in Finland. This resulted, in January 1975, in the decision to file an application to arrange the XIX URSI GA in the Helsinki area. The proposal was approved at the 1975 General Assembly, in Lima, and the Finnish radio scientific community, under the direction of Professor Martti Tiuri (Figure 2), started their hard work.

The conference took place in early August 1978 (Figures 3 and 4). In the opening ceremony, in the Finlandia Hall, in Helsinki, speeches and salutes were heard from Martti Tiuri (the President of the Finnish Member Committee and Chairman of the Organizing Committee), Jaakko Numminen (Secretary General of the Ministry of Education), Pentti Laasonen (Rector of the Helsinki University of Technology), and Jean Paul Voge (President of URSI), among others. The scientific sessions were held in the premises of Helsinki University of Technology, in Otaniemi, Espoo.

Figure 4. Taken at the 1978 URSI General Assembly banquet showing two future Presidents of the Finnish Member Committee: Ismo Lindell (back left), and Martti Hallikainen (center right).

Figure 5. The Finnish and Swedish member committees have maintained close contacts throughout the years. The leadership of SNRV (Svenska Nationalkomittén för Radiovetenskap, the Swedish Member Committee of URSI) participated in the 2013 Finnish URSI Convention: (l-r) Henrik Wallén (Secretary, URSI Finland); Ari Sihvola (Chair, URSI Finland); Gerhard Kristensson (Chair, URSI Sweden); Carl-Henrik Walde (Secretary, URSI Sweden) (photo: Juhani Kataja).

The General Assembly attracted 885 participants and an additional 180 accompanying persons. The expenses of the organization of the meeting were about 247 000 FIM (around 210k€ in the 2019 rate). Considerable financial support from the Ministry of Education (100 000 FIM, equal to84 k€, thus making 40% of the total budget) was a clear sign of the Government of the Republic of Finland's benevolent attitude to science.

7. The 21st Century

Radio science is an essential element of modern society and this is especially true in Finland. Even though Finland is a relatively small country (with less than one thousandth of the world's population, and with a gross national product only 0.3% of the world), the relative number of Finnish scientists participating in URSI conferences and in the administrative organs of our Union is considerable. Also, at the national level, scientific and technical activities within all the ten Commissions of URSI were fully active in 2020. Finnish URSI conferences on radio science (Figure 5) are arranged regularly [25]. Table 1 lists the officers of the Finnish Member Committee over the 67 years of its existence.

One hundred years after the birth of URSI, radio science is in a healthy shape in Finland.

8. Sources

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Table 1. The Presidents, Vice Presidents, and Secretaries of the Finnish Member Committee of URSI from the founding in 1952 to the end of the current triennium, 2020.

President	Vice-President	Secretary
Viljo Ylöstalo (1952–1959)	Jaakko Tuominen (1952–1959)	Pentti Mattila (1952–1968)
Jaakko Tuominen (1959–1965)	Jouko Pohjanpalo (1960–1962)	
	Martti Tiuri (1963–1965)	
Martti Tiuri (1966–1990)	Tor Stubb (1966–1975)	
		Ismo Lindell (1969)
		Seppo J. Halme (1970–1971)
		Yrjö Sirkeinen (1972–1974)
		Ismo Lindell (1975)
	Seppo J. Halme (1976–1981)	Martti Hallikainen (1976–1981)
	Juhani Oksman (1982–1983)	Olavi Koistinen (1982)
		Ari Sihvola (1982–1983)
	Ismo Lindell (1984–1990)	Martti Hallikainen (1984–1989)
		Ari Sihvola (1989–1990)
		Keijo Nikoskinen (1990)
Ismo Lindell (1991–1996)	Martti Hallikainen (1991–1996)	Ari Sihvola (1991–1996)
Martti Hallikainen (1997–2005)	Ari Sihvola (1997–2005)	Juha Hyyppä (1997)
		Jaan Praks (1998–2006)
Ari Sihvola (2006–2020)	Erkki Salonen (2006–2014)	
		Liisi Jylhä (2007)
		Jaan Praks (2008)
		Henrik Wallén (2009–2020)
	Markku Renfors (2015–2017)	
	Jaan Praks (2018–2020)	

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Part of the History of Radio Science in France

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1. Introduction

Today, URSI-France is active in all of the URSI Commissions and also organizes a scientific workshop every year. Other national committees, notably European, are invited to participate. Related publications appear in the Electricity and Electronics Review (REE, under the aegis of SEE, https://www.see.asso.fr/) and in the Proceedings of the Academy of Sciences, *Comptes Rendus Physique*.

Nationally, radio broadcasting began at the beginning of the 20th century with the discoveries by Édouard Branly, Camille Tissot, General Gustave Ferrié and other inventors presented chronological below. However, the history of radio science began well before this; for example, the work of Auguste Coulomb.

Pasteur said that "In the field of science, chance favours only the minds that have been prepared". This is certainly true, although most scientific progress is also a collective work with many actors, some of them unfairly forgotten. The reader will hopefully forgive any omissions in this chapter, as the field of radio science, with its roots in electromagnetism, is large and the participants numerous, even when limited to France.

After a general history of radio science, more specific themes are presented. Metrology, propagation, and detection are general topics while the reconfigurable Internet of Things is a more recent specialization. Finally, the French involvement in the European Incoherent Scatter (EISCAT) Scientific Association, radio astronomy and electromagnetism in biology and medicine are covered.

2. Before URSI

It is obvious that radio science in France, as in many countries, started well before the first meeting of URSI; held in Brussels, in 1922. The latter was a major milestone in the unification of research efforts and an international extension of standardization and regulation internationally.

Starting, in France, with Charles Augustin de Coulomb (1736-1806) [1], known for his experiments to determine the force exerted between two electric charges, whose law bears his name.

We can also make a detour, with Jean Baptiste Joseph Fourier (1768-1830). Although not involved in electromagnetism, the revolutionary tool that he invented to calculate the diffusion of the heat, the Fourier transform, has many applications in radio science e.g., to obtain the frequency spectrum of a temporal signal.

Continuing, André-Marie Ampère (1775-1836) made important discoveries in electromagnetism and was acknowledged by the Scottish physicist James Clerk Maxwell as the Newton of Electricity [2]. He discovered fundamental aspects of the electrical properties of matter and built the theoretical foundations for its understanding. His name was given to the international unit of the intensity of the electric current: the ampere.

Up until 1820 electricity was mainly known from Alessandro Volta's battery and Coulomb's balance. Magnetism and light were also known. Between these three orders of phenomena no relationship was established and ignorant of their intimate nature, scientists could not even determine and regulate their properties. In 1820, the Danish physicist, Hans Christian Oersted, discovered that an electrical current deviated a nearby magnet. Starting from this simple observation, in a few weeks Ampère had laid the foundation for a whole science to which he gave the name of electromagnetism. The fundamental characteristics are:

- the identification of magnetism and electricity;
- the explanation of the Earth's magnetic field;
- the design of particulate currents existing in magnets and magnetic sheets.

Ampère invented the concept of an electric current. He attributed a direction and amplitude to this given by the right-hand rule, which was also known as Ampère's "little guy". Pursuing his analysis further, Ampère gave a mathematical form to the phenomenon observed, making it possible to predict and calculate related effects.

Ampère gave the first expression for the force exerted by a magnet and Jean-Baptiste Biot, helped by Félix Savart, were quickest to state the law, which bears their name, of the force exerted by an infinitely long wire on a magnet, and then on another wire. In the competition between these men, Pierre-Simon de Laplace, who was then 71 years old, intervened as an arbitrator and the law of interaction was also named Laplace's law! [3]

The history of telegraphy is long, going through first the semaphores of Claude Chappe, telegraph of Samuel Morse and the arrival of radio. Ampère's influence on the history of electric telegraphy can be summed up in the following sentence published in his 1820 memoir:

> One could, by means of as many wires and magnetized needles as there are letters, and by placing each letter on a different needle, establish, with the help of a battery placed far from these needles, and which one will make communicate alternately by its two ends to those of each conductor, a sort of telegraph suitable for writing all the details that one would wish to transmit across any obstacle whatsoever. By connecting to the battery a keyboard whose keys carry the same letters and which establish communication by their depression, this means of correspondence could take place with relative facility and would require only the time necessary to touch on the one hand and to read on the other hand each letter.

Finally, it would be difficult not mention Michael Faraday, on the other side of the channel; another famous scientist who discovered induction in 1831 and with whom Ampère maintained some epistolary exchanges and reciprocal admiration.

Notably, 2020 will be the 200th anniversary of the discovery of Electrodynamics by André-Marie Ampère (1775-1836). Among other places of celebration, his birth place at Poleymieux-en-Mont-d'Or (near Lyon) SEE and the Society of A-M Ampère's friends will organize several scientific and historical events over the year.

Augustin Fresnel (1788-1827), with his famous lenses, launched modern physics in the 1800s. With rudimentary means, and the help of his Norman village's locksmith, he built a micrometer to measure the position of interference fringes. A drop of honey on a hole drilled in a thin sheet of metal provided him with a short focus lens [4]. In 1815, before Ampère's Memoir, 27-year old Fresnel opposed Newton's corpuscular theory of light, accepted until then. By experimenting with the diffraction of light, he laid the foundations for his vibratory theory of light. He added corrections later, in 1818, when he presented the results of his research at the Academy of Sciences by offering for discussion the paradoxical properties of light. Nowadays extremely thin and flat Fresnel lenses are made with metasurfaces (by means of apertures in a metallic film).

Later, in 1862, at the Paris Observatory, Léon Foucault determined the speed of light using a rotating mirror. Specifically, his experiment showed that the speed of light in water was lower than in air, confirming the wave theory according to which the speed of light is inversely proportional to the refractive index of the medium. Camille Gutton, second president of URSI France, resumed his laboratory work from 1909 to 1914, and made a direct comparison of the speed of light and of radio waves using the birefringence of Kerr cells. The last two decades have seen the emergence of metamaterials, which are artificial materials with negative or close to zero refractive indices, opening new degrees of freedom for the control of electromagnetic waves. The pioneers are Victor Veselago, David Smith, Willie Padilla and John Pendry.

In 1829, Augustin Louis Cauchy (1789-1857) established equations for the propagation of light. He established the polarization modes of plane waves, highlighted by Fresnel's earlier work. Cauchy, interested in boundary conditions at an interface, established an empirical law for the dispersion of the refraction index, later obtained from Maxwell's equations. He found David Brewster's results on the variation of the polarization angle during reflection or refraction. The polarization of electromagnetic waves can be used for example with Orbital Angular Momentum (OAM) to increase the data rate for future communications systems (including 5G).

Figure 1. The radioconductor ("musée Branly").

3. The 20th Century and the Birth of URSI

3.1 Édouard Branly (1844-1940)

In 1889, Heinrich Hertz had just completed his experiments to check Maxwell's theories. In the mid-1880s, the Italian physicist Temistocle Calzechi Onesti investigated a tube of metal filings, which is normally electrically highly resistant, although under electric oscillations conducts electricity. Édouard Branly was aware of Hertz and Onest's experiments. In the November 24, 1890, Proceedings of the Academy of Sciences, Branly revealed the discovery, which he called a radio conductor, without taking a patent [5]. Indeed, Branly succeeded in making a remote wireless close an electric circuit, the emitter being a spark generator and a tube of metal filings acting as a receiver for the electric waves produced by the spark. Branly made the essential observation that conduction is removed by tapping on the table. The device therefore allows the transport of information.

Branly had thus demonstrated the principle of radioconduction and named the tube with metal filings the radioconductor (Figure 1). When Édouard Branly presented his discovery to the French Académie des Sciences, the term radio was then used for the first time together with the word radioconductor.

Édouard Branly is one of the forerunners of radio technology and his results were later taken up by Guglielmo Marconi, who learned much from his work and quickly saw the potential of wireless telegraphy. He later did that, in association with John Ambrose Fleming, who made the connection between Maxwell and Marconi [6].

It is also interesting that Branly's receiver principle was used by Christian Hülsmeyer in 1904 in the first radar with his Telemobiloskop system, probably not known to the scientific community because the experiments stopped soon after a failure.

3.2 Gustave-Auguste Ferrié (1868-1932)

Marconi's radio communication experiments were successful at increasing distances and in 1901 he succeeded in connecting Europe and Northern America, wirelessly, by radio; a giant leap at that time. However, research also continued in France, in particular through Fernand Ducretet's work developing links from the top of the Eiffel Tower. Subsequently, under the guidance of Gustave-Auguste Ferrié, French military telegraphy made considerable progress and became the most advanced in the world, as explained below [7].

In 1899, Captain, Ferrié was in charge of following the wireless telegraphy tests conducted by Marconi between France and England. From this time, he continued to work in the radio frequency field.

A scientific visionary, with the operational side probably guided by his military education, in 1909 Ferrié considered that the technique had advanced enough to start the development of true wireless applications, especially onboard airships, airplanes and military ships. Time of the initial meridian was transmitted to all positions that the Eiffel Tower could reach in liaison with the Observatoire de Paris, This application, organized within the Bureau des longitudes in Paris, was particularly important because it allowed ships to accurately determine their position, revolutionizing the determination of longitude differences. France was placed first in the distribution of the hour worldwide with these results and subsequently Paris was chosen as the headquarters of the Bureau International de l'Heure.

Some highlights of Gustave-Auguste Ferrié's career were:

- The realization, in 1901, of the link between Côte d'Azur, in France, and Corsica.
- In 1902, a telegraphic link was made between Martinique and Guadeloupe in order to rescue the island devastated by the eruption of Mount Pelée.
- From 1903, the efficiency of his equipment used with the Eiffel Tower was increased.
- In 1908, he experimented with operational mobile devices in Morocco.
- Radio equipment was provided in the strongholds of the east, before the First World War (1914-1918).

He had a huge field of activity. He intervened in networks of direction-finding, systems of listening, locating by sound, telegraphic connections, and aviation radio.

In 1919, Gustave Ferrié was promoted to General, in 1921 he was elected president of the wireless network (TSF) of the League of Nations, and in 1922 he was elected to the Academy of Sciences. From 1922 he was also President of the International Union of Geodesy and the International Astronomical Union.

He organized the development of the industrial production of the essential high-performance triode tube TM, necessary for transmission and reception. After the First World War victory, he had the great idea of converting the Eiffel Tower transmitter for civil use, creating the first broadcasting station; the commercial receivers using triode TM components were subsequently manufactured in great numbers (Figure 2).

The first General Assembly of URSI was held in July 1922, in Brussels. At that time, only four National Committees formally existed: Belgium, France, United Kingdom, and the USA. However, the same year the following committees joined the Union: Australia, Spain, Italy, Japan and the Netherlands. Two scientists from Norway participated actively in the work of the Assembly as observers.

The Agenda of that first Assembly was drawn up by General Ferrié and Robert Goldschmidt, of Belgium, who would were elected, respectively: President and Secretary General of the Union. Among the topics considered by the Commissions, General Ferrié quoted in particular:

- Measurements of the electromagnetic field and its variations,
- Study of variations in radio goniometrical measurements.

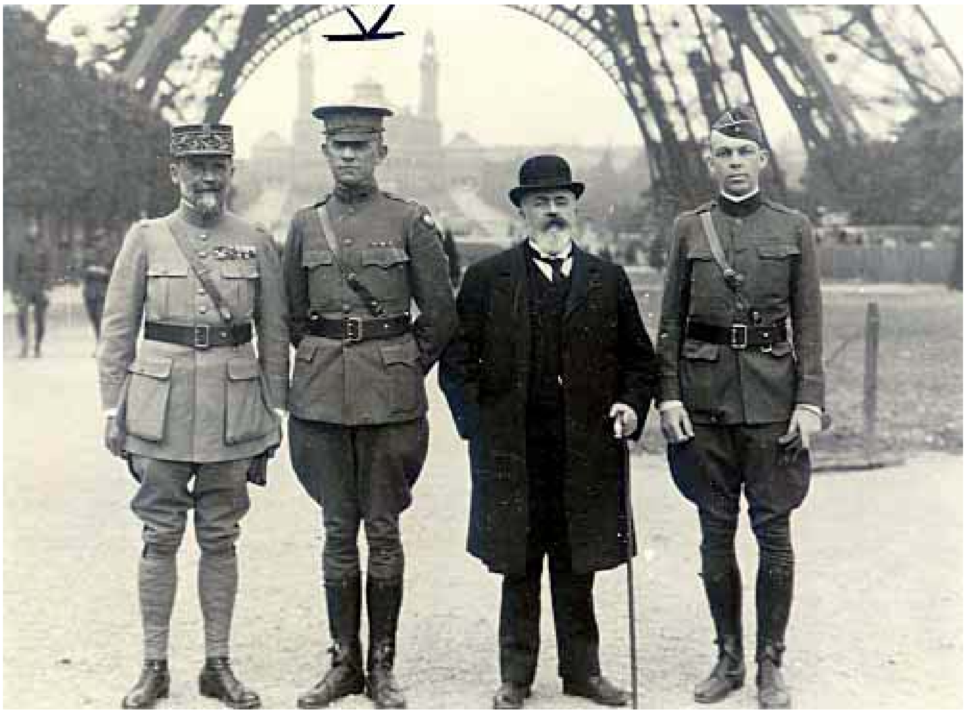

Figure 2. General Gustave-Auguste Ferrié on the left (with, on his left, Major Edwin Armstrong and then Prof. Henri Azariah Abraham) (IEEE History Center).

This also brings us back to the early days of URSI-France, when General Ferrié was the first President of the French committee from 1928 to 1932. General Ferrié was joined in this task by Camille Papin Tissot, representing the naval field, and Camille Gutton, for the aircraft field.

3.3 Jean Perrin (1870-1942)

Before going ahead with wireless applications, let's consider the electron, which when in motion produces a magnetic field. The discovery of the electron is intimately linked to that of cathode rays, which date back to Faraday, who, in 1835, observed electric discharges in an imperfect vacuum. In 1891, concurrent with Ferrié, with a more fundamental approach, George Johnstone Stoney introduced the term electron and in 1894 estimated its charge (10^{-20} C). Jean Perrin plays a noteworthy role in this field at this time.

In 1895, Jean Perrin's reports to the Academy of Sciences summarized the research:

> Some with Goldstein, Hertz or Lenard, think that this phenomenon is due, like light, vibrations of the ether or even that it is a short wavelength light. It is easy to imagine that these rays have a rectilinear trajectory, excite the phosphorescence and impress the photographic plates. Others, with Crooks or J.J. Thomson, think that these rays are formed by negatively charged matter with great speed. And then their mechanical properties, as well as the way in which they curve in a magnetic field, are well conceived.

Jean Perrin performed an experiment with a cathode ray beam received by a Faraday cylinder that showed the cathode rays were negatively charged. Shortly after, Joseph John Thomson repeated the Perrin experiment and deduced that the residual gas in the tube ionizes under the action of cathode rays creating a screen that prevented the magnetic action on the electrons. By creating a better vacuum, the electrons were deflected. Hendrik Lorentz and Pieter Zeeman developed Maxwell's theory and realized, before J. J. Thomson's publications, that the field and the particles interacting with the field must be distinguished. In 1896-1897 the two physicists gave the first evidence for the existence of electrons (Zeeman effect). In 1900, Pierre and Marie Curie show that the beta rays are the same as cathode rays [3].

3.4 Paul Langevin (1872-1946)

Paul Langevin worked on magnetism and introduced Albert Einstein's theory of relativity to France.

In 1904, Langevin reported on the recently discovered physics of electrons and the following year he conducted experiments on atmospheric ions from the Eiffel tower. He used Ludwig Boltzmann's statistical physics to interpret, as observed by Pierre Curie, that the susceptibility of paramagnetic materials varies with temperature. Magnetic materials consisted of a multitude of small magnets created by electrons moving in a closed orbit. The magnetic properties of these materials were then interpreted by Langevin as the balance between the tendency of small magnets to align, and the thermal agitation that tends to give them a random direction. This theory was published in 1905. Thanks to his work, he participated in the advent of modern physics. In 1908 he proposed an equation, which bears his name, to describe the random motion of particles in a liquid (Brownian motion) [8].

3.5 Camille Papin Tissot (1868-1917)

Camille Papin Tissot was the French naval officer who established the first French operational radio links at sea.

In 1896, while the works of Oliver Lodge and Marconi concerning the TSF were still little known, Tissot took up Hertz's theories and the experiments of Branly, and Alexander Stepanovich Popov, to pursue parallel, independent research on the school ship, Borda. He built himself wireless telegraphy equipment with the help of E. Branly and of the manufacturer Eugene Ducretet, for whom he subsequently developed radio equipment. In 1898, he established the first French operational radio link at sea between the Borda and the semaphore of the Parc aux Ducs in the city of Brest, around 2 km from the ship. Camille Tissot, supported by the Minister Delcassé, Minister of the Navy, was able to buy equipment and proceed with his research and tests [9].

In 1898, Camille Tissot established radio contact between the island of Ouessant and the continent, creating the first wireless telegraphy station in France. This station subsequently became Ouessant TSF and was active until 1943, moving to Le Conquet after the war. Using this equipment, in 1899, he organized a large-scale test campaign and achieved communication over the air in French Brittany.

In 1907, Tissot demonstrated wireless telegraphy by transmitting a time signal to set the chronometers of ships at sea. On January 22, 1908, he proposed creating the office of the Bureau des longitudes, a daily transmission service from the Eiffel Tower. The office proceeded with the installation of this service on May 23, 1910 and it was subsequently extended to transmit longitudes. In 1907, Tissot and Félix Pellin designed a tuneless galenoid receiver for merchant ships to receive these signals. In 1911, a committee of French industrialists, led by Émile Girardeau, requested his technical expertise on patents during a series of lawsuits between the British Marconi company and the global wireless industry. Marconi subsequently lost the lawsuits and the monopoly on wireless telegraphy [10].

3.6 Camille Gutton (1872-1963)

As early as 1915, General Ferrié had assigned the French physicist, Camille Gutton, to the Central Establishment of the Military Telegraphy, in Paris, which he directed. He employed him to study the potential offered by the three-electrode lamp. Quickly, Camille Gutton designed and developed radio-receivers for the army to use for terrestrial transmissions and air links. Consequently, in 1917 he was able to establish, for the first time, a radio link between two aircraft, and between an aircraft and the ground. The success of these transmissions triggered the launch of the experimental equipment industry. Camille Gutton had an engineering job in direct contact with the production plants and Captain Brenot established practical air-ground links [9].

This equipment was immediately adopted by the Allied (English and American) armies. At that time, Camille Gutton also gave courses to Allied commanding officers in charge of communications. These courses, delivered in front of the top-level world radio operators, greatly enhanced his reputation and after the war were, after some reworking, published in a successful book entitled *Telegraphy and Wireless Telephony*. This period was marked by the great friendship that bound him to General Ferrié and which contributed to a fruitful collaboration between these two scientists, whose qualities happily complemented each other [11].

3.7 Pierre Lejay (1898-1958)

Pierre Lejay was President of URSI from 1952 to 1957, and elected president of ICSU (International Council for Science, now the International Science Council, ISC), in 1957.

After collaborating with the Méridien Service and the Paris Observatory Service from 1922 to 1926, in 1926 he went to the Zi Ka Wei observatory, in China, to make longitude measurements. He returned to the Paris Observatory in 1930, as director. His areas of interest were geodesy, the upper atmosphere (the observatory had a goal of climate prediction), the ionosphere, and radio propagation.

In 1933, Lejay and Fernand Holweck developed the Holweck-Lejay pendulum, which made precise gravimetric measurements. This pendulum accompanied him on many journeys around the world and led to the creation of a gravity map of the Earth.

He created and managed the International Gravimetric Bureau and the French Ionospheric Bureau [12].

3.8 Pierre Bernard François David (1897-1987)

Pierre Bernard François David was a French engineer, and a pioneer of radiocommunications, radar, and of his creation: an electromagnetic detection system, called the David barrage or barrier. It was a bi-static diffraction radar and was the only French electromagnetic detection systems operational at the beginning of the Second World War.

In 1927, in collaboration with René Mesny, David conducted the first electromagnetic detection experiments of aircraft. The first experiments took place in 1927, at Le Bourget, in France, and detected the radio noise emitted by aircraft engines. These experiments were not totally conclusive, and soon showed their limitations. At their conclusion, David expressed a concept close of the modern radar, in a Soleau envelope memorandum, dated June 5, 1928. That was the origin of radar development in France. Indeed, he thought of transmitting a short-wave signal to produce a reflected emission from an aircraft.

Several times, between 1934 and 1935, David demonstrated the effectiveness of his barrage, which was the first French electromagnetic detector able to detect the passage of an aircraft while giving an estimate of its speed and direction. Paul Labat conducted tests as part of his duties within SEMT (Transmission Equipment Study Section) and also in support of the Navy. These tests detected aircraft at an altitude of 8000 m and a distance of 5 km. In addition to detecting the instantaneous presence of the aircraft, the speed was known to ± 10% and its direction to ± 10°, the calculations taking about 90 minutes. The maturity of this technology earned him several orders from the air force and navy, deployment hastened by the approach of the Second World War [13].

3.9 Maurice Ponte (1902-1983) and Henri Gutton (1905-1984)

Many people believe the resonant-cavity magnetron was invented in February 1940, by Randall and Boot from Birmingham University [14]. However, in the Second World War, the French played a key role. Maurice Ponte, Henri Gutton, and Camille Gutton's development work was provided to the Allies.

Maurice Ponte was an URSI-France President and became President of CSF (Compagnie générale de la télégraphie sans fil) in 1960.

In 1932, Maurice Ponte extended the American and Japanese work and created an industrialized version of the magnetron for field applications. Ponte said:

> at the time Japanese magnetrons remained without any practical result, they needed intensive magnetic fields, impractical outside a laboratory. And magnetron theory was still fragmentary. I started the quest with a theoretical and experimental study of those magnetrons which appeared the simplest to me, i.e. designed with two semi-cylindrical anodes surrounding a cathode filament.

In 1932, Maurice Ponte, at SFR/CSF, revived Okabe's magnetron concept and built several highly efficient oscillating valves working within the wavelength range 3 m to 70 cm. Two years later Henri Gutton succeeded him and began work on multi-segment, resonating anode design M-16 (wavelength 16 cm).

The M-16 found immediate applications in radio-link communications, particularly in a naval obstacle detector (an early decimetric radar) tested on board the liner Normandie from mid-1935. On July 20, 1934, CSF filed a patent for a mobile object detection device. The naval obstacle detector was improved in a dedicated laboratory established in 1936 at Le Havre.

In 1937 Eric C. S. Megaw, in Wembley GEC laboratory, used a thoriated-tungsten cathode with some success and advised Gutton to test it in the M-16. Gutton decided to insert a cylindrical cathode in his tube, coated with oxide, and indirectly heated by a separate filament. This technique, which was used in classical triodes, was immediately successful at higher powers with easier cooling, higher resistance to early burning, and better efficiency due to the reduced inter-electrode space.

A new oxide, fitted to the M-16, giving a peak power of up to 300 W, was shown to Megaw on his last visit in June 1939, and he was provided with a second sample to be tested at Wembley. This promising exchange was delayed by the outbreak of war, and in the meantime, Gutton improved his record: in late 1939, a new eight-segment anode and oxide-coated cathode M-16 delivered a peak-power record of 1 kW at 16 cm. In 1939, Maurice Ponte developed an aircraft detection system for the city of Paris that was close to what would later become radar.

In April 1940, the war situation had become critical in France and in May 1940 the oxide-coated and indirectly heated cathode was taken to Wembley by Ponte, accompanied by Paul Labat, for the French government. It was their final input and had a noticeable influence on the emergence of the British multi-cavity anode invention [15].

The first test of the cavity anode of Randall and Boot immediately proved promising. During his visit, Ponte was kept away from the cavity secret and absolute secrecy was immediately imposed on their work. After being introduced to the secret in April 1940, Megaw understood and immediately planned an improved six-cavity model with a sealed-off vacuum housing, a working pulse mode and with an oxide-coated cylinder with a 0.45 cm diameter that re placed the spiral filament in the E-1189 GEC prototype. This prototype was an essential part of the cargo sent by the Henry Tizard mission to the US [16].

3.10 Robert Alexandre Camille Bureau (1892-1965)

Robert Alexandre Camille Bureau was a President of URSI-France. He was a French physicist and meteorologist specializing in transmissions.

Promoting the use of radio in 1920, Bureau supported the meteorological ship Jacques Cartier collecting data by sending information via the Eiffel Tower to the Office national météorologique. In return, the ship broadcasted the weather forecast to the other ships.

Bureau and Pierre Idrac made high altitude measurements of temperature and atmospheric pressure and are recognized among the fathers of radiosondes. One of the main balloon borne measurement problems was recovering the balloon and data after the flight, which could fail in the case of a balloon explosion. Léon Teisserenc de Bort established the French Meteorological Observatory of Trappes in 1896. In 1926, at this location, the Bureau and Idrac tried to improve data collection by adding a low-power radio transmitter to balloons. By 1927 tests were fully successful and transmissions could be received at various French stations, even from the stratosphere. From then on, Bureau designed successive models of light radio instruments for transmitting high-altitude atmospheric measurements. Between 1929 and 1930 several radiosondes were built and tested, and they soon also measured the altitude profile of wind .by direction finding) and relative humidity [17].

3.11 André Clairon (1947-2015)

André Clairon developed the first French Cesium atomic fountain, as a laboratory frequency standard. It achieved time stability for the second with an accuracy that was the best in the world for more than ten years. In the 1980s, the metrology of time-frequencies and lengths evolved, with the definition of the second changing in 1967. Atomic clocks had become the scientific choice for both time and length magnitudes.

In 1978, Doctor in Quantum Optics André Clairon joined the Primary Laboratory of Time and Frequencies (within the Observatoire de Paris), now the LNE-SYRTE. His knowledge of physics, quantum optics, stabilized lasers, and electronics led him, both in teams and collaborations, towards the development of frequency standards, including atomic clocks (optically pumped jets, atomic fountains), and measurement of frequencies, from microwave to the visible. One of his many inputs had a key role in the ACES mission (with the Kastler-Brossel Laboratory of Ecole Normale Supérieure in Paris) under the aegis of ESA, and in particular its central element: the PHARAO instrument (a clock with cold atoms in space, under the auspices of CNES).

André Clairon contributed to French research and to the spectacular progress of time-frequency metrology. His international fame confirms this, as well as the large number of scientific awards he received (including the Rabi Prize in 1996) [18].

3.12 Jean-Claude Simon (1948)

Jean-Claude Simon was one of the first researchers to work on Semiconductor Optical Amplification (SOA) in France, at CNET. In the late 1970s, with the development of single-mode fibers whose chromatic dispersion was considerably lower than the modal dispersion of the multimode fibers previously used, attenuation became the main limitation for a range of terrestrial and underwater systems: A simple amplification, without the need to reformulate the signal, could considerably simplify the repeaters. The concept of direct optical amplification seemed to be an alternative to optoelectronic repeaters, and the first experimental work on semiconductor optical amplifiers (SOAs) was published in the early 1980s. At the end of the 1980s, research on direct optical amplifiers accelerated. Until then, optical transmission systems used only one carrier. However, in order to cope with the ever-increasing demand for long-distance transmission capacity, it seemed advisable to juxtapose several modulated carriers in the fiber, spectral multiplexing making it possible to exploit the phenomenal bandwidth of optical fibers (several tens of terahertz). However, the need to periodically amplify this optical channel multiplex with optoelectronic repeaters posed a huge cost penalty. Indeed, repeaters were only able to treat one channel at a time, so it was essential to install in each regeneration station as many repeaters as channels present in the multiplex. On the other hand, a single direct optical amplifier operating on the principle of stimulated emission and endowed with a fluorescence line width of a few terahertz, made it possible to simultaneously amplify all the multiplex of optical channels. It was this perspective that accelerated research on optical amplifiers in the 1980s [19].

3.13 Claude Berrou (1951) and Alain Glavieux (1949-2004)

Claude Berrou and Alain Glavieux are the co-inventors of turbocodes, an important signal, data processing, and detection scheme that can approach the Shannon limit.

When published in October 1996 the article “Near Optimum Error Correcting Coding and Decoding: Turbo Codes” in the *IEEE Transactions on Communications*, confirmed for the international coding community that a French Brittany team had revolutionized digital transmissions. Indeed, since the founding work of the American Claude Shannon, published in 1948, it was accepted that in a noisy digital communication channel, if the average level of disturbances did not exceed a certain threshold and if the information was coded with appropriate redundancy, the receiver could identify the original message without any errors. In practice the effectiveness of error-correcting codes was limited. For decades researchers had struggled to overcome this, ending up judging it unachievable. Claude Berrou and his colleague and co-author Alain Glavieux wondered why not use a common principle in electronics, that of feedback, and reinject part of the output signal as input. Indeed, the turbocode principle stems from a simple idea, being composed of two elementary codes that provide horizontal and vertical definitions. In order to decode, the system proceeds by iteration, vertical decoding confirming or invalidating horizontal decoding, and vice versa. The outputs (hypotheses) of a decoder feed the inputs of the other.

Turbocodes were born, after which dozens of teams in the world explored and exploited this new coding/decoding technique, resulting in more than four hundred patents being filed worldwide so far. Today, 4 to 5 million turbodecoders exist and offer very high speeds in wireless networks such as 3G and 4G. The gain obtained by the method requires transmitting only half of the classical power for the same quality. Turbocodes were also used on the Mars Express spacecraft, launched in June 2003 [20].

4. A Selection of Scientific Domains of Historical and Current Activity

4.1 Electromagnetic Metrology

The first standard in the world, the meter, was a product of the French revolution with grievances demanding a universal measure. The electric units arrive later, in 1937. France remains engaged in that field, notably in time-frequency metrology for radio science.

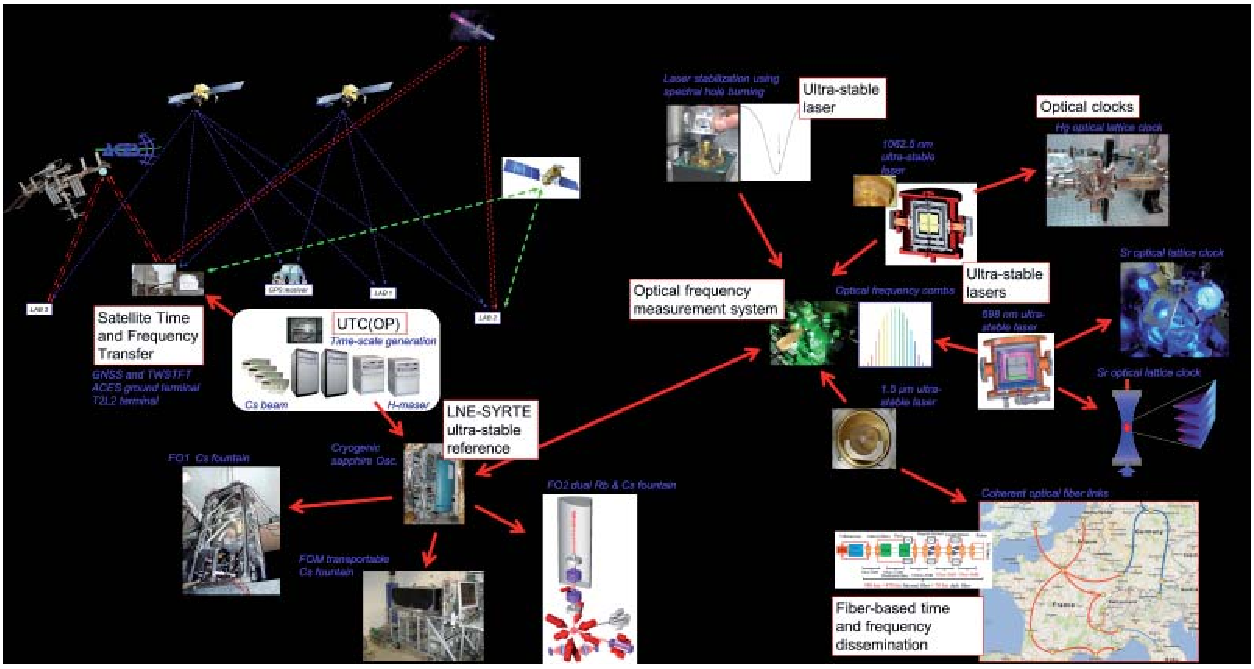

Figure 3. High scientific level time and frequency metrology developed in SYRTE at the Observatoire de Paris.

Commission A of URSI-France aims to promote the development and improvement of new measurement techniques and calibration methods; primary standards, including those based on quantum phenomena, the production and diffusion of frequency standards, and time references; characterization of the electromagnetic properties of materials, physical constants, and properties of engineering materials, including nanotechnology; electromagnetic dosimetry methodology, and measures for health diagnostics, applications and biotechnology, including bio-sensing; measurement in advanced communications systems, space metrology, and other applications, including antenna measurements, and propagation techniques.

As part of the research and scientific developments carried out in France during the last two decades, which are covered by the areas of Commission A, a non-exhaustive list of the main milestones obtained is provided: Time and Frequency Metrology: Cold atomic frequency standards, called atomic fountains that operate in the microwave field and are produced in Laboratoire National de Métrologie et d'Essais - Système de Références Temps-Espace (LNE-SYRTE), have reached exceptional levels of accuracy, of the order of about 10^{-16} [21], which had not been achieved before. France, with three clocks of this type [two cesium fountains (Cs) and a double cesium-rubidium fountain (Cs-Rb)] provides significant weight (about 40 %) of the International Atomic Time (Temps Atomique International, TAI) calibration, established by the Bureau International des Poids et Mesures (BIPM) (Figure 3). However, studies of these standards showed that it will be difficult to consistently improve the accuracy of these systems. Subsequently, many studies were initiated in France on frequency standards in the optical field (Figure 3); in particular, neutral-atom systems such as strontium (Sr) and mercury (Hg). Recently, a significant improvement in the stability of Sr optical clocks was obtained, of the order of $7\times10^{-16}/\sqrt{\tau}$ where τ is the averaging time. This has led to a clear improvement in the accuracy of French clocks (uncertainty of 2.1×10^{-17} achieved in June, 2017). This enabled France to first provide an optical clock for the computation of TAI, made by the BIPM, and second to improve the second (using Rb) [22]. The national time reference, Coordinated Universal Time of the Observatoire de Paris UTC(OP), is also the basis of the French legal time. It is generated from a reference hydrogen maser (Figure 3), whose output signal is controlled using a micro-phase stepper, which has used French atomic fountain data for daily frequency corrections since 2012, making UTC(OP) one of UTC's best real-time realizations (better than 5 ns). The difference between UTC(OP) and UTC (Coordinated Universal Time) is determined by the BIPM from comparisons of remote clocks, made in metrology laboratories (i.e., LNE-SYRTE). In France, this has been done continuously since January 2005 by Two-Way Satellite Time and Frequency Transfer (TWSTFT), with an expanded uncertainty of less than 4 ns ($k = 2$); one of the lowest transfer link uncertainties at the international level. Results published monthly in the BIPM key comparison database (CCTF-K001.UTC) provide metrological traceability of the national time scale UTC(OP) to the SI second.

Many important advances developed at LNE [23] in electrical metrology are highlighted. For instance: the development of voltage references from Josephson junction networks was an important step for electrical metrology in the 1990s, and for DC voltage applications with relative repeatability uncertainties of the order of 10^{-11}, in recent years. The substantial studies and progress in the field of solid-state physics (and for the entire field of nanotechnology) allowed the development of pulse-controlled Josephson junction networks, and generated the development of voltage references for AC current, with uncertainties of the same order as for direct current. These advances are important for other areas of metrology research (such as the redefinition of the kilogram, the consistency of some fundamental constants, among others) as well as industrial applications.

Advances in nanotechnology have resulted in the development of quantum resistance networks based on the quantum Hall effect, which allows the realization of resistance standards over wide ranges of values that have multiple applications in metrology: e.g., redefinition of fundamental constant values, and determination of units. The goal is to make quantum resistances with the lowest possible uncertainties (levels of around 10^{-10}). The results are impressive since several quantum resistors of different values were realized at these levels of uncertainty. In addition, advanced systems such as MEMS (Micro Electro Mechanical System) have initiated new developments in achieving references in electrical metrology in both low and high frequency.

The third quantum effect provides a quantum current standard. After the discovery of the mono-electronic tunnel effect, transistors (with tunnel junctions) were produced. The current values in these junctions are low values, and cryogenic current comparators were developed with very low noise levels. This helped achieve a unique experience, the metrological triangle. The combination of the three quantum systems, Josephson effect, Hall effect, and mono-electronic effect is unique in the sense that it will provide Ohm's law at low levels of uncertainty, deepening the values of the fundamental constants that arise in different effects: e.g., Planck's constant, and the electronic charge.

In parallel, an experiment was developed to provide a better value of Planck's constant using the watt balance. This experiment was carried out to study the stability of the kilogram in time; the kilogram is the only unit defined by an object.

A new reference standard for radiotherapy was developed. In order to better estimate the absorbed dose delivered to the patient during X-ray treatment, a reference standard for irradiation beams of small section was designed in France by LNE-LNHB (Laboratoire National Henri Becquerel).

Applications for Civil Engineering and Health Control were established at the GeM laboratory, in Nantes, where studies on the mechanisms and behaviors of fiber Bragg gratings (Fiber Bragg Gratings and Long Period Gratings) under mechanical stress highlighted the mechanisms that govern their response to curvature. Solutions to make components insensitive to curvature, as well as applications ranging from civil engineering to health control, are of particular interest.

French metrology laboratories have participated in international work on the Revision of the International System of Units (SI) and on the definition of time scales, embodied in two resolutions adopted at the 26th meeting of the General Conference on Weights and Measures (CGPM), at Versailles in November 2018.

4.2 Propagation

Surprisingly, Henri Poincaré published La science et l'hypothèse (Flammarion Editor, 1916) during the preparatory years before the foundation of URSI, a critical analysis of Ampère's famous report *Theory of electrodynamic phenomena, exclusively based on experience* (1826). By reviewing all the outcomes published since the discovery of electrodynamics, by Ampère (1820), Henri Poincaré provided a synthesis of EM theory such as we conceive it today, underlining all the hypotheses established over time.

Propagation underlies all the applications beginning with G. Marconi (1901) and a few others. In most cases the emitted signal was a discharge of a capacitor, but rapidly sine waves were produced by alternators of high power and long wavelength. At the receiving end, the coherer (Figure 1) from E. Branly was rapidly improved (Radioconduction, 1890). The triode lamp (Lee de Forest, 1906), constantly improved, was key to all radio-techniques. The quantity and the diversity of the needs resulting from the Great War, as well as the experience obtained, increased the need to understand propagation phenomena. The first theoretical work was undertaken shortly after Marconi (i.e., Arnold Sommerfeld, 1909; later on, K.A. Norton, 1941). However, both the complexity of the matter and its mathematical formulation prevented easy numerical solutions. Arnold Sommerfeld studied the propagation of electromagnetic waves along a single conductor, then in the 1950s Georg Goubau improved the metallic cylinder performances by adding a dielectric coating in order to increase the confinement. Tahsin Akalin, 2005, worked on planar structures at terahertz frequencies with many applications, including the study of biological entities using split ring resonators or slow-wave topologies, combined with microfluidic channels.

After the first world war, it rapidly appeared that research on EM wave propagation necessitated international cooperation and a few scientific societies of various countries met in Brussels to set up the International Union of Scientific

Radiotelegraphy. The French Committee of this Union, set up by the Academy of Sciences, organized, by early July 1922, a number of high-power daily signals transmitted by French stations; these signals, called URSI signals, were produced three times a day from the stations at the Eiffel Tower in Paris, Nantes and La Croix d'Hins respectively, at wavelengths of 2 600, 9 000 and 23 450 m.

The series of publications *La théorie et la pratique des Radiocommunications* (Delagrave Editor, 1925) directed by Léon Bouthillon [24, 25] is representative of the wide spread interest in the subject. At that time, a close cooperation started between URSI and The International Telegraphic Union (1865, named ITU in 1932) within the CCIR (International Radio Consultative Committee, integrated in 1992 into the ITU-R). This is the reason why URSI, up to now, is a member of the Radiocommunications Sector of ITU, free of charge.

After the World War II, France contributed significantly to the study of propagation, in particular through the work of CNET (Lucien Boithias, Jacques Deygout, Pierre Misme, Philippe Waldteufel, Jean-Claude Bic, Hervé Sizun), and many ITU-R documents still explicitly refer to this work. The steadily increasing capacity of computers supported the development of numerous methods for forecasting propagation and developing practical models. These models are necessary, for example, in establishing cellular networks or in evaluating the efficiency of weapon systems. As a result, propagation is now an integral part of all radiocommunication system development and standardization.

In order to resolve the practical difficulties due to the diversity of applications over the course of a century a broad amount of theoretical and experimental work was undertaken. Among the various points to take into account, frequency band, physical properties of media, and the Earth with its meteorological phenomena are the most important. The particular characteristics of propagation within ionized media, cold or hot plasmas, also had to be added.

In order to better and more efficiently evaluate the EM environment, the public institutions of Direction Générale pour l'Armement (DGA) and Office National d'Etudes et de Recherches Aérospatiales (ONERA), together with French industries, recently agreed to set up an inventory for an easily accessible database of knowledge (ENVIREM 2019, 2-3 July 2019, Palaiseau, France). The characterization of EM noise is part of the project.

It should be mentioned that, for a long time, the forecasting of a useful EM field did not take into account other interfering fields. Nowadays, given the spectral density of applications in the same frequency bands, it is important to point out this situation for most systems. A thorough knowledge of the RR (Radio Regulations of ITU-R) is essential. The many technical documents published by ITU, mainly those related to propagation, are a significant help in this respect. Thanks to these publications, a fair comparison can be established between two or more pieces of equipment, evaluating them on the same basis.

As an example of ITU-R general documentation, the reader can see the Handbook on Meteorology, ref. ITU-R, R-HDB-262013-OAS-PDF-E.

4.3 Radio Location

By 1930 to 1935 the idea of radar was already looming in some countries (e.g., France, Germany, United Kingdom, USA) [26]. It arose from well-understood radio techniques as well as teams of engineers and competent scientists. This included, for instance, the LNR (Laboratoire National de Radioélectricité) laboratory in Paris, founded by General Ferrié, the first President of URSI, followed by Camille Gutton and Pierre David [27]. However, the difficulty at that time was to have high-power HF transmitters, which led to the development of a means of detection such as HF barriers (Barrières HF, Chain Home). Soon, progress at very short wavelengths led to building continuous or pulsed devices. The installation of a radar on board the transatlantic liner Normandy (1935) is a well-known example.

The concept of radar, such as we know it today, was closely related to the generation of very short-wave transmissions at sufficiently high power. Maurice Ponte (doctoral thesis directed by Louis de Broglie) became Director of the Tubes Division of SFR company in France. This coincided with the setting up of LCT (Laboratoire Central de Télécommunications) by ITT in Paris. This company installed the first TV transmitter on the Eiffel tower in Paris and a long-range air-surveillance radar on the island of Port-Cros (South of France) in 1940, based on the same transmitter.

As was the case during the First World War, the belligerent countries produced increasingly different types of equipment; transmitters and antennas being obviously at the center of interest and research. After the war, a common effort from all involved parties (Administrations and private stakeholders) succeeded in rapidly reconstructing an efficient industry to the point that high-quality equipment could be produced for the commercial market and not only for the armed

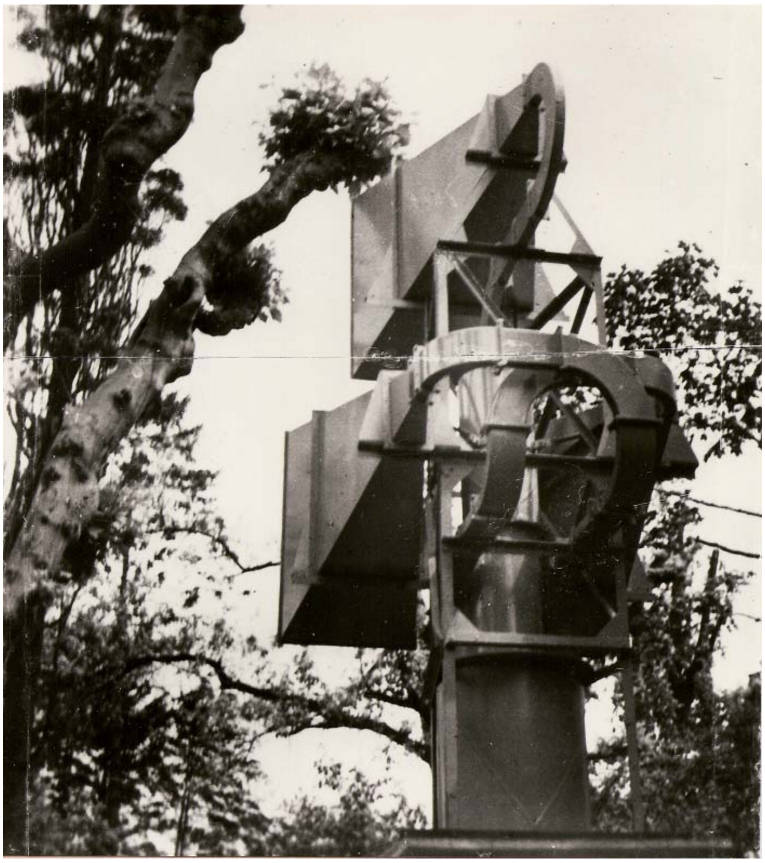

Figure 4. An offset antenna fire control radar (Monopulse) in Saint-Mandrier (France) (coll. J.M. Gutton).

forces. Among the public organizations, there are the Tubes and Microwaves Division of CNET, directed by Georges Goudet, the CNES (space), and the CEA (atomic energy). Among the companies, Thomson-CSF, which later became Thales, LCT, and Dassault Electronique contributed to the reputation of the industrial branch with, for example, the long-range, air-surveillance radars, the remarkable Cyrano series, and the series of air control radars (e.g., the Palmier radar). Some classified patents were developed, such as those of Henri Busignies (1941, USA) [28], related to the Doppler radar. Solid-state semiconductors were rapidly used in receivers and for signal processing [29], the latter benefiting most to the point of becoming the third main sub-assembly of a radar. Moreover, due to signal processing, the structure of transmitters and antennas were modified and, in some cases, these could be merged (e.g., the Arabel radar). At ONERA (Defense and aeronautics), the radar department has been active since the 1970s (e.g., Gravesn Nostradamus radars). Thus, the civil and military applications diversified into ground base, airborne and satellite borne equipment for meteorology, Earth observation, and air security [30- 32].

The onboard satellite sensors, in particular the Synthetic Aperture Radar (SAR), deserves special mention. Given their high cost, most of the previous projects were carried out in the European framework of ESA (Sentinel-1A in 2014 and Sentinel-1B in 2016), or internationally. The quantity and variety of available data over the last 40 years is due to the steady and continuous improvement of sensors, which today provide high dynamic range images [33]. For instance, the French committees of ISPRS and URSI, i.e. SFPT and URSI-France, respectively, particularly cooperate in the framework of URSI Commission F. The XXIV ISPRS Congress, which will be held in Nice (France) from 14 to 29 June 2020, will be a good opportunity for the two Unions to pursue their cooperation. The next International Radar Conference (SEE, IET, IEEE, CIE, Engineers of Australia) was held in Toulon (France) (September 23-27, 2019).

The Radio Location (RL) Service (in the sense of ITU) is increasingly in competition with other Services that apply for more frequency bands, in order to get access to frequency spectrum. Since the beginning, RL Services benefitted from large parts of the spectrum, so as to obtain high spatial resolution, imagery, and automatic target recognition.

Thanks to the continuous improvement of receivers and signal processing, passive observation has become essential for scientific applications e.g., Soil Moisture Ocean Salinity, SMOS, satellite.

The multiplicity of radar activities was stimulating (e.g., Figure 4) and for many years important theoretical research benefited from the most recent mathematical results. While, for many years, detection was based on a priori hypotheses tests, obviously schematics of clutter and targets (i.e., Swerling's models), these tests are presently increasingly done in the real-time evaluation of the environment. This is necessary, especially as the spectrum is increasingly crowded by all kinds of signals. In addition, for some applications the information renewal rate is increased [28, 29].

Propagation in all kinds of media, and the evaluation of target characteristics, are closely related to radio location, the results of which are indispensable. A theoretical deepening of all these subjects is still underway.

In radio astronomy, frequencies are also used, as long as they are in a spectral window allowing reception on Earth. From 1953, in Nancay, Professor Yves Rocard used a radar system to make a radio telescope. Millimeter radio astronomy began to settle in 1985 in the Plateau de Bure in the Hautes-Alpes, based on interferometry.

4.4 Transmitters

Radio transmission methods have developed significantly over the last 100 years. Spark discharge generators, damped waves, electronic tubes, and HF high-power, solid-state devices. Technically, the diversity of applications, of bandwidths, and transmitter power, and the extraordinary development of emissions has to be stressed. This includes solid-state devices, gridded tubes (triodes, tetrodes, etc.,) linear beam tubes, and crossed field tubes (Magnetron, cross-field amplifiers). Without these developments, it would have been nearly impossible to produce radars. This is an area where fundamental physics and empirical science support each other.

The radio interference problem is complex because it is shared between transmission and reception. Interference must be considered well in advance when defining the operational and technical characteristics of a system. The problem of EM compatibility can be particularly critical in systems containing several transmitters and receivers, as for example on aircraft carriers and at airports.

4.5 Reconfigurable Internet of Things

One of the latest major technological revolutions is related to Information and Communication Technologies and Sciences (ICTS). The progressive, massive deployment of connected objects, the Internet of Things (IoT), to transmit different types of data; for instance: pressure measurements, pollution, temperature, hygrometry, videos, and small-scale measurements for medical needs (e.g., insulin levels, heart rate). Real time can also be important: i.e., autonomous vehicles, remote surgery. The research and engineering communities are faced with scientific and technological challenges that combine reliability and latency of transmissions with autonomy and complexity of on-board processing of connected objects.

Almost all sectors are concerned: health, agriculture, transport, industry, construction, surveillance, intervention forces. This section illustrates the IoT's impact on the development of sustainable cities.

Indeed, in recent years, the number of people living in cities has increased dramatically. By 2030, nearly 60% of the world's population will live in an urban environment [34]. However, the exponential growth of the urban population represents a major challenge for the development of efficient infrastructures that meet the needs of, for instance, the transport, health and safety, and environmental sectors. These challenges must be addressed to ensure sustainable urbanization. The Internet of Things is one of the most promising solutions to address this issue. For example, if we know the traffic load in real time, the efficiency of existing transport systems can be considerably improved. Similarly, accurate and real-time measurement of the pollution rate would make it possible to manage the phenomenon more effectively. Many cities around the world have deployed sensor network platforms to support urban detection. For example, New York and Chicago have deployed platforms to collect data on road traffic, environment, and public services [35], not to mention various other experimental platforms developed for research purposes [36].

However, many research opportunities related to IoT are still to be explored. One is illustrated in Figure 5 showing three platforms for temperature, noise, and pollution measurements. Each platform can be logically divided into three subsystems: data acquisition, transmission, and processing. Moreover, each of these platforms is most often characterized by the use of a unique technology such as ZigBee, 6LowPan, and Lora. Each is characterized by its own communication protocol, range, flow rate, and energy constraints [37]. Finally, these platforms are usually dedicated to a single type of application: pollution measurement, road traffic, temperature, or video surveillance.

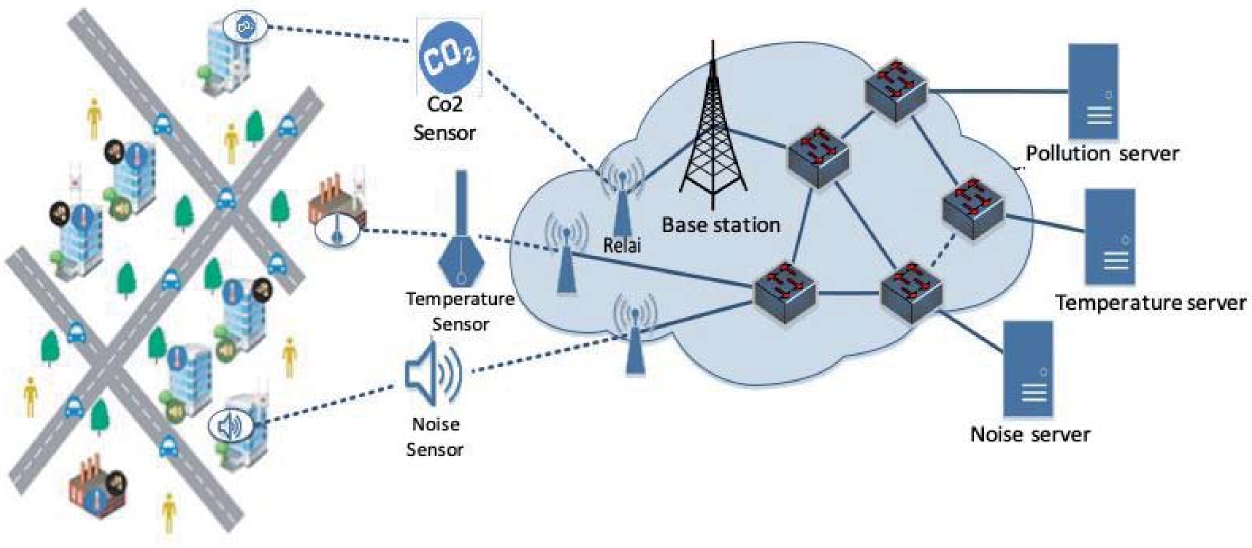

Figure 5. An illustration of an Internet-of-Things system in a smart city.

This mono-technological and application-oriented approach has several disadvantages:

- Inefficient use of resources: Since application control logic is embedded in hardware devices, it is difficult to improve resource allocation by dynamically optimizing data acquisition, transmission, and processing. For example, since there is no approach to dynamically control the collection and transmission of data in sensor network platforms, they continuously transmit data to remote servers, even if the data is unwanted for certain periods of time and therefore the energy of the sensor platform and network bandwidth is wasted.

- Inflexibility for potential application changes: Under this approach, infrastructure and applications are closely coupled, i.e., the application intelligence is implemented in the sensor platform, gateway, and server. Any changes related to an application require the re-customization of the physical infrastructure, which is complex, error-prone, and sometimes costly.

- Long development and deployment cycle, and high maintenance cost: each application must develop and deploy its own platform of sensors, gateway, and remote server from scratch, so the overall time to develop a new application is long. The long development and deployment cycle, as well as the significant investments required, significantly increases the difficulty of deploying new applications, thus inhibiting application innovations. In addition, each platform, or application, must deploy and manage its own sensors, which requires a huge investment in equipment deployment and maintenance. Many sensor platform modules, such as radio, power, and microcontroller, could be shared to reduce the overall cost.

In this context, new architectures for IoT, such as the one based on the SDN (Software Defined Networks) paradigm, are being considered. In the case of the SDN, the architecture is generic, composed of elements (sensors) that can be programmed and therefore reused and shared between different applications.

The sensors in this architecture are managed by a logically centralized entity, or controller, which allows:

- an abstraction of the physical layer, reducing the complexity of the network while increasing its re-configurability;

- a global vision of the network, ensuring efficient use of resources, both energy and bandwidth.

The proposed architecture also provides a programming interface that permits rapid development and deployment of new services, reducing operational and capital expenditures.

4.6 French Participation in the European Incoherent Scatter (EISCAT) Scientific Association

The development of an incoherent scatter radar system took place in France in 1965, several years after the initial implementation of similar systems in the United States, Peru, and the United Kingdom. The French system was different. It used continuous waves and had a bistatic configuration, with a transmitter at Saint-Santin and the receiver at Nançay (300 km from the point of transmission), and later a quadristatic configuration. This allowed average ion mass and vector measurements due to the excellent spectral quality.

An incoherent scatter radar can monitor the thermodynamic properties of the ionosphere and of the thermosphere. The French community joined Finland, Germany, Sweden, Norway, and the United Kingdom developing an auroral incoherent scatter radar that operated over the three Scandinavian countries. This gave birth to the European Incoherent SCATter (EISCAT) Scientific Association. The radar became operational in 1981 [38].

4.7 Radio Astronomy

4.7.1 The Beginnings

The nature of electromagnetic waves, recognized in the 19th century, prompted the idea that stars could emit both light and radio waves. Around 1900, researchers in different countries attempted, in vain, to detect radio emissions from the sun. Among them was Charles Nordmann, who observed from Mont Blanc. Cosmic radio signals were first detected in 1931 by Karl Jansky, in the USA. While searching for the origin of perturbations in transatlantic radio telephone communications, he found that the Milky Way was a radio source. The development of radar technology during the World War II led to the detection of the sun, and researchers and engineers turned towards the astrophysical use of radio techniques. Radio astronomy was the first use of electromagnetic waves, other than visible light, as an astronomical research tool.

4.7.2 The Early Years of Radio Astronomy in France

In France radio astronomy started, as elsewhere, with surplus military equipment from World War II. After early individual attempts, Yves Rocard, at the Ecole Normale Supérieure, planned a general endeavor that was put into practice by Jean-François Denisse and Jean-Louis Steinberg. Early efforts, at ENS and Meudon, later in Marcoussis, near Paris, focused on technical developments in solar physics. However, it rapidly became clear that a larger, more remote site, far from the man-made radio noise of the Paris region, was needed to build extended instruments. In 1953, a site was found in central France, near the village of Nançay, where radio astronomy developed under the auspices of Paris Observatory, at Meudon.

Interferometry, the combination of individual antennas to form a much larger radio telescope, overcomes the intrinsically coarse spatial resolution at radio waves. In Nançay, the 32-element interferometer discovered a new type of radio emission from the sun, produced by magnetically confined electrons in what we now call coronal mass ejections (Boischot and Denisse 1957). This was a new piece of evidence that the solar corona was a highly dynamic medium.

While interferometry improved spatial resolution, a large total collecting area is needed to detect faint cosmic signals. In Nançay the large radio telescope, consisting of a plane tiltable mirror of 200 m × 40 m and a spherical mirror of 300 m × 35 m, was opened in 1965. It is still used, 24/7, to observe a broad range of objects from comets, pulsars, and galaxies, to quasars.

4.7.3 Diversification: Radio Astronomy in Space and at Millimeter Wavelengths

The terrestrial radio window is limited: below 10-20 MHz, as the ionosphere reflects radio waves back into outer space. Steinberg pioneered recognition that radio observations from space would open a new observing window. In 1963, he founded the space research department (DESPA) of the Paris Observatory, in Meudon. Several satellites carried, and still carry, radio spectrographs developed by DESPA, and its successor, Le Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique, LESIA, to observe solar radio bursts and probe the solar wind plasma.

The exploration of the radio domain at millimeter wavelengths was boosted by the discovery of the interstellar CO 2.6 mm line. Many other molecules have spectral lines in the mm and sub-mm range that are sometimes only accessible from space. With the help of US astronomers, Bordeaux Observatory developed a small mm-wave solar interferometer in the 1970s, which was later modified into an instrument for astrophysical spectrometry, and moved to the Plateau-de-Bure, in the French Alps.

French institutes participated in an exemplary collaboration with the German and Spanish communities, developing IRAM (Institut de Radio Astronomie Millimétrique) with two observatories, hosting an interferometer on the Plateau-de-Bure, which is now called NOrthern Extended Millimeter Array (NOEMA), and a 30 m telescope at Pico Veleta (Spain).

4.7.4 Today's Radio Astronomy in France

Radio astronomy remains an invaluable tool for astrophysics. The Nançay observing station supports a wide range of studies in e.g., solar and heliospheric physics, planetary emissions, comets, pulsars, stars, galaxies, large-scale structures, the cosmic dawn era, and distant radio bursts. For this, it hosts an unparalleled complementary set of instruments for dm-m-wave imaging and spectroscopy. The Radioheliograph, Decametre Array and Observations Radio pour Fedome et l'Etude des Eruptions Solaires (ORFEES) spectrograph support fundamental research on solar physics and sun-heliosphere relations within the framework of ambitious ESA and NASA solar satellite missions (e.g., SoHO, Parker Solar Probe, and in the future Solar Orbiter), as well as space weather applications (especially in cooperation with the French Air Force). The Nançay Radio Telescope remains a key element in the accurate timing of pulsars, which aims at an alternative detection of gravitational waves, and in studies of galaxies.

New developments in radio astronomy focus on large, international interferometric arrays to achieve high spatial resolution and high sensitivity. Nançay hosts two new low-frequency instruments: (1) An observing station of the international Low-Frequency Array (LOFAR), whose stations from Ireland to Poland create an instrument of 1000 km baseline operating at the 1.2-10 m wavelength (2) The NenuFAR array of 1800 small antennas, more sensitive than LOFAR, and capable of observing up to 30 m wavelength. It started observations in 2019 and is one of the Pathfinders for an international radio telescope of unprecedented size: the Square Kilometer Array (SKA), with up to a square kilometer collecting surface (i.e., a hundred times that of the Nançay Radio Telescope) and up to a 3000 km long baseline, operating in the 2 cm-6 m wavelength range, in Australia and South Africa. The French radio astronomy community is working actively on both the technology and science of the SKA.

At millimeter waves, observations must be conducted at high altitude to reduce atmospheric absorption. The experience gained by French laboratories and IRAM placed them in an excellent position to participate in development of ALMA, the Atacama Large Millimeter / submillimeter Array. IRAM is now one of the ALMA nodes for European astronomers, while maintaining and operating its two observatories at top level. At sub-mm wavelengths, astronomical observations may need to be made from space. French laboratories were involved in various instruments for balloon-borne (PIROG, Pronaos), and space observatories (Odin, Herschel), and on planetary probes (Rosetta cometary orbiter, and JUICE / THz instrument for Jupiter and its Icy moons - in development), and are promoters of the SPICA infrared space observatory project.

4.8. Bioelectromagnetics

The French Bioelectromagnetic developments were fueled by an active community of researchers in URSI-France, as well as other international bodies. For example, in the last ten years, two members of URSI-France (Commission K) were Presidents of the European Bioelectromagnetics Association (EBEA): Lluis M. Mir (2012-2014) and Isabelle Lagroye (2016-2018). The present President of the BEMS (the Bioelectromagnetics Society), René de Sèze, is also a member of URSI-France. Other members of URSI-France Commission K are also in the council / board of these two learned societies, the most important ones world-wide in this field. For example, Maxim Zhabodov (present Vice-President of URSI-France Commission K), Alexandre Legros (secretary of BEMS), and Florence Poulletier de Gannes, Philippe Lévêque. This community gathers every year at a one-day meeting organized in Paris by Joe Wiart, who from 2014 was also the Chair of the URSI Commission K, exceptionally for two consecutive mandates.

The areas of interest of the French Bioelectromagnetics community are related to the interaction of electromagnetic fields with biological objects. However, they cannot cover all the aspects of this subject and are focused in several domains.

Among them, the effects of the mobile phone signals (nowadays extending to the 5G) were explored, in particular the aspects related to sleep and thermal regulation in vivo in rats (R. de Sèze, INERIS, Verneuil En Halatte) [39]. Novel techniques to explore in vitro potential cellular reactions to EMF exposure were investigated using Bioluminescence Resonance Energy Transfer (BRET) approaches (Yann Percherancier, IMS, CNRS, Bordeaux) [40]. The effects of millimetric waves were explored at a cellular and molecular level (Yves Le Dréan, Maxim Zhadobov, CNRS, Rennes) [41]. They were found to exist and were solely dependent on the thermal effects of the radiation [42, 43]. The potential issues with body-implantable antennas [44], able to collect information from your body through specific sensors and then transmit this information, are studied by M. Zhadobov and his colleagues.

The French have contributed in short and intense electric or electromagnetic pulses. In a world-wide competition, two French teams lead respectively by Marie-Pierre Rols and Justin Teissié from the IPBS laboratory of CNRS at Toulouse, and by Lluis M. Mir from the VAT laboratory of CNRS at Villejuif, have shown particular skills advancing this. The main effect explored is the perturbation of the cell membrane structure when the cells are exposed to pulses [45]. The effect is broad as it can occur not only using DC pulses of durations extending over more than seven orders of magnitude (from a few nanoseconds to several hundreds of milliseconds), but also electromagnetic waves up to several tens of kilohertz in vitro [46], and in vivo [47]. Of course, the amplitude of the signal will be different as a function of the pulse duration, the number of pulses, and the repetition frequency in the case of the application of more than one pulse (mostly, only a low number of pulses is delivered) [48]. Typically, the magnitude of the electric field (or of the electric component of the EM wave) can extend from several thousands of V/m to several millions of V/m in the case of the ultrashort pulses of e.g., 10 nanoseconds duration. Indeed, the effects that are explored are always below the thresholds that can generate thermal effects. Thus, the effects that are explored are not related to the Joule effect and all its consequences on the living cells components (e.g., protein denaturation) or physiology (e.g., cell structures disruption).

Because the cell outside and the cell inside are conductive media (due to the presence of ions that are necessary to the functioning of the biological molecules and structures), and because the cell membrane is a strict insulator (due to its hydrophilic core, which is a strong barrier that cannot be crossed by water or ions), the voltage differences imposed by the external electric/electromagnetic pulses concentrate at the level of the cell membrane. The cell membrane is thus a kind of antenna that amplifies the voltage differences applied. For a classical eukaryotic cell with a radius of 10 µm, the amplification can reach a factor of 2 000. The membrane is, therefore, the target of the pulses and the consequence is that above given thresholds in pulse amplitude, pulse duration and number of pulses, the membrane loses its impermeability to water, to ions, and to other water-soluble molecules. For electrical engineers, it can be compared to a capacitance that reaches its breakdown voltage. This phenomenon is primarily known as cell electroporation, also termed cell electropermeabilization or cell electropulsation. Under appropriate pulse conditions, the phenomenon is fully reversible, meaning that the cell membrane fully recovers its impermeability a few minutes after pulse delivery. Of course, under more drastic conditions, the cell membrane structure cannot recover from the electrically-driven perturbation and the phenomenon, termed irreversible electroporation, leads to cell death in spite of the fact that it remains basically a non-thermal effect [49].

In order to describe, understand, and analyze all the aspects of cell electroporation, Mir's team (primarily biologists) benefited from extended multidisciplinary collaborations in France (and abroad as well), with electrical engineers (P. Leveque, CNRS, Limoges; Riccardo Scorretti, ENS Lyon), mathematicians (Clair Poignard, INRIA, Bordeaux), chemists (Mounir Tarek, CNRS, Nancy), and not forgetting the collaboration with the Rols' biologists group. Only an interdisciplinary approach was possible to explore such a complex phenomenon as the interaction of the electric/electromagnetic pulses with the cells in vitro and in vivo. These results also shed light on the interactions with less intense fields, or with other types of electromagnetic pulses or waves.

The major interest in this research lies in applications of the phenomenon to medicine and biology, as well as in the food and environment industry, e.g., the involvement of the French groups in the International Society on the Electroporation-Based Technologies and Treatments. In the year of URSI's centenary, 2019, the 3rd World Congress on Electroporation and Pulsed Electric Fields in Biology, Medicine and Food & Environmental Technologies was organized in Toulouse by M.-P. Rols and Eugene Vorobiev. In medicine, the anti-cancer treatments based on cell electroporation, conceived by L. M. Mir, have continued to spread both in human and in veterinary clinics. The electrochemotherapy is based on the reversible electroporation of the tumor nodules after the injection of a non-permeant cytotoxic drug to the patient, the bleomycin that will kill only the electroporated cells when they divide, thus basically the tumor cells, and not the normal cells nearby. The treatment is almost devoid of side effects, and it is highly effective (irrespective of the tumor origin, on the average about 70 to 80% of the treated nodules completely disappear after a single treatment session, and the treatment can be repeated). L. M. Mir, who invented the electrochemotherapy in 1991 [50] and brought this treatment into clinics afterwards [51], received the URSI Balthazar van der Pol Gold Medal in 2017, during the Montreal GASS.

5. URSI Awards

From the first days of URSI, France existed at its core (remember that its first President was French). The impetus inherent in this participation has stimulated research in the domains of URSI and, as a result, has given France a leading role in radio science. The recognition of the merits and advances by some scientists led to a number of URSI awards, with the first being given in 1987.

- In 1987, Roger Gendrin received the John Howard Dellinger Medal for “Study of waves of natural origin propagating in the surroundings of the Earth, and their influence on the behaviour of the magnetosphere”

- In 2005 Didier Massonnet received the Appleton prize “For his outstanding work on radar imaging and satellite radar interferometry, a technique combining high frequencies, propagation and digital signal processing”

- In 2014, Francesco Andriulli received the Isaac Koga Gold medal “For contributions to computational electromagnetics, specifically the development of preconditioned and stable integral equation solvers”

- In 2014, Jean-Pierre Berenger received the John Howard Dellinger Medal “For seminal work on the development of breakthrough absorbing boundary conditions for computational electromagnetics in radiosciences”

In 2017, Lluis Mir received the Balthasar van der Pol Gold Medal “For leadership in Pulsed Electric Fields Applications in Biology and Medicine: fundamentals of cell electroporation in vitro and in vivo, and development of anti-tumour electro-chemotherapy, from inception to clinical use.”

6. Education in Radio Science and Dedicated Institutes

One of the specialties of French higher education was the creation of engineering institutes, under the control of technical ministries that were sometimes two centuries or more old. Thus, radio science had a long track record in education and research in France, which hopefully will continue into the future.

In particular, in 1878, under the French President MacMahon, Adolphe Cochery, Director of the service of Posts and Telegraphs, created the Superior School of Telegraphy, whose first director was Ernest-Édouard Blavier. Later, the school moved to rue Barrault in Paris and became ENST (today Télécom Paris). The development of telecommunications during this period led the State to create two sister schools: in 1977, the National School of Telecommunications of French Brittany (ENST Bretagne, today IMT Atlantique); and in 1979, in Brest, the National Institute of Telecommunications (INT, today Télécom Sud Paris), in Evry.

Éleuthère Élie Nicolas Mascart established the École supérieure d’électricité (now part of CentraleSupelec) and the adoption of international electrical units. General Ferrié brought its development to the formation, in 1912, of a TSF section at the École supérieure d’électricité. The school was a veritable nursery for radio operators and its development provided highly qualified personnel for the public service, civil aviation, the merchant marine, the Citroën Yellow Cruise in 1931, and Paul Emile VICTOR’s polar expedition. The first public transmission of television in France took place in 1931, with a resolution of 30 lines (based on the development of Fernand Holwek jointly with Edouard Belin in 1927) between the laboratory of the Compagnie des compteurs and the amphitheater of the École supérieure d’électricité, then located at Malakoff. Also, the word television first appeared in 1900, on the occasion of the international congress of electricity, as part of the Universal Exhibition of Paris [3].

The Central School of TSF (Wireless Telegraphy), after the First World War, was born in 1919, in Paris, under the leadership of a young petty officer, Eugene Poirot and has the current name, ECE. In 1926, Mr Lavigne, his instructor in Morse, left and he became the director.

Aside from these specialized institutes delivering the grade of Master in Engineering, radio science is taught widely in basically all scientific universities in France, a number of them having engineering institutes as one of their components (e.g. Phelma as part of Grenoble INP, Télécom Saint-Etienne, Télécom Strasbourg). Some institutes are also separate or private, such as ESIEE in Marne La Vallée, ISEP in Paris, EFREI in Villejuif or ISEN Group of schools, and others.

7. Conclusion

This chapter has attempted to highlight a set of important people and activities related to radio science and to the history of URSI in France. This is, obviously, far from exhaustive and it is genuinely hoped that it will be understood as such, especially by un-named researchers, if they are still alive, or by their relatives. This caution applies also to laboratories and scientific domains, obviously, as URSI has a large spectral width (expressed by its 10 Commissions) and cannot be summarized in a few pages.

In conclusion, we hope that these few pages will bring a positive, although limited, insight into the historical role of France in radio science.

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100 Years of URSI and Radio Science in Germany

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1. Introduction

In 2019, the International Union of Radio Science (URSI) was founded in Brussel, Belgium, exactly 100 years ago. Subsequently, scientists have united in this organization making numerous, significant contributions to radio-science research and to this day it is an honor for countries to be a member of URSI. This also applies to Germany, which at the end of the 19th century independently contributed to the development of radiotelegraphy and participated in wireless-communication research. Heinrich Hertz, for example, contributed decisively to the discovery of electromagnetic waves in 1886-88, laying the foundation for the development of radio science. However, that was just the end of a development that began with James Clerk Maxwell’s work on the electromagnetic field. He described electromagnetic waves around 1864. In the following years Maxwell‘s theory was studied by a small international group of scientists, mainly from England, France, Russia, Italy, and Germany. Gradually, they understood the significance of the new theory of electromagnetic fields. They were the so-called Maxwellians: Oliver Lodge, Oliver Heaviside, Henry Poynting from England, Professor George Francis FitzGerald from Ireland; Henri Poincaré and Édouard Branly from France; Alexander Stepanowitsch Popow from Russia; Augusto Righi from Italy; and Hermann von Helmholtz, H. Hertz, and Braun from Germany. This small group of scientists from different countries worked theoretically and experimentally with the new concept leading to a new way of communicating using electromagnetic waves. Their contribution was the essential foundation for the later Nobel Prize winners: Guglielmo Marconi and Ferdinand Braun. In reality, the theory of electromagnetic waves and their applications were only successful through international scientific cooperation.

The first steps to manage the high-frequency electromagnetic-wave spectrum were taken in 1903 and 1906 [1] at the International Wireless Telegraph Conferences in Berlin, and in London, 1912 [2, 3, p. 41, 4]. However, scientific research in the field of electromagnetic-wave propagation was not a focus of these conferences and cooperation was interrupted by the First World War.

The historical development of URSI has been described in some detail in the past by significant members of the URSI [5-9] but because many sources were unavailable German participation could not always be presented in detail. Currently, Albrecht’s contribution [10], on the history of German participation in the URSI, is available. However, it is written in German, and in incomplete in terms of German membership before World War II. That will be made covered here. In addition, we want to highlight German contributions to URSI activities in radio science, which were achieved during German membership. Also, the URSI Member Committee organization in Germany following its resumption in 1954 until today will be addressed.

Figure 1. Robert B. Goldschmidt (public domain, Wikipedia).

Figure 2. Karl Franz Eduard Schmidt (University Halle).

2. Scientific Telegraphy Before 1919

G. Marconi, Adolf Slaby, and F. Braun's early experiments with wireless telegraphy showed that the range and propagation of electromagnetic waves in free space raised a number of questions. These became even more urgent when in 1901 Marconi unexpectedly managed to create a wireless link between Europe and America.

Initially, some papers on this topic appeared. In 1909, Arnold Sommerfeld, in his paper "On the Propagation of Waves in Wireless Telegraphy" [11] summed up the state of research of the time and added his own thoughts. He addressed two current points of view, namely: Max Abraham's work that investigated the propagation of electromagnetic waves as a space wave; and the reflections of André-Eugène Blondel and Ernst Lecher who expressed the view that "wireless telegraphy is about an analogue to the wire waves and that the earth has a significant influence on the propagation of waves" [11, p. 667].

This idea was elaborated in several works by Jonathan Zenneck. Arnold Sommerfeld's doctoral candidate Herman William March also dealt with the subject in his dissertation, in 1911, and also referred to the work of John William Nichelson and H. Poincaré from 1910, who found that "assuming a completely conductive earth the results of practical wireless telegraphy are inexplicable since the amplitude of the waves is attenuated very rapidly (namely exponentially)" [12, pp. 29-30]. It became clear that despite some early progress, there were no easy solutions.

Around 1912 the first ideas on how such problems can be tackled internationally were considered. According to an article in *Nature*, July 6, 1914 [13], the Belgian chemist and science organizer Robert B. Goldschmidt (Figure 1) and the German physicist Prof. Karl Schmidt (Figure 2) from the University of Halle, developed the idea to explore the scientific foundations of wireless telegraphy in a European network at the Conférence Internationale De l'Heure, in Paris, in October, 1912 [14, 15].

Goldschmidt's first activities in the field of wireless telegraphy went back to 1907 when he drew attention to radiotelegraphic experiments from the Brussels justice palace. Together with the French engineer Raymond Braillard he was commissioned by the Belgian King, Albert I, to create a wireless connection to the Belgian Congo. A corresponding radio station was built in the royal palace of Laeken [16, 17]. K. Schmidt, 1903, had studied the physical fundamentals of wireless telegraphy and had written numerous papers on various problems.

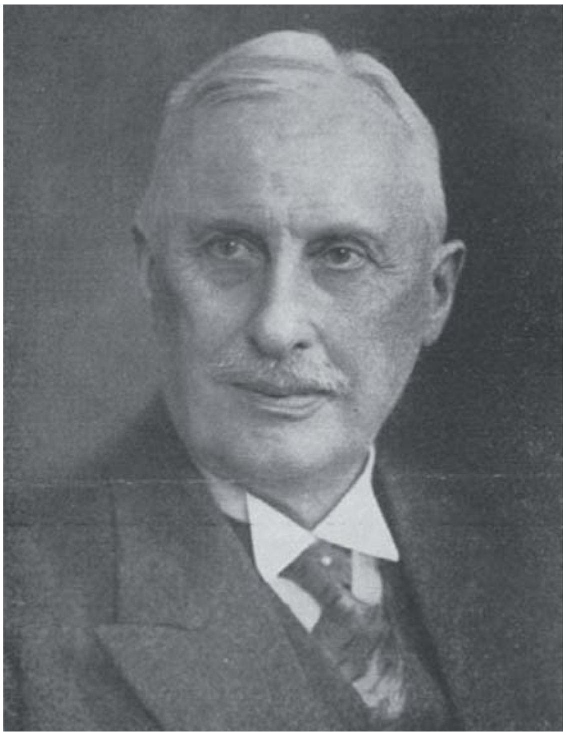

Figure 3. Max Wien (Karl-Willy Wagner [85]).

A first meeting of a group of scientists took place in October 1913, in Brussels, and formed the CITSFS (Commission Internationale de Télégraphie sans Fil Scientifique) [13]. A provisional committee was established along with the general rules for the organization. It was also decided that Goldschmidt's station in Brussels should send out electromagnetic signals at regular intervals to be intercepted and measured by experimenters in Belgium and other countries. An executive board was also elected in Brussels: President William Duddel (UK), Vice-President Max Wien (University of Jena) (Figure 3), Secretary-General Robert B. Goldschmidt and his deputy R. Baillard. Another German member of the Commission, besides K. Schmidt, was Karl Vollmer (University of Jena), from France professors Gustave Ferrié and Henri Abraham, and Prof. Vanni from Italy were members of the commission. The first national committees in Belgium, France, and Great Britain were already established and committees followed in Germany, Austria, Russia, Italy, and Switzerland. This was the last meeting of the CITSFS because shortly afterwards, in 1914, World War I began and the commission was unable to continue its work. Wireless communication immediately became a means of warfare for the Central Powers as well as for the Allies. The telegraphy station in Leaken was also a victim of the beginning of World War I because "on Wednesday, August 19, of the year 1914 the most contradictory rumors reached Brussels. Some folks affirmed that the Germans were at Louvain and would not stay to enter the capital" and therefore, Brussels Radio Station was destroyed in 1914 [18].

In 1912, in the United States, there were two smaller groups dealing with wireless telegraphy and telephony: The Wireless Institute, and The Society of Wireless Telegraph Engineers, with their leading representatives, Alfred N. Goldsmith, John V.L. Hogan, and Robert H. Marriott. A new organization, The Institute of Radio Engineers (IRE) was founded in 1912 [19] and Marriot became its first President. During World War I wireless telegraphy increasingly became a key technology for all belligerents and international cooperation was no longer possible. Although commercial wireless communication technology was dominated by the American Marconi Wireless Corporation until the beginning of the First World War, the English parent company owned only 25% of that company. The largest shareholder was General Electric. General Electric and AT & T developed the concept of the high vacuum electron tube [20] based on the earlier concepts of Fleming, de Forest, and von Lieben, which radically changed wireless technology in a few years [21] and then the new technology was used also by European companies such as Siemens & Halske [22] and Telefunken [23] in Germany and Philips in Holland. In particular, AT & T's Bell Laboratories pursued an advanced approach to industrial research. By 1917, electron-tube-based wireless communication technology had evolved and became crucial in the final phase of the war, when the US entered.

3. Foundation of the URSI in 1919 and German Telegraphy Scientists

With the onset of the First World War virtually all international relations between the scientists in the enemy camps was interrupted. Since the German academies played an important part in the organization of scientific exchange the entire system of international relations in the scientific fields collapsed. The world was not only divided into Central Powers, Allies and Neutrals, but in October 1914 ninety-three major German scientists published an outrageous patriotic manifesto "To the Cultural World" (Manifesto of the Ninety-Three) [24, 25] which complimented another 3000 professors. After all, many of the scientists in the respective armies worked to win the war for their country. In doing so, they followed the path described in the Manifesto causing hitherto unimaginable destruction. The delicate international band of science was torn by this manifesto of German scientists, which these days mirrors the view of the moderately irrational reasons leading to the First World War [26].

Clearly, international scientific cooperation needed reorganizing after the war. The state of cooperation at the end of World War I was presented in an article in 1919 by Campbell who described the creation of the International Research Council (IRC) in detail [27]. In October and November 1918 representatives of the leading academies of the major Allied nations had meetings in London and Paris and in July 1919 the IRC was formed in Brussels [28] with an executive committee formed by representative of Britain, France, Belgium, USA, and Italy. The former Central Powers: Germany, Austria, Hungary, and Bulgaria were excluded by statute while former neutral countries were to be admitted only by a three-quarters majority vote [28, p. 249]. Then the new Council promoted the founding of international unions such that Unions of Astronomy, of Geodesy and Geophysics, of Pure and Applied Chemistry, of Mathematics, and of Radio Telegraphy were formed in 1919 [29]. One of these unions was the International Union of Scientific Radio Telegraphy that was founded in July 1919 [30]. To become a member of one of these Unions a country had to be a member of the IRC so that Germany and the other Central Powers could not be members of URSI. Consequently, Germany was not represented at the 1922 URSI General Assembly, or the meeting of the Interallied Technical Committee for Radiotelegraphy, held in the summer of 1921 with representatives from the United States of America, France, Great Britain, Italy, and Japan. In addition, the Treaty of Versailles had stipulated

> If within five years after the coming into force of the present Treaty a new convention regulating international radio-telegraphic communications should have been concluded to take the place of the Convention of July 5, 1912 this new convention shall bind Germany even if Germany should refuse either to take part in drawing up the convention, or to subscribe thereto [31]. This restriction did not disappear until January 1925 [32].

Although there was opposition to the exclusion of the former Central Powers it took years before the Statute of the IRC was changed, in 1926. After a relatively complicated development described in detail by Cock [28, p. 264] the participants of an Extraordinary General Assembly in June 1926 unanimously decided to invite the leading academies of the former Central Powers, Germany, Austria, Hungary, and Bulgaria to join [29; p. 391, 33].

However, against the wish of the German Government, the German Academies, in particular, vigorously rejected the invitation. Hungary and Bulgaria joined IRC in 1927 and 1934, respectively. The main reason for the decision by German academies was that only one of their four conditions were satisfied by changing of the IRC statute. Another condition was

> that not only should the regulation banning German entry be annulled, but that it should be declared that the reasons for excluding Germany were annihilated. Cock commented that the intention was apparently to avow that there never had been any valid reason for keeping Germany out [28, pp. 267-268].

The academies of Austria were ready to join IRC in 1926, but only if Germany would join. This could not be accepted by the IRC Executive Committee at that time, which was quite understandable in view of the 1914 manifesto by German scientists. Nevertheless, Sir Austen Chamberlain said, at the dinner given by the British Government to the delegates of the International Geographical Congress at Cambridge (held from July 18-25, 1928),

Figure 4. Karl-Willy Wagner (TU Berlin, Institut f. Nachrichtentechnik).

Figure 5. Jonathan Zenneck (Public Domain, Wikipedia).

> German statesmen had been welcomed to the Society of Nations as colleagues and as friends; they had contributed fully to the discussions and he hoped that before long German men of science would accept the welcome which awaited them. If a solution of the present difficulties can be found and they are enabled thereby to accept the invitation to join the Research Council they will be able to take part in the discussions on the existing statutes and to assist in drafting such modifications in them as will make for the greater efficiency of the organization as a whole [29, p. 391].

Austria joined the successor to the IRC, ICSU, in 1949, the Federal Republic of Germany in 1952, and the German Democratic Republic in 1961 [28, p. 268].

Although Germany was not a member of the IRC, members of the URSI Executive Council apparently tried to convince German scientists to work with URSI. Such an opportunity arose during the International Radio Consultative Committee (CCIR) meetings in The Hague between September 9 and October 10, 1929 [34]. The President of URSI, the French General Ferrié, and the Secretary-General of the URSI, Robert Goldschmidt, contacted Karl Willy Wagner (Figure 4), the President of the Heinrich-Hertz-Society for the Promotion of Radio Wave Engineering, in order to talk to him about German scientists participation in URSI. URSI took an active part in the creation of the CCIR, as Struzak, Tjelta, and Borrego wrote in their article on the history of radio-frequency management. The second URSI General Assembly, and the ITU radio conference in Washington in 1927, were jointly organized and URSI took an active part in the creation of the CCIR [2]. However, Wagner was reluctant since, as he wrote later on to Zenneck, the question of the participation of German scholars in URSI did not seem to be sufficiently clarified [35]. Another attempt was made by URSI, concerning the CCIR meeting in Copenhagen, from May 27 to June 8, 1931.

URSI President Ferrié wrote a letter to B. van der Pol, on May 19, 1931, in which he started as follows

> According to the statutes of URSI, the president of science men can definitely invite to general meetings, if these scientists belong to the countries that belong to the URSI, or may belong to the URSI, which is the case with German Scientists. It is therefore with the greatest pleasure that I will make these invitations [36].

Ferrié asked URSI Secretary-General Goldschmidt to write a letter to some German scientists including an official invitation especially to Wien and Wagner who were already known to him. Goldschmidt sent a letter of invitation to Wagner on May 21, 1931 [37]. In this letter Goldschmidt emphasized that this invitation was expressly addressed also to Wien, Barkhausen, and Zenneck (Figure 5) since their addresses were not available to him.

Receiving Goldschmidt's invitation from Wagner, Zenneck [38], Wien, and Barkhausen informed Wagner they opposed the invitation, drawing attention to what they considered was a lack of recognition by URSI of German scientists in the field of wireless technology, and the very late date of the invitation. Wagner wrote in corresponding letters [39] to Barkhausen and Zenneck that URSI was not opposed to German membership in terms of its statutes and that URSI leaders were already trying to get Germans involved. An obstacle would be, as already stated, the lack of membership in the IRC, which was rejected by the German side. Finally, only Wagner participated in the CCIR meeting in Copenhagen where he heard of the letter from Barkhausen to B. van der Pol on 30 May 1931 in which Barkhausen probably expressed clear criticism of the URSI. On 3 June 1931, still from Copenhagen, Wagner wrote to van der Pol [40] that he repudiated the letter by Barkhausen and explained to him the state of relations between Germany and URSI. He emphasized that URSI President General Ferrié and all the participants deeply regretted the absence of Wien, Zenneck, and Barkhausen. Wagner hoped that Barkhausen's letter would not seriously affect relations with URSI.

It has already been pointed out that German engineers and scientists had made numerous contributions to radio technology in the context of URSI. The scientific understanding of the physical processes that make wireless telegraphy and telephony possible was of primary importance. In particular, the propagation of electromagnetic waves over long distances was the focus of many scientists working together in URSI. Zenneck, a former colleague of Braun, worked on scientific topics in the field of radio technology from an early stage and it is no coincidence that from the beginning he participated in discussions on Germany's admission to URSI. As Zenneck's biography shows [41] his outstanding radio science achievements were recognized by foreign colleagues. In December 1914, Zenneck, together with Braun, traveled to the United States as a patent expert and was arrested as a dangerous alien enemy, in April 1917, after the US entered World War I. He was interned in the United States from where he could not return until July 1919. The outstanding reputation that both Braun and Zenneck had among their peers in the United States was highlighted by Fellow grades awarded to both of them by the then recently-founded Institute of Radio Engineers [19, p. 604]. In 1915 Zenneck published the influential monograph "Wireless Telegraphy" [42], which was a heavily revised translation of his well-known 1905 monograph [43]. In 1928, Zenneck was selected as a recipient of the IRE Medal of Honor, which he received "for his contribution to original researches in radio circuit performance and to the scientific and educational contributions to the literature of the pioneer radio art" [44].

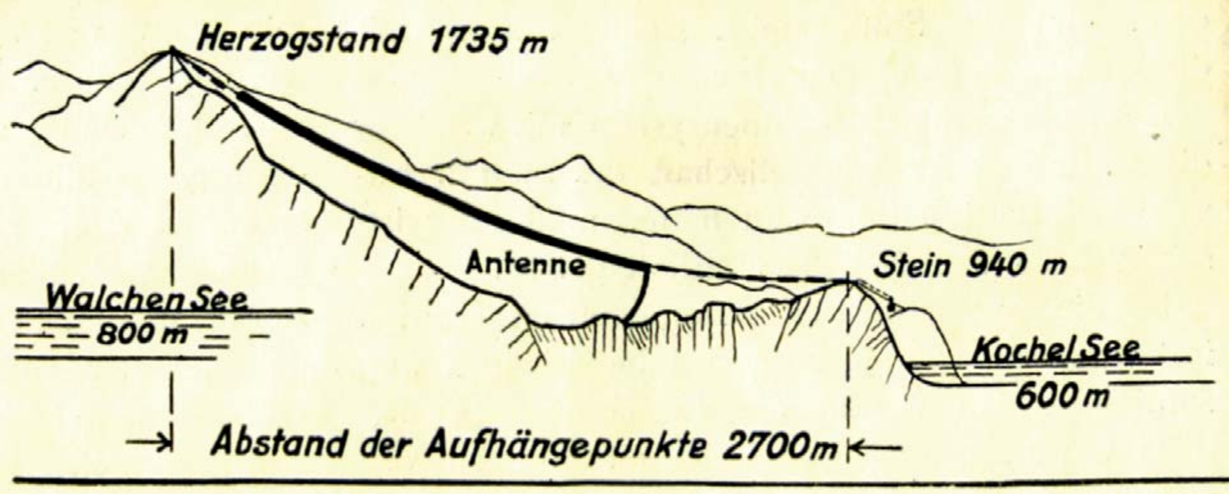

Figure 6. Mount antenna at Herzogstand 1926 (Otto Scheller [80, p. 242]).

In the late 1920s Zenneck began a new research area, which was later called ionospheric research. Walter Dieminger described the situation in a 1974 article as follows:

> After 1924, when Appleton and Barnett in the U.K., and Breit and Tuve in the U.S.A. had experimentally proven the existence of a reflecting layer in the upper atmosphere, three groups in Germany immediately became interested in the study of the phenomena involved. (One of these groups was Zenneck's group at the Technical University Munich) and furthermore: Early in the thirties a fourth group became active at the Heinrich-Hertz-Institut in Berlin under the leadership of [Gustav] Leithäuser one of the German pioneers in radio science [45, 46].

Zenneck's group started echo soundings by radio waves, studied the variation of the refractive index of gases for centimetric wavelengths in the presence of ions and electrons, and the optical equivalent of radio wave propagation in a layered medium. The method of echolocation was systematically studied at Herzogstand [47-49, 50], in the Bavarian Alps, where Zenneck formed a research group that included many young researchers such as Johannes Plendl, Georg Goubau, Walter Dieminger, Rudolf Eyfrig, and Karl Rawer. They were not only important for ionospheric research, but also contributed to the establishment of the new URSI National Committee of the Federal Republic of Germany after World War II. From 1930 onwards, the broadcast station built by C. Lorenz AG [51], in 1920, (Figure 6) was opened for research at the Physics Institute of the Technical University of Munich. In 1934, permission to use the station Herzogstand was once again extended by the Reichspostministerium [52].

Dieminger described the fourth group's work, above, as follows:

> It was this group which, following a recommendation of Wagner (1934), sent the German expedition to Tromsö during the Second Polar Year where it met Appleton and his team from the U.K. [45, p. 2090] [53,54].

Other groups worth mentioning were K. Försterling, H. Lassen, and H. Rukop of the University of Cologne; E. Quäck and H. Mögel from the Telefunken company; and F. Vilbig and his co-workers from the German Reichspost.

It is obvious that these research groups and their results [45] were of great interest to the scientists organizing URSI.

The next official contact by Goldschmidt, the URSI Secretary-General, was recorded in a letter on December 1, 1933 [40]. Zenneck was offered a timely invitation to attend the General Assembly in London, which took place 12 to 19 September 1934. However, even though Zenneck received the invitation in time, after a long period of reflection, he declined the offer to participate. In his letter [55] no indication can be found whether he had changed his rather restrained attitude to URSI.

The new URSI president, Edward V. Appleton, proceeded on the same line as his French predecessor, General Ferrié, but now the Secretary-General, Goldschmidt, wrote a letter [56] to the German Ministry Der Reichs und Preußische Minister für Wissenschaft, Erziehung und Volksbildung on February 24, 1935. The letter began with the following statements:

> We would like to ask you to consider the possibility of international cooperation between German scientists interested in scientific radio-telegraphy and those who are currently members of the National Committees affiliated to our Union

and furthermore

> According to our new statute, this cooperation could be realized through the creation of a German National Committee (Comité National Allemand), which joins our union.

On June 1, 1935, the Ministry designated Jonathan Zenneck as the German URSI representative and appointed three other members to assist Zenneck [57]. Although Zenneck was grateful for his appointment as the German URSI representative, he was concerned about some of the other representatives. It took almost a year of intense discussion with the Ministry before Zenneck found acceptable compromises. Finally, on February 6, 1936, the Ministry convened a select group of experts interested in scientific radio technology for a founding meeting of the German URSI Member Committee, which took place on March 5, 1936 [58]. The German Member Committee statute was sent as an attachment to this letter. In the protocol of the founding meeting the Ministry was represented by Ministerialrat Mentzel and the chairman was Zenneck [59]. Furthermore, the areas of responsibility of the five Commissions and their subgroups were defined in more detail and corresponding experts in Germany were identified. The Ministry representative reported that the contribution to URSI, which, according to the statutes was eight unitary units for countries of more than 20 million inhabitants, corresponded to a vote of five to be taken by the Ministry. Germany thus would have made a contribution of 800 Goldmark. Finally, the protocol was accompanied by a list of the participants at the meeting. It contained a total of 25 names, including Heinrich Himmler's brother, who was a senior engineer at the Reich Broadcasting Corporation, some specialists in military radio technology, and some well-known wireless telegraphy and telephony scientists such as Heinrich Barkhausen (TH Dresden), Leo Pungs (TH Braunschweig), Hans Rukop (Telefunken-Gesellschaft für drahtlose Telegraphie m.b.H.), Jonathan Zenneck (TH München), and Hans-Georg Möller (University Hamburg) all of whom had accepted Invitations to join the new committee [60].

In a letter [61] dated May 5, 1936, the Ministry informed Zenneck of his appointment as chairman of the German URSI committee and he immediately expressed his thanks [62]. In a further letter [63], June 2, 1936, URSI President Appleton thanked the Ministry for the establishment of the German National Committee and highlighted its appointment of high-level scientists including the appointment of Professor Zenneck as the new Chairman. On March 12, 1936, the Deputy Secretary-General, A. Dortimont, from the URSI office in Bruxelles, said to the Ministry: "It is with great satisfaction that our Union is aware of your decision on the forthcoming official creation of a German National Committee of the URSI" [64]. In the following months the Ministry appointed some of the chairmen and deputy chairmen of the German Commissions. However, Zenneck was unable to send the full list of committee chairmen [65] to URSI Deputy Secretary-General Dortimont before October 28, 1936, although his letter [66] was already written by June 2, 1936, with questions on the constitution of the German National Committee.

The correspondence in the estate of Zenneck shows that he was very active after taking office as President of the German National URSI Committee. He coordinated the exchange of measurements by German scientists with URSI and repeatedly promoted the purchase of Comptes Rendus General Assemblies by German institutions. Undoubtedly, strengthened by these activities Zenneck was able to go to the URSI General Assembly, which took place from 4 to 14 September 1938, in Venice and Rome in Italy [67]. The first participation by a German National Committee delegation was a great success because, from their reports [68], the delegation was greeted warmly by the President and the Secretary-General of URSI and also the scientific committees were formed including German members. Zenneck was unanimously elected as one of the Vice Presidents of URSI.

After the General Assembly, further activities of the German National Committee are documented in Zenneck's estate. However, almost exactly a year later the Second World War began with the German troops' attack on Poland and the subsequent declaration of war by France and England. After the surrender of Poland followed more acts of aggression, first on the Benelux countries, France, and a little later on Denmark, Norway and England, which resisted the attacks, and finally the Soviet Union. As a result of the wars, Germany was responsible for the death of more than 50 million people. At the same time, after the appointment of Adolf Hitler as Reich Chancellor of the German Reich, the persecution and imprisonment of Germans with Jewish beliefs or relationships with these people, and many other groups, was extended to all conquered European countries. The beginning of systematic annihilation, especially of citizens of Soviet states with Jewish beliefs, after the beginning of the war of aggression against the Soviet Union by German troops and SS units, was extended to occupied Europe after the so-called Wannsee Conference. Extermination camps such as Auschwitz-Birkenau were created for the murders, which were now carried out on a factory-scale. Among the approximately 6 million people: children, women, and men of all ages, there were of course many scientists.

Among them was the French Professor Henri Abraham, who, from 1923 to 1927 [69, p. 149], was the first chairman of the URSI Commission On Radio Measurements and Standards, and Eugène Bloch. Abraham and Bloch were murdered in Auschwitz-Birkenau in 1943 and 1944 at the age of 75 and 76, respectively. Abraham was well-known because he, together with Eugène Bloch, had invented the multivibrator in 1919. It should be noted that the circuit was later referred to as flip-flop, which was invented by William Henry Eccles, a former president of URSI and first chairman of the Commission Atmospheric Disturbances [69, p. 148, 152], and Frank W. Jordan, was invented 100 years ago, just like the multivibrator.

At this point Henri Abraham and Eugéne Bloch should be thought of as two of so many who lost their lives and were murdered during 1933-1945.

Even after the beginning of World War II the URSI Secretariat, in Brussels, was able to continue its activities, at least in part until German troops attacked and occupied Belgium, in May 1940. J. Howard Dellinger, then one of the Vice Presidents of URSI, described the situation in the following manner:

> For four years mail service between England and Belgium was cut off, said President Appleton in London, and the Secretariat in Brussels had no communication. I wrote to the Brussels Secretariat in August 1940. Miss Streatmans, the office assistant, said that she was trying to keep the office open but that Commander Dorsimont (Acting Secretary-General) and Major Herbays (Editor) were prisoners of war in Germany [7].

From Zenneck's estate it appears that in a letter dated July 29, 1940, to the Ministry of Science, Education and Popular Education, he sought the release of Secretary-General Dorsimont but to no avail [41, p. 455]. Dellinger proceeded [7, p. 318-319] that "URSI work in the National Committees in the various countries also declined to nearly zero…but....The spark of life was not extinguished."

4. URSI After World War II: The Accession of the Federal Republic of Germany

In 1945, the terrible Second World War ended and international activities in radio science could be resumed within the framework of URSI. The General Assembly, delayed by six years, took place in Paris in September 1946. The German National Committee and its President Zenneck were not invited. This was understandable after the war's devastating consequences for the whole world and the undoubted responsibility Germany had for it.

Figure 7. Walter Dieminger (Hartmann [67]).

Figure 8. Karl Rawer (privately owned Bernhard Rawer).

Like in Paris, Germany was not represented at the following General Assemblies in Stockholm (1948), Zürich (1950), and Sydney (1952). Meanwhile, two German states had formed in 1949: the Federal Republic of Germany (FRG) and the German Democratic Republic (GDR). Parts of the former German Reich were administered by the Allies: England, France, the Soviet Union, and the USA. As a consequence, continuing Germany‘s membership in URSI was not possible and a new attempt had to be made to involve German scientists internationally in radio science.

The initiative for further cooperation in URSI was taken up by the members of Zenneck's Ionosphere Research working group, who originally worked in the research institution at Herzogstand. Up until 1945 Zenneck and Goubau devoted themselves to exploring the ionosphere at Herzogstand while many of their scientific staff left his group after completing their academic work and took up new positions. In 1937, Dieminger (Figure 7), was working in the German Air Force radio navigation testing center, in Rechlin (Mecklenburg). In 1943, as Head of the Central Office for Radio Consultancy (Z.f.F) in Leobersdorf, in Lower Austria, he made radio predictions for the German Wehrmacht. In 1939, K. Rawer joined Dieminger‘s group and followed him to Leobersdorf. Of course, this service ended in 1945, at the end of the war. From the end of 1944 until the beginning of 1945 the central office settled (for military reasons) to Ried (Austria) and was then renamed Fraunhofer-Institut Ried im Innkreis [70].

After the war, the military part of the Z.f.F., including Rawer (Figure 8), was moved to Kochel and handed over to the American army. Then, as Bodo Reinisch and Kristian Schlegel wrote

> At the end of the war in 1945, Rawer's group accepted the invitation of Yves Rocard in Paris to establish an ionospheric prediction service in Germany's French Zone. In spite of the difficult postwar conditions an ionospheric vertical incidence sounding station came to life in 1946 at Schloss Neuershausen near Freiburg under the auspices of the French Service Prévision Ionosphérique de la Marine (SPIM) [71,72].

The remaining part of the Z.f.F., including Dieminger, remained in Ried in the Inn Valley, i.e., in the Soviet zone in Austria, but was transferred by the British army to Lindau/Harz in the British zone, in February 1946 [73]. In his historical sketch of URSI Germany H. Albrecht summed up:

> So it was possible that two from the German Z.f.F. merged Research groups continued to work in the civil field on the very important field of prediction for wave propagation across the ionosphere and to establish research institutes, namely the Institute for Ionospheric Research in Lindau/Harz under W. Dieminger in the British zone and the Breisach Ionosphere Institute under K. Rawer in French occupation area. [10, p. 9].

To facilitate data exchange, the Ionosphere Working Group, founded in 1950 from Dieminger and Rawer's institutes, was joined by the central telecommunication office (FTZ) of the Deutsche Bundespost, from Darmstadt, the German Hydrographic Institute, from Hamburg, and the Central Office for Weather Service, from Bad Kissingen [10, p. 9]. The first working group meeting took place on May 1, 1950, in the training center of the German Federal post office in the castle Löwenstein, in Kleinheubach, near Miltenberg (Figure 9). Research institutions from both German states participated in the Ionosphere Working Group. Following the former BDR policy, the participants from the GDR were described as participants from the East Zone. In 1951, at the next conference, which was now called Kleinheubacher Tagung, a provisional German URSI Landesausschuss was founded and the honorary chairman was Geheimrat Zenneck [74]. At the 1952 URSI General Assembly, in Sydney, Australia, the German Research Foundation (DFG) applied for admission of a National Committee of the Federal Republic of Germany to URSI. This was accepted by URSI members [10, p. 9]. From that time, the annual

Figure 9. Schloss Löwenstein, in Kleinheubach (photo Rainer Lippert, Wikipedia [83]).

Figure 10. Miltenberg, on the river Main (photo Wolfgang Mathis).

contribution to URSI was paid by the DFG. In Braunschweig, June 6, 1953, the URSI National Committee of the Federal Republic of Germany was formed with Dieminger as President and Leithäuser (TH Berlin) as Vice-President [75]. The Ionosphere Working Group, with E. Regener as its chairman, initially continued to exist in parallel [76]. At the 1954 URSI General Assembly, in The Hague, the admission of German scientists from the FRG into URSI was achieved. The 1954 URSI General Assembly was extensively reported at the 1954 Kleinheubacher Tagung.

5. The German Participation in URSI Since 1954

After the admission of the German Member Committee to URSI its members worked swiftly on the structure of the URSI Commissions, which had been adopted at the 1948 Stockholm General Assembly:

I - Radio Measurements and Standards
II - Radio and Troposphere
III - Ionospheric Radio
IV - Magnetosphere
V - Radio Astronomy
VI - Radio Waves and Circuits
VII - Radio Electronics

The Member Committee, together with the Ionosphere Working Group, organized the annual Kleinheubacher Tagung, occasionally joined by the Communications Technology Association (NTG: Nachrichtentechnische Gesellschaft) of the Association of German Electrical Engineers (VDE: Verband Deutscher Elektrotechniker) acting as the official co-organizer. Up until the end of the 1970s the Kleinheubacher Tagung Conference was chaired by the Chair of the Ionosphere Working Group, who was appointed annually. Subsequently, the conference leader was elected by the German Member Committee General Assembly. In line with URSI's interests, the Kleinheubacher Tagung initially focused on electromagnetic-wave propagation and its associated areas. Over time, this was extended to encompass the entire telecommunications sector and the extended interdisciplinary fields of interest to URSI. [10, p. 12]. Contributions to the Kleinheubacher Tagung were compiled each year, after the conference, in the report series *Kleinheubacher Berichte* and published by the Deutsche Bundespost, later Deutsche Telekom AG.

From today's point of view, it is obvious that the emphasis on wave propagation, which naturally transcends borders and was handled by the Ionosphere Working Group, helped the German Member Committee to regain international prestige relatively quickly. The German Member Committee participated at the General Assemblies of Boulder (1957), London (1960), and Tokyo (1963) and contributed through the relevant Commissions to the International Geophysical Year 1957/58 and to the International Year of the Quiet Sun (IQSY) 1964/65. The topic of space research was particularly noteworthy. In addition, a reorganization of URSI was discussed at the 1963 Tokyo General Assembly. It was certainly a pleasure to host the General Assembly of 1966 in Munich. Perhaps it was also a late tribute to the former Vice President of URSI and Honorary Chairman of the German Member Committee, J. Zenneck, who had taught at the Technical University of Munich and had passed away in 1959.

At the 1966 General Assembly, in Munich, discussions about the reorganization continued. Initially, this led to the setting up of a separate Commission VIII entitled Radio Noise of Terrestrial Origin, an issue previously dealt with under Commission IV in Sub-commission IVa. In addition, two Commissions were renamed, i.e., Commission II was called Radio and Non-Ionized Media, and Commission III became Ionosphere. Some issues discussed by Commission I, as well as impressions and some photos from the General Assembly in Munich, can be found the National Conference of Standards Laboratories newsletter [77].

From a German point of view, there is another issue that arose at the Munich General Assembly. Until 1966 some research institutions in the GDR, such as the institutes in Potsdam and Kühlungsborn [78], were closely associated with the corresponding FRG institutions. The scientists from the GDR also participated in the FRG URSI Landesausschuss report to the Kleinheubacher Tagung, and their work were published. After the Munich GA this was no longer possible [10, p. 11]. At the 1969 GA, in Ottawa, Canada, an application was made from a GDR URSI national committee. In his Report of the International Union of Radio Science of XVI URSI General Assembly, 1969, the URSI Secretary-General, C. M. Minnis, reported that the German Academy of Sciences in Berlin (DDR) was admitted to represent its territory. Subsequently, at the 1972 Warschau General Assembly, the Nationalkomitee für Radiophysik und Radiotechnik der Deutschen Demokratischen Republik (NK URSI) (National Committee of Radio Physics and Radio Technique of German Democratic Republic) presented their own report. The first President of the NK URSI was Hans Frühauf (TH Dresden), Ernst August Lauter became Vice-President and Jens Taubenheim [79] was Secretary, both from the Heinrich-Hertz-Institut of the Deutschen Akademie der Wissenschaften zu Berlin (GDR). At the beginning of the 1980s Christian-Ullrich Wagner (Zentralinstitut für Solar-Terrestrische Physik (ZISTP) of the Deutschen Akademie der Wissenschaften zu Berlin (GDR)) was the next President, and in 1988 Matthias Förster (Astrophysikalisches Institut der Akademie der Wissenschaften der DDR (ZIAP) in Potsdam) became Secretary. In spring 1989 C.-U. Wagner passed away and Dieter Felske (Institut für Kosmosforschung (IKF) of the Deutschen Akademie der Wissenschaften zu Berlin (GDR)), provisionally headed the NK URSI. Because of the political situation in the GDR during the re-unification period, secretary M. Förster had to do most of the work and he also represented the NK URSI at the 1990 Prague GA (a personal note from M. Förster).

It took until the late 1990s before the FRG and GDR radio scientists could work closely together again. At the first Kleinheubacher Tagung, after the re-unification, on October 3, 1990, they met for common work [10, p. 11]. In the following years the research institutes in Germany were reorganized and thus cooperation became even more penetrating. The members of the Landesausschuss, of the FRG, continued their work, focusing on the annual Kleinheubacher Tagung meeting until the Kleinheubach meeting in 2000.

Dieminger, was the first President of the URSI National Committee of the BDR until 1968 and was then appointed Honorary President. From 1968 to 1978 W. Becker was President and H. Severin (Univ. Bochum) Vice President. In 1978 H. J. Albrecht became President of the URSI Landesausschuss of the FRG and R. Wielebinski and H. Lindenmeier, respectively, were the Vice-Presidents. This was followed in 1978 by Klaus Dorenwendt, with K. J. Langenberg as Vice-President. Obviously, for the daily work in the Landesausschuss and the organization of the Kleinheubacher Tagung the Secretary is crucial. From 1953 this role was filled by W. Menzel, H. Fleischer, Alfred Ochs, Rudolf Eyfrig, K.H. Kappelhoff, Thomas Damboldt, and Rolf Valentin until 1999.

In 1960, the FRG Member Committee was also successful in the international committees of URSI. Udo Adelsberger (PTB Braunschweig) who in 1933, together with Adolf Scheibe, developed a famous quartz crystal clock at the Physikalisch-technische Reichsanstalt (PTR) and who explored the variation in the Earth's rate of rotation [80] was the first German Chair of an URSI Commission and headed URSI Commission I Radio Measurements and Standards from 1960-1963. From 1969-1972 Rawer was Chair of URSI Commission III Ionosphere. Between 1975 and 1981 the URSI Commissions were given a new structure

A - Electromagnetic Metrology
B - Fields and Waves
C - Signals and Systems
D - Electronic and Optical Devices and Applications
E - Electromagnetic Noise and Interference
F - Remote Sensing and Wave Propagation: Neutral Atmosphere, Ocean, Land, Ice
G - Ionospheric Radio and Propagation
H - Waves in Plasmas
J - Radio Astronomy

In 1990, some Commissions received new designations and Commission K, Electromagnetics in Biology and Medicine was added. German committee members Volkmar Kose, PTB Braunschweig (1981-1984: A), Hans-Georg Unger, TU Braunschweig (1981-1984: B), Richard Wielebinski, Max-Planck-Institut für Radioastronomie (MPIfR), Bonn (1984-1987: J), Rudolf Saal, TU Munich (1987-1990: C), Ulrich Stumper, PTB Braunschweig (1993-1996: A), and Kristian Schlegel, Max-Planck-Institut für Aeronomie, Katlenburg-Lindau (1993-1996: G) all became Commission Chairs [10, p.8]. Dieminger was Vice-President of URSI, from 1963-1969, and President from 1969-1972; and Honorary President from 1978-2000. H. J. Albrecht was Vice-President from 1984-1990 [10, p. 8].

Members of the German FRG Member Committee were also elected to the Board of Officers before the turn of the millennium.

Leading up to 2000, both the German State Committee of the Federal Republic of Germany and the NK URSI of the GDR contributed effectively to almost all URSI areas of interest. However, unfortunately, there is not enough space to list all these research contributions. The *Proceedings of the URSI General Assemblies*, as well as the *Kleinheubacher Berichte* of this period, give a good overview of German radio scientists' contributions.

6. German URSI Member Committee Beyond the Year 2000

The year 2000 can, in a sense, be seen as a time of reorientation for the German Member Committee. The integration of the former GDR NK URSI members was successfully completed and contributed to the strengthening of URSI in Germany. As a result of the reorganization of Deutsche Telekom AG, after 2001 the Kleinheubacher Tagung was held in the nearby city of Miltenberg. This was a first step in decoupling URSI Landesausschuss from Deutsche Telekom AG. The *Kleinheubacher Berichte*, which was printed by the Deutsche Telekom AG until 2001 and distributed almost free of charge to the participants of the Kleinheubacher Tagung, ceased. As a consequence of these changes a moderate conference fee was introduced and it was not clear whether the Kleinheubacher Tagung would easily overcome these changes. Today we can say that URSI Germany not just successful survived, but these necessary changes to the Kleinheubacher Tagung, with its new formats and offers, has become even more attractive, particularly for young scientists.

Figure 11. The Karl Rawer Gold Medal.

Figure 12. The former German URSI President, Dr. Larissa Vietzorreck, presenting Prof. Dr. Dieter Bilitza with the Karl Rawer Gold Medal at the GASS 2017 in Montréal, Canada [84].

This reorientation was initiated by K. J. Langenberg, who was President of the Landesausschuss of the FRG from 1999 to 2008, and his Vice-President Gottfried Mann. In 2008, W. Mathis became President, remaining with Langenberg until 2017. From 2014, Larissa Vietzorreck held the position of Vice-President. Together with Secretary Eckard Bogenfeld (Deutsche Telekom AG) who held the office since 1999, the modernization process has steadily continued. Also, Ludger Klinkenbusch (Univ. Kiel), President of German Landesausschuss of the BRD since 2018, follows this line.

Larissa Vietzorreck was the first woman elected to the FRG URSI Landesausschuss board. During her term as Vice-President she was deeply and successfully involved in the work of the Landesausschuss. For example, the FRG URSI Landesausschuss contacts increased with the member committees of our neighboring countries, she participated in the preparation and implementation of the work of the Executive Committee for the GASS in Beijing in 2014, together with M. Chandra she improved the concept of the FRD Landesausschuss Young Scientist Award, and finally she carried out the essential work for the foundation of the Karl Rawer Gold Medal. At the 2017 Montreal GASS Vietzorreck presented the Medal to Dieter Bilitza (Figure 12), Karl Rawer's former research associate. In 2016, Vietzorreck became President of the FRG URSI Landesausschuss and chaired her first Kleinheubacher Tagung in 2017. Unfortunately, and surprisingly for URSI members, she died only a few weeks later after a serious illness [81]. After the provisional leadership of Mathis, L. Klinkenbusch was elected as new President of the German URSI Member Committee in 2018.

Because the National Committee had to charge fees for the Kleinheubacher Tagung, it was necessary to establish a tax-efficient legal form for the National Committee. The conversion into a non-profit organization was an expedient solution and from 2001 was called URSI Landesausschuss in der Bundesrepublik Deutschland.

The German Telekom AG no longer wanted to participate financially after 2001, so a printed publication of the Kleinheubacher reports was no longer possible. Therefore, an Open Access journal *Advances of Radio Science* was founded with Copernicus, who for many years had helped the Local Organizing Committee to organize the Kleinheubacher Tagung. The archive of the journal is available on the homepage of the URSI Landesausschuss in der Bundesrepublik Deutschland.

The move to Miltenberg meant that parallel sessions now had to take place in different buildings. In order to promote a corporate spirit for participants, which was also called the Spirit of Kleinheubach (Geist von Kleinheubach) in the castle Löwenstein in Kleinheubach, meetings were held where all participants could be present. Typically, Wednesday morning is scheduled for sessions where highly regarded international scientists present interesting topics in an overview lecture. In order to increase the attractiveness of the Kleinheubacher Tagung for younger participants, the German URSI Member Committee Young Scientist Awards were made, for the first time, in 2012. Here, Chandra brought in his experience in the selection of candidates for a Young Scientist Award at the General Assemblies. This extraordinarily successful concept was later developed further by Vietzorreck and Klinkenbusch and is today an integral part of the Kleinheubach Tagung.

A tradition dating back to the beginning of the Kleinheubacher Tagung, after World War II, was a piano recital designed by URSI members. It probably started with the concerts of J. Taubenheim and K. Suchy at the castle Löwenstein, in Kleinheubach [10, p. 11]. After founding the NK URSI of the GDR, the concert series was interrupted, but recommenced with a piano concert on the evening of October 3, 1990, exactly on the day of the German re-unification. Subsequently, Richard Klemm took over the organization of these concerts until 2011. Since 2012 the main social event, free to all participants of the Kleinheubach Tagung, is an evening boat cruise on the river Main and a buffet dinner. This event was well received and has already become a tradition.

Since 2000, the member committee of the FRG has continued to be successful in the international committees of URSI. K. Schlegel, Max-Planck-Institut für Aeronomie, Katlenburg-Lindau was Vice-President of URSI from 1999-2002 and President from 2002-2005. Peter Russer, TU Munich (2002-2005: B), M. Chandra, TU Chemnitz (2008-2011: F), K. J. Langenberg, Univ. Kassel (2008-2011: B), Günter Steinmeyer, Max-Born-Institut Berlin (2014-2017: C), and Frank Gronwald, Univ. Siegen (since 2017: E) were all Chairs of URSI Commissions.

In 2017 the German Member Committee was successful with the foundation of a medal in honor of Karl Rawer (Figure 11). With the help of Matthias Förster, Bodo Reinisch and other URSI colleagues, as well as the URSI Board of Officers with its former president Paul Cannon, Vietzorreck completed the establishment of the Karl Rawer Gold Medal for the National Committee. Karl Rawer was also very pleased about the Gold Medal [82].

The Proceedings of the *General Assemblies of the URSI* and the *Advances of Radio Science* provide a good overview of the contributions of German radio scientists, as we cannot go into further details here.

7. Conclusions

German scientists had already provided significant contributions to radio science by the end of the 19th century and took part in the first conferences and in the establishment of first Commissions on this topic. Because of their shared responsibility for two disastrous world wars, Germany and German scientists were excluded from participation in relevant international scientific organizations, including URSI, for many years. However, in each case, after a reasonable period of time, German radio scientists were invited to participate in international cooperation, including within URSI.

Based on original letters and reports, this article gives new insights into Germany‘s difficult path to URSI between the World Wars and after the Second World War. New details were also included regarding the situation during the time when two German countries existed and after the re-unification in 1990. Finally, it summarizes how German scientists worked in URSI and its Commissions.

International cooperation is the basis for peace as well as for good science. Therefore, the National Committee of the Federal Republic of Germany has, from the beginning and especially in recent years, intensified scientific exchange particularly with our neighboring countries such as France, Austria, Poland, the Netherlands, and the Czech Republic. Also, in the name of the German Member Committee, I would like to end this report with the statement by Hans J. Albrecht in his essay in 2005: “Taking into account the great value of the interdisciplinary orientation of the Union, it can be assumed that further intensive cooperation in URSI for the international union as well as for us, for the Landesausschuss, will be of great benefit” [10, p. 14-15].

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An Imaginative Electrical-Mechanical Engineer Becoming a Global Physicist: Nicholas C. Christofilos

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Abstract

Nicholas C. Christofilos (1916-1972) was a key figure in modern applied electromagnetic physics of the mid-Twentieth Century. He had radical ideas in various fields, such as accelerator technology, the physics of the interaction of charges within the ionosphere, and radiation at extremely low frequencies (ELF). His life's adventure in connection with his scientific and technological achievements is presented. The following major revolutionary scientific topics he was involved with are described: (a) accelerator technology, (b) the induction of an ionized zone on global scale around the Earth, and (c) the radiation of ELF waves by a gigantic-scale Earth-based antenna structure. His legacy today is also discussed.

1. The Early Life of N. C. Christofilos (1916-1949)

Nicholas C. Christofilos was born in 1916 in Boston to Constantine and Eleni Christofilos, who were immigrants from Greece. The family repatriated to Greece in 1923, and Nicholas grew up in Athens. He graduated in 1938 from the School of Mechanical-Electrical Engineering of the National Technical University of Athens (NTUA). Actually, until the mid-1960s NTUA was the only higher engineering university in Greece. From its foundation in 1837, it has played a significant role in the history of modern Greece.

It is known that young Nicholas was very interested in emerging technologies. He in fact built radio receivers even before entering NTUA. After his graduation from NTUA, he started to work in an elevator company, and continued during the whole period of the second Word War. Greece entered the war when it was attacked by Italy on October 28, 1940. The Greeks repelled the Italian attack, but went under the occupation of Nazi Germany in April 1941, which continued until October 1944. The people of Greece paid one of the highest prices of the war.

During this tragic period, Christofilos continued his work as an elevator engineer, while he simultaneously started getting interested in atomic physics. He later mentioned that a book written by Siegfried Flügge, *Introduction to Nuclear Physics*, influenced him to start studying particle physics. After the liberation of Greece from the Axis, he started studying topics of modern physics at the library of the United States Information Service. It was in 1946 that he started to conceive the idea of an accelerator similar to a synchrotron by studying possible methods to oppose the repulsion forces between particles having the same electrical charge. Instead of publishing his work, he preferred to submit patents filed in the USA and Greece. Despite the advice of his close friend and physics professor, Theodoros Kouyoumzelis, to publish his work, he preferred to file patents, sending copies of them to Livermore Radiation Laboratory at Berkeley [1].

In the following sections, the scientific career of Nicholas C. Christofilos is briefly reviewed under the major topics on which he worked.

2. Toward the Idea of Generating a Focused Beam of Charges

In the patent application that he submitted to the United States Patent Office on March 10, 1950, under the title "Focusing System for Ions and Electrons" [2], Christofilos (realizing that it was impossible to generate a focusing static field having a linear dependence on spatial coordinates) proposed a field with continuous spatial variation. Assuming the particles moved along the x axis, the components of the force field restoring the beam stability were proposed to be

$$P_x = 0 \,,$$

$$P_y = -\varepsilon y \sin\left(2\pi x/\lambda\right), \qquad (1)$$

$$P_z = \varepsilon z \sin\left(2\pi x/\lambda\right),$$

where ε and λ are constants. Considering again a particle moving parallel to the x axis and at a distance $z = z_0, y = 0$, the force exerted on this particle is

$$P_z = e\varepsilon z_0 \sin\left(2\pi x/\lambda\right). \qquad (2)$$

Because the force, P_z, varies periodically while the particle moves along the x axis, the particle undergoes forced oscillations at a frequency

$$f = \beta c/\lambda\mu = \varepsilon\lambda^2 \Big/ \left(4\pi^2\beta^2 V\right), \qquad (3)$$

with βc being the velocity of the particle. Because of these oscillations, the distance from the orbit oscillates around the mean value of z_0 according to

$$z = z_0\left[1 - \mu \sin\left(2\pi x/\lambda\right)\right], \qquad (4)$$

where

$$\mu = \varepsilon\lambda^2 \Big/ \left(4\pi^2\beta^2 V\right), \qquad (5)$$

and V is the voltage of the particle.

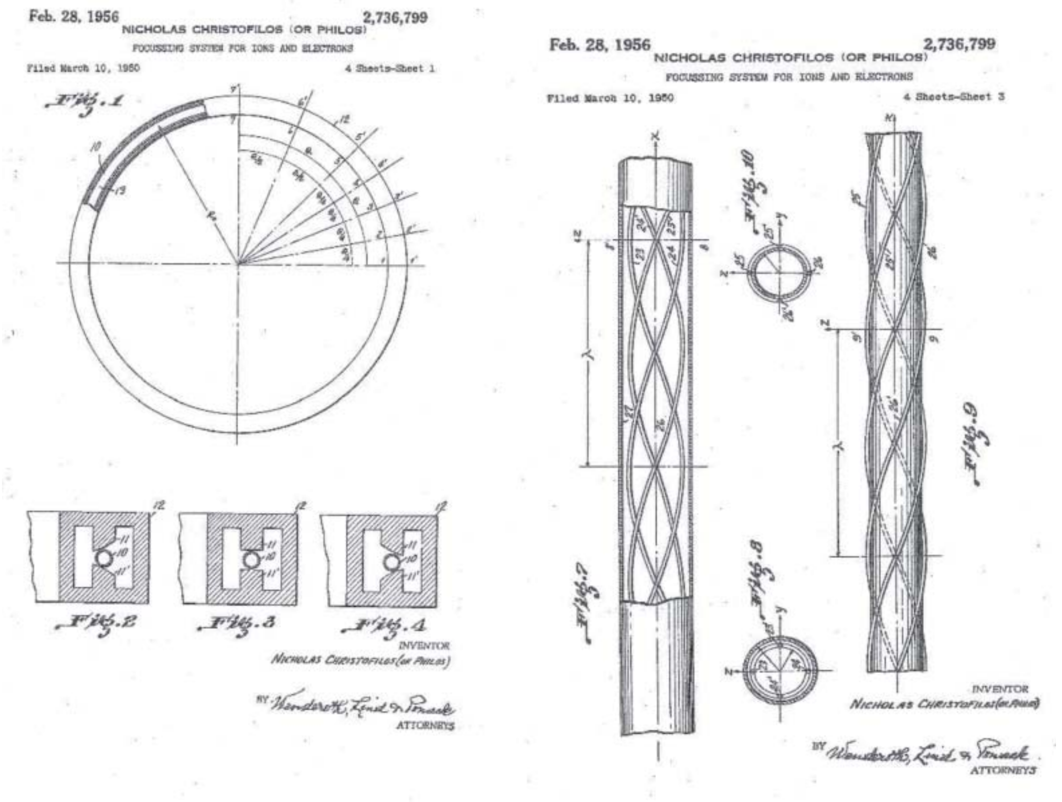

Figure 1. Focusing schemes proposed in the patent [2] of Christofilos.

In the patent mentioned, Christofilos then stated the following:

From the above investigation it was found that a focusing system based on the new principle fulfills the requirements of the ideal focusing system in that it focuses the particles from all directions towards a predetermined orbit and the focusing force increases as the distance from said orbit increases.

This new principle can be applied in different ways either electrostatically or electromagnetically.

Christofilos next proposed the application of this principle to accelerators where the particles were guided in circular orbit of constant radius by a time-varying magnetic field. The new focusing principle was realized by properly shaping the magnetic poles between which the guide field was produced. In particular, in linear accelerators the new focusing principle could be realized by means of suitable conductors helically surrounding the orbit and connected either to a high-voltage source or energized by a high-intensity current (see Figure 1).

As it was noted, a six-year period passed for this patent to be issued. This was because, unfortunately, Christofilos' discovery went unnoticed for a few years. Of course, the reason was that his work didn't appear in a scientific journal, which surely would have attracted the interest of laboratories vigorously working on particle accelerators in the post-second-World-War period. In 1952, the principle proposed by Christofilos was actually rediscovered by E. Courant and H. Snyder, following an earlier idea by M. S. Livingston to examine the behavior of particles in alternately placed magnets [3].

In 1953, Christofilos visited the USA. In the Brooklyn Public Library, he read an article of Courant et al. [3]. Somehow believing that his idea had been used without credit to him, he rushed to Brookhaven Laboratories. After some excited discussions with John Blewett, both sides acknowledged their independent invention. A position was immediately offered to Christofilos, and he joined the group designing the 28 GeV alternating-gradient synchrotron. At Brookhaven, Christofilos contributed to the design of the drift tubes for the 50 MeV proton LINAC.

In accelerator technology, the principal interest of Christofilos was the Astron project. In Greek, Astron means "star," and the project concerned the development of a thermonuclear-reactor project. Because of the classified nature of this proposal, it was decided that this project should be moved to Livermore (now Lawrence Livermore Laboratory). In 1956, he hence joined Livermore, where he worked until his death.

3. The Work of N. C. Christofilos on Accelerators: Astron Technology

In April 1953, Christofilos attended a meeting of Project *Sherwood*. At that time, this was the code name for the USA's program of controlled nuclear fusion. He presented his idea that he had worked on in Greece and was named *Astron*.

The fundamental principle of Astron was to inject high-energy electrons into a magnetic mirror (called the "tank"). Electrons captured by the mirror would build up a layer of current near the external surface of the cylindrical tank. This electron layer was named the *E-layer*. In turn, the E-layer would itself generate a strong magnetic field. As it got stronger, this magnetic field would reach a critical density at which it was expected to "reverse" and fold into a new closed-line configuration, thus generating a continuous confinement area. After this, the fusion fuel would be injected inside this volume, where there would follow heating by the interaction with the E-layer to raise it to fusion temperature.

At that time, the Astron proposal was attractive since it proposed a solution to one of the fundamental problems of the magnetic-mirror concept: having open magnetic field lines and fusion leaking out of this opening. When these efforts were ongoing, the Sherwood project was a classified project and Christofilos – not yet having obtained clearance – was assigned to work in Brookhaven on the theory of Astron. The conceptual diagram of the Astron system is shown in Figure 2.

After receiving his clearance in 1956, Christofilos moved to Lawrence Livermore National Laboratory (LLNL) to start experimental work on Astron. After two years of intensive work, he was able to present his Astron concept at the 1958 Atoms for Peace Conference in Geneva, organized under the auspices of the United Nations.

During the decade of 1960, Christofilos and his colleagues worked intensively on Astron. As is always the case, numerous practical problems were faced in the implementation of the Astron concept, such as the traveling back of electrons into the accelerator area. Christofilos used resistor wires that slowed the electrons after entering the tank and thus no longer possessed energy to flow back. In addition, Christofilos, having only a Diplom Engineer degree and because of his plethoric character, didn't have the best relations with the physics establishment of the time.

In 1967, despite the good stability of the E-layer, the Astron system achieved only 6% of the diamagnetic field required to reverse the field. At this stage, opposition of a review committee to the continuation of the funding started. The lack of powerful computer-simulation capabilities that would help solve experimental problems was an objective difficulty. Several modifications to the time schedule of pulsing electron beams improved the system, but it was still far away from the target of achieving the desired confinement.

The end of the Astron project came with the sudden death by heart attack of Christofilos in September, 1972. The project was finally shut down in June, 1973. After the death of Christofilos, the project was directed by Richard Briggs.

Detailed information on the history of the Astron project can be found in the article by Elisheva R. Coleman [5]. A 1968 photograph of Christofilos is given in Figure 3, which the authors believe strongly reflected his character.

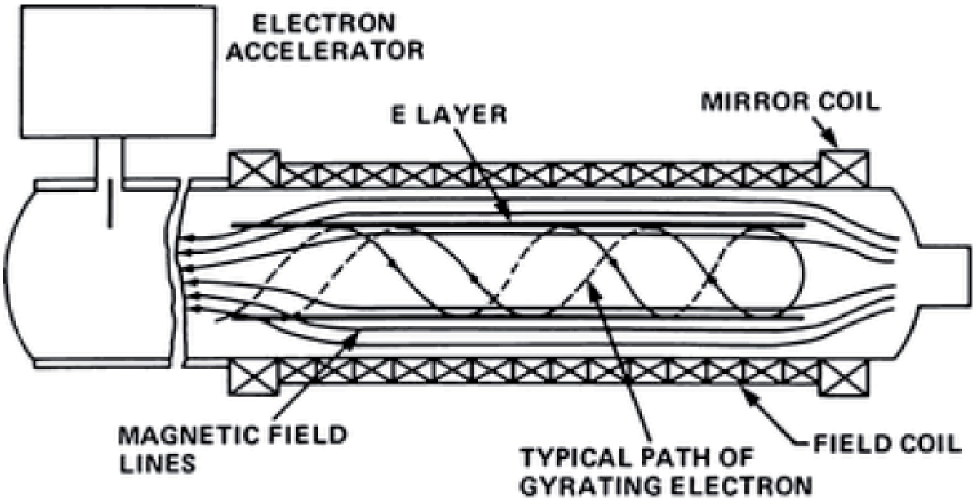

Figure 2. The Astron fusion concept [4].

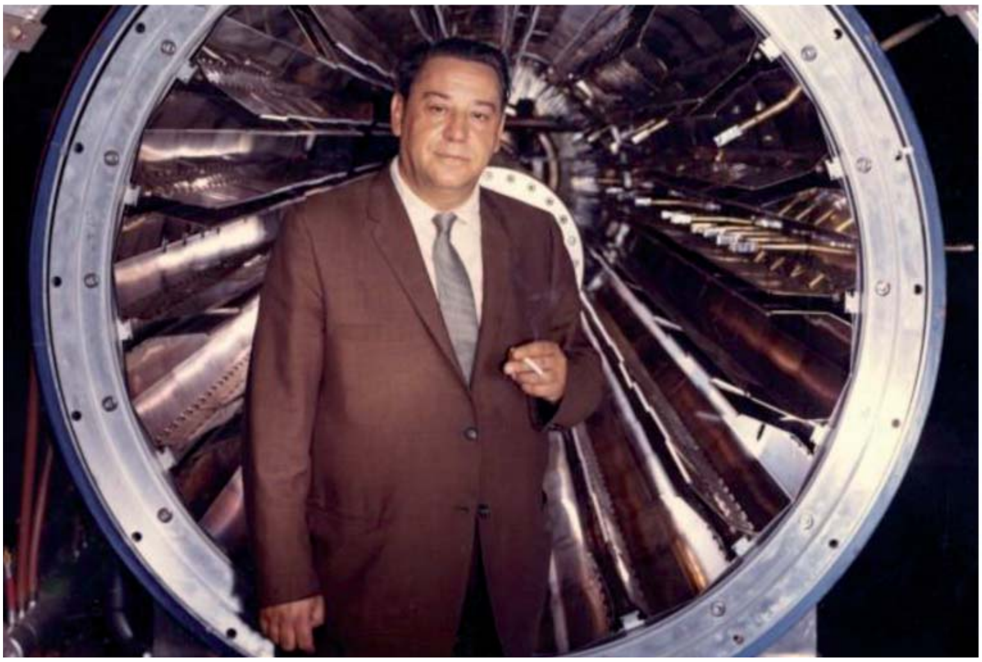

Figure 3. Nicholas Christofilos in front of the Astron "tank" (1968) [6].

4. The Global Electrification of the Earth's Planetary Ionosphere: the ARGUS Experiment

In a different research area, Christofilos was behind a unique experiment in 1958. This was at the infancy of satellite technology, aiming to create an artificial electron belt around the globe. As was mentioned many years later in an unclassified report [7]:

> In late August and early September of 1958, Navy Task Force 88 (TF 88), consisting of nine ships and approximately 4,500 men, secretly conducted three high-altitude nuclear tests in the South Atlantic. The operation was conducted under the code name ARGUS. In each of these tests, the task force launched from the missile trials ship USS Norton Sound, a specially modified X-17a three-stage ballistic missile carrying a low-yield nuclear warhead, which was detonated high in the Earth's upper atmosphere. Upon completion of these launchings on 6 September, the task force departed the operating area for Rio de Janeiro, Brazil, and then to home ports in the United States. Not until March 1959 did the United States Government acknowledge that TF 88 had been sent to sea to conduct those nuclear tests....
>
> The ARGUS nuclear tests grew out of an experiment proposed by Nicholas Christofilos, a physicist working at the University of California Radiation Laboratory at Livermore (UCRL), California. In late 1957 and early 1958, Christofilos examined the possibility of creating an artificial radiation belt in the upper regions of the Earth's atmosphere with a nuclear detonation at an extremely high altitude. Naturally occurring belts of electrically charged particles trapped above the Earth had been discovered by Explorer I, the first satellite launched by the United States in early 1958, and had been named the Van Allen belts in honor of the man who directed the experiment that discovered them. The charged radiation in these belts consists of high-energy electrons and protons. The primary sources for these particles are the disturbances on the sun's surface. The particles are ejected from great flares and come toward the Earth where they are trapped by the geomagnetic field. The magnetic field bends the flight path of these particles because of their electric charge. Some of the particles are forced into a corkscrew-like motion along the north-south direction of the Earth's magnetic field.
>
> Christofilos theorized that a nuclear detonation several hundred miles above the Earth acting as a source of beta particles (electrons originating from an atomic nucleus) would produce a shell of high-energy electrons (trapped radiation) in the upper atmosphere, oriented along the Earth's magnetic field like the naturally occurring Van Allen belts. The following paragraphs give a simplified description of the physical processes involved in trapped radiation.

After the completion of this spectacular experiment, in a paper in 1959, Christofilos published the theoretical basis of the Argus experiment [8]. The proposed idea was given in the above-mentioned report and is depicted in Figure 4. The

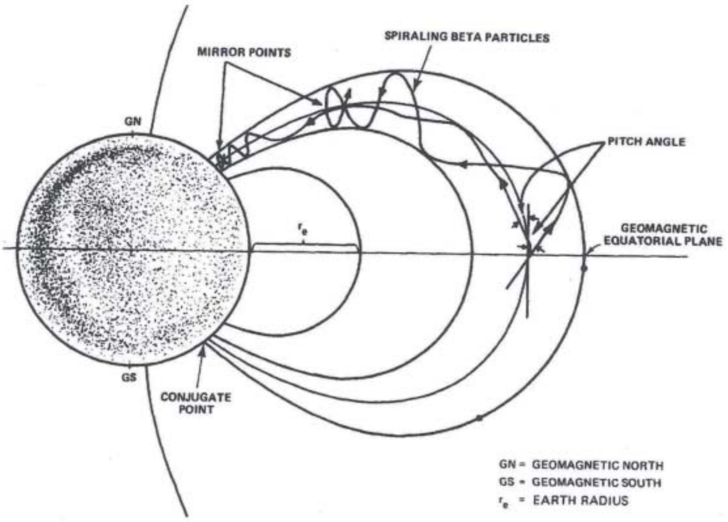

Figure 4. The principle of operation of the Argus experiment [7].

Earth's magnetic-field lines, running between the two magnetic poles, rise to great heights of several Earth radii while they also form the Earth's magnetic equator. If properly injected near the magnetic lines, the beta (electron) particles can create a stream going up and down between magnetic conjugate points. As stated in the above-mentioned report:

> Christofilos' theory was of major interest to the US government, particularly the Department of Defense (DoD), because of the possible effects of an artificially created radiation belt on defense systems. For example, a sufficiently powerful electron source, such as a nuclear warhead of several megatons yield, if detonated high above the Earth, might seriously degrade radio and radar transmission and reception in the 50- to 200~MHz band. Such a radiation belt might also damage or destroy the arming and fusing mechanisms of an intercontinental ballistic missile passing through it. A third possibility was that the radiation belt might endanger crews of orbiting space vehicles that entered the belt.

An interesting video on the Argus operation is available at [7].

According to the United States Atmospheric Nuclear Weapons Tests report DN6039F [7], the results of the Argus experiment were as follows:

> The results of the ARGUS operation proved the validity of the Christofilos theory. The establishment of an electron shell derived from neutron and beta decay of fission products and ionization of device materials in the upper fringe of the atmosphere was demonstrated. The operation not only provided data on military considerations but also produced a great mass of geophysical data, pure scientific material of great value.

5. A Global ELF Transmitter to Reach Submarines at Large Depths

Another "mega" project, undoubtedly attributed to Christofilos, was the *Seafarer* project of the United States Navy. This was intended to develop an extremely-low-frequency transmission system for transmitting signals to submarines while they were at up to 200 m depth from the sea surface.

From the beginning of radio-transmission technology, it was well known that in order to send signals to submerged submarines, one must use frequencies less than 30 kHz, since the salty sea water strongly attenuates signals. Common systems used by many navies utilize the frequency band 15 kHz to 50 kHz to send signals to submarines while they are at a periscope depth of 2 m to 10 m. The well-known formula for penetration depth is

$$\delta = 1\Big/\sqrt{\pi f \mu_0 \sigma}\,, \qquad (6)$$

where *f* is the radiation frequency, $\mu_0 = 4\pi \times 10^{-7}$ H/m is the free-space magnetic permeability, and $\sigma = 2$ to 5 S/m is the sea's conductivity. This relationship establishes the limitation of the depth at which a submarine can receive signals. Going to large depths requires a suitable decrease in the frequency. In the case of the Seafarer (a successor to the *Sanguine*) project, the frequency seems to have been selected at 80 Hz.

However, there is a fundamental difficulty in radiating at low frequencies, since an antenna that has a size comparable to the wavelength of the radiation to be transmitted is needed. In the case of the mentioned 15 kHz to 50 kHz band, as a standard choice, vertical monopoles with a loading structure to increase the antenna capacitance were used. In practical terms, since vertical towers cannot be higher than about 400 m to 500 m, from a practical standpoint transmission less than 10 kHz cannot be achieved, since such short monopoles will have less than 1% radiation efficiency.

Christofilos' idea was to develop a loop antenna in a plane perpendicular to the Earth's surface by selecting a region of the Earth with very low conductivity, so the loop antenna would not be short circuited by the Earth medium. This idea is presented in Figure 5.

In order to implement the idea of an ELF antenna as proposed by Christofilos, an area having the desired properties in the Michigan peninsula as shown in Figure 5 was selected, and an experimental ELF transmission system was developed. Electromagnetic analysis of the ELF antenna was rather easy, considering that at such low frequencies both the ionosphere (starting with the D-layer at a height of 60 km) and the Earth medium can be approximated as perfect conductors. This results in a spherical waveguide structure being excited by a loop antenna.

Project ELF, which became operational in 1989, consisted of two transmitters: one near Clam Lake in Northern Wisconsin, and the other at Republic, in Michigan's Upper Peninsula. Perpendicular loops were used for providing worldwide coverage. The Wisconsin antenna consisted of two lines, each about 14 miles (22.4 km) long. The Michigan antenna used three lines, two about 14 miles (22.4 km) long, and one roughly 28 miles (44.8 km) long. The ELF antennas, resembling an ordinary power-distribution line, were located above ground in cleared right-of-ways that were 70 ft (21.3 m) to 100 ft (30.48 m) wide. The antennas consisted of two conductors in Wisconsin and a single conductor in Michigan. The transmitter sent an electrical current through the antenna cables into the Earth at the ground terminals. The end of each antenna element was terminated with one to three miles (1.6 to 4.8 km) of buried horizontal ground wire and, typically, one or more arrays of well-type electrodes extending to depths of 100 ft (30.48 m) to 300 ft (91.4 m). The current then flowed back to the transmitter through the Earth, completing the circuit. Most of the Earth current flowed deeply and dispersed through the nonconductive bedrock underlying the ELF system around and between the two sites. The power required for the Michigan and Wisconsin sites was reduced to less than 5 MW and eight acres for the transmitter sites. A fundamental difficulty of sending signals at ELF frequencies such as 70 Hz to 80 Hz is the heavy atmospheric noise in the Earth-ionosphere cavity. This implies that only very-low-rate data (several seconds per bit) could be sent using such signal modulation as minimum frequency-shift keying.

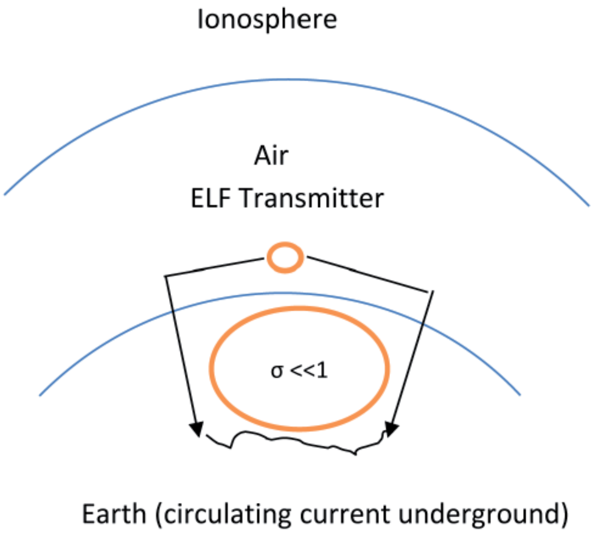

Figure 5. The vertical-plane loop antenna.

However, ELF transmitters have been the object of protests since their inception, starting with environmental concerns. There was strong opposition from the citizens of Wisconsin and Michigan, calling the project a nuisance. On September 30, 2004, the plug was pulled on Project ELF. A surprise Navy announcement signaled the end of 36 years of first local, then global, opposition to the Navy's giant transmitter system.

6. Conclusions

Nicholas C. Christofilos was born in USA, and repatriated to Greece when he was seven years old. He was educated at the National Technical University of Athens, which was the only technical university of Greece at that time. He grew in the interwar period in Greece, which was a turbulent time, following a tragic period of Nazi occupation followed by a civil war as the first hot clash of the cold-war era. Despite all these circumstances, Christofilos self-educated himself and, clearly due to his talent and devotion, was at a very early age involved in modern-physics topics, primarily in particle accelerators. There is no doubt that he had the intuition to generate new ideas, but was also able to convince non-scientific authorities to undertake large-scale projects. His ideas were creative and, although difficult to achieve, were correct. He certainly was lucky that the 1950s were a time that ideas were appealing to the establishment. He received several awards For his scientific achievements, including from the Franklin Institute in 1963, and the American Hellenic Progressive Association in 1959 [1]. In 1960, he importantly was also recognized for his great contributions by Richard Nixon (then sitting Vice President, and future President of the USA) in his article on the "Scientific Revolution" [9].

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Radio Science in Hungary

1. Commission A: Electromagnetic Metrology

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Emeritus Consultant, Research Institute for Telecommunication

The main activities of URSI Commission A, Electromagnetic Metrology, in Hungary are calibration and measurement methodologies, characterization of the electromagnetic properties of materials, physical constants, and the properties of advanced engineered materials. These activities are carried out in support of national and industrial priorities.

The Metrology and Technical Supervisory Department (MKEH) of the Government Office of the Capital City of Budapest (BFKH) is responsible for scientific metrology and its enforcement under the management of the Minister for National Economy. (The former National Office of Measures (OMH) merged into the Hungarian Trade Licensing Office (MKEH) on 1 January 2007, and on 1 January 2017 MKEH it was subsumed into BFKH.) One of the main tasks of BFKH is to maintain the national standards, their international comparisons and to disseminate the outputs of MKEH. There are thirteen regional legal metrology sections working in the government offices that carry out verification and inspection.

The National Media and Info-communications Authority of Hungary (NMIAH) also carries out metrology measurements to support the licensing of radio facilities. The NMIAH has installed a national electromagnetic field monitoring and information network under the auspices of the National Research Institute for Radiobiology and Radiohygiene (NRIRR). The measurement program involves collecting data from twenty-five area monitoring instruments that are moved to new locations every two weeks. Measurement spots are typically educational institutions, nurseries and schools situated close to radio facilities. Tests are also carried out occasionally on the request of private individuals. The nationwide monitoring system in Hungary and the Web publication of its results address public concerns in relation to the health hazards of the electromagnetic fields.

In the 1980s and 1990s, device and transmission system characterizations were the main focus of Hungarian URSI Commission A research, [1-16]. However, during the last few years electromagnetic material parameter measurements and non-destructive testing have been emphasized due to the demand of the car, aero, nuclear [17, 18] and other high technology industries. Guided wave and transmission type material parameter measurements are used to characterize ferrite materials used in EMC shielding and anti-reflection coatings, [19, 20].

The generation and measurement of electromagnetic fields for radiated immunity testing in open-area test sites are rather expensive and time-consuming. Further the environmental and meteorological conditions strongly influence the measurements. Therefore, E field probes, THz and millimeter-wave thermopile detection antennas have been developed and researched for radiated immunity tests and human exposure measurements over a wide frequency range, [21-26].

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Figure 1. The material parameter measurement setup [20].

2. Commission B: Fields and Waves

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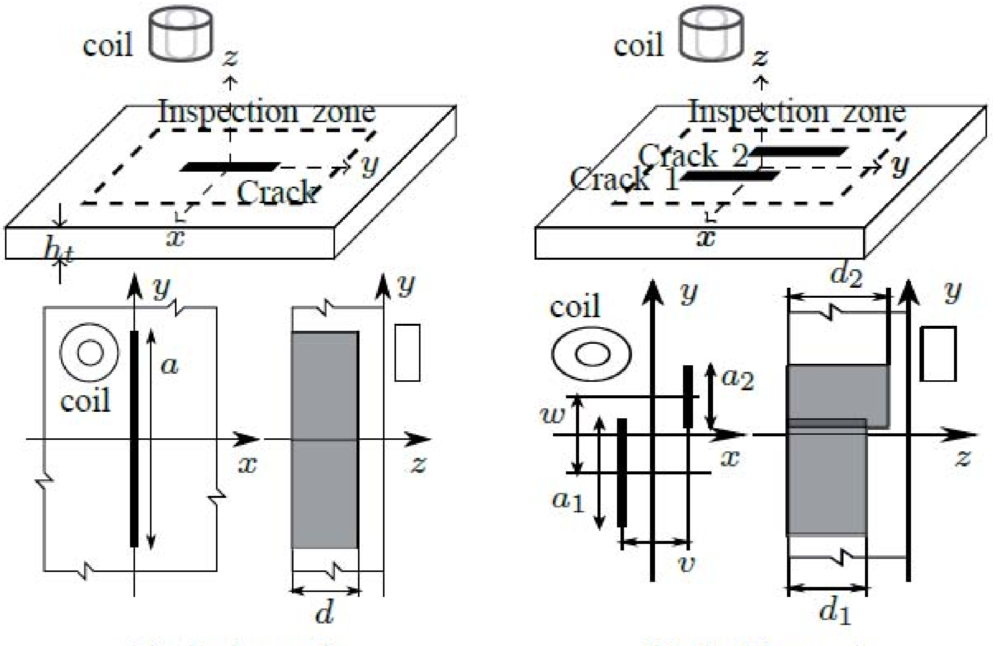
The main interests of Commission B in Hungary lie in the fields of time- and frequency-domain analysis [1,2], wave propagation in inhomogeneous media (especially plasmas) [3-6], antennas [7-15] and radar imaging.

The solution of electromagnetic optimization or inverse problems usually first require the solution of the direct problem and consequently, the numerical burden is significant. This has inspired the use of surrogate models that replace the complex direct simulation and provide approximate results at a much lower computational cost, [16 -18]. Between 2012 and 2015, this work was supported by a grant from the Hungarian Scientific Research Fund (OTKA), K-105996: "Surrogate modeling for the solution of electromagnetic inverse problems". In this framework, both electromagnetic simulation tools with special attention on the requirements of surrogate modeling were developed and surrogate modeling algorithms were also studied. One full-wave model was developed, that ensures numerical stability at both the high and the low frequency limits. Another full-wave model was developed for the simulation of frequency selective surfaces (FSS) using an impedance-type boundary condition that is applicable over a wide frequency range.

Both approaches are ready for coupling with surrogate model assisted optimization methods. The latest developments of surrogate modeling algorithms are related to optimal database generation methods. Such databases are used to store pre-calculated direct problem solutions (i.e., training data). The choice of the direct problems to be stored is a complex optimization problem and a sampling strategy based on adaptive mesh generation was reported.

The above methods were transferred to the industrial applications of nondestructive testing (NdT) in the framework of the project "Development of Inversion Procedures based on the Exploitation of Database of Simulated NdT Signals" funded by the French Commisariat á l'Énergie Atomique et aux Énergies Alternatives (CEA), during the years 2015-2016.

Figure 2 illustrates some experimental eddy current NdT measurements and Figure 3 describes the results of computer simulation of material impedance.



(a) single crack (b) double cracks

Figure 2. Eddy-current test examples: a non-ferromagnetic plate effected by a single crack (a) or by two cracks (b).

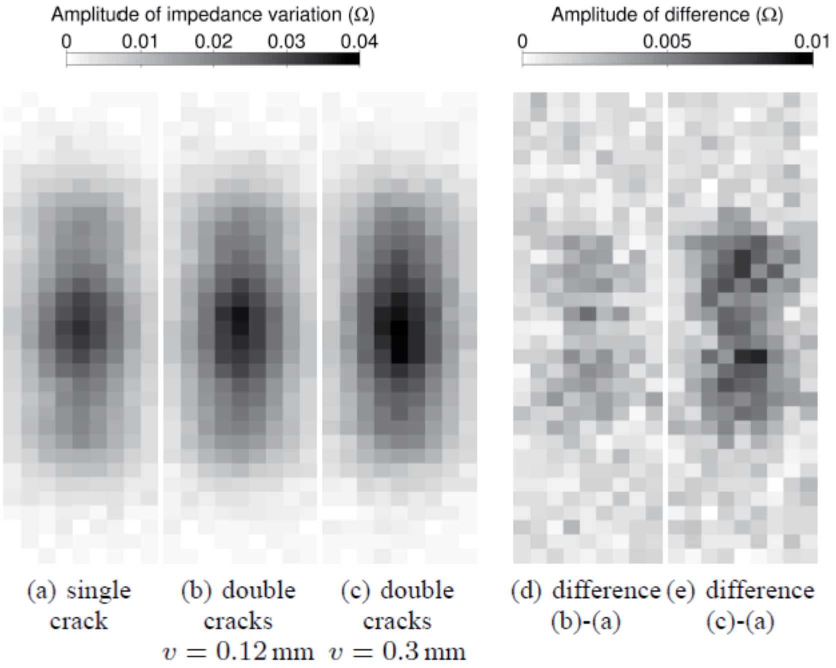


Figure 3. Amplitude images of simulated impedance variations at SNR = 20 dB for $v = 0.12$ mm, 0.3 mm, and their differences with the single-crack case.

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3. Commission C: Radiocommunication Systems and Signal Processing

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The Hungarian Commission C activities have principally focused on the physical layer of communications systems and microwave photonic components and subsystems [1-4]. This includes telecommunication applications [5-9], millimeter wave radio over multimode fiber [10-14], millimeter wave propagation [15], software networks and software radio [16, 17].

In the COST Action “Optical Wireless Communications” (IC1101) the visible light communication (VLC) channel was investigated. System demonstrators for VLC applications have been built with industrial cooperation.

Optical access network studies are organized around funding from the Hungarian Scientific Research Fund (OTKA PD 109288, Investigation of in-line and reflective semiconductor optical amplifiers for broadband optical access). This includes simulation and measurement of a semiconductor colorless optical unit for wavelength division multiple access optical networks, together with theoretical and experimental investigations of a proposed dispersion compensation method for millimeter wave radio over multimode fiber systems.

The possibility of combining linear and circular polarized antennas for indoor positioning techniques based on signal strength measurement, [18, 19] was investigated.

Another microwave photonics research field is millimeter wave and terahertz radio frequency signal generation using photonics methods. A comparative study of different system configurations and an investigation of the stability and performance of the generated signal are subjects of heightened interest, [19, 20].

A quickly developing research area is free space optical quantum communication, where we explore photon statistics, laser polarization states and laser sources.

The High Speed Networks Laboratory (HSNLab) at BME has performed the following research projects: SmartActive Squash - IoT Sport Analytics, Deterministic Networks-Time Sensitive Networking, Software based Ternary Content Addressable Memories, Optimal Cloud and Dataplane.

In the TAMOP FIRST Hungarian national project (2012-14) TV White Space was investigated and a new model was developed for cognitive radio applications. Recent activity also includes participation in Ka/Q band (20 – 40 GHz) propagation and communication experiments as part of the ESA (European Space Agency) Alphasat program. To study the propagation behavior of the satellite-Earth radio channel a two-band satellite beacon receiver station was developed, built and has been operated since 2014. The receiver station in Budapest is part of an international measurement network over Europe, [21-24].

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4. Commission D: Electronics and Photonics

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Research and development activities in the Hungarian Commission D: Electronics and Photonics are traditionally associated with the design of integrated circuits and novel active devices. They have a special focus on thermal [1-5] and reliability issues of electronics, microelectronics [6-12], photovoltaic devices and solid-state lighting; on Micro-Electro-Mechanical Systems (MEMS) and smart system integration including the practical realization of Cyber Physical Systems (CPS) and Internet of Things (IoT) applications [13-16]. In 2016, these activities were supported by an EU FW7 project and two H2020 projects (EuroCPS and Delphi4LED) and three different national Hungarian Scientific Research Fund (OTKA) projects. The following subsections provide details of the most important topics and results achieved.

4.1 System on a Chip

Nowadays the focus of digital system design is shifting towards system on a chip equipped with run-time configurable, application-specific macrocells. Numerous tasks have to be taken over from the instruction-set microprocessors in order to cope with the ever-increasing performance requirements, while the design effort has to be kept low to handle time-to-market pressure and reduce design cost. In the framework of this research, novel solutions for digital system modeling and synthesis are being investigated. The central demand placed upon the target method is to simultaneously ensure the productivity and the possibility of detailed architectural optimizations. These somewhat conflicting requirements are well-known by the existing approaches but they are usually handled in a mutually exclusive manner; HLS (High Level Synthesis) tools are used when the development time is the primary objective and detailed hand-crafted RTL (Register-Transfer Level) modeling is applied in the case of highly timing-sensitive and/or power-critical designs. To find a common ground for the contradictory needs, a novel abstraction level (Algorithmic RTL) and a formal language (Algorithmic Microarchitecture Description Language, AMDL) have been introduced. Using the proposed technique, the designer may describe the behavior and define the micro-architectural details, in a unique algorithmic language environment. An AMDL-VHDL synthesis method has also been developed, which ensures the compatibility with the traditional digital system design flow. Based on the design efficiency investigations performed so far, it may be concluded that the proposed modeling means is a promising candidate for fulfilling the gap between HLS tools and hand-optimized RTL.

4.2 Heat Sink Structure Technology Research

In case of microscale heatsink structures, which are the integral parts of modern chip or package level cooling concepts, many fabrication steps have to be fully developed before a successful chip-level cooling system is ready to be used. Recently we developed and presented a refined manufacturing technology that allows integration of microchannel based cooling solutions with IC chips, 3D stacks of chips or with solar cells. Besides the new heat sink structures we also further developed a characterization method aimed at such cooling devices. The method is based on thermal transient measurement followed by structure function analysis. Our recently improved characterization method is able to account for possible non-ideal heat transfer processes. A new method was also introduced to create a ladder-type analytical thermal model of different microscale channel-based heat sink structures which facilitates the determination of the temperature distribution along the channel as a function of the channel geometries (see Figure 4), the thermal properties of the fluid and the wall temperature(s). This model was implemented in a conventional thermal field solver to augment the capability of simulating the thermal impact of integrated heat sink. This allows the study of the operation of system-on-package (SoP) devices by electro/logi-thermal simulation.

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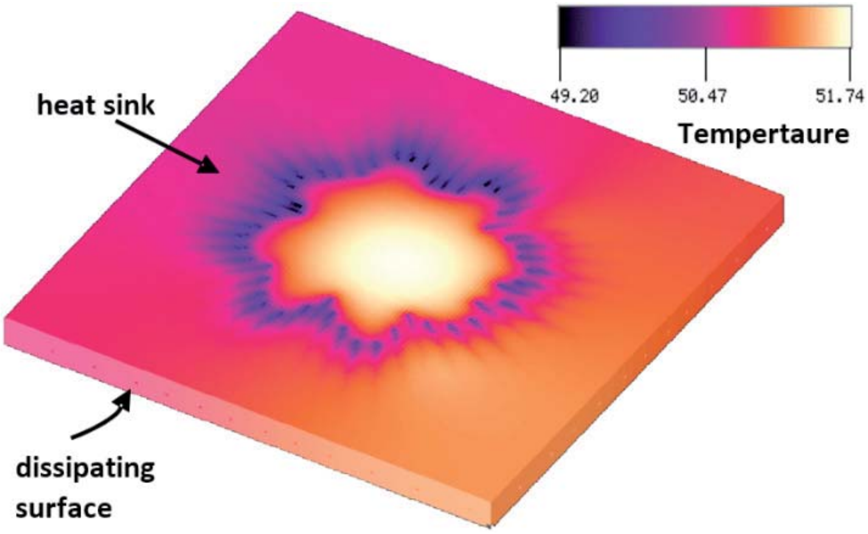

Figure 4. Thermal simulation results of our new microchannel-based cooling system simulated with the help of a recently developed compact thermal model of microchannels.

5. Commission E: Electromagnetic Environment and Interference

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Commission E, Electromagnetic Environment and Interference, in Hungary is focused mainly on projects supported by the government. These include genotoxic studies of 50 Hz ELF magnetic fields; evaluation, using alkaline in-vitro comet-assay techniques, of DNA damage to human lymphocytes due to exposure to ELF magnetic fields (at the National Research Institute for Radiobiology and Radiohygiene (NRIRR)) and ELF exposure surveys near residential electricity distribution transformer stations [1-7] and related mitigation approaches [8, 9].

Further, the study of the possible effects of 900/1800 MHz GSM-like microwave fields on male reproduction by in vivo evaluation of male mice serum testosterone levels and red blood cell count (National Institute of Chemical Safety (KBI)) is undertaken. Other studies include the effects of exposure to 50 Hz magnetic fields [10, 11] and GSM radio frequency radiation on pineal melatonin synthesis by the perfusion system of pineal glands in vitro; RF exposure survey near base stations (NRIRR and industry) [12]; miniature E-field probe development for RF dosimetry using a thick film method (Hungarian Academy of Sciences Research Institute for Technical Physics and Materials Science (MFA)) and instantaneous, in vivo effects of GSM-like pulsed 900 MHz RF irradiation on spontaneous neural activity of medial prefrontal cortical neurons in rats (NRIRR and the University of Pécs).

As described in relation to Commission A, the National Media and Info-communications Authority of Hungary (NMIAH) also carries out metrology measurements to support the licensing of radio facilities.

A number of other reports related to EM fields and health (NRIRR) have also been published [13-20].

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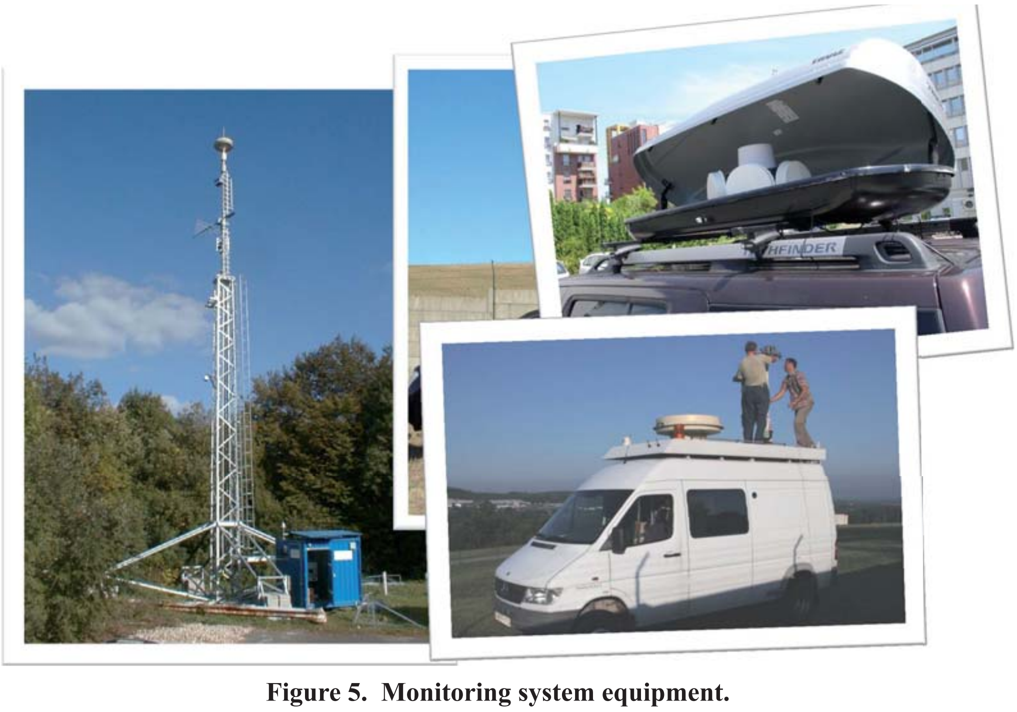

Figure 5. Monitoring system equipment.

6. Commission F: Wave Propagation and Remote Sensing

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6.1 The Moon radar

The first success of Hungary in the remote sensing community was the Moon-radar experiments in 1946 [1]. In March 1944, Zoltán Bay had recommended using the radar for scientific experimentation, including the detection of radar waves bounced off the Moon. The scientific interest in the experiment arose from the opportunity to test the theoretical notion that short wavelength radio waves could pass through the ionosphere without considerable absorption or reflection. Bay's calculations, however, showed that the equipment would be incapable of detecting the signals, since they would be significantly below the receiver noise level. The critical difference between the American and Hungarian apparatus was frequency stability, which DeWitt achieved through crystal control in both the transmitter and receiver. Without frequency stability, Bay had to find a means of accommodating the frequency drifts of the transmitter and receiver and the resulting inferior signal-to-noise ratio. He chose to boost the signal-to-noise ratio. His solution was both ingenious and far-reaching in its impact. Bay devised a process he called cumulation, which is known today as integration. His integrating device consisted of ten coulometers, in which electric currents broke down a watery solution and released hydrogen gas. The amount of gas released was directly proportional to the quantity of electric current. The coulometers were connected to the output of the radar receiver through a rotating switch. As the American radio astronomers Alex G. Smith and Thomas D. Carr wrote some years later [1]: "The additional tremendous increase in sensitivity necessary to obtain radar echoes from Venus has been attained largely through the use of long-time integration techniques for detecting periodic signals that are far below the background noise level. The unique method devised by Bay in his pioneer lunar radar investigations is an example of such a technique."

6.2 Radar Experiments and Research

Nowadays the main activities of Hungary in the area of Commission F are associated with radar developments (active and passive) and radiowave modeling, [2, 3]. The radiowave modeling research especially studies millimeter wave meteorological propagation effects for terrestrial and satellite links and remote sensing [4-15].

The Department of Broadband Infocommunication and Electromagnetic Theory (HVT) joined the international project "Multichannel Passive ISAR Imaging for Military Applications (MAPIS)", from 2014 to 2017, with the participation of nine institutes from five countries. The project was coordinated by the European Defence Agency. The scope of the project included both research and development related to passive radars. This included antenna array characterization,

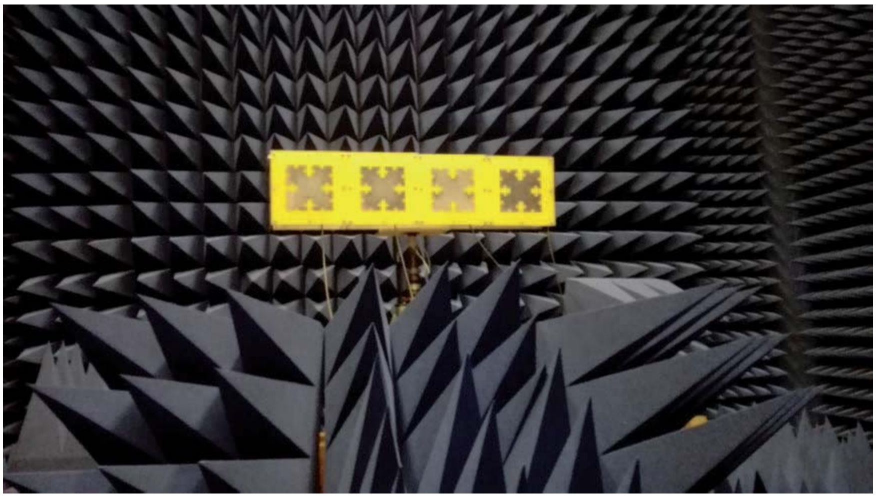

Figure 6. A linear antenna array with an inverse Koch fractal patch antenna.

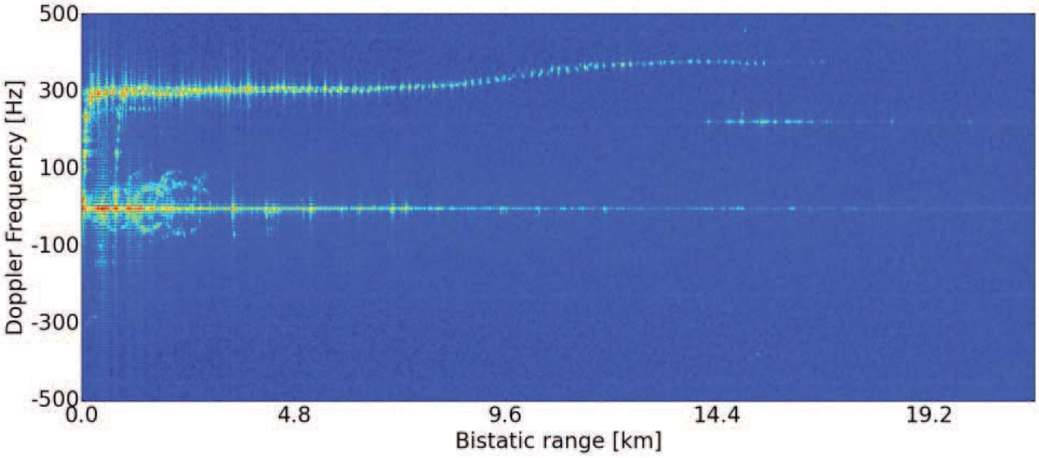

Figure 7. The track of a landing airplane in the range-Doppler matrix using the MSIR method [2].

adaptive beamforming, space-time adaptive processing, coverage measurement and simulation of the emitters (e.g., video broadcasting), along with target tracking and ISAR imaging algorithms. The Hungarian activities centered on experimental hardware, digital adaptive beamforming using a 4-channel DVB-T band passive radar and ISAR imaging algorithms in the context of a wideband active imaging radar. Special attention was paid to the challenging detection problems of small-sized unmanned aerial vehicles (UAVs) [2].

The Hungarian ESA Project, Integrated Sentinel-1 PSI and GNSS Technical Facilities and Procedures for Determination of 3D Surface Deformations caused by Environmental Processes is a cooperation between Geodetic and Geophysical Institute, Sopron and the Department of Broadband Infocommunications and Electromagnetic Theory. The goal of the project is to combine Sentinel information warfare images processed by integrated persistent scatter interferometry (PSI) with GNSS observations on important areas where the use of traditional PSI methods are limited due to complex or unstable ground coverage. Analytical investigations and numerical simulations on corner reflectors were made to determine the limits of truncation. Scaled (5:1 ratio) corner reflectors have been manufactured and measured in an anechoic chamber [16].

Figure 8. The manufactured face-to-face IBs for Sentinel-1 3D InSAR applications [16].

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7. Commission G: Ionospheric Radio and Propagation

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The main center of ionospheric radio and propagation research in Hungary is located in the Geodetic and Geophysical Institute, which operates under the auspices of the Hungarian Academy of Sciences. For one and a half decades scientific leadership was provided by Section II (Social and Historical Sciences).

Research data is provided by the state-of the art ionosonde located at the Széchenyi István Geophysical Observatory in North-West Hungary, in Nagycenk (IAGA code: NCK). Its McIllwain number is L =1.9 and, therefore, this station is optimally situated to observe midlatitude ionospheric processes. The station has a geomagnetic latitude of 46.17°, a geomagnetic longitude of 98.85°, and an inclination (dip angle) of 66.83°. Research on irregularities in the ionosphere, the propagation of radio waves and monitoring Schumann resonances are the primary activities of the Institute [1-18].

The Institute has had a major impact on the activities of the Hungarian geophysical workshops and research centers (mostly universities and colleges) and on the organization and management of the research. The Institute maintains wide international contacts through several projects run in co-operation with foreign partner institutions.

7.1 Satellite Links

The modeling of the propagation of GPS radio signals through a homogeneous ionosphere has shown that the paths of the L1 and L2 frequency signals differ by several centimeters [19-21] which is important for some applications.

The ionosphere also includes irregularities which can scatter radio signals. Two types of irregularities have been studied. One of the groups includes the sporadic-E layers that, contrary to the thick or steady layers in the E, F1 and F2 layers, come and go. Sporadic-E occurs at all latitudes but their causes are various. The other group are field aligned irregularities with diameters of the order of 100 m perpendicular to the field lines and of the order of 10 km along the field lines.

7.2 Geomagnetic Pulsations

The 11 August 1999 total solar eclipse was studied using a large array of instruments in Central Europe including many observatories and additional temporary stations established by Japanese, German and Hungarian groups. Related studies demonstrated that the amplitude of the field line resonance (FLR) pulsations decreased in and around totality by a factor of two, and this decrease moved with the projection of totality on the ionosphere. This decrease of the FLR-type pulsations, was interpreted as due to a change in the eigen-period of the field line as a consequence of a change in the charged particle distribution along that field line. An effect was also found in the phase of the (magnetic or electric) perpendicular components and geomagnetic induction. This study showed that field line resonances are sensitive to external changes (the interplanetary magnetic field), but also to internal changes, such as the change of the charged particle distribution.

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8. Commission H: Waves In Plasmas

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Since the 1975 reorganization of the URSI Commission the activities of the Hungarian Commission H community can be grouped in three areas: 1) Ground-based observations of ULF and VLF phenomena, 2) Instruments for space plasma experiments and 3) Theoretical solutions of Maxwell's equations on plasma waves.

8.1 Ground-Based Observations of ULF and VLF Phenomena

The Automatic Whistler Detector and Analyzer Network (AWDANet) [1] seeks to detect and analyze lightning generated whistlers in near real-time to provide estimates of cold electron densities in the magnetosphere, particularly the radiation belts. The network (Figure 9) has around 25 operating stations, 15 of them are equipped with an on-site real-time analysis capability.

The main focus in the past 45 years has been on understanding the origin, propagation and coupling of Pc3 and 4 ULF waves (period 45 – 100 s). Pc3s are generated in the upstream solar wind and penetrate deep into the magnetosphere as compressional waves [2-4]. This global mode drives toroidal Alfvén mode field line resonances (FLRs) with latitude dependent period.

References [5] and [6] showed that Pc3 waves of upstream origin can even reach the equatorial topside ionosphere, where they can be observed by low earth orbiting satellites as compressional ULF waves. This result was unexpected and led to the revision of models of MHD wave propagation and MHD wave-ionosphere interaction [7].

A coordinated network for the observation of ULF waves along the 100° magnetic meridian has been established, including stations from Finland (IMAGE), Poland, Slovakia and Hungary. In 2012, the network was merged with the South European SEGMA array forming EMMA, the European quasi-Meridional Magnetometer Array (Figure 10). Based on EMMA a plasmasphere monitoring system has been developed capable of providing near real-time plasmaspheric density estimates for a wide range of L-shells (L = 1.5 – 6.1). This work was funded by an EU FP7 project, PLASMON [8]. The monitoring system exploits the plasma density dependence of the FLR frequency along a given field line. The two networks are capable of monitoring the density variations in the magnetosphere during space weather events [8]

8.2 Instruments for Space Plasma Experiments

A new ULF-VLF wave instrument-family has been developed and successfully operated on several satellite experiments. The first Signal Analyzer and Sampler (SAS) instrument flew on ACTIVE satellite [9], SAS-2 operated on COMPASS-2 satellite [10]. The enhanced SAS-3 instrument monitored space weather related phenomena on the Chibis-M [11] and RELEK/Vernov satellites as well as within Obstanovka-1 mission on the International Space Station [12]. SAS-3 instruments are under development for the Trabant satellites and Obstanovka Phase-2 missions for the International Space Station (expected starts are in 2023-2024).

8.3 Theoretical Solutions of Maxwell's Equations for Plasma Waves

A new full-wave solution of Maxwell's Equations was developed for whistler-mode waves propagating in the magneto-ionic medium [13]. This solution can describe the propagation of short impulses with arbitrary initial shape and includes solutions for electron as well as proton whistlers in homogeneous, inhomogeneous and lossy plasmas. This solution has been extended to moving media [14] and for general relativistic situation [15].

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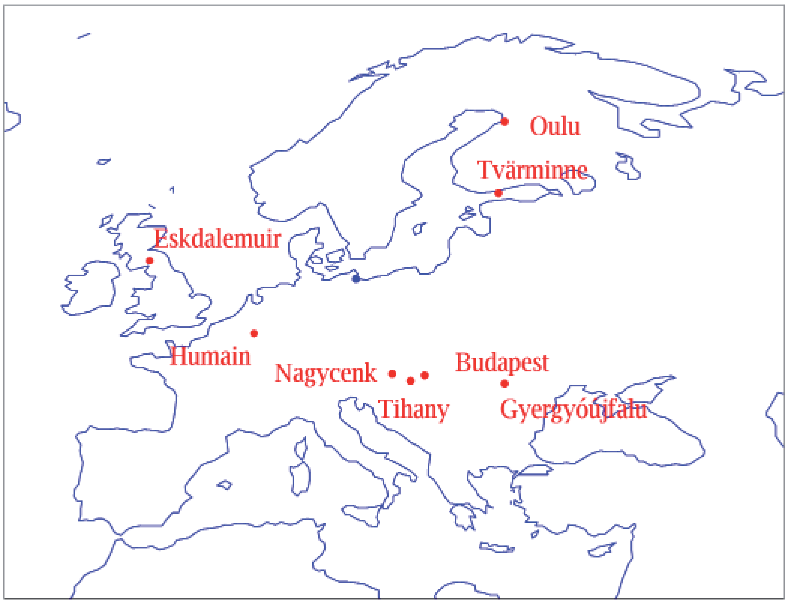

Figure 9a. A map of the AWDANet stations in Europe. The names printed in red are operational stations, and those

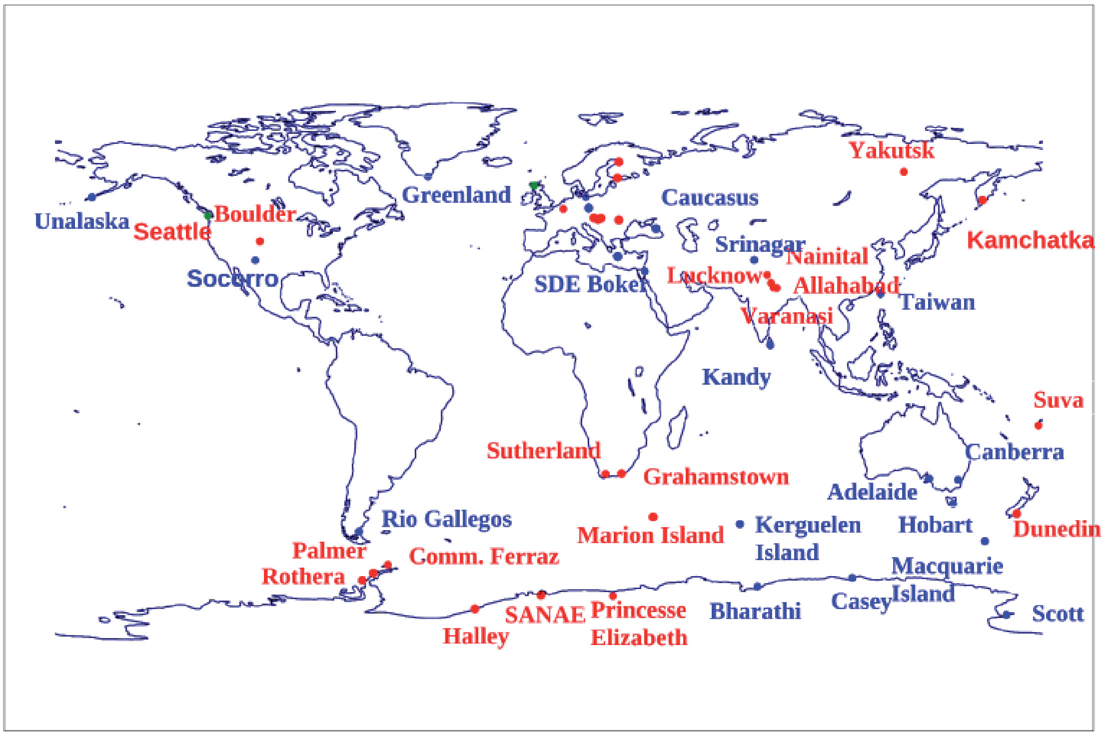

Figure 9b. A map of the AWDANet stations worldwide. The names printed in red are operational stations, and those printed in blue are planned stations.

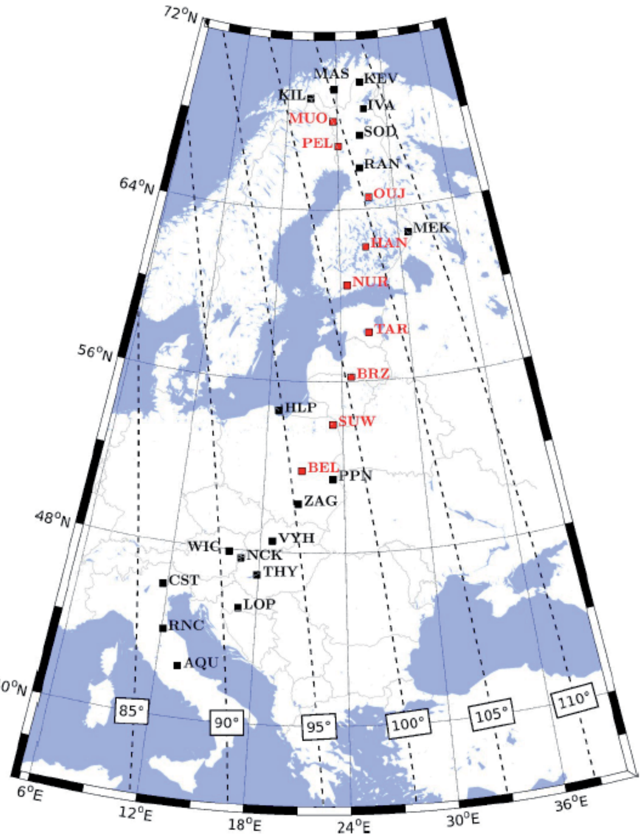

Figure 10. A map of the EMMA stations.

9. Commission J: Radio Astronomy

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SGO-Satellite Geodetic Observatory
Hungary

The Satellite Geodetic Observatory of the Institute of Geodesy, Cartography and Remote Sensing (FOMI) is Hungary's first, and still only, astronomical infrastructure. Its aim is to undertake research studies and adapt satellite-based technologies to improve and modernize the Hungarian geodetic infrastructure. The Observatory building was officially opened on 26 November 1976, but during the preceding years the organization was established and the preparation of research tasks was started. During its 40-year plus history the Observatory has carried out essential research and delivered infrastructure and services.

At the 40th anniversary Observatory in 2012 a historical exhibition was opened which displays the evolution of tools and equipment used in the Observatory during this period. Nine posters give an overview of the history from construction, through classical research trials, to novel applications of Global Navigation Satellite Systems (GNSS).

9.1 GNSS Analysis Center

In the SGO, GNSS data processing has more than two decades of history. Since 1993 it has used the Bernese software package for basic scientific research, R&D activities and national and international service commitments. The purpose of scientific analysis is to determine high precision geodetic, geophysical parameters such as station coordinates and tropospheric parameters. Currently the Bernese 5.2 software package and the GIPSY OASIS II and GAMIT software are used.

9.2 GNSS Geokinematic Investigations

The advent and rapid development of satellite geodesy since the late 1980s initiated geokinematic research studies to determine the velocities of the Earth's lithospheric plates. Applications of satellite positioning have also gained leading role in research areas related to other Earth physics disciplines thanks to the low cost and the multipurpose usability of the devices. Today GNSS is used from the global to the local scales (plate tectonics, plate boundary zones, and also intraplate studies) in order to monitor crustal deformation.

9.3 Satellite Radar Interferometry (InSAR)

Interferometric Synthetic Aperture Radar (InSAR) is a state-of-the-art remote sensing technique able to measure and monitor displacements and it provides new perspectives in geophysics, geology and geodesy. In its simplest form, InSAR combines two accurately aligned SAR images of the same scene into an "interferogram' by computing the differences in the phase of the radar waves. This technique is able to retrieve surface movements and velocities with unprecedented resolution and precision. Its huge advantage is that no field survey markers are necessary as appropriate elements of the natural and constructed environment can be used. Thanks to this capability, and in contrast with any other deformation measurement technology, historic radar data, dating back to 1992 can also be used. The introduction of the InSAR technology and its applications were initiated by the Satellite Geodetic Observatory in 2000. Since then we have built up the knowledge base, human resources have been allocated and trained, and the IT infrastructure had been procured and installed. We use the GAMMA software, which provides a variety of InSAR solutions and data products in an integrated way. We also established and developed and maintained an integrated reference marker infrastructure, the Sentinel Geodetic Base Network (SENGA), which collocates various geodetic technologies and reference networks, [1, 2].

9.4 VLBI Related Research

The Satellite Geodetic Observatory has been involved in space VLBI research since the mid-eighties. This research concentrates on both astrophysical and geodetic applications of the new observing technique. One of the main activities has been to develop user assistance software in order to help the user community prepare observing proposals in response to announcements of opportunity in connection with space VLBI satellites. In the 1990-2018 period ten national (OTKA/NKFIH) projects for VLBI and GPS geokinematic research were performed.

The Space VLBI Assistance Software (SPAS) has been developed since 1993 using the software engineering standards of the European Space Agency (ESA 1991), with the first version of SPAS released in June 1995, [3-5]. Together with other two user support software packages, SPAS was used for the VSOP proposal preparation simulating space VLBI experiments by checking satellite constraints, ground VLBI and tracking network availability and assessing the expected data quality, [6-18].

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10. Commission K: Electromagnetics in Biology and Medicine

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The main activities related to the interaction of electromagnetic fields with biological systems have taken place in the National Research Institute for Radiobiology and Radiohygiene (NRIRR) in Hungary.

10.1 A Brief history of the Institute for Radiobiology and Radiohygiene

Following a 1994 decision by the Hungarian Government, an Institute was founded on 1 January 1957 by the Ministry of Health under the name, Central Research Institute for Radiobiology and this was renamed on 1 January 1959 the Frédéric Joliot-Curie Central Research Institute for Radiobiology.

As a consequence of changes in domestic and international requirements and policies, especially the launch of the domestic nuclear energy program, the responsibilities of the Institute expanded. This included the national coordination and implementation of radiohygiene research and other activities, including workplace and environmental radiohygiene and later research and development of radioactive therapeutic preparations. As a consequence, the Institute expanded and was renamed on 1 January 1963 as the "Frédéric Joliot-Curie" National Research Institute for Radiobiology and Radiohygiene (NRIRR). The Institute has become the professional center of the country for radiation health. The NRIRR was designated by the World Health Organization (WHO) in October 2004 as a WHO Collaborating Centre for Radiation Emergency Medical Preparedness and Radiation Health. Activities of NRIRR related to its tasks within the WHO Radiation Emergency Medical Preparedness and Assistance Network (WHO/REMPAN) are described in [1-13].

10.2 Exposure Measurements (ELF-MF)

The research group reviewed the findings of exposure assessment studies carried out in European countries on the exposure of the general public to low frequency (LF) electric and magnetic fields (EMFs). This review showed that outdoor average extremely low frequency magnetic fields (ELF-MF), in public urban environments, range from 0.05 to 0.2 mT, but stronger values (of the order of a few mT) may occur directly beneath high-voltage power lines, at the walls of transformer buildings, and at the boundary fences of substations. In the indoor environment, high values have been measured close to several domestic appliances (up to the mT range), some of which are held close to the body, e.g., hair dryers, electric shavers. Common sources of exposure to intermediate frequencies (IF) include induction cookers, compact fluorescent lamps, inductive charging systems for electric cars and security or anti-theft devices. No systematic measurement surveys or personal expositmetry data for the IF range have been carried out and only a few reports on measurements of EMFs around such devices are mentioned. According to the available European exposure assessment studies, three population exposure categories were classified by the authors regarding the possible future risk analysis. This classification should be considered a crucial advancement for exposure assessment, which is a mandatory step in any future health risk assessment of EMF exposure, [14,15].

10.3 Exposure Measurements (RF)

Currently, the data most widely available on exposure of the general public to radiofrequency (RF) electromagnetic fields (EMF) within the 10 MHz – 6 GHz range relate to radio and television broadcasting, base stations for telecommunications and mobile phones, cordless (DECT) phones, RF identification tagging systems, and wireless communications applications, such as Wi-Fi, wireless local area network (WLAN) and worldwide interoperability for microwave access (WiMax). The political interest in emissions from these devices, and their potential association with various health effects, continues to increase, and it is anticipated that more data on public exposure to EMF in the whole-frequency spectrum will become available over the next few years. The newest generation of mobile telecommunications networks—LTE (long-term evolution), which will coexist with the existing technologies occupying the microwave spectrum—represents another growing source of RF EMF that is expected to add to RF exposure in the near future. Narrowband and broadband measurement methods of assessing exposure levels to RF fields have been applied in the range from several MHz to 10 GHz. Most of them were focused on exposure in the frequency range of mobile telecommunications (base stations), [16-20].

Public exposure to radiofrequency (RF) radiation caused by digital broadcast (DVB-T) stations and mobile cellular systems stations was evaluated. For DVB systems, broadband RF measurements were performed at 351 recording points around 28 broadcast towers in Hungary. Qualitative analyses were performed of the RF field strength in four different ranges from the towers, [19-20].

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Ireland and the Birth of Global Wireless Communications Services

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Abstract

Through the early history of radio science and engineering, Irish people have played extraordinary roles. Perhaps the most outstanding figure is Guglielmo Marconi, the Irish-Italian Nobel-laureate, inventor of wireless communications. The Irish dimension of his pioneering discoveries, technical developments, public demonstrations, and commercial exploitation of wireless, discovery of the ionosphere all deserve to be highlighted. Another outstanding Irish person was Belfast physicist John Bell, who found a way to resolve the four-decade-old Einstein-Bohr controversy, and opened up new and important research fields, such as quantum encryption and quantum computing. Irish woman, radio astronomer and astrophysicist Jocelyn Bell-Burnell is the discoverer of pulsars in 1967. Long before these three, Nicholas Callan, academic and catholic priest, made major contributions to foundational electrical circuits and devices, especially his induction coil with its specific application to the early spark-gap wireless transmitters. In addition to these four big names, this article also considers, briefly, many other Irish scientists and engineers who have made significant contributions to the phenomenal 20th and 21st centuries' global expansion of electromagnetic radio science, from low frequencies to microwave, millimeter-wave and terahertz frequencies, many of whom have participated actively in URSI Commissions, scientific symposia and journal publications and continue to be active in radio-science research to this day.

1. Marconi's Ireland is Birthplace of Wireless Communications

Ireland has a unique place in the discovery and creation of wireless radio-communication. The story centers on Irish-Italian Nobel-laureate Guglielmo Marconi (1874-1937), Figure 1, whose name is synonymous with wireless. From a home-spun wireless transmitter-receiver in his attic near Bologna, he moved to London and then to Ireland in the 1890s. Within a decade Marconi had added a whole new exciting and revolutionizing dimension to world-wide communications as well as significant discoveries and inventions. The revolution quickly went global and continues to the present day in broadcast radio and TV, terrestrial and satellite, from the telecommunication, tele-command and tele-control space systems for Voyager and Pioneer probes as they explored to edge of our solar system and beyond, for landing a man on the moon, for the space station and space telescopes, and for all modern planet exploratory probes, on to the creation of our incredibly wireless interconnected world through cellular generations (now entering 5G), and ever faster Wifi, Bluetooth, through to intelligent wireless networking, the pervasive Internet of Things (IoT), and a host of other evolving wireless technologies and services on which our world and lives have come to depend.

There were also some less visible, though significant Irish contributors to the birth of wireless communications. One, in particular, was Marconi's Irish mother, Annie Jameson Marconi, Figure 2. Another was her nephew, and Marconi's first-cousin, Henry Jameson Davis, for his financing, business management, and patent protection contributions. Others include Trinity College Dublin (TCD) graduate Edwin Glanville, a radio scientist and engineer; Belfast-man Lord Kelvin, William Thompson, for his ribbon-cutting commercial launch of wireless communications; and the Maynooth academic, Catholic priest and scientist Fr. Nicholas Callan, for his induction coil, which was an all-important component for Marconi's spark-gap transmitter.

Figure 1. Guglielmo Marconi, received the Nobel prize in Physics, 1909, in recognition of his contribution to the development of wireless telegraphy.

Figure 2. Annie (Jameson) Marconi with her sons Guglielmo and Alfonso, c. 1877.

1.1 Romantic Elopement

The story begins with the unlikely, but amazing elopement of Guglielmo's parents, 24-year-old Annie Jameson and 41-year-old Giuseppe Marconi, in 1864. Annie (Anne Fenwick Jameson) was from Daphne Castle, Enniscorthy, Wexford, 120 km south of Dublin, Ireland. Over 2,000 km away, Giuseppe lived in Bologna, Italy. For generations his family lived in the hilly Capugnano village, on the lower regions of the Apennine mountains, about 50 km southwest of Bologna in the direction of Florence.

1.2 Love at First Sight

How could such a long-range elopement come about in the 19th century? One might claim it was her singing! Some years before, Annie, still perhaps in her teens, was sent by her family to Bologna to study singing at the Accademia Musicale [1, 2]. "A pretty girl...with a glorious singing voice and a will of her own," was how her granddaughter Degna Marconi (1908-98; Figure 15) described her. (Degna was Marconi's second daughter by his first wife Beatrice, Bea, O'Brien (1882 - 1976). Bea was from Co. Clare, Ireland. They married on 16 March 1905.) In Bologna, Annie stayed with the de'Renoli family who were banking business contacts of the Jamesons. As it happened, the de'Renoli's household was also a second home to their son-in-law Giuseppe. Their daughter, Guilia, who married Giuseppe in 1855, died aged 24 in 1858 leaving a distraught Giuseppe and their 2 year-old son Luigi [2]. Destiny intervened and the encounter with Annie happened. For Annie and Giuseppe, it was love at first sight. Smitten, she abandoned the "*bel canto*," and returned to Ireland to ask her parents' permission to marry. He being Italian, seventeen years her senior, a widower with a child, and a Catholic, while the Jamesons were Scot-Presbyterians, said no. While accepting their decision graciously, the couple nonetheless secretly continued their romance by smuggled letters between Enniscorthy and Bologna until, coming of age, Annie travelled through England into France and he from Bologna. In Boulogne-Sur-Mer, on the north coast of France, they met again, eloped, and married on 16 April 1864. They then headed south to Bologna to live in Giuseppe's estate home, Villa Griffone. For modern day mobile communication users the world over, and all the wireless fruits that followed, perhaps we could call it a marriage made in heaven!

Her family in Ireland quickly and pragmatically came to terms with the marriage, especially when one year later their first son Alfonso was born. There followed a nine year wait for her second child, Guglielmo, born on 25 April 1874. Guglielmo inherited Annie's blue eyes, as well as her love of music, poetry and grace, and the astute commercial business flare of the Jamesons. The eponymous John Jameson Whiskey distillery in Dublin, founded in 1780 by her grandfather, was then and still is world renowned [3, 4]. The Jamesons were part of the entrepreneurial industrial-revolution culture then in full flight. Guglielmo was also gifted with the indefectible will, tenacity and persevering work ethic of both Annie and

Giuseppe. To these one could add his incipient inventive engineering bent and his vision and convictio. At the young age of 20, in 1894, he saw the commercial potential of 'Hertzian waves'. Here were the seeds of his amazing success launching and driving the global revolution of wireless communications. Something of this is captured by the eminent **Thomas Edison**'s in his message to the distinguished guests at a dinner held in Marconi's honor, 13 January 1902, organized by the American Institute of Electrical Engineers (AIEE) [5], referring to him as "(that) young man who had the monumental audacity to attempt, and succeed in, jumping an electrical wave clear across the Atlantic Ocean."

1.3 Wireless Communications Also Has an Irish Mother

If Guglielmo is the father of wireless communications, Annie is its mother, not so much in the technical aspects, but more in her determined, practical and direct support of all her son's endeavors. He himself acknowledged it in the opening sentence of his autobiographical notes [6]: "I owe what success I have had more than anything to the encouragement and inspiration of my mother."

This was in contrast to his father's early negative view [1]. A business man, Giuseppe had followed in the footsteps of his own father, Domenico, who built a very successful property- and agri- business in Capugnano and Bologna, which included the purchase of the extensive Villa Griffone estate. To him, his son's electro-technical interests and activities behind the locked door of their large attic seemed more like a useless hobby and a complete waste of time (perdita completa di tempo, as he remarked [7]). His skepticism vanished, however, when he saw his son's first attic demonstration of the wireless ringing of a bell, and he finally opened his wallet. From the beginnings in the attic, and through the early years, Guglielmo had the continuous support of Annie's enthusiasm, her faith in his work, and his inventive abilities, and her practical appreciation of his determination to advance his inventions. She also helped with money for his home-made experimental apparatus.

1.4 First Non-Line-of-Sight Wireless Communication

With the hard-won help of Giuseppe's initial money, he moved to experimenting over distance in the grounds of Villa Griffone. It was there, in August 1895, that he achieved the first non-line-of-sight wireless communication, transmitting his favourite Morse S signal over 3km (1.5 miles), across intervening hilly ground. His brother Alfonso was at the receiver, and communicated successful reception back to Guglielmo by firing a gun [7, 8]. Now, in two ways, he had definitively moved beyond Heinrich Hertz's 1888 experiment verifying James Clerk Maxwell's theoretical proposal, arising out of his four equations unifying electromagnetic (EM) theory, of EM waves radiating and propagating at the speed of light. Firstly, Marconi had discovered that non-line-of-sight wave propagation happened. The great theorists of his day believed this was not possible, and had no explanation for it for some time. Secondly, real, relatively in-expensive, wireless communication was possible. Amazingly, despite the great minds studying EM phenomenon, such as Hertz himself, Oliver Lodge (tuning/syntony, with his first resonant circuit invented and already patented in 1893), and Eduard Branly (coherer detector inventor). It also included their neighbor and the Marconi's acquaintance at Bologna University, the great experimentalist, Augusto Righi (spark-transmitter inventor, although it had already been invented by Nicholas Callan years before, in 1836 in fact). He helped Marconi, but only by allowing him to work in his laboratory and have access to the University's library. This provided access to such key publications as Oliver Lodge's 1894 Hertz memorial lecture. Hertz had died prematurely that year, aged 36. Marconi seemed to be alone in the world in realizing this communication potential. He could hardly believe this to be the case, but knew he had to move quickly to commercialize it.

1.5 Alla Lungara or to London

Marconi drafted his first business plan and sent it to the Italian Minister for Post and Telegraphs, explaining his proposed wireless telegraph machine and requesting investment funding. The Minister is said to have written on it Alla [to the] Lungara [7]. This referred to the then mental hospital of Santa Maria della Pietà on Via della Lungara, in Rome! Marconi later disputed this happened [2]. However, his daughter, Degna, goes into some detail about all of this, and his, and the family's, initial despondency on receiving a rejection letter [1]. In the right person, such rejection can temper the will, and even stimulate lateral thinking and more ambitious solutions. In any case, it was at this time that Annie's intuition and optimism played a decisive role. She was the first to realise the potential of his invention for ship-to-shore and ship-to-ship communication, which added a previously unheard of dimension to maritime safety [7]. The UK was then the world's greatest maritime nation. That is where they should go, and she set to work on her considerable Irish-UK family connections, especially those she felt sure "would understand what had to be done" [1] and received back encouraging replies. Marconi, in 1913, recorded his own recollection of this [2, 9 (Marconi 54)]: "I was advised by my mother's [Irish] relatives that England was […] the country in which, owing to its large fleet, extensive coast and largest shipping interests, my invention would be most readily employed."

Another local family friend, Carlo Gardini, Honorary Consul at the United States Consulate in Bologna, also helped. He wrote a letter of introduction to the Italian Ambassador in London, Annibale Ferrero, a friend, who in response encouraged Marconi to come to England, and advised that he should not reveal his invention until he had patented it [2]. So, aged 21, he packed up all his apparatus (induction coils, spark gap, tapping keys, relays, coherer, bells and so on), most of it ingeniously home-made, and he and Annie both headed to London, arriving in Dover in January 1896. Customs officers seeing Marconi's various electrical contraptions in his luggage immediately contacted the Admiralty in London. This, in fact, was a return to England, as he had imbibed the English air as a child when Annie had brought him and his brother Alfonso to live in Bedford, from 1876 to 1880. Through this, and through Annie's home-schooling, his command of English was already good.

1.6 Multi-Million Pound Investment by Irish Whiskey Distillers and Grain Merchants

Annie's influence, and her Irish business connections among her relatives, now came into their own. Her nephew, Henry Jameson Davis, a milling machinery engineer held in high regard in Dublin and London business circles was crucial. He attracted a staggering Stg£100,000 financial investment in 1897 (equivalent to about 7M Euro today, 2019). The importance of this to Marconi's success cannot be overstated. Jameson Davis's standing, and his own, Annie's and Giuseppe's financial commitment, helped win over wealthy Irish grain merchants connected to the whiskey business, persuading them to become directors and to underwrite the credit line of a new Wireless Telegraph and Signal Company, which he formed on 20 July 1897, with himself as Managing Director and Marconi as Technical Director [10]. These were men who had little or no understanding of electro-technology or Marconi's invention. Edwin Glanville (1873-1898), a young Irishman and a brilliant TCD graduate in mathematics and experimental science, who was taken on by Marconi in early 1897, reveals this in a letter to his family, 21 November 1897. He wrote, in reference to the company directors at a shareholder meeting that same month, "They asked idiotic questions...." He explicitly excluded one director, Robert Goodbody, from his criticism [7].

In 1900, the company changed its name to include Marconi's name. This recognized he was their most valuable asset, which was also the persistent strong advice from Annie and Giuseppe. Financially, ever more involved in it, and seeing their son's star rise rapidly in the international media, apart from family pride, both had a strong intuitive insight into the implications of having the company named after him. Almost immediately that proved perceptive [1].

1.7 First Wireless Telegraphy Patent and First Public Demonstrations

Prior to this, Jameson Davis encouraged and helped Marconi to take out the world's first patent for wireless telegraphy, which was granted on 2 July 1897 [11, 12]. Through an associate, A. A. Campbell Swinton (a Scottish engineer, who would later become the first advocate of all-electronic television [13, p. 123]), he arranged an introduction to Sir William Preece, the formidable Chief Engineer of the General Post Office (GPO), UK.

Skeptical about the reality of radiating EM waves, Preece nonetheless invited Marconi to demonstrate his wireless communication to him and to others. This he did without delay on 27 July 1896, showing it operating between the Central Telegraph Office, located on Newgate Street, St Martin's Le Grand, London, where the BT Centre now stands, and GPO South, Carter Lane, 330 yards (300 m) away, with the transmitter on one roof and the receiver on the other. A much impressed Preece went on to provide some GPO support for follow-up demonstrations to UK army and navy military top brass, visiting military from allies, including Italy, and to senior GPO engineers, on Salisbury Plain in England, over distances first of 1.25 miles in Sept 1896, then 4 miles in March 1897, and then 9 miles in May. Preece's support included releasing to him, in late 1897, George Kemp, a 45-year-old knowledgeable and experienced electrical technician. Glanville, in a letter to his family 21 November 1897, mentions that they, the company, had taken on Kemp [7]. Kemp remained Marconi's chief technical assistant until his death, in 1933.

Preece's initial warm welcome and support for Marconi can be credited to his regard for Jameson Davis and Campbell Swinton. Not long afterwards, however, this cooled to the extent that, around 1898, Sir John A. Fleming, inventor in 1904 of the thermionic diode valve, and key consultant to Marconi for the transatlantic experiments, was to advise him: The less you have to do with the GPO the better [7]. The problem was two-fold. Preece seemed to remain skeptical about radiating EM waves but was convinced about the potential for wireless communication by non-radiation wireless induction and had committed significant GPO resources to develop this [14]. This is the principle underlying near-field communication (NFC) widely in use today, especially for small payment transactions such as credit card tapping. The induction field in theory and in practice dies off rapidly with distance from the antenna. Preece's expensive and rather vain project eventually floundered. Also, apparently, he now perceived the Marconi Company challenged the GPO's legal monopoly on telegraph transmission. The UK's 1868 Telegraph Act had given the Postmaster-General power to acquire, work and maintain all telegraph installations in the UK, on land and within its territorial waters. The hardening of this opposition further forced Marconi to pursue the maritime focus his mother foresaw for the commercial exploitation of his wireless communication invention.

1.8 To Ireland - First Commercial Wireless Communication Services

The year 1898 saw a variety of Marconi's successful experiments and well publicized pilot demonstrations. These included wireless links over sea, mainly along the English Channel, such as Alum Bay, Isle of Wight and Bournemouth (in January), and the South Foreland Lighthouse near Dover with the East Goodwin lightship off Dover (in December) [2, 7, 15]. These achievements were celebrated and Marconi feted in British and international media, giving rise to considerable excitement. Experimentation included testing new circuit components and designs, of antenna geometries and configurations, and mapping wireless path transmission characteristics. Glanville and Kemp were key to all this work. In December 1898, the company set up the first wireless equipment factory in Chelmsford, Essex.

In 1898, Marconi's first commercial contract brought him to Ireland. It is evident from his hiring of Glanville, whose family had deep Dublin roots, and from Glanville's family letters through 1897 and 1898, that Ireland was always in his sights [7]. Its geographical position made it central to the shipping routes between Northern Europe and North America. Furthermore, Ireland was already strategically important in the birth of global communications, as the first Europe-America intercontinental submarine cables were laid from Valencia Island, on Ireland's south-west coast, to Heart's Content, Newfoundland, Canada.

From 1866 onwards, the cables across the Atlantic Ocean were an astounding commercial success, just as their fibre optic successors are up to the present day, now of course forming the intercontinental backbone segment of the global Internet and the information market. They displaced much (though not all) of the profitable, sophisticated but often dangerous New-World news-gathering enterprise that entrepreneur Paul Julius Reuter had set up, and which was a key component establishing him and his renowned Reuters News Agency [16, 17]. By arrangement, his boats from Crookhaven and Fastnet Island, in the southernmost corner of Ireland, intercepted the incoming transatlantic steamers thereby scooping the news from the New World ahead of the competition. It was then transmitted by land-based telegraph cable from Crookhaven to London, for publication in The Times and other European newspapers. He himself had built the 125 km telegraph connection linking Crookhaven to Cork in the 1860s [7]. That part of the lucrative business of communicating the expected time of port arrival of transatlantic ships, which had successfully crossed the Atlantic, to ship owners and insurers like the Lloyds company, and to cargo owners nonetheless continued, along with relaying personal messages from ships' passengers.

1.9 Kelvin and Tennyson Cut the Ribbon on Commercialized Wireless Communication

Marconi's dream of commercializing wireless communications, for which he worked day and night, got an unexpected boost, in the person of the renowned and elderly Lord Kelvin. An Irishman from Belfast, Lord Kelvin, William Thompson (1824-1907), was the chief engineer for the 1850s and 1860s transatlantic cables projects. Marconi invited him and his friend, Lord Tennyson, and their wives, to Needles Hotel, Alum Bay, on the Isle of Wight, to see a wireless demonstration over water. Highly skeptical about wireless telegraphy until that day, 3 June 1898, Kelvin was so impressed that he insisted Marconi accept payment for three telegrams from him to key people [1, 7, 9 (Marconi 142)]. His telegram texts unambiguously proclaimed the telegrams were paid for with the words, "[…] transmitted commercially through the ether (sic) from Alum Bay."

Given Kelvin's stature, not of course lost on Marconi, this was an announcement to the world and especially to the GPO (Preece was one of the three recipients) that the commercial stage of Marconi's invention had now started. It was the equivalent of Cutting the Ribbon on the opening of commercial wireless telegraph services. Tennyson's telegram to his nephew that day, also paid for, likewise proclaimed and further underscored the reality that wireless telegraphy had moved beyond just being a scientific discovery and an engineering preserve, to become a service open to all people, even poets!

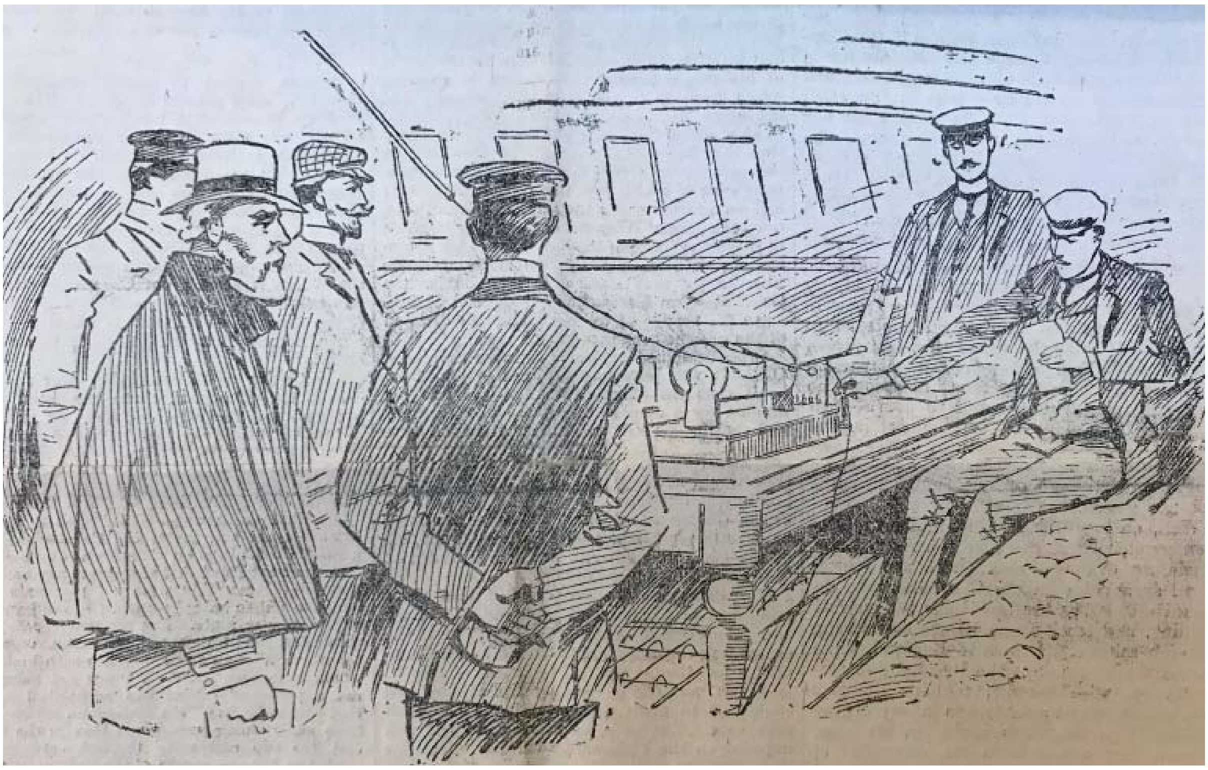

Figure 3. On board the Flying Huntress paddle-steamer tug-boat, 20 July 1898. Marconi on right, TCD Professor George F. Fitzgerald second from the left, Catholic University (now UCD) Professor Gerald Molloy third from the left. [19] (Credit: Bodleian Library, Oxford).

1.10 Rathlin Island – First Commercial Contract and Tragedy

In fact, as with many such ribbon-cutting openings, the new business had already begun. Just days before Marconi had received his first commercial contract from Lloyds to set up a wireless link in the north east of Ireland between Rathlin Island and Ballycastle, to report on their incoming ships passing through the north channel between Ireland and Scotland. On the 4 June, the day after the ribbon-cutting, Kemp left for Ballycastle, followed by Edwin Glanville, to start building the wireless link installation. The first successful test transmission was on 6 July 1898, and the installation was fully completed and operational by 25 August. It was, however, accompanied by tragedy as the young Glanville was killed on Sunday 21 August in a fall from the cliffs on Rathlin while pursuing his hobbies of geology and bird watching. The shock and grief of his family was shared deeply by Marconi.

1.11 Contrary Winds

Marconi now began to experience the harsh reality of commercial politics. Preece, exercised his powers under the 1868 Telegraph Act, and intervened and ordered the Rathlin - Ballycastle link be shut down [7]. He replaced it with one of his beloved wireless induction links. It was a short-lived project, and was to be his only successful in-service induction link. At this remove, Preece's actions and motivations look petty and regressive. Unfortunately, they heralded many such commercial legal battles Marconi was later to face on both sides of the Atlantic [2].

1.12 Sports News and Entertainment: The First Prescient Wireless Live-Streaming Service

The popular annual yachting regatta at Kingstown (on the south side of Dublin Bay; today, Dun Laoghaire) caught the imagination of Dublin upper classes, as well as the general populace. On the 20 and 21 July 1898 the regatta was about to get a major publicity boost. Two sister Dublin newspapers, the Daily Express and the Evening Herald [2] celebrating a centenary, had the idea to invite Marconi to provide a live wireless report of the regatta. He jumped at it, immediately grasping the public relations opportunity. He wrote from Dublin to his father, on 13 July, telling him in a matter-of-fact

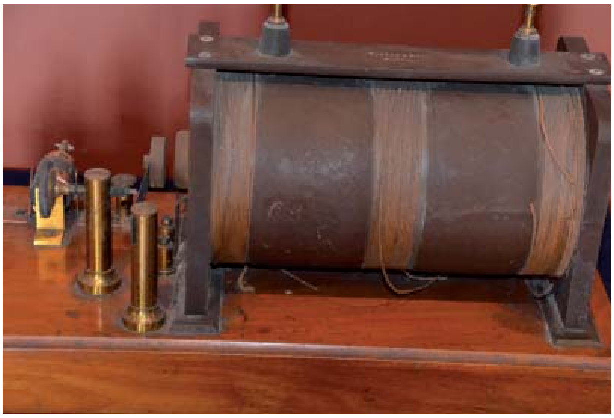

Figure 4. The induction coil used by Marconi on board the Flying Huntress, Dublin, 21 July 1898. (Credit: National Science Museum, St. Patrick's College, Maynooth, Ireland).

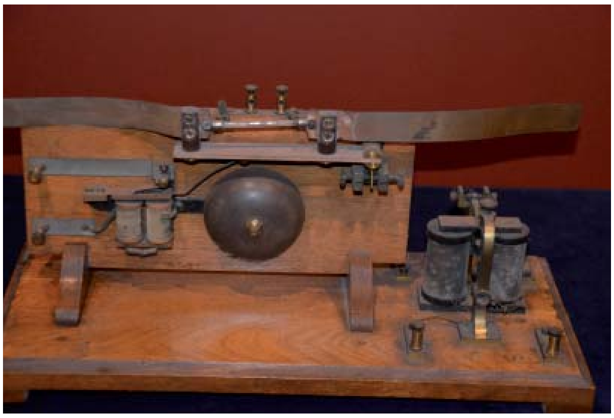

Figure 6. The glass tube receiver-coherer with vibration de-coherer mechanism, and bell used by Marconi on board the Flying Huntress, Dublin, 21 July 1898. (Credit: National Science Museum, St. Patrick's College, Maynooth, Ireland).

Figure 5. The spark gap-rig used by Marconi on board the Flying Huntress, Dublin, 21 July 1898. (Credit: National Science Museum, St. Patrick's College, Maynooth, Ireland).

way about his role in the upcoming yachting regatta. Clearly, the plan was evolving. He thought that his apparatus would be on several yachts. However, the solution was to hire the Fly Huntress, a paddle steamer tug-boat (122.5 x 20.2 x 10.6 ft) [18] and use it. He rigged up his wireless transmitter and receiver on board, and set up another station in the Harbor Master's Office in Dun Laoghaire (now Moan Park House), which was manned by Glanville and Kemp. On the Flying Huntress, Marconi and his retinue, Figure 3 [19], followed the races some 7 to 10 miles out in the Bay, often it seemed of sight of Dun Laoghaire. Marconi, as the telegrapher, sent about 700 wireless reports to the land station. These were phoned into the city centre newspaper offices and posted on the office windows, causing fascination, excitement and joy; and also, consternation and chagrin, especially among the betting fraternity.

There was hardly a better way to convey to the world the starkly disruptive role of the new wireless communications than this first-ever use of it in journalism, and that for live streaming of yacht racing results! This bringing of upper-class sports entertainment closer to spectators, fans and common folk in Dublin, was almost prescient. In it, Marconi foreshadowed the immense impact wireless communications would have in all areas of mass media, of social and socialite life, and in entertainment. It was in stark contrast with the sober boardroom talk of a coming era of wireless maritime safety services, and of military, industrial, commercial and banking services, all of which attracted big investors.

1.13 Dublin Populace Meet Marconi in Action with his Magic

The two reports in the Dublin Daily Express of the 21 July, one by an unnamed journalist [7, 20], and the other by TCD Professor George F. Fitzgerald in layman's language [7, 21], are brilliant and historic. Both men were among a small group with Marconi on the Fly Huntress, who keenly observed him and the wireless transmissions in action.

Figure 7. The twenty-four-year-old Marconi, published in the Dublin Daily Express on 21 July 1898. [19] (Credit: Bodleian Library, Oxford).

Much of the wireless equipment used that day, Figures 4-6, came either from the physics laboratories in the Catholic University, through Professor Gerald Molloy, who coincidentally was a student of Professor Nicholas Callan's, whose induction coil invention was used in this demonstration, or from TCD from Professor Fitzgerald laboratory, organized by Glanville, who was a graduate of Fitzgerald's. Kemp brought the sensitive coherers, which Marconi himself had designed and fabricated, from the wireless installation they had just begun constructing for Lloyds in Ballycastle.

1.14 Wresting Nature's Secrets From Her

For the Daily Express journalist, under the apologetic by-line of An Unscientific Observer [20], all the wireless apparatus components on the boat seemed simple to describe and yet, when connected up, made for something mysterious. He witnessed Marconi's touch "wresting nature's secrets from her." Forces invisible and unknown since the beginning of the world were being uncovered and tamed before their very eyes. He was in awe at the youthfulness of this 24-year-old magician, Figure 7:

> [A] tall, athletic figure, dark hair, steady blue eyes, a resolute mouth, and an open forehead, […] his manner was at once unassuming to a degree and yet confident. He speaks quite freely and fully, and quite frankly defines the limits of his own as of all scientists' knowledge as to the mysterious powers of electricity and the ether (sic) [...] [His] face shows a suppressed enthusiasm which is a delightful revelation of character.

Following the regatta, in August, Molloy gave two public lectures on wireless telegraphy to packed houses, with Marconi giving live demonstrations. The excitement of the audiences was palpable with the sense of their being [20], "[P]rivileged to assist at an experiment that was destined to revolutionize our means of communication and link nation to nation by the strong yet subtle bonds of the viewless winds."

1.15 First Wireless Stock Exchange Transaction

The Kingstown Regatta was the occasion of another first. William Goodbody, a Dublin banker and recently appointed director of Marconi's company (eventually there would be nine of the Irish Goodbody family involved in the company [2]), was with Marconi on the tug boat. From there, while completely out of sight of the shore, he placed a securities purchase order to the Dublin Stock Exchange by wireless telegram. The order was executed and the confirmation wirelessly reported back to him [2]. This was the first ever wireless financial transaction and, being sent from the Flying Huntress, it also heralded the end of those days of "dolce far niente" (pleasant idleness) when one could escape out at sea!

1.16 Developing His Commercial Market

More publicity was to follow quickly. Much reported in British newspapers, in the same month of August 1898, were messages sent over an ad hoc Marconi's wireless link between the Prince of Wales, on his royal yacht Osborne moored in Cowes Bay, and his mother Queen Victoria, two miles away in her Summer residence, Osborne House, on the Isle of Wight. On 27 March 1899, the first cross-channel wireless signals were exchanged between South Foreland lighthouse and Wimereaux, France [15]. For political reasons, the link was short-lived, but it drew still more international newspaper headlines, especially in France and Italy [22, 15]. Flush from this run of successes and very favorable local and international publicity, Marconi was determined to capitalize on it and realise the wide range of commercial opportunities he and the company envisaged. Also, he needed to start generating income. The first that beckoned was like a wireless re-invention of Reuter's successful Crookhaven business plan of the 1860s [16, 17], but much more. In Ballycastle, the Lloyds contract taught him the value to them and others of knowing more accurately the expected arrival times of transatlantic

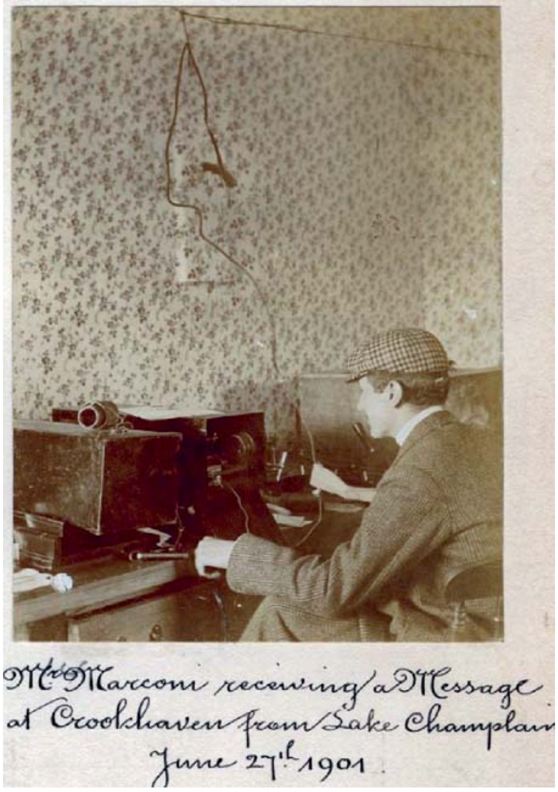

Figure 8. Marconi at his wireless set in what is now called Marconi House, in Crookhaven, Ireland, 27 June 1901, (Credit: Bodleian Library, Oxford [9]).

ships. This information was an important update on the estimation based on the departure date from American ports, already communicated by submarine cable. To this, he could add passengers' personal and commercial wireless telegram traffic to and from passing ships, and the provision of maritime safety through ship-to-shore wireless communications. In all this, he was completely successful.

1.17 Crookhaven and 29 June, 1901, Discovery

Following this Reuter's strategy, in 1901, he erected a wireless station in Crookhaven, located at the furthest south-westerly point of Ireland. The small fishing village is a beautiful end-of-the-world spot, the first and last to be seen by ships traversing the Atlantic between Northern Europe and North America. Initially his station was based in what is now called Marconi House [23, 24], where Marconi himself lived and worked when in Crookhaven, Figures 8 and 9. There, on 29 June 1901, he received his first signals from Poldhu, in Cornwall, on the south-west tip of England, some 250 miles away. It was a result to confound the experts. We now know that that reception and that day marks the discovery of the ionosphere and the first experimental evidence for its existence. His reception of the signals from Poldhu only happened because they were reflected back to earth by the ionosphere. Indeed, as he himself knew, he was beyond "the limits of his own as of all scientists' knowledge" [20]. Six months later, in Newfoundland, he would astound the world even more.

Figure 9. The historic Marconi House and antenna rig (Credit: Sue Hill). Here on 29 June 1901, Marconi received the signal transmitted from Poldu in Cornwall, while not realizing that he had discovered the ionosphere, and had obtained the first experimental evidence of its existence.

Figure 10. Maria Elletra Marconi, Guglielmo's daughter with Maria Cristina Bezzi Scali, his second wife, whom he married in 1927. This 1998 photo was taken of her outside Marconi House in Crookhaven, the house where her father lived, worked and made ground-breaking discoveries of the ionosphere and radio wave transmission. The Jameson advertisement seen through the window makes a nice connection back to Annie, Marconi's Irish mother, and Elletra's grandmother. (Credit: Sue Hill).

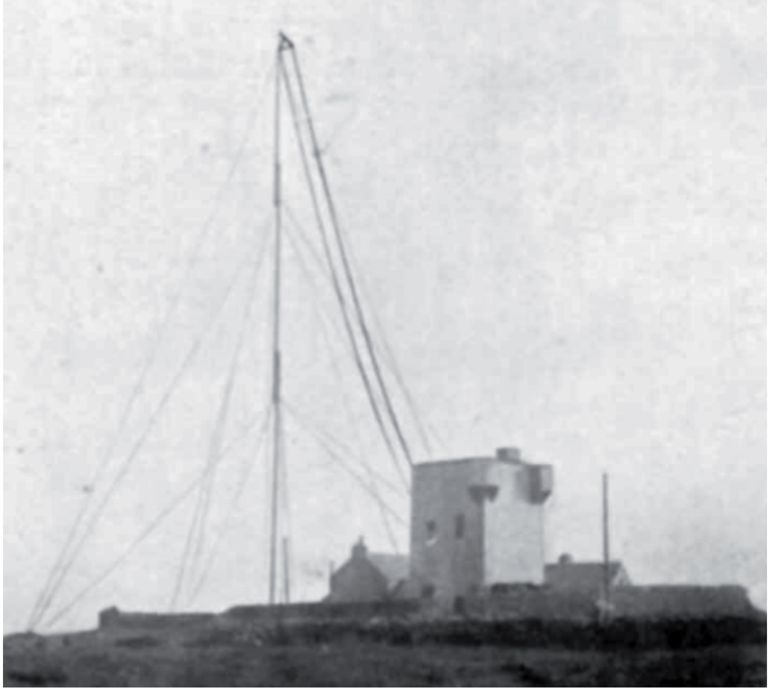

Figure 11. The 1901 station erected on Brow Hill (300 ft altitude), Crookhaven, Co. Cork, the most south-westerly point of Ireland and Northern Europe. (Credit: [25] and Bodleian Library, Oxford).

Marking Crookhaven's importance in her father's life, Maria Elletra Marconi, (1930-), his daughter by his second wife Cristina Bezzi-Scali, (1900-1990), visited Marconi House there during the centenary celebrations of 1998, Figure 10, unveiling a memorial plaque there.

1.18 Annie Marconi's Intuition Becomes a Reality

To improve the quality and range of communication, he moved the station to the old Napoleonic era signal tower on top of the nearby 300 ft Brow Hill, building a larger, more permanent antenna structure, Figure 11. This tower was one of the ring of watch towers built around Ireland at the beginning of the 19th century as a defensive network against a threatened Napoleonic invasion. Finola Finlay gathered some beautiful sketches and photos of Brow Hill in her article [25].

In 1904, he also built a radio station at the Light House, on Fastnet Rock, offshore. Both stations were equipped with coherer receivers. Accounts by two of Marconi telegraphers stationed there, Leach [26] and Boyle [27], provided magnificent insights into the engineering apparatus, operations, and the amazing growth of ship-to-shore communications for north transatlantic shipping. This arose rapidly and required two telegraphers per shift who busily worked a full 24-hour round-the-clock schedule. They also described some great ship rescue incidents, and the typical day-to-day life for the wireless telegraphers in Crookhaven.

1.19 Through Wireless to Love

Bill Boyle also tells how he found the greatest love of his life there, in the nearby village of Goleen: "It was from hereabouts I took away the most loving and beloved of wives the most devoted and selfless of mothers to be my dearest companion through 45 happy years."

Here we glimpse some of the invisible unintended ripples flowing from Marconi's pioneering work that touched lives and changed destinies to their greatest spiritual depths in ways completely unknown to him but perhaps, if he did know, he would envy.

1.20 From Crookhaven to Global Commercial Profitability

What happened in Crookhaven would become the model for a rapid growth of similar stations not just in Ireland, in Malin Head on the north west tip of Ireland and in Rosslare in the south east, but in all maritime nations. The global maritime wireless market was Marconi's and his Company's target, to expand such solid and profitable services throughout the European maritime nations first and then further afield, while also courting and cultivating navy and army military interest and business in England, Italy and France, in developing military-oriented land and sea wireless services [28].

There was constant and rapid development and improvement in the transmitter and receiver equipment. Especially good progress was being made on tuning. Marconi's method of separating signals into different bands was granted a patent in April 1900 and by good fortune happened to be allocated a striking and memorable number; 7777: a chance happening, but it helped to establish the fame of the "Four Sevens" patent [29].

1.21 Trans-Atlantic Wireless Bridge

Marconi, personally, had a still bigger goal in mind: to follow his hunch that somehow wireless signals could span the Atlantic. If so, that was fame in itself. But more, it meant not just ocean-wide ship-to-shore communications, but also the opening up of revolutionary competition with the submarine cable companies. As night literally follows day, all the Hertzian-wave experts of the time held non-line-of-sight EM wave radiation to be impossible. Maxwell's equations and Hertz's own 1988 experiments, dictated EM waves travelled in straight line-of-sight lines. Right from his successful and unexplained Villa Griffone non-line-sight transmission experiments, Marconi was stubborn in his belief that they were missing something, that it was possible.

In the days following that 29 June 1901 reception in Crookhaven of Morse signals from Poldhu, improvements were made to the antenna in Poldhu and by mid-July he was receiving strong, excellent signals in Crookhaven. All the more then, his confidence and determination to bridge the Atlantic grew. He hired Professor John Ambrose Fleming of University College London to design high powered transmitters for Poldhu with a radiation power of around 12 kW [30]. He headed to Newfoundland. After expensive storm-damage mishaps destroying large antenna structures on both sides of the Atlantic, on 12 December 1901, Marconi and Kemp, at the station on Signal Hill, St. John›s, Newfoundland, through their 152 m (500 ft) kite-supported antenna, received Fleming's Morse S ("three dots") transmissions from Poldhu some 3500 km (2200 miles) away using the best Alexander Graham Bell telephone receiver then available [5]. Marconi noted in his diary the simple entry, "Sigs. at 12:30, 1:10 and 2:20." The astounded public reacted with great excitement [9 (Marconi 160)]. While many academic experts were dumb-founded, some unbelieving, and some lost in admiration and searching around to explain how it could have happened, e.g., the efforts of renowned engineers and inventors Dr. Michael I. Pupin of Columbia University and Professor Elihu Thomson of General Electric Company [5]. He was the Guest of Honor at the AIEE Annual Dinner in the Waldorf-Astoria, New York on 13 January 1902 and was there showered with plaudits by the most distinguished of American electrical engineering entrepreneurs and academics [2, 5].

The commercial implications of his achievement were staggering. The submarine cable companies were especially shaken. Since Marconi and Kemp were the only witnesses to the signal reception in Newfoundland, skepticism was voiced in certain powerful quarters. However, this was quelled after Christmas, when, with his wireless station rigged up on the SS Philadelphia, right from their departure from New York, on 22 January, Marconi unambiguously recorded Morse S signals from Poldhu, both day and night, all the way back across the Atlantic. This further lit up the newspapers. It was indeed heady stuff. Marconi's fame reached stardom status. His wireless bridging the Atlantic was hailed as the start of a new era of global wireless communications.

1.22 Personal Life Also in the News

His fame brought focus on his personal life. During these same days, there was much ado about his relationship with American Josephine Holman. In fact, it was big in the American newspaper social columns following their engagement the previous April. However, things were not well between them and instead of an announcement of a marriage date, on 21 January, by mutual agreement, she announced their break-up [2, pp. 185-189]. Marconi, it seems, was a master of compartmentalization in such a way that the many comings and goings in his personal life, then and later; and he did long for stable family life, while always of great interest to the press, had no obvious impact on his professional activities.

1.23 Discovering the Ionosphere

Marconi, with his 250-mile Crookhaven-Poldhu radio link, as noted above, and now with his successful trans-Atlantic radio link, had made a startling scientific discovery. Unbeknownst to him, he had detected the ionosphere. This region, found 60 km above the earth, of sun-induced plasma layers of ionized particles that envelopes the Earth. Those layers were of varying density, depth and height related to the particles' composition, their weights and charges, and the level of the Sun's UV light exposure. Like a mirror for light, the ionosphere was reflecting Marconi's radiated waves in the 10 kHz - 40 MHz frequency range impinging on it below at a certain incidence angle. These waves, reflected back to earth, were then reflected again by the sea and so on, in effect travelling entrapped between the ionosphere and the ocean, which acted as it were as a waveguide.

Missed by all the EM experts of his day, the ionosphere's existence had in fact been hypothesized some years before, in 1878, by Scottish magnetician Balfour Stewart [31 - 33], as the only remaining explanation for the diurnal variations in the Earth's magnetic field [31]:

> I am driven by the method of exhaustions to look to the upper regions of the atmosphere as the most probable seat of the solar influence in producing diurnal magnetic changes, and the only conceivable magnetic cause capable of operating in such regions must be...convective [electrical] currents established by the Sun's heating influence in the upper regions of the atmosphere […] moving across lines of magnetic force […] which [thus] act upon the magnet.

Marconi had not only detected its presence and blindly put it to the service of wireless telegraphy, but also he gathered the first experimental evidence of the variable configuration of the ionospheric layers with sun exposure, as predicted by Balfour Stewart, deriving this from the significant and quite predictable variation of the day-night signal quality.

This amazing accidental discovery is poorly credited to Marconi in the scientific world but in retrospect it is comparable with the Bell Labs microwave engineers Arno Penzias' and Robert Wilson's serendipitous 1965 detection of the cosmic microwave background radiation, the first experimental evidence of the Big Bang. In full recognition, they were awarded the Nobel physics prize in 1978. In the flurry of analyses responding to Marconi's challenging discovery, Oliver Heaviside [34], and Arthur Kennelly [35], independently in 1902, and still ignorant of Balfour Stewart's work and hypothesis, suggested the existence of conducting layers. Heaviside rather casually suggested the likely mechanism of how Marconi achieved the long-distance communication [34] as follows: "There may possibly be a sufficient conducting layer in the upper air. If so the waves will so to speak, catch onto it, then the guidance will be by the sea on one side and the upper layer on the other."

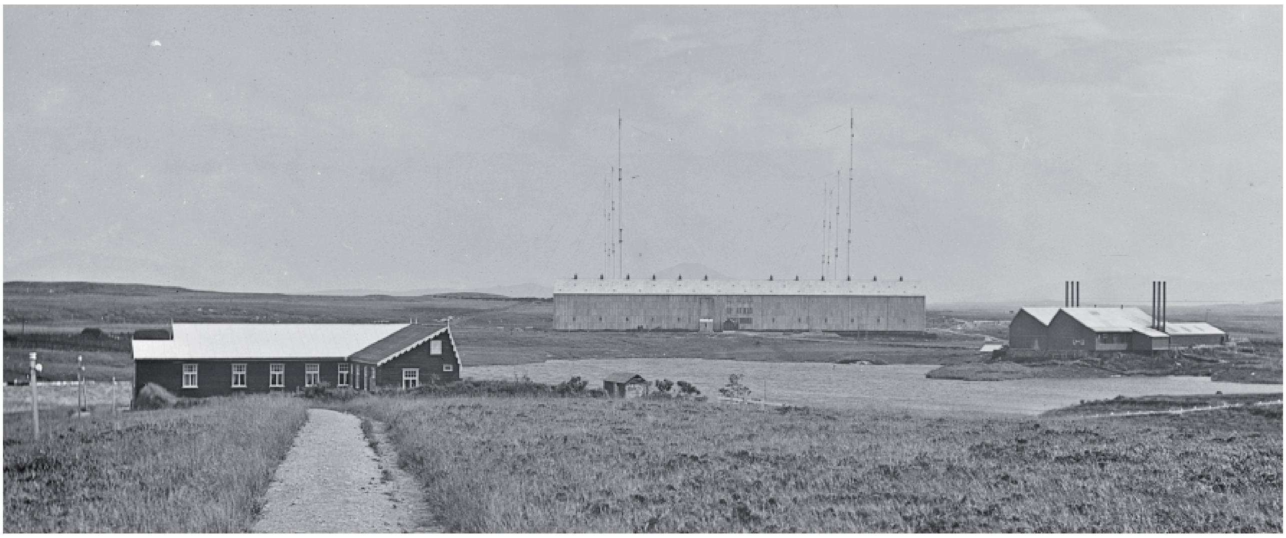

Figure 12. The original wireless station buildings at Clifden, Ireland, c. 1907, and the European endpoint of the first commercial transatlantic wireless telegraph communications link. In the center is the 350 foot-long condenser building, arranged in two long wings housing the 1800 condenser plates, with the transmitter-receiver room sandwiched between them and connected to the massive 200 ft high antenna stretching out perpendicularly to the rear of the building (barely visible). On the right is the power generation building. (Credit: Robert French, photographer; reproduced courtesy of the National Library of Ireland from the Lawrence Collection, L_CAB_04374.).

Figure 13. The plates of the massive 1.8 µFarad tuning air-condenser at Clifden were housed in a building measuring 350 (L) x 75 (W) x 33 (H of eaves) feet, approximately 107m x 23m x 10m, arranged in two long wings with the transmitter-receiver room sandwiched between them. It was composed of 1,800 galvanized steel sheets, each measuring 30 x 12 feet, suspended from the cross members by porcelain rod insulators in the shape of a V, as shown in the photo. (Credit: Clifden and Connemara Heritage Society).

Figure 14. The massive 30 x 12 feet condenser plates of the 1.8 µFarad tuning air condenser at Clifden. (Credit: Clifden and Connemara Heritage Society).

Their explanations gained little traction until, in 1924, Joseph Larmor (1857 - 1942), another Belfast man who became the Lucasian Professor of Mathematics at the University of Cambridge, advanced an insightful reasoned hypothesis of the Heaviside layer being in fact a plasma of free charges, ions and electrons caused by the Sun's radiation, forming a waveguide with the sea and Earth [36]. The following year, 1925, Eduard Appleton, who was in close communication with Larmor, published further experimental proof of the existence of these plasma layers [37], for which he received the 1947 Nobel Prize in Physics. Both Larmor's and his papers are usually credited with marking the beginning of the research fields of ionospheric studies and plasma physics [38], research which continues to the present day, as URSI scientific symposia bear witness. However, this credit and credit for the ionosphere discovery surely more justly belongs to Balfour Stewart and Marconi.

1.24 Transatlantic and Global Wireless Marconigram Services

Following his wireless bridging of the Atlantic, Marconi set about his commercial dream of an intercontinental wireless communications services. Despite hiccups, such as initially focusing on longer wavelengths rather than shorter, he chose Derrygimla bog just south of Clifden, Co Galway, Ireland, not far from Beatrice's ancestral family home of Dromoland Castle, to set up the quite massive radio station, Figure 12.

The lower the frequency, the ever larger the structure of the antenna system. The directional antenna structure for the 45 kHz (wavelength of 6.7 km) Clifden transmission was a massive 1 km, supported by eight 64 m high masts. While the crude tuning of the signal transmission produced bands that were narrow compared with the broad impulse band generated by the spark-gap transmitter system, it should be said that the actual frequency bands of the transmissions were not certain. The measurement of frequency, and the understanding of its importance, especially with respect to ionospheric reflections, and frequency division multiple access, were still quite primitive, with consequent errors and failures. The radiated spark-generated signal emanated from a 20 kV rotary spark generator, which had been designed by Marconi himself [39], powered by a turf-burning, steam-driven, 300 kW generator plant. The 1.8 µFarad tuned circuit capacitance required a gigantic air-dielectric condenser with 1800 plates of galvanized iron housed in a building over 100 m in length, Figures 13 and 14. A similar installation was built at Grace Bay in Newfoundland.

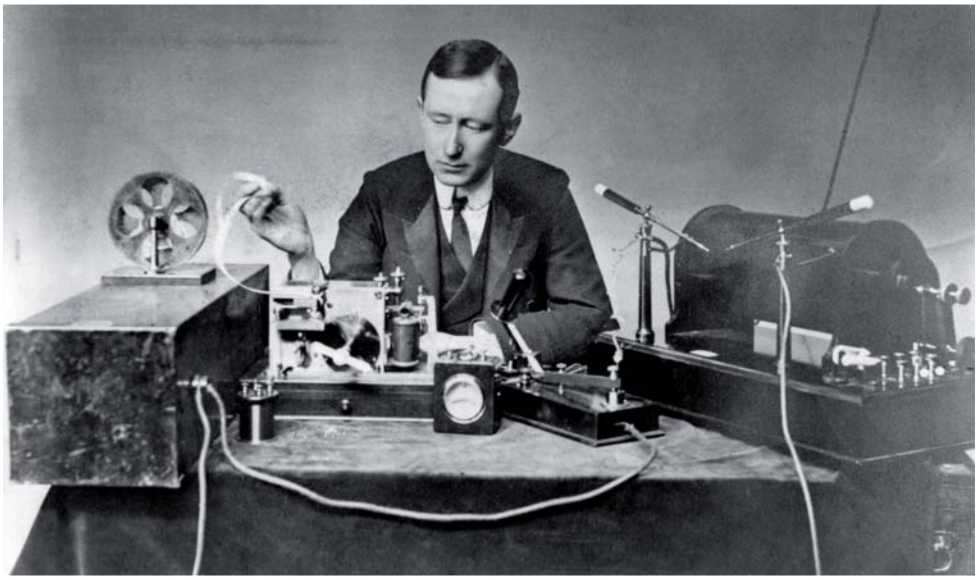

Figure 15. Marconi, c. 1902, with a transmitter and receiver set similar to the one used in Clifden. (Credit: Clifden and Connemara Heritage Society)

Reliable trans-Atlantic transmissions began in October 1907 to great fanfare and with telegram exchanges between famous people such as Lloyd George and Theodore Roosevelt, Figure 15. The Marconigrams (Marconi's business branding was unparalleled for his time) were half the price per letter of those sent by transatlantic cable. Most of the traffic was between London and New York, and so was relayed over landlines to and from the wireless stations. His high-risk, high-cost trans-Atlantic investment venture became a commercial success and probably saved Marconi's company from bankruptcy.

1.25 Titanic Disaster

The shocking Titanic disaster happened on the night of the 14 April 1912 with the loss of over 1500 lives. By this time, all large shipping had wireless communications, with the Marconi Company being the leading equipment and wireless operator suppliers. The Marconi telegrapher on the Titanic was Jack Phillips, who had worked for several years in Clifden.

Figure 16. Family photo, 1918, of Beatrice and Guglielmo Marconi with three of their children (left to right) Degna (1908-1998), Giulio (1910-1971) and Gioia (1916-1996); their first daughter, Lucia, died shortly after birth in 1906. Beatrice (nee O'Brien; 1881 - 1976) was from Dromoland Castle, Co. Clare, Ireland. They married in 1905 and divorced in 1927.

On his 1.5 kW Marconi wireless set, he contacted and stayed communicating with the RMS Carpathia and other ships coming to the rescue, heroically staying at his post until the wireless room itself was flooded. His efforts resulted in the saving of over 700 lives, though not his own. As the role of wireless in saving lives came to be appreciated, Marconi's standing soared. As he wrote to his wife Beatrice, Figure 16, on the 16 April [2],

[…] although only a few were saved everyone seems so grateful to "wireless." I can't go about New York without being mobbed and cheered. Worse than Italy.

Frank Sprague, US inventor, told Marconi, referring to the rescue ship RMS Carpathia [40]:

> When tomorrow night, some 700 or 800 persons land in New York, they can look to you as their saviour.

It brought a huge boost to the company's fortunes with the share price jumping, almost overnight, from 50p to Stg£10 (today equivalent to about €500).

1.26 First East-West Wireless Trans-Atlantic Telephony Call

Initially, Marconi's telegraph link between Ireland and Canada was half-duplex. As the business quickly grew to full capacity, he made it full duplex by locating a separate receiving station 16 km (10 miles) to the north of Clifden, in Letterfrack (1913 - 1917), an arrangement mirrored in Grace Bay. The techniques for communication in different frequency bands and managing multiple access to a channel were only then evolving.

In 1913, for $25,000, the company acquired a near complete radio station in Ballybunion about 90 km south of Clifden, Figure 17. Potential competitors, Universal Radio Syndicate, had built it but had gone into liquidation before ever operating it commercially. The Marconi company bought it primarily to keep out other competitors.

Here another bit of radio science history happened. After the First World War, on its 500 foot steel mast, Kerryman Michael Daly affixed the aerial by which Marconi engineers H. J. Round and W. T. Ditcham then succeeded in making the first east-west wireless transatlantic voice telephony call, on the 19 March 1919[1]to the Cape Breton station, Nova Scotia, Canada, on the wavelength of 3,800 m, using thermionic triode valves in the transmitter and a power supply of 2.5 kW [6, 42]. This successful use of high power triodes in the transmitter brought the era of the spark-gap transmitter to a close [6, 43].

1.27 Birth of Broadcast Radio Services

While not convinced of the benefits or commercial potential of broadcast radio e.g., [44], the successful transmission of voice led directly to Marconi doing broadcast trials at the company's Chelmsford station with a 15 kW transmitter, and then, to great acclaim, the historic first broadcast of the soprano Dame Nellie Melba in June 1920 [45]. This and further music broadcasts were so well received, he changed his mind on the importance of wireless broadcasting services, and now directed energy and resources into these. This in turn led to the invitation, by the GPO Postmaster-General in 1922, to the Marconi Company and several other large companies to form the British Broadcasting Company, later renamed Corporation, and now know commonly as the BBC.

From 1924 Marconi began demonstrating shortwave and relatively more power efficient broadcast transmissions exploiting skywave propagation, that is, via ionospheric reflection over large distances, up to 4000 km and more. This directly led on to the birth of what was later called the BBC World Service, which continues to the present day [6].

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1 It was not of course the first wireless transmission of voice as such. Reginald A. Fessenden, in the USA, achieved this in a one-way transmission over 1600 m using a crude 10,000 per second spark-gap transmitter in December 1900 [41]. Once the feasibility was seen the engineering followed led in the main by Fessenden. The first one-way transatlantic wireless voice transmission was west to east, on 21 October 1915, of the voice of engineer B. B. Webb from a transmitter in Arlington, Virginia to a receiver on the Eiffel Tower in Paris, manned by the (then) Western Electric Company engineers H. E. Shreeve and A. M. Curtis [42]. In 1919, using 3 main valves, Marconi's transmission technology was significantly advanced and reduced in size compared to the 300 valves used in the 1915 trial.

1.28 Changing Times

Crookhaven station was acquired by the British Post Office (BPO) in 1914 by which time its usefulness to the Marconi company had declined. The BPO leased it to the Royal Navy. With the disastrous First World War giving it a new lease of life. Clifden continued in profitable service until 1922 when it and the Crookhaven station were destroyed in the Irish civil war because of the presumed strategic use being made of them by one side of the combatants. Marconi was distraught at the loss of his gigantic station in Clifden. Another station he had built in 1914 in Caernarvon, Wales, took over all the transatlantic traffic. By 1920, only two Marconi-built marine radio stations remained operational in Ireland: those at Malinhead in the north west, and one he'd set up in Valentia island, in Kerry, before he sold the Crookhaven station. These provide a continuous service to shipping and marine rescue and safety services even to the present day [46]. Both stations were administered by the British Post Office up to the 1 June, 1950, when they were handed over to the Irish Dept. of Posts and Telegraphs. During 1956, the Dept. of Transport and Power took over the administration of the Aviation Radio stations, the ones which had been built at Ballygireen and at Shannon, both in Co Clare, and the one in Dublin. On the 1 April, 1967, Malinhead and Valentia Radio Station joined forces with the Aviation Radio Service and became known as the Aviation and Marine Radio Service (AMCS), initially under the Dept. of Transport & Power [27]. While responsibility moved among different Government Departments, these vital services have greatly expanded and developed and all the more so with Ireland being a member of the EU. This is a full story in itself; for another day.

1.29 Clifden — Seat of the First Wireless Radio Propaganda

It is reckoned that the first propaganda use of wireless was in the 1916 Irish rebellion against British rule. Under the direction of one of the leaders, James Connolly, the rebels surreptitiously used Clifden to send news of the rebellion to the USA [47, 48]. This was not of course the first military oriented use of wireless communications. This had already happened; for instance, the secret communication wireless link Marconi helped set up between France (from the Eiffel Tower, Paris) and Russia, bypassing Germany prior to the First World War (WWI) [49].

1.30 Looking Back on Marconi in Ireland

Ireland was at the heart of Marconi's successful ground-breaking pioneering work that launched a wireless revolution on the world that continues to this day. His Irish mother and her family played decisive roles in the story. Apart from several enthusiastic local voluntary efforts in such places as Crookhaven, Mizen Head, Clifden, Ballycastre, and Dun Laoghaire, to date, in comparison with Italy, Ireland as a nation has not done much to commemorate the man and his achievements. Reasons for this are multi-faceted, including his deep identification with Italy in the latter part of his life; the Ireland-UK political dynamics of the time around Ireland's war of independence; the destruction of his stations during the subsequent Irish civil war; his troubled public domestic situation including the breakdown, divorce and controversial annulment in 1927 of his marriage to Beatrice [2] followed by his and her second marriages; his move to Italy and the growth of his political involvement with Mussolini's fascism in the late 1920s and 1930s; and his roving ambassadorial mission in justifying Italy's invasion of Ethiopia in 1935, which caused consternation in the League of Nations of which Éamon de Valera was President at the time. De Valera was to go on to dominate Irish politics, including as Prime Minister and President, from around that time through to the 1970s. These matters are well covered in publications such as Sexton's [7] and Raboy's [2].

Staying within the history of the Irish contribution to radio science, we conclude this abbreviated Marconi story with three quotations. First, Bridgman's colorful Physics World piece in 2001, captures his enchantment and success [50]:

> There cannot be many people who screwed up at school, failed to get into university, and then went on to win a Nobel Prize for Physics. But at least one did, and with good reason: he made radio happen. In a few years of manic activity, Irish-Italian Guglielmo Marconi managed to transform an obscure piece of maths into a social upheaval.

The second is from Gioia, his third daughter with Bea O'Brien, Figure 16. As a tribute to her father, she founded the Marconi Society and the annual prestigious Marconi Award. Speaking in the context of the success of the Apollo missions to the moon in the 60s and 70s, the world hearing live Neil Armstrong's famous words as he took the first steps of mankind on the moon, and especially the role of reliable radio communication links reaching over the 400 km distance to help solve the gravest emergency situation encountered with Apollo 13 and bring about the safe return of the three astronauts, she told an audience assembled at the United Nations, in 1985 [51]:

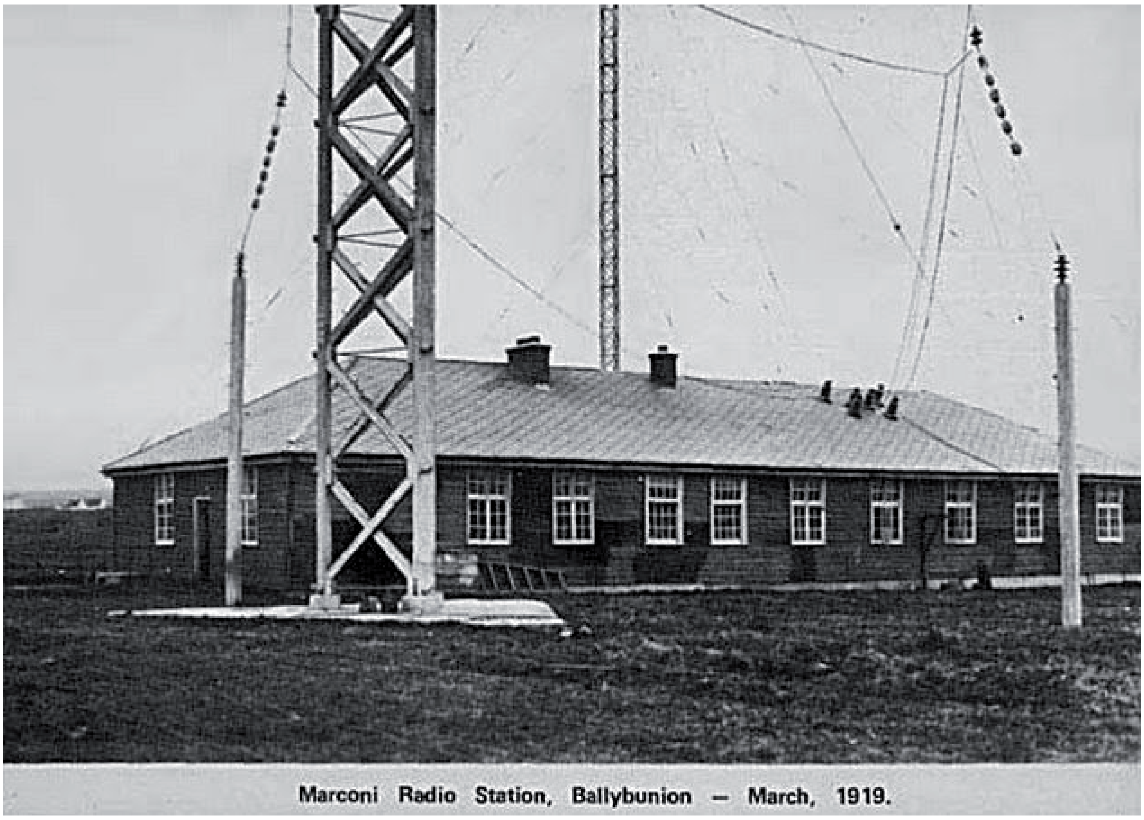

Figure 17. The Ballybunion Wireless Station, 1909; site of the first east-west transatlantic wireless voice transmission, 19 March 1919,

> It could be claimed that the way opened up by [my father] reaches to the stars because the conquest of space could not have been possible without the radio electric links that ensure the communications, the remote control, the telemetering, the communications between space vehicles and ground stations […]

The third is from Marconi himself, in 1937, on the fortieth anniversary of his first experiments and in the year he died. In his usual understated manner, he soberly sums up his own contribution to radio science [28]:

> Wireless is now available to shipping for communication by means of long, medium and short wave telegraphy and telephony, bringing to the ship information regarding time, weather conditions, navigational warnings, and news of happenings in the world at large, as well as facilitating social correspondence for passengers, and keeping ship-owners in touch with their ships. On shore, a system of wireless coast stations has been organized by all maritime countries for communications with their ships; and wireless beacon stations have been established for the purpose of providing signals by which ships can take their bearings with their direction finders. So far as the sea is concerned, therefore, quite apart from developments which have taken place in communications on land, I feel that my early belief in the possibility of this form of communications has been fully justified. As one who is deeply attached to the sea, I am proud to have been able to render this service to the sea-going community.

Also, in that year he expressed, in a USA radio broadcast, his high hopes for the benefits for the common good that radio could bring [44]:

> We have now reached a stage in the science and art of radio communications, when the expression of our thoughts can almost instantaneously and simultaneously be transmitted to and received by our fellowmen practically in every spot of the globe […]
>
> In radio we have a fitting tool for bringing the people of the world together, for letting their voices be heard, their needs and aspirations be manifested. The significance of this modern means of communication is thus fully revealed: a wide channel for the improvement of our mutual relations is available to us; we have only to follow its course in a spirit of tolerance and sympathy, solicitous of exploiting the achievements of science and human ingenuity for the common well. I am firmly convinced of the possibility of realizing this ideal […]

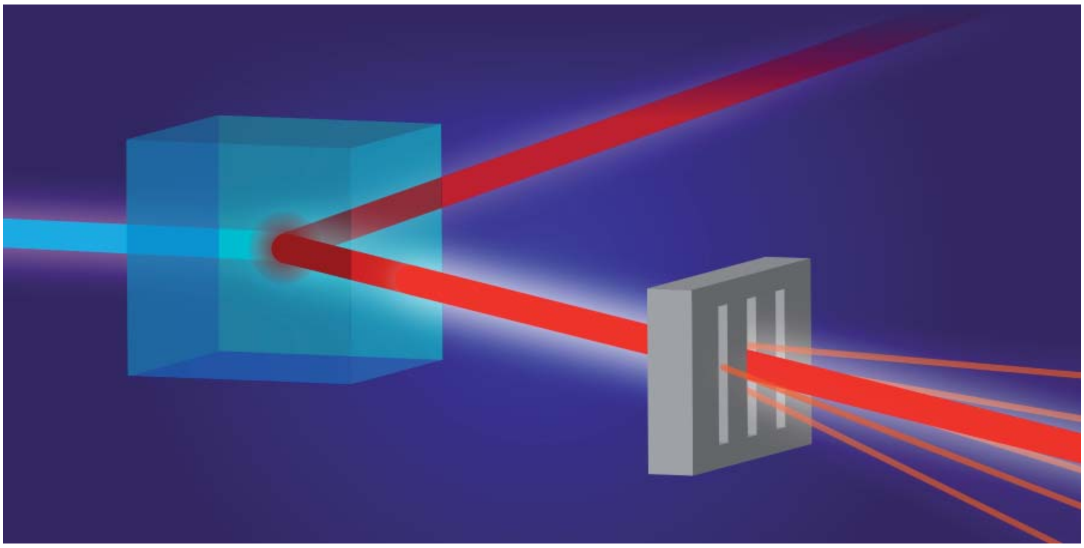

Figure 18. Quantum X-ray imaging takes razor sharp pictures with less radiation. Quantum X-rays are produced when a diamond splits a beam of radiation in two. (Credit: APS/Alan Stonebraker).

2. John S. Bell: From Bell's Theorem to New Quantum Sciences, and the Fundamental Nature of Reality

There is a veritable explosion of research papers being published in the new quantum information sciences, such as Quantum Computing, Quantum Information Theory, Quantum Cryptography, Quantum Imaging (Figure 18) [52], Quantum Metrology, and even Quantum Energy Teleportation (QET) [53]. Recent URSI scientific symposia have seen this, and similar specialist fundamental-research conferences e.g., [54]. It is well recognized that these, along with the current research focus on fundamental particle physics, and the physics of the early universe, owe a debt of gratitude to the contributions of Irishman John S. Bell (1928-1990), Figure 19, who, in developing his "Bell Theorem" of non-locality [55], really is their forerunner and father [56, p. 199], laying therein the foundation for these modern quantum research fields.

From humble beginnings in Belfast, as a child he was excited by science and from age 11 was determined to be a scientist. Unable to afford secondary school fees, his family sent him as a pupil to the free-education Belfast Technical

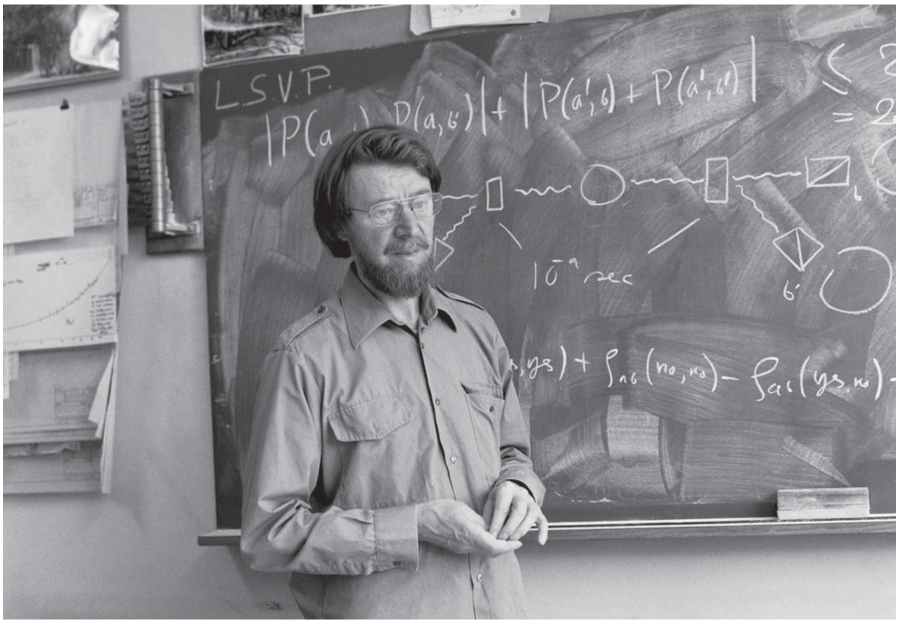

Figure 19. John Bell and his famous theorem, in 1982, CERN, Geneva. (Credit: CERN).

School. Graduating from there, he was appointed as a laboratory technician in Queen's University, Belfast (QUB), and from there was granted permission to enroll on QUB's science degree program. He qualified with a first-class honors degrees in experimental physics (1948), and mathematical physics (1949). He pursued his particular interest in quantum mechanics (QM) in the Atomic Energy Research Establishment at Harwell, near Oxford (from 1949-60), with a period in Birmingham University (1951-54), and then, with his collaborating physicist wife, Mary Ross, in the Centre for European Nuclear Research (CERN) in Geneva (1960-90) where he worked almost exclusively on theoretical particle physics and on accelerator design. However, almost as a hobby he reflected much on the foundations of quantum theory, and especially mulled over the Einstein-Bohr controversy with their conflicting views on the fundamental principles about the nature of reality. It was only when he went on a sabbatical leave to the USA in 1963-64 that he set his mind to try to find a way to resolve the controversy or at least point to a way out of it. This he successfully did in developing his famous theorem, today called Bell's Theorem and Bell's Inequality. He himself referred to it as his non-locality theory, in that no local model of reality can explain the results of a particular experiment [57].

At the nob of the controversy, Einstein was convinced that science was based on an observer-independent reality (realism) and on locality, that is, that there can be no faster-than-light interaction between events. From this standpoint, he sought to show QM to be an incomplete theory as it was directly at variance with these two principles. His best articulation of this was the paradox he presented in 1934 with Podolsky and Rosen [58]. Bell addressed this in his now famous 1964 paper [55], setting out an inequality theorem whereby this paradox could be experimentally tested. One could also say that by this theorem he not only found a pathway out of the paradox but reopened the foundations of QM physics to experiment.

Interest in his paper was, however, minimal until, taking up the challenge in the 1970s Clauser [59], and then in the 1980s, Alain Aspect [60, 61], undertook the difficult experimental task. Their experiments, especially Aspect's, showed Bell's inequality theorem was violated. The implication was that either the assumption of realism or of locality had to be sacrificed; an earth-shattering vista. In effect, no local model of reality can explain the results of a particular experiment Herbert [57]. The results meant that fundamental questions about the nature of reality raised by the theorem are inescapable. Bell, who preferred to stick with the realism principle and sacrifice locality, in commenting on the experimental outcomes, said: "One wants to be able to take a realistic view of the world, to talk about the world as it is really there, even when it is not being observed" [62].

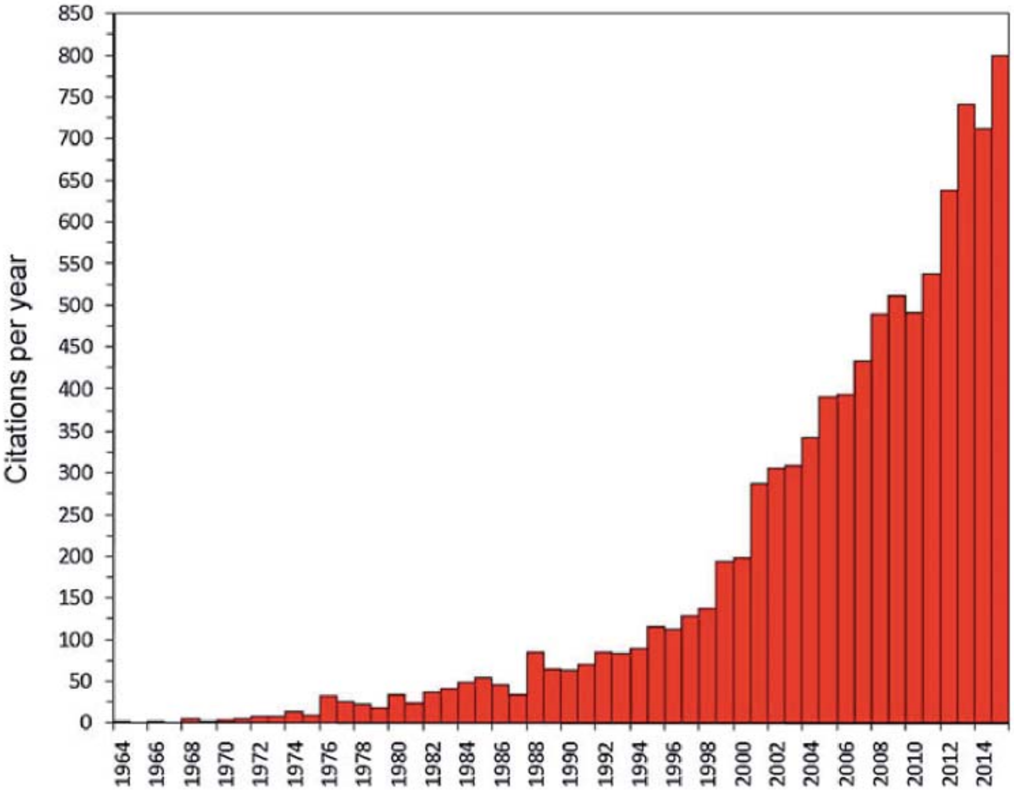

Figure 20. Fifty-year citation profile of John Bell's famous 1964 paper (Credit: Google Scholar).

> The theorem tells you that maybe there must be something happening faster than light, although it pains me even to say that much. The theorem certainly implies that Einstein's concept of space and time, neatly divided up into separate regions by light velocity, is not tenable. But then, to say that there's something going faster than light is to say more than I know. [63]
>
> This result has since been further confirmed by ever improved experiments. As R. A. Bertlemann and A. Zeilinger in 2017 relate [54],
>
> [M]ore recently, it became possible to create entanglement in other systems, such as atoms or ions in traps or superconducting devices. In such experiments, the case against local realism, the viewpoint excluded by Bell's theorem, and for quantum mechanics became stronger and stronger, and more and more loopholes for the experiments were closed.

It is notable for both budding and mature scientists that it took some 25 years, in the 1990s, before realization of his paper's significance took off. The profile of its citation frequency over the fifty-one years 1965-2015, Figure 20, tells its own story. The 1990s saw the beginnings of the third generation of Bell experiments, and the field of applications of entangled states. The latter was exemplified by experiments on quantum teleportation, quantum cryptography, long-distance quantum communication, and the realization of some of the basic entanglement-based concepts in quantum computation [54].

2.1 Impact Today

Bertlemann's and Zeilinger's summary captures this [54]:

> Today, Bell's theorem and the underlying physics of entangled states have become cornerstones of the evolving technology of quantum information. Violation of Bell's inequality has become a litmus test for the realization of quantum entanglement in the laboratory. It has become part of the common understanding that a loophole-free Bell experiment is the final and definitive demonstration that quantum cryptography can be unconditionally secure. Also, entanglement swapping, the teleportation of an entangled state, is central for quantum repeaters, which are expected to be the backbone of a future worldwide quantum internet. Furthermore, Bell's theorem, as a fundamental contradiction between local realism and quantum mechanics, has been extended to higher dimensions and multiparticle systems.

Bell biographer Andrew Whitaker [64], credits him with having "changed our perception of physical reality and the nature of the universe."

Bertlemann and Zeilinger claim that physicists agree that Bell would have definitely received the Nobel Prize if he had lived longer. This was, for instance, expressed explicitly by Daniel Greenberger in an interview given at their conference "Quantum [Un]Speakables II" Vienna [54]: "Of course, people more and more appreciate John Bell's beautiful work. He was essentially starting the field, his work was totally seminal, and if he were alive he certainly would have won the Nobel Prize!"

2.2 The Man Himself

To get a glimpse of the kind of person this man was who has made such outstanding contributions to the foundations of quantum mechanics, the late quantum physicist and philosopher Abner Shimony lets us have his insight [54]:

> His [Bell's] passion for understanding, uncompromising honesty, simplicity of lifestyle and demeanor, dignity, courtesy, generosity to other scientists, and passion for social justice were combined into a character that was inspiring to all who had the privilege to be acquainted with him.

2.3 Last Word

In itself, and for all that has followed in the new quantum research fields, it would seem that the 1977 description of Bell's Theorem and its results by Henry Stapp of the Lawrence National Berkeley Laboratory, California [65], "[T]he most profound discovery of science, is most insightful and may well prove to be the most apt."

Figure 21. Dame Jocelyn Bell Burnell, 2014 (Credit: Royal Society of Scotland).

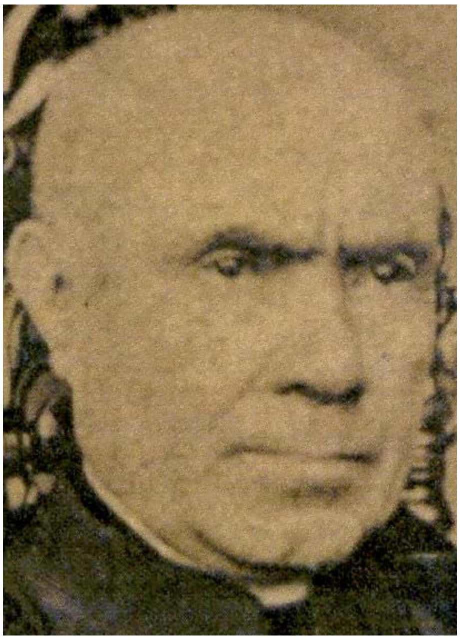

Figure 22. Reverend Professor Nicholas Callan (Credit: St. Patrick's College, Maynooth, Ireland).

3. Jocelyn Bell Burnell - Pulsar Discoverer, 1967

Dame Susan Jocelyn Bell Burnell,DBE,FRS,FRSE,FRAS,FinstP, Figure 21, was born 15 July 1943 in Lurgan, Northern Ireland. She is an astrophysicist who, as a postgraduate student, was the first to detect and observe pulsars in 1967 [66 - 69]. She has been credited with [70], "[O]ne of the most significant scientific achievements of the 20th century."

The discovery was recognized by the award of the 1974 Nobel Prize in Physics but controversially she was not included. It went rather to astronomer Martin Ryle and her research supervisor Anthony Hewish who was first author on the paper announcing the discovery [68]. Her name was second on that paper. Hewish was the designer of the Interplanetary Scintillation Array (ISA) radio telescope instrument with which she detected the pulsars signals. She had helped build the ISA. It covered over 4 acres, 16,000 m^2. (It has since been expanded to more than double that area.) It is made up of 4,096 dipole antennas in a phased array and operating at a radio frequency of 81.5 MHz (3.7 m wavelength) [71]. She alerted Hewish's attention to the presence of unexpected regular pulses in her tracking data. These proved to be the discovery of pulsars, which we now know to be dense cores of exploded stars. It was Hewish and Ryle who did the bulk of the analysis and interpretation of the pulsar signals for the paper. Having discovered the first pulsar, she went on to find several more.

Jocelyn Bell has lived a distinguished academic career at the University of Southampton, University College London, and the Royal Observatory, Edinburgh, and served as the Professor of Physics at the Open University, President of the Royal Society of Scotland, President of the Institute of Physics, and Pro-Chancellor of Trinity College Dublin. She has been recognized with many outstanding honors and awards [72], including the J. Robert Oppenheimer Memorial Prize (1978), Herschel Medal (1989), Michael Faraday Prize (2010), Royal Medal (2015), and Grande Médaille (2018).

4. Nicholas Callan and the Callan Induction Coil

Father Nicholas Joseph Callan (22 December 1799 - 10 January 1864) [73], Figure 22, was an Irish priest, scientist and inventor. In particular, in respect of his place in the history of radio science, he is the inventor of the induction coil (1836), which became a key component in the first generation of wireless transmitters, the spark-gap transmitter, used by Marconi in his early radios at the end of the 19th century.

Callan was born in Darver, County Louth, Ireland. He studied in Maynooth and Rome's Sapienza University, where he became acquainted with the works of pioneers in electricity like Galvani and Volta. In 1934, he became Professor of Natural Philosophy (what we call Physics today) in St Patrick's College, Maynooth, County Kildare (then the national seminary for the Catholic Church in Ireland; today National University of Ireland, Maynooth, NUIM) from 1834 until his

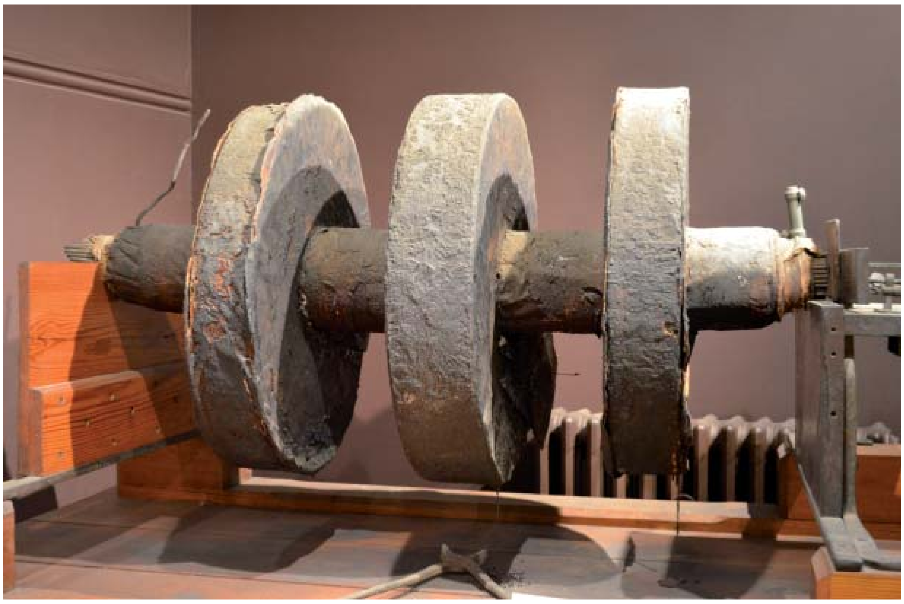

Figure 23. One of Callan's massive Induction Coils (1863), which produced voltages of 600kv and sparking gaps of 15 inches. (Credit: National Science Museum, St. Patrick's College, Maynooth, Ireland).

death. He was an inventive genius, although his inventions such as the spark gap inductor, various batteries including the Maynooth Battery [74, 75], the self-exciting dynamo, electric motors and more, were subsequently attributed to others. His great work is only recently getting due recognition. His invention of the induction coil was not officially credited to him by the world of physics until 1953 [76].

One of his brilliant students was Gerald Molloy (1834-1906) who went on to become Professor of Natural Philosophy and Rector at Cardinal Newman's Catholic University in Dublin (later to become University College Dublin). Molloy accompanied Marconi on the Flying Huntress in the famous wireless demonstration at the 1898 Kingstown Regatta, Dublin. Following that, he gave lectures with Marconi to packed houses in Dublin, in August 1898. It is through Molloy's successor that the National Science Museum, Maynooth, now has parts of the wireless apparatus used by Marconi on the Flying Huntress.

Influenced by William Sturgeon and Michael Faraday, especially by their inventions of the soft iron electromagnet (Sturgeon), and electromagnetic induction (Faraday), in 1834 Callan brought these two inventions together and began the work that led to the invention of the induction coil in 1836 [77]. It should be pointed out, as Sexton does in [7] to correct the record in various places, that Callan's invention "owns nothing, precisely nothing, to Faraday's iron ring experiments." It produced an intermittent high-voltage alternating current from a repeatedly-interrupted, low-voltage, direct-current supply. It was the forerunner of the step-up transformer found today in a wide range of consumer electrical products. It is also noteworthy, as Sexton [7] also points out with near disbelief,

> that both primary and secondary coils were successfully insulated by Callan using the famous viscous gutta-percha obtained from tropical trees which was subsequently used in the 1860's to insulate the transatlantic cables.

Figure 23 shows a later giant induction machine Callan constructed. It has a primary coil consisting of a few turns of thick wire wound around an iron core and subjected to a low voltage (usually from a battery). Wound on top of this is a secondary coil made up of many turns of thin wire. An iron armature, and a make-and-break mechanism, made from clock parts, repeatedly interrupts the current to the primary coil at about 20 times a second, producing a high-voltage, rapidly alternating current (AC) in the secondary coil. This generated sparks that jumped over 38 cm (15 inches) between the secondary terminals, at an estimated 600 kV electric field potential between them.

4.1 First Man-Made EM Radio Wave Transmission

This was the world's first transformer, and it generated the largest man-made bolts of electricity yet seen. Importantly, these were different from lightning in that they were controlled, regular, rapid, repetitive bolts. What we know now, but Callan did not know then, was that he was radiating, that is transmitting, for the first time in the history of mankind, regular repetitive bursts, or very wideband impulses, of EM waves. There was no one yet on the planet with a receiver to detect them.

5. Other Irish Wireless and Radio Science Contributions

There are other significant contributions from Irish people over the last sixty years that need more time to be seen in their proper perspective. Such a historical review will be challenging because of the depth and breadth of their life-time research work and contributions. A brief list of contributors divided into two groups of ten and sixteen follows.

5.1 Impulse Communication in 1896 to Impulse Communication in 2019!

Fittingly, as this article began with a world-renowned industrialist who started wireless telegraph communication with what we now would regard as the crude spark-gap transmitter emitting impulses of almost uncontrollably-wideband EM radiation with bandwidth containment technology only gradually evolving. The last in the following list of ten outstanding contributors is another modern impulse transmission system engineer. He is the Irish industrialist, Michael McLaughlin, who is achieving world fame today (2019) for his ingenious secure position location inventions utilizing carefully designed impulses of ultrawideband (UWB) signals in the 3 to 10 GHz band.

5.2 Ten Outstanding Contributors

John (Seán) O. Scanlan, MRIA, University College Dublin (UCD), 1937 - 2017, Professor of Electronic Engineering, UCD, 1973 - 2002, Figure 24. RIA gold medal awardee, among many other awards, he was one of the outstanding figures in the field of circuit synthesis, receiving wide acclaim in particular for his fundamental contributions to distributed circuit synthesis methods central to filter design in use today for microwave, millimetre wave and TeraHertz transmitters and receivers.

Figure 24. (left to right) A. D. (Tony) Fagan, Máirtín. S. O'Droma (author), J. O. (Seán) Scanlan, Orla Feely, and T. J. (Tom) Brazil, on the occasion of Seán Scanlan being awarded the Royal Irish Academy Gold Medal, December 2011.

Michael C. Sexton, MRIA, University College Cork (UCC), 1933 - 2016, Professor of Electrical Engineering, UCC, 1976 - 1994. His work on plasma physics and especially his contributions to EM wave radio propagation impairments arising from difficult weather conditions are outstanding.

J. A. Carson Stewart, MRIA, 1937 - 2017, Professor Electrical Communications QUB, was renowned for his research contributions and leadership in the field of Microwave and Millimetre Wave Devices and Circuits.

Thomas (Tom) J. Brazil, MRIA, 1953 - 2018, UCD academic 1980 - 2017, including as Professor of Electronic Engineering from 2002, Figure 24, made major contributions to modelling and design of microwave and millimetre wave nonlinear, high-power, solid-state amplifiers.

Anthony (Tony) D. Fagan BE (1973), PhD (1977), 1952 -, UCD academic, 1980-2017, Figure 24. RIA Parsons medal awardee, his contributions to digital signal processing are having an impact on systems from high speed communications, software defined radio, medical imaging through to measurements instruments used in gravitational-wave interferometers.

M. Peter Kennedy, MRIA, President of the Royal Irish Academy, 2017 to date, Professor of Microelectronics, UCC, 2000 - 2017, Professor of Microelectronic Engineering, UCD, 2017 to date. RIA Parsons medal awardee, he has made important contributions to chaos theory in electronic systems and to circuit synthesis design and analysis of nonlinear dynamical systems for applications in communications and signal processing.

Vincent Fusco, MRIA, Queen's University Belfast (QUB), 1957 -,Professor of High Frequency Electronics, 1996-, and CTO of Institute of Electronics, Communications & Information Technology. IET Mountbatten Medal awardee, he has made outstanding contributions to microwave and millimetre wave antenna design, self-tracking antennas, nonlinear phase conjugating surfaces and synthetic electromagnetic materials.

Orla Feely, MRIA, UCD academic since 1992, Professor of Electronic Engineering, since 2010, and Vice President for Research, Innovation and Impact since 2014, Figure 24. D. J. Sakrison Memorial Prize winner, she is renowned for her outstanding and innovative research in the field nonlinear circuits and systems applicable to microwave, millimetre wave and TeraHertz transmitters and receivers.

Eric C. S. Megaw MBE (1908 - 1956) Dublin born, QUB educated engineer who, in 1940, refined the radar cavity magnetron, increasing its output microwave power 200-fold to 100 kW.

Michael McLaughlin, Founder of Decawave Ltd 2004, is the father of the global ultrawideband (UWB) radio positioning industry [78] with application in Internet of Things (IoT) such as automobile security, factory automation, sports tracking and asset tracking. Going far beyond the possibilities of GPS, his inventions, he holds 49 patents in UWB, enable rapid, versatile and efficient determination of the location of devices indoors and outdoors to centimeter accuracy, all at a low power, low cost, single system-on-a-chip, which combines UWB RF circuit design, antenna design and signal processing. McLaughlin is the key protagonist in the formation of the first international UWB positioning standard (IEEE 802.15.4a).

The list of giants of science and engineering in Ireland does not end there. Many others are presently active in research and engineering in EM microwave and millimeter wave fields and domains. Among them could be counted: Prof. M. Ammann, Technical University of Dublin (TUD), in antenna design; Prof. C. Brennan, Dublin City University (DCU), in radio propagation modelling; Prof. R. Farrell, National University of Maynooth (NUIM), in power amplifier design; Prof. P. Gallagher, Dublin Institute of Advanced studies (DIAS), with an All-Ireland team of mainly academic astrophysicists from across Irish universities, working on LOw Frequency ARray interferometer astronomy, LOFAR); Prof. G. Wrixon as academic and founder of Farran Technology, a millimeter-wave product development company, Dr. K. McCarthy, and Prof. P. Murphy, UCC, in MMICs and Mixed-Signal ICs; Prof. W. Scanlon, QUB and Tyndall National Institute, Cork; Dr. A. Zhu, UCD, on digital predistortion equalization in power amplifier design; Prof. M. Connelly, University of Limerick (UL), on optical wireless communications; Dr. J. Walker, UL, on geostationary satellite based universal precision timing extraction; Dr. I. Ganchev, UL, and Dr. M. S. O'Droma, UL, Fig. 24, on ubiquitous consumer wireless world (UCWW) concepts and wireless billboard channels; and also RF nonlinear power amplifier behavioral modelling. Significant research on microwave electromagnetics and electromagnetic tracking and navigation in medical applications is being done by Dr P. Cantillon Murphy, UCC and Dr M. O'Halloran, NUIG. Outstanding among the industrialists would be Analog Devices International whose R&D base in Limerick since the 1970s have contributed immense range of RF inventions through engineers like Mike Keaveney, integrating them into a wide variety of applications for industrial, healthcare, consumer, communications infrastructure and automotive electronics devices and measurement instruments. This list is far from complete but gives some indication of leading-edge, radio-science research activity in Ireland today.

The work mentioned above would fall mainly under the domains of URSI Commission C, D, and K, while much would find its main applications in radio communication engineering. The work is also serving other URSI scientific interests such as astronomy and cosmology (Commission J). Their contributions found an historical context in a 1981 Radio Science in Ireland review paper [79], the 1995 IEE proceedings of an international conference on 100 years of Radio [80].

5.3 Optical Astronomy

I do not address in this article contributions in optical astronomy, which in modern Ireland goes back at least to the amazing Birr Leviathan 72 inch (1.8m) telescope [81 - 85], built by William Parsons, 3rd Earl of Rosse (1800 - 1867), one of the great line of Parsons engineers, on his Birr castle estate. From 1845 until 1917, for more than 70 years, this was the largest telescope in the world. More recently, 2017, B. Parsons, 7th Earl, has worked with Professors P. Gallagher, T. J. Brazil and others mainly from the scientific astronomy research community in Ireland to construct the LOFAR radio-telescope station IE613. The international LOFAR telescope (ILT) is a Netherlands-based international network of low frequency radio telescopes. The Birr station is the most western one and adds considerably to the LOFAR baseline. In 2018, it observed for the first time a billion-year-old red-dwarf flare star called CN Leo, almost 7.9 light years away (75 trillion km), catching the stellar flare exploding in the star's atmosphere [86].

In this context, I'd also briefly mention Howard Grubb FRS FRAS (1844 -1931), a Dubliner, who made large optical telescopes for Greenwich and for observatories around the world, invented the reflector sight, perfected the periscope, and his instruments played a crucial and historical role in measurements to test the Theory of Relativity in the solar eclipse of 1919 [87]. For strategic reasons, during WW1 a thriving industry of optical instruments in Dublin, which had grown up during the 19th century, was closed down and moved to Britain.

Other activities deserve mention, but as URSI generally does not include optical astronomy within its remit, nor is it included under the umbrella of Ireland's URSI concerns, I end here.

6. Ireland's Active URSI History, 1978 - 2019

It is worth recording that Ireland's membership of URSI was the initiative mainly of Professor J. O. Scanlan, UCD, through the Royal Irish Academy. He drew in academics from universities across Ireland to lead particular URSI Commissions in Ireland. Professor B. K. P. Scaife, TCD, served as the first President of the Irish URSI Committee of Official Members, 1978 - 1981. Succeeding presidents in chronological order were: M. O'Donnell, 1982 - 1984; Professor M. C. Sexton, UCC, 1984 - 1986; Professor J. O. Scanlan, UCD, 1987 - 1989; Professor B. K. P. Scaife, TCD, 1990 - 2000; Professor M. C. Sexton, UCC, 2000; Professor J. A. C. Stewart, QUB, 2001 - 2005; Professor T. J. Brazil, UCD 2006 - 2008; Dr. M. S. O'Droma, UL, 2009 - 2019.

Irish official Commission members and Irish researchers participated over the years in the many URSI international symposia and activities. In Ireland itself, a key URSI activity has been the running of the biennial communications and radio-science research colloquium in Academy House, Dawson's St, Dublin, the seat of the Royal Irish Academy. The next such colloquium will be the 19th in the series and is scheduled for Oct 2020, with Dr. Roger O'Connor, Director at the Irish Government Department of Communications, Climate Action & Environment as the Organizing Committee Chairman.

7. Conclusion

In this URSI centenary review of aspects of its own history, and that of radio science in countries where it is active, our focus has been on four big 19th and early 20th century names on the island of Ireland, and their foundational contributions, through to the late 1960s: Marconi, Bell, Bell-Burnell and Callan. This being a radio-science history article, not surprisingly, Marconi dominates and some new aspects of his pioneering work are drawn out. However, in terms of history still in the making, the growth of John Bell's standing as father of quantum sciences seems unstoppable. I have also identified major Irish radio science contributors over the sixty years up to the present day, and concluded with a brief summary of URSI activities in Ireland since it joined URSI in 1978.

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A Century of Radio Science in Italy: History, Developments and Perspectives

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[9]Università di Pisa
[10]Università di Roma "Tor Vergata"
[11]CNR, Sesto Fiorentino
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1. Introduction

A century has passed since Italy joined the Union Radio Scientifique Internationale (URSI) in the International Research Council (IRC) during the First IRC General Assembly (GA) inaugurated in Brussels on July18th, 1919, by King Albert I of Belgium [1]. Three years later, in 1922, during the First URSI GA held again in Brussels, the Italian membership was ratified under the representative role of Consiglio Nazionaledelle Ricerche (CNR), a young National Research Council still under organization (officially established on Nov. 18th, 1923). For the development of radio science and relationships with URSI, the first CNR president Vito Volterra appointed an ad-hoc committee of experts, composed of university professors and researchers employed in military and civil institutions. Initially called Comitatoper gli Studi di Radiotecnica under the prestigious chairmanship of Guglielmo Marconi (Figure 1), eventually known as Comitatodi Studio per la Partecipazione del CNR all'URSI (briefly referred to as "URSI-CNR Committee" in the following), this group of experts continued to be important over the years.

After a century, not much has changed, and everything has changed as well. Still, the URSI-CNR committee is periodically appointed through an executive order signed by the CNR president, and continues to serve the national scientific community, providing proposals for the effective Italian participation in URSI activities and the necessary support to CNR in radio-science matters. Meanwhile, the set of research interests has greatly expanded from just four URSI Commissions in the twenties, whose terms of reference were common background for all the involved participants, to ten different, highly specialized research fields. Consequently, a richer, heterogeneous and multidimensional community, otherwise living apart in separate entities, has the effective opportunity to meet and exchange fruitful ideas.

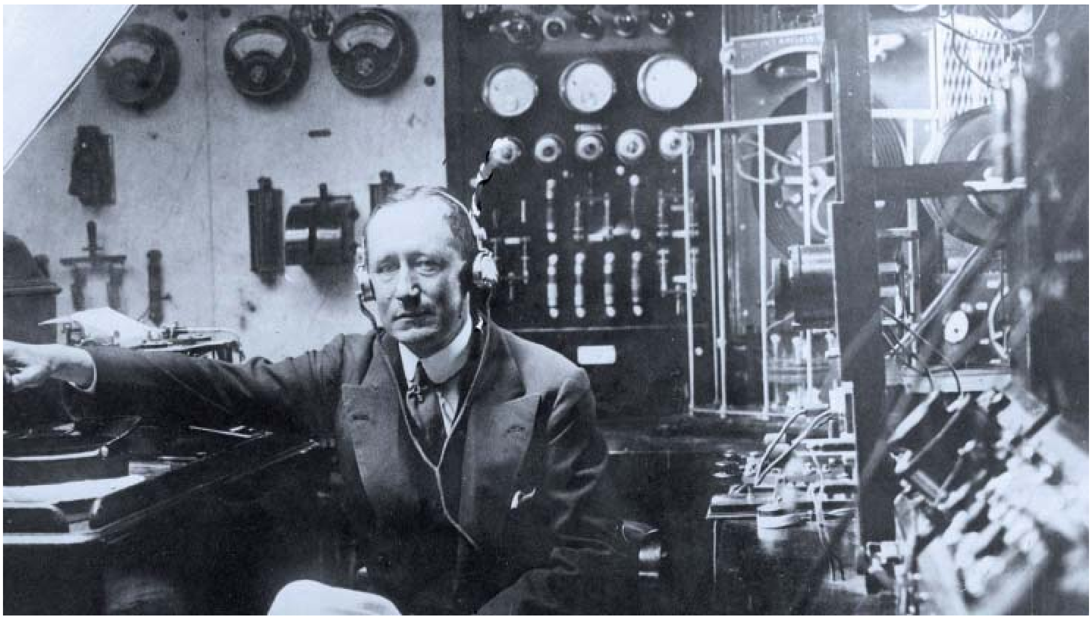


Figure 1. Guglielmo Marconi (1874-1937), Nobel Prize in physics and pioneer of radio telegraphy.

As current members of the URSI-CNR committee in the centennial, the authors are part of this community and owe previous generations of Italian radio scientists a debt of gratitude for the long path travelled across the years. This work is a humble and limited contribution to acknowledge them by recapping the history of radio science in Italy, starting with the achievements of early-time pioneers and traveling through their main successors. In this timeline, the VI (Venice/Rome, 1938) and the XXI (Florence, 1984) URSI GAs are recalled, in Section 2, as two symbolic milestones. Research of modern times, new developments and future perspectives are covered for each URSI Commission in Section 3. Finally, in Section 4 a short description of the future XXXIII URSI General Assembly and Scientific Symposium (GASS) to be held in Rome in 2020 concludes this paper as a consolidation of the strong link between Italian researchers and URSI.

2. Brief Historical Notes

2.1 The Pioneers

Inventions in radio technology anticipated and fostered advances in radio science. In this respect, the contribution of Italian pioneers between the late XIX century and the first World War was astonishing, starting with the figure of Guglielmo Marconi (1874-1937, Nobel prize, 1909). Son of an Italian landowner and an Irish mother, he did not attend any school as a child, being instructed at home by hired tutors, and later following some lectures on Hertzian waves delivered by Augusto Righi (1850-1920) at the University of Bologna. In his early twenties, he started experimenting with wireless transmission of telegraphic signals in his father's estate of Pontecchio. He excited grounded monopole antennas with spark gaps and used coherer tubes as receivers, reaching a transmission distance of 3 km. After he tried in vain to involve the Italian government in a large-scale exploitation of his invention, he finally got funding in 1897 from the British government, through which he was able to file patents and open the "Wireless Telegraph &Signal Company" in London. Soon, several achievements gained vast resonance in the world (e.g., the 51 km communication between the sides of the English Channel in 1898). Nevertheless, his dream was something judged to be impossible by his contemporaries, namely, a transatlantic wireless link between Europe and America. In the general, scepticism of academicians (maintaining that the Earth's curvature would prevent communications above 300 km), was challenged on the night between Dec. 11th and 12th, 1901. Marconi was able to hear the first message, the letter "S", in St. John of Terranova (Canada), transmitted from Poldhu (England) at a distance of about 3500 km along the ocean. Nobody knew about the ionosphere at the time, and still for many years the reason for Marconi's success was subject of lively debate for theoreticians. Reporting here on the rest of the life of such a giant and all his achievements is impossible. With his pragmatism, he literally invented radio technology and most of the questions and problems that radio scientists were called to answer and solve in the following years.

At the foundation of URSI in 1919, Giuseppe Vanni (1862-1934), director of Istituto Radiotelegrafico Militare in Rome, was appointed Vice-President (an office he held until his death), as well as chairman of Commission IV (liaison

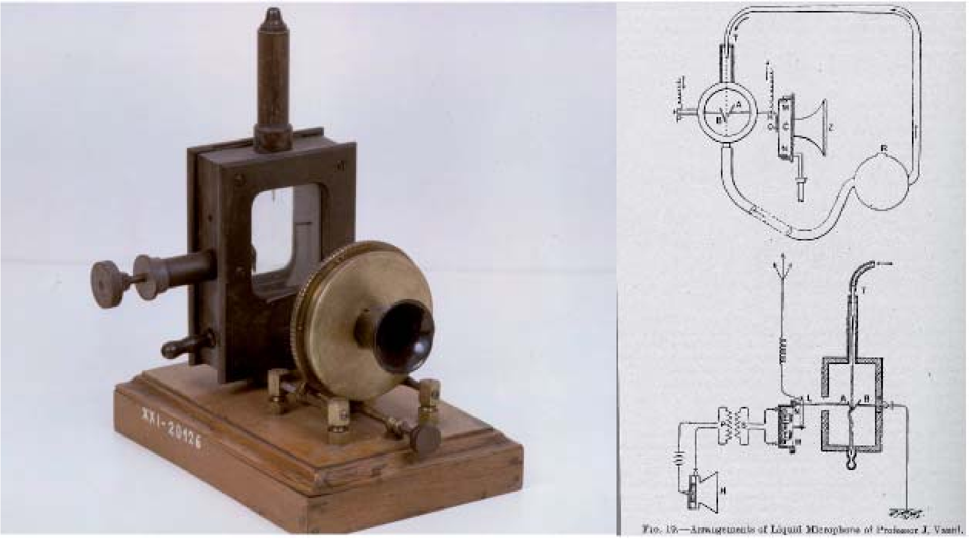


Figure 2. The 1911 “liquid microphone” of Giuseppe Vanni, URSI Vice-President from 1919 to 1934: original device (with broken parts) and principle drawing.

avec les opérateurs, les praticiens, les amateurs et le sciences connexes). Vanni is mainly remembered for pioneering achievements in radio telephony, when high-frequency sinusoids replaced the previous ineffective spark gaps, and it was understood that not only telegraphy, but also transmission of voice through amplitude-modulated signals was possible. Unfortunately, carbon microphones were unable to withstand the high power needed by radio transmitters. Similarly, the young vacuum-tube technology was still unable to provide high-power amplifiers. The solution proposed by Vanni was a “liquid microphone,” (Figure 2) which exploited a metallic lamina vibrating in a flow of acid water kept circulating by a pump. Thanks to this device, he set the 1911 world-record radio telephone communication sending his voice across a distance of 1000 km between Rome and Tripoli (Libya).

After a few years, the golden age of thermionic valves began. Triodes and other devices were put into use even before working principles were fully understood. In 1917, one of the first seminal papers on triode modeling [2], though written in Italian, attracted the attention of the international community and encouraged many researches. It was written by a professor in the Naval Academy of Livorno, Giancarlo Vallauri (1882-1957). Later in 1923, with the collaboration of Marconi, Vallauri designed and opened the most powerful radiotelegraphic station in the world, in Coltano (Pisa), allowing inter-continental communication with the African colonies (Libya, Eritrea, Somalia), China, and the Americas. Hethen moved to Turin and became rector of the Polytechnic, founder and first president of Istituto Elettrotecnico Nazionale (IEN) “Galileo Ferraris,” an advanced research institute. In URSI, G. Vallauri served as chairman of the above-mentioned Commission IV from 1938 to 1946.

Many other Italian radio scientists of the early period should be at least mentioned. Quirino Majorana (1871-1957), professor of physics in Bologna, contributed to radio telephony and made early discoveries about electronic tubes, later brought to perfection by W. Schottky. Gen. Giuseppe Pession (1881-1947) was firstly involved in radiogoniometry for the Navy, then director of Posts and Telegraphs, and URSI Vice-President from 1938 to 1946. Antonino Lo Surdo (1880-1949), eclectic physicist, founder of the National Geophysical Institute (ING), devoted a significant part of his research activity to radio science and its application to Earth science. Giorgio Abetti (1882-1982), astrophysics and director of the Arcetri Observatory in Florence gave fundamental contributions to the observation of solar phenomena and their effects on radio propagation. Gen. Luigi Sacco (1883-1970), serving for two World Wars as commander of military communications, and cryptography expert, was also an active researcher in radiophysics. Father Ernesto Gherzi (1886-1973), Jesuit, was a pioneer of scientific meteorology based on radiocommunications, working in England (with sir Appleton), Italy, China, USA, and Canada. Ivo Ranzi (1903-1985) carried out the first ionospheric measurements in Italy and the detection of cosmic rays in Eritrea.

2.2 The VIth URSI General Assembly: Venice/Rome, 1938

After decades of technological advancement, the Italian radio scientists of the thirties were eager to organize an URSI GA, initially foreseen in 1937 but later delayed until September 1938 just to make sure that all details were perfect for an ambitious and hectic programme. In the political climate of that time (Italy was ruled from 1922 by the autarchic regime

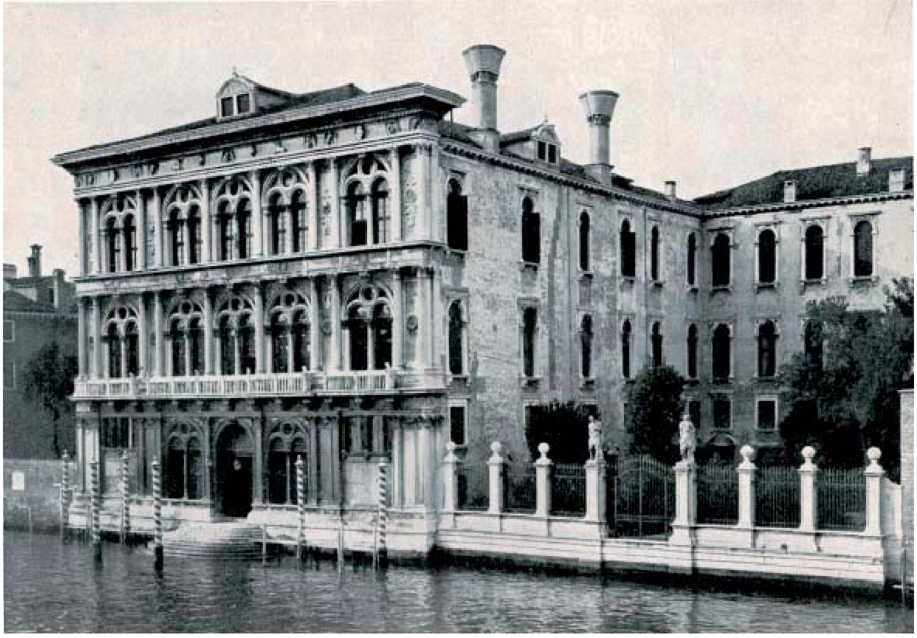


Figure 3. VI URSI GA, Venice, 1938: Vendramin-Calergi Palace, venue of the event.

led by the "Duce" Benito Mussolini), scientific conferences were seen by the government as occasions for propaganda, to demonstrate power and excellence to a selected international audience capable of orienting opinions in foreign countries. The organizational aspects were actually led by a notable official of the Fascist party, Count Giuseppe Volpi di Misurata (1877-1947), senator, president of Confindustria (General Industry Confederation). He provided support for the venue, by opening one of his superb mansions, palace Vendramin-Calergi on the Canal Grande in Venice (Figure 3) where, on purpose, he founded an institution called Centro Volpi di Elettrologia, to host scientific conferences on electrical subjects, starting with the VI URSI GA held from Sept. 4th to 8th , 1938. Count Volpi took much care of social events, including a concert in the Fenice Theatre, a tour of his Palladian villa in the countryside of Asolo, a gala evening in the Casinò, and an express-train transfer to Rome, where the closing session was solemnly held on Sept. 10th in the frescoed Marconi Hall of the CNR headquarter. Once in the eternal city, the delegates were offered a tour of the main monuments and, in the following days, of the national radio stations (Italo Radio in Torrenova for telecommunications, and EIAR in Santa Palomba for broadcasting), the Aeronautical Research Centre in Guidonia, as well as another train journey back to the

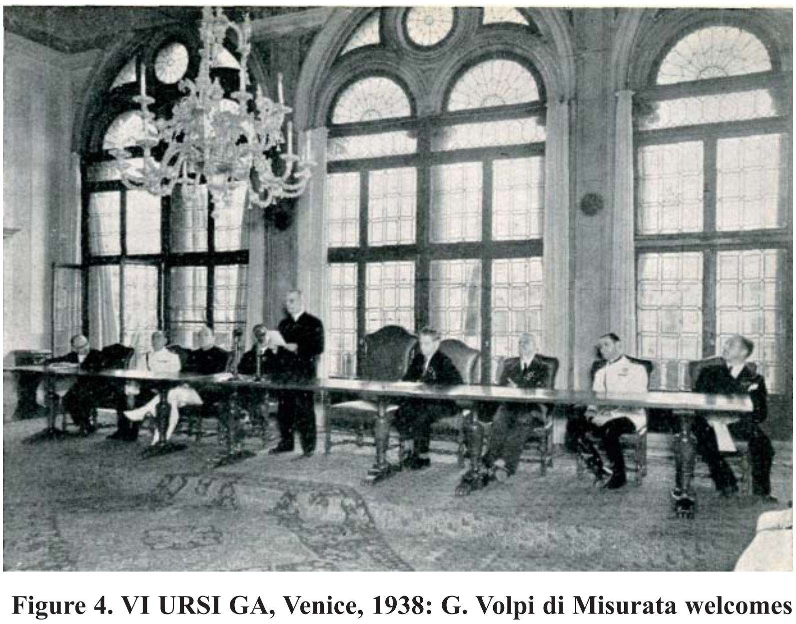


Figure 4. VI URSI GA, Venice, 1938: G. Volpi di Misurata welcomes the attendees to the opening session on Sunday, September 4.

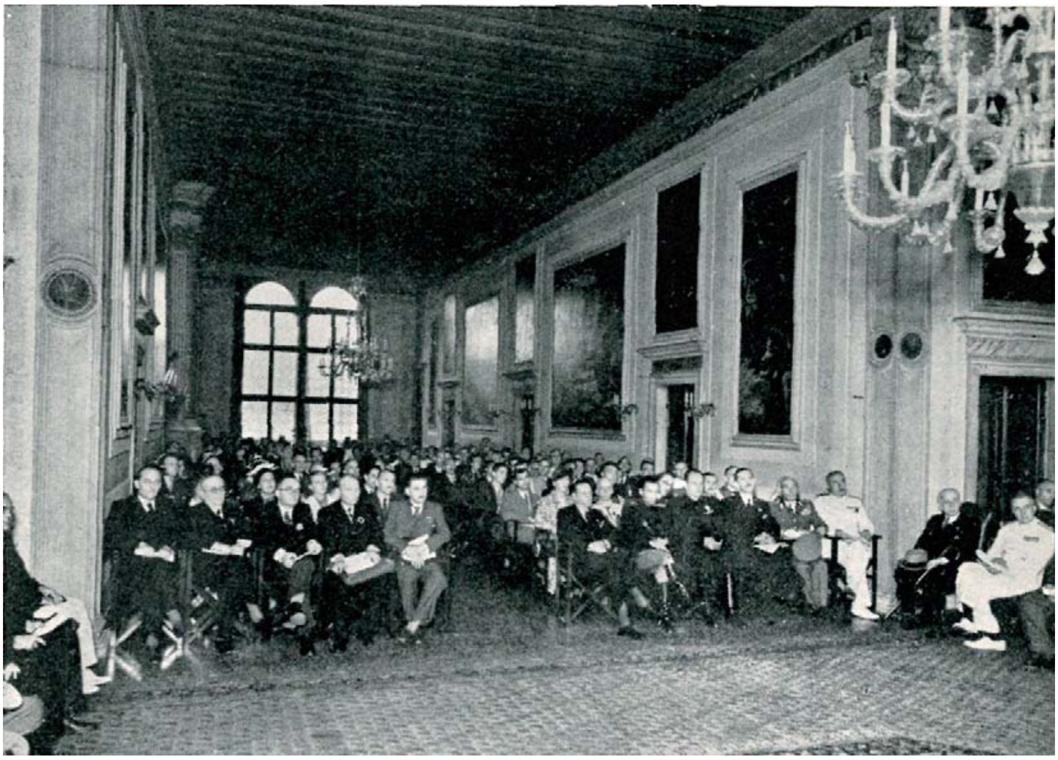


Figure 5. VI URSI GA, Venice, 1938: Attendees at the opening session.

north of the Country, stopping first at Livorno Naval Academy, and finally ending in Turin with a visit of the advanced IEN labs [3, 4]. Onlyon Sept. 15th ,1938, about a hundred pampered yet probably exhausted participants were able to return to their hometown, in Italy and foreign countries including Germany (invited to URSI for the first time, removing a ban dating back to IRC origins [1]), Belgium, France, Japan, the Netherlands, Switzerland, Sweden, UK, and USA.

The opening session on Sunday, Sept. 4th (Figure 4-5) was dominated by a wide-ranging address by URSI president Edward Victor Appleton (1892-1965). The British physicist (Nobel prize, 1947) started his speech with a commemoration of the recent demise of Marconi and R. Goldschmidt (former URSI Secretary), warmly welcomed the German newcomers, and continued by discussing the state of radio science after the V GA of London, 1934 [5]. Some URSI officials and delegates attending the GA are photographed in Figure 6.

In total, 115 papers were presented to five Commissions (though only a few of them were orally illustrated, according to past usages). Meetings were mainly collegial debates on the state of research, new challenges, international collaboration, and next resolutions [6]. From the minutes, no tensions and fears of a dramatic historical period can be detected. The delegates in Rome resolved to schedule the VII URSI GA for 1940 in Paris, France. They could not know how the devastation of a new World War would have severely divided and wounded the humankind by then. Eventually, the next GA was really held in Paris, but in 1946 and in a very different world.

2.3 The Post-War Period and the XXI URSI General Assembly, Florence, 1984

La Ricostruzione (the Reconstruction) is the significant term used in Italy to indicate the decade after World War II, characterized by enthusiastic willingness to take concerted actions, to work together despite the ruins, and to construct, on the basis of a democratic Constitution, a better Country that defines itself as “founded on labour”. In a few years, the economic and social fabric was revitalized, universities and research centres were reorganized. Several radio scientists of those and subsequent times left an indelible mark of their work. A short description of the most authoritative radio scientists of this so-called second generation follows. Nello Carrara (1900-1983), professor in Livorno and Florence, was already well known for the word “microwave” that he had firstly coined in a paper dating back to 1932 [7]. In 1946, he founded the Institute for Research on Electromagnetic Waves (IROE) of the CNR in Florence. With their research activities on microwaves and radars, Carrara and his colleague Ugo Tiberio (1904-1980), professor in Livorno and Pisa

Figure 6. VI URSI GA, Venice, 1938: Front row, l-r: B. Van der Pol (Netherlands), J. Zenneck (Germany), E. V. Appleton (UK), G. Volpi (Italy), G. Pession (Italy), M. Philippson (Belgium). Second row, l-r: G. Vallauri (Italy), A. Dorsimont (Belgium), not identified, E. Herbays (Belgium), not identified.

and recognized as the "father" of Italian radar, contributed to the birth of important national maritime and aerospace industries. Mario Boella (1905-1989), professor in the Polytechnic of Turin, is remembered for contributing to modern telecommunications and electronics. Gaetano Latmiral (1909-1995), professor in the Naval University Institute of Naples, was among the founders of a modern school of electromagnetic fields in Italy. Giorgio Barzilai (1911-1987), professor in New York (Polytechnic of Brooklyn) and Rome, was known for his research on microwaves. Claudio Egidi (1914-2009), researcher at IEN and professor at the Polytechnic of Turin, gave noteworthy contributions to metrology (especially time measurement). Francesco Carassa (1922-2006), rector of the Polytechnic of Milan, was a protagonist of Italian initiatives in satellite communications. Ermanno Nano (1928-2006), professor in the Polytechnic of Turin, was the first Italian expert in electromagnetic noise and interference, with an active role in URSI Commission E and CISPR. Gianni Tofani (1939-2015), astronomer at the Arcetri Observatory, was one of the main contributors to radio astronomy in Italy.

In the Eighties, the Italian community was ready to host the URSI GA again. The XXI edition was held in Florence, at the conference centre Palazzo deiCongressi and nearby Centro Affari from Monday Aug. 27th to Wednesday Sept. 5th, 1984 (excluding a two-day break in the weekend). The URSI-CNR committee appointed an ad-hoc GA organizing committee composed of V. Cappellini (chairman), A. M. Scheggi (executive secretary), G. Barzilai, G. Biorci, F. Carassa, G. Dal Monte, G. d'Auria, C. Egidi, E. Nano, N. Rubino. The scientific programme was coordinated by an international group formed by the URSI officers W.E. Gordon (President, USA), J. Van Bladel (General Secretary, Belgium), W. J. Granville Beynon (former President, UK), and A. L. Cullen (Vice-President, UK) [8].

About 1000 participants from 49 countries attended the regular sessions organized by nine URSI commissions, where 372 papers were presented strictly under invitation [9]. Additionally, three general lectures on highly topical content were given to the whole body of participants in distinct days, namely, "Very Long-Baseline Interferometry" by R. T. Schilizzi (Netherlands), "Twenty Years of Satellite Communication" by J. V. Evans (USA), and "Solitons in Biology" by A. Scott (USA) [10]. In parallel to regular sessions, four "open symposia" (i.e., non-invited papers submitted to a call) were organized on specific topics: 1) "Interaction of Electromagnetic Fields with Biological Systems" chaired by M. Grandolfo (Italy) and E. Postow (USA); 2) "Data, Signal and Image Processing" chaired by J. L. Lacoume (France), D. Jones (UK), and K. Tsuruda (Japan); 3) "Active Experiments in Space Plasmas" chaired by R. L. Dowden (New Zealand), P. Stubbe (Germany) and J. Fejer (USA); 4) "Radio Techniques in Planetary Exploration" chaired by K. Runcorn (UK) and G. Beynon (UK). These open symposia added 129 papers to the overall scientific conference [9].

An interesting aspect was the presence of 43 Young Scientists (19 from developing countries), not so large for todays' standard, but significant of an on-going generational evolution [9]. One of them, Asta Pellinen (Sweden), was also one of

Period	Members of the URSI-CNR National Italian Commitee
23/09/1985 16/09/1994	G. Barzilai[32], E. Bava[10], P. U. Calzolari[21], F. Carassa[19], G. Dalu[6], G. D'Auria[32], F. De Marco[8], P. Dominici[15], **C. Egidi**[10], F. Fedi[9], G. Fiocco[32], G. Franceschetti[27], G. Gerosa[32], M. Grandolfo[17], S. Leschiutta[10], L. Millanta[3], ***E. Nano***[20], A. Paraboni[19], A. M. Scheggi[3], G. Tartara[19], G. Tofani[18], G. Tomasetti[2], Rod. Zich[20]
27/12/1995 30/05/2002	A: S. Leschiutta[20], ***E. Bava***[19], F. Giannini[33]; B: G. Gerosa[32], Rod. Zich[20], G. Franceschetti[5]; C: G. Tartara[19], F. Carassa[29], G. Immovilli[26]; D: R. Sorrentino[30], **A. M. Scheggi**[3], C. Naldi[20]; E: E. Nano[20], A. Longoni[19]; F: F. Fedi[9], A. Paraboni[19]; G: P. Dominici[32], P. Spalla[3]; H: A. Gilardini[1], G. Perona[20], G. Falciasecca[21]; J: G. Tofani[18], G. Grueff[21]; K: P. Bernardi[32], F. Bardati[33], A. Chiabrera[24]
31/05/2002 05/05/2008	A: S. Leschiutta[20], ***E. Bava***[19]; B: G. Gerosa[32], R. Tiberio[35]; C: G. Tartara[19], M. Luise[31]; D: R. Sorrentino[30], C. G. Someda[28]; E: E. Nano[20], Ric. Zich[19]; F: F. Fedi[9], P. Pampaloni[3]; G: P. Spalla[3], B. Zolesi[15]; H: G. Perona[20], G. Falciasecca[21]; J: **G. Tofani**[18], S. Montebugnoli[2]; K: P. Bernardi[32], F. Bardati[33]
06/05/2008 13/07/2011	B. Carli[7]; M. Brenci[7]; A: P. Tavella[16], ***E. Bava***[20]; B: G. Manara[31], F. Bardati[33]; C: M. Luise[31], M. Lops[22]; D: **R. Sorrentino**[30]; E: F. Canavero[20], S. Pignari[19]; F: P. Pampaloni[7]; C. Capsoni[19]; G: P. Spalla[7], B. Zolesi[15]; H: G. Perona[20], G. Falciasecca[21]; J: R. Ambrosini[11], S. Montebugnoli[11]; K: P. Bernardi[32], G. D'Inzeo[32]
14/07/2011 31/12/2014	**R. Sorrentino**[30]; S. Paloscia[7]; A: ***P. Tavella***[16], L. Callegaro[16]; B: G. Manara[31], M. Pastorino[24]; C: M. Luise[31], S. Buzzi[22]; D: S. Selleri[29], G. Marrocco[33]; E: F. Canavero[20], S. Pignari[19]; F: P. Pampaloni[7]; C. Capsoni[19]; G: B. Zolesi[15], M. Materassi[7]; H: D. Farina[4], A. Tuccillo[8]; J: R. Ambrosini[11], P. Bolli[12]; K: G. D'Inzeo[32], F. Apollonio[32].
06/05/2015 31/12/2018	**R. Sorrentino**[30]; ***P. Tavella***[16]; A: L. Callegaro[16], P. Carbone[30]; B: M. Pastorino[24], G. Manara[31]; C: S. Buzzi[22], M. Luise[31],; D: S. Selleri[29], G. Marrocco[33]; E: S. Pignari[19], ***C. Carobbi***[23]; F: C. Capsoni[19], S. Paloscia[7], G: M. Materassi[7], C. Scotto[15]; H: G. Granucci[4], M. Cavenago[14]; J: R. Ambrosini[11], P. Bolli[18]; K: G. D'Inzeo[32], F. Apollonio[32].
16/04/2019 31/12/2022	**R. Sorrentino**[30]; I. Rendina[5]; A: F. Lamonaca[34], S. Pisa[32]; B: M. Pastorino[24], G. Manara[31]; C: F. Santucci[25], M. Luise[31]; D: G. Marrocco[33], S. Selleri[29], E: ***C. Carobbi***[23], G. Spadacini[19]; F: S. Paloscia[7], C. Capsoni[19]; G: M. Materassi[7], C. Scotto[15]; H: M. Cavenago[14], L. Figini[4]; J: P. Bolli[18], M. Messerotti[13]; K: F. Apollonio[32], L. Crocco[5]

Legenda: **President and Italian delegate in the URSI council: bold**; ***Secretary: bold italic***; Commissions: A-K; Commission Chair: underlined;
Affiliations: 1: Alenia (Roma), 2: CNR (Bologna), 3: CNR (Firenze), 4: CNR (Milano), 5: CNR (Napoli), 6: CNR (Roma), 7: CNR (Sesto Fiorentino, Firenze), 8: ENEA (Frascati, Roma), 9: Fondazione "Ugo Bordoni" (Roma), 10: Ist. Elettrotecnico Naz. "Galileo Ferraris" (Torino), 11: Ist. Naz. Astrofisica (Bologna), 12: Ist. Naz. Astrofisica (Cagliari), 13: Ist. Naz. Astrofisica (Trieste), 14: Ist. Naz. Fisica Nucleare (Legnaro, Padova), 15: Ist. Naz. Geofisica e Vulcanologia (Roma), 16: Ist. Naz. Ricerca Metrologica (Torino), 17: Istituto Superiore di Sanità (Roma), 18: Osservatorio di Arcetri (Firenze), 19: Politecnico di Milano, 20: Politecnico di Torino, 21: Univ. Bologna, 22: Univ. Cassino, 23: Univ. Firenze, 24: Univ. Genova, 25: Univ. L'Aquila, 26: Univ. Modena, 27: Univ. Napoli, 28: Univ. Padova, 29: Univ. Parma, 30: Univ. Perugia, 31: Univ. Pisa, 32: Univ. "La Sapienza" Roma, 33: Univ. "Tor Vergata" Roma, 34: Univ. Sannio di Benevento, 35: Univ. Siena

Figure 7. Members of the URSI-CNR National Committee from 1985 to the present.

the few female attendees. She recently went back to those days in a pleasant column of the Radio Science Bulletin, speaking about the role of women in radio science [11]. She recalls "At the get-together event, I felt totally lost. The other participants looked like my father's generation, serious Humphrey Bogart-type gentlemen from the black-and-white movie era". While URSI and its GA were surely reflecting the state of society, yet changes were in the air, and young women were finally finding a well-deserved role in science and technology. In this connection, the Secretary of the GA organizing committee, Anna Maria Verga-Scheggi (1929-2015), must be remembered for her contributions to lasers and as director of IROE.

3. Activities of URSI Commissions

In recent years, most of the organizers of the Florence GA, followed by their alumni, and new generations of radio scientists have been actively involved in the URSI-CNR committee (Figure 7). Their work is here summarized for each URSI Commission, together with new developments and perspectives on national research in radio science.

3.1 Commission A: Electromagnetic Metrology

Since the early times, the field of electromagnetic precision measurements was a strongly developing area driven by progress in science and technology and the evolving needs of industry. In the following is a non-exhaustive report on the state of the art and the new challenges in a broad variety of electromagnetic metrology disciplines in which Italian researchers have made their contribution [12, 13]. These include microwave metrology (extending its frequency range up to THz), vector network analysers calibration, complex permittivity of materials, human safety and health, Internet of Things (IoT) and time synchronization.

The efforts in microwave metrology to fulfil the "terahertz (THz) gap" are opening new measurement scenarios especially concerning THz high-precision molecular spectroscopy. Hz-linewidth transitions represent key molecular signatures and the THz range can be considered a novel molecular fingerprint region. Some applicative examples are: the study of star formation and decay through the discrete lines emitted by light molecular species (98% of the photons emitted since the Big Bang fall in the THz gap); the study of ozone depletion, pollution monitoring, and global warming through the THz thermal emission from gases in the stratosphere and upper troposphere [14].

An important contribution to the field of electromagnetic metrology concerns the calibration and uncertainty evaluation for vector network analysers. In particular, the basic research development of simplified calibration techniques for two ports and multiport [15] find current applications in most commercial instruments. More recently, a complete, robust, analytical solution suitable for real-time calculations of S-parameter measurement uncertainty was developed [16].

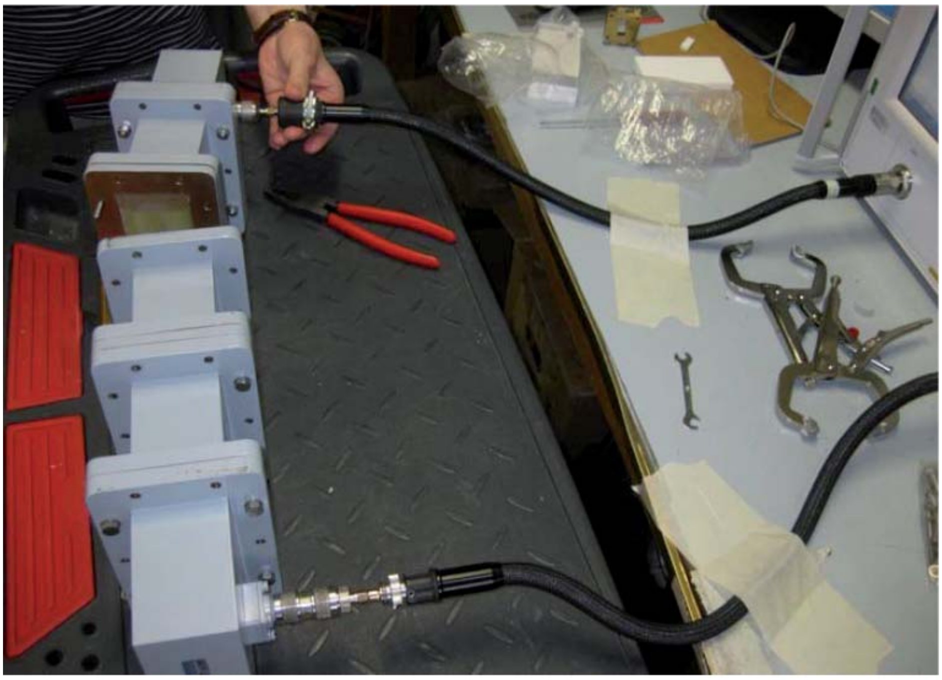


Figure 8. The WR430 measurement system proposed in [17] for evaluating dielectric permittivity of granular materials in the 1.7 to 2.6 GHz band.

One of the most widespread and studied electromagnetic measurements is the one related to complex permittivity of materials. Besides the direct evaluation of permittivity, this kind of measurement is interesting because it permits the indirect assessment of different properties of the material under test (Figure 8) [17]. One of the most studied and established applications is the assessment of the moisture content of materials and the different measurement solutions that were proposed suitable for non-homogeneous materials [18].

Concerning human safety and health monitoring, several papers deal with the design of measurement methods for the evaluation of the human exposure to electromagnetic fields [19] and to assess the traceability of measurements of vital signs and health parameters.

Current researches concentrate on measuring quantifiable properties of microwave electronics [20], the robustness of integrated circuit materials, and advanced integrated-circuit testing to radiated electromagnetic fields [21]. This research, together with those devoted to shared spectrum management, will facilitate a world where diverse wireless devices and systems can coexist [22].

At global level, the realization and dissemination of time and frequency standards is typically achieved by exploiting satellite systems [23]. Locally, synchronization is typically obtained by sharing signals [24]. In IoT systems the synchronization is typically achieved by the exchange of messages among smart objects, and the main challenges are the heterogeneity of the devices, the energy consumption constraints [25], and that some objects are mobile. Consensus seems a promising synchronization paradigm because it is robust to network topology changes [26] and admits the reduction of the average system energy consumption.

3.2 Commission B: Fields and Waves

The research activity of the Italian Commission B (Fields and waves) has a long history with relevant contributions in almost all areas related “to field and waves, encompassing theory, analysis, computation, experiments, validation and applications.” At the Italian national level, all scientific activities belonging to Commission B are associated with the SocietàItaliana di Elettromagnetismo (SIEm) (Italian Electromagnetics Society). SIEm was founded in 2002 and all Italian universities working on engineering electromagnetics have a SIEm Unit with a representative in the SIEm Council. Every two years, SIEm organizes a national meeting on engineering electromagnetics: the Riunione Nazionale di Elettromagnetismo (RiNEm) (Italian National Meeting on Electromagnetics), which were held several times in combination with the URSI-CNR Committee. The first President of SIEm was Prof. Roberto Sorrentino, followed by Prof. Paolo Lampariello, Prof. Paolo Bassi, and Prof. Giuseppe Mazzarella.

Figure 9. A picnic in the wood: the social dinner at the EMTS 2016 meeting of the School for Young Scientists (Espoo, Helsinki, Finland). The school was held on Sunday August 14, before the main conference, and took place in the Finnish Nature Centre Haltia in the Nuuksio National Park. The topic of this short course was "Electromagnetic Fields and Waves: Mathematical Models and Numerical Methods."

The major event, i.e., the URSI Commission B International Electromagnetic Theory Symposium (EMTS) has always had strong participation by the Italian scientific community, with a considerable number of technical contributions. Moreover, the EMTS was held twice in Italy. The first time took place in Stresa in 1968, where a reduced number of Italian scientists (working in universities and research centres) provided important contributions, in which rigorous approaches, strongly founded on Maxwell equations, was the characterizing element, largely affecting successive studies in the field of applied electromagnetics in Italy [27].

During the years, the Italian community working on themes related to URSI Commission B has grown significantly. In 2004, the EMTS was held in Pisa [28]. The scope of the symposium covered all areas of electromagnetic theory and its applications. In particular, a total of 421 papers were selected to be presented at the symposium. A rich set of sessions were organized, that is, 62 oral sessions, 4 plenary sessions and 1 poster session. They included both progress in traditional Commission B topics, such as electromagnetic theory, guided waves, scattering and diffraction, and emerging topics such as metamaterials, ultra-wide band applications, practical aspects of ground penetrating radars, and others. One of the key features of the Pisa EMTS was a series of plenary sessions, held every morning, entitled: "Perspectives into the History and Development of Electromagnetics - Past, Present, and Future."

Since 1996, the activities connected to Commission B have been coordinated at a national level by the URSI-CNR Committee under the guidance of prestigious scientists, whose names are reported in Figure 7. As far as the Italian contribution at international level is concerned, it is worth mentioning that Prof. Giuliano Manara served as the Chair of URSI Commission B for the triennium 2011-2014. Under Prof. Manara's guidance, the URSI Commission B School for Young Scientists was established. In particular, the first session of the School was organized at the Hiroshima EMTS in 2013. The instructors of the school were Prof. Prabhakar H. Pathak and Prof. Donald R. Wilton, and the title of the school was: "Fundamentals of Numerical and Asymptotic Methods." Since 2013, URSI Commission B School for Young Scientists have been regularly organized on an annual basis coinciding with the main URSI conferences (GASS, AT-RASC, EMTS), reaching its sixth edition at the 2019 EMTS, held in San Diego (California, USA, May 27-31, 2019). The school, whose instructors are selected from among leading scientists of Commission B, provides an important occasion for Young Scientists to learn the fundamentals and future directions in the area of electromagnetic theory and applications from the corresponding lectures. The school is also a way to let the youngest researchers in the URSI Commission B context get together, socialize, and start a friendship that will hopefully continue for all their scientific professional lives (Figure 9). URSI tradition places a strong emphasis on young scientists, which is why in 2014, URSI introduced the election of an URSI Early Career Representative (ECR) among the officers of each Commission. Indeed, Dr. Andrea Michel (University of Pisa) was elected Commission B ECR at the 2017 URSI GASS in Montreal, for the triennia 2017-2020 and 2020-2023.

In recent years, the Italian scientist participation in URSI Commission B related activities has increased further. Presently, the URSI Commission B Technical Advisory Board (B-TAB) includes 7 members from Italy (Matteo Albani, Francesco Andriulli, Giuliano Manara, Andrea Michel, Paolo Nepa, Matteo Pastorino, Giuseppe Schettini). In the 2019 EMTS more than 10 scientific sessions were organized or chaired by Italian scientists and about 30 scientific contributions included the participation of members of Italian research teams. The main subjects of these contributions were: scattering and diffraction, antennas and reflectarrays, metasurfaces, wireless applications, RFID, reverberation chambers, inverse problems and imaging, and numerical techniques [29]. This list of topics highlights the main directions in which the Italian research related to the URSI Commission B has recently moved.

3.3 Commission C: Radiocommunication Systems and Signal Processing

In celebrating the first century of the URSI, we cannot miss acknowledging the fundamental role that radio science has played in the development of communication and radar systems to a large extent through many outstanding contributions of both research and related industrial development [30]. As we cannot compress in a single page the more than 100 year-long history, we can just take the opportunity to focus on a few relevant activities that currently involve the whole national community and then emphasize how the long-lasting tradition has implicitly fed the latest developments.

Again, moving on from early impressions, the radio medium has exhibited unique features in supporting communications with mobile entities at larger and larger distances: starting with the first communications with aircraft and then moving to the challenging space exploration missions required by deep space communications, the role, and the many contributions of the Italian community, are apparent. Early efforts were made in technology in the experimental divisions of the Italian Air Force to support the pioneering missions over the North Pole between the First and the Second World War. Leading researchers like Ugo Tiberio and Algeri Marino [31, 32] promoted fundamental advances in theory and practice for radars and communications, and then supported the development of the Italian academic community after the Second World War as they joined the faculties in the University of Pisa and Rome, respectively.

Still along the way of exploiting the unique features of the radio medium to enable long distance communications, Italian scientists and industries have actively contributed to the development of high capacity radio relay systems and satellite communications. Just mentioning two leading academics: Francesco Carassa and Francesco Valdoni played pioneering roles in conceiving and developing modern satellite systems for digital communications in the nineties [33, 34]. They are considered the fathers of ITALSAT, the first satellite with fully regenerative transponder and on-board switching matrix that was designed and built by Italian industry in the eighties. On the industrial side, Guido Vannucchi and Telettra deserve particular mention as leading innovators of digital radio relay technology.

While the interest for very-long-range communications is still alive, and Italian industry has developed advanced solutions for space exploration (i.e., the transceiver for the Rosetta rocket that delivered beautiful pictures of comets a couple of years ago), it is clear that modern scientific and industrial interests were strongly motivated by the “pervasive communication” feature of the wireless medium, which can, in turn, be exploited over shorter and shorter distances. For instance, again, the modern scientist can recognize the insight of A. Marino, who was still a talented high school student when, motivated by Marconi’s experiences, he clearly predicted the advent of modern personal communications and Internet of Things in a paper [32] published in 1912! Following this theme, we can acknowledge the relevant contributions by the Italian academic community (just to mention a few, Sergio Benedetto, Ezio Biglieri, Gianni Immovilli, Marco Luise, Umberto Mengali, Aldo Paraboni, Silvano Pupolin, Guido Tartara) in the development of fundamental techniques underlying digital cellular communications and the inputs provided by the industrial community (e.g. CSELT research centre of Turin) in the definition of the first pan-European GSM standard for cellular digital telephony during the eighties.

Moving closer to the today’s radio arena, it can of course be stated that the latest developments towards 5G wireless technologies are eventually implementing the true pervasiveness of the radio medium that was in the minds of researchers a century ago. While on one side, 5G is formally defined as a next generation in the evolution process of cellular mobile radio systems, it is more often interpreted as a revolution that enables connections of people and things in an integrated and global eco-system that explicitly includes novel application domains for telecoms. For example: the 5G Automotive Association (5GAA) and the 5G Alliance for Connected Industries and Automation (5G-ACIA) were recently constituted in order to let telecom manufacturers and operators work elbow-to-elbow with big industrial assets of some relevant “verticals” like automotive (Figure 10) and industrial automation. The declared objective is to design and develop the 5G network infrastructure to satisfy unprecedented challenging requirements, especially from safety critical applications. While providing the traditional industrial domains the clear perception of the breakthrough that pervasive connectivity can

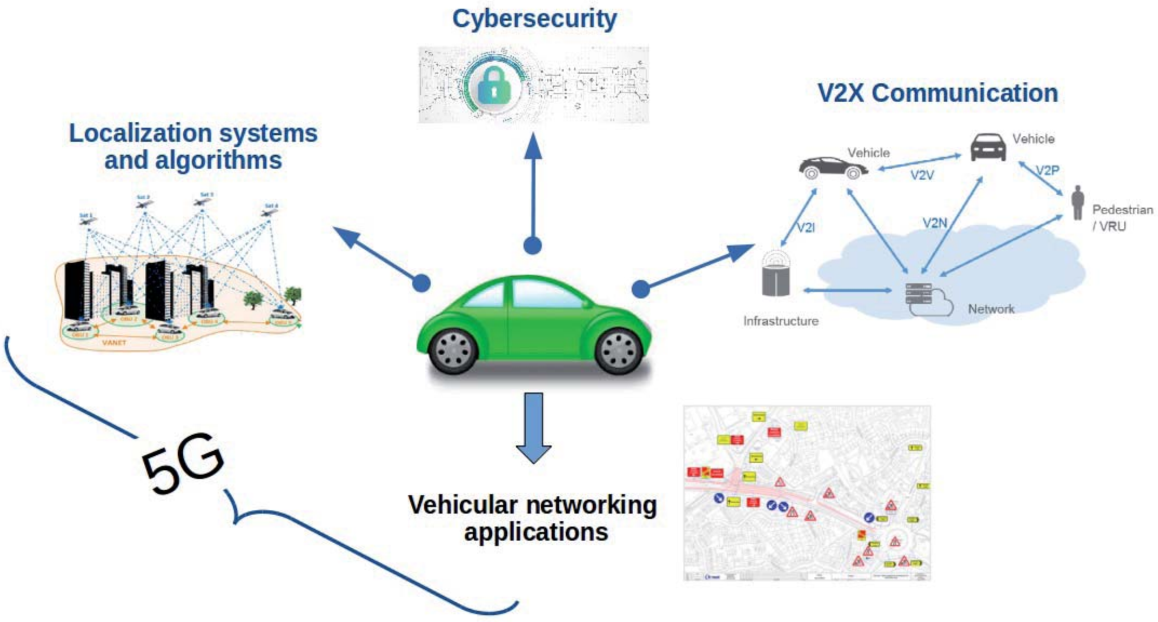


Figure 10. Pervasive communications and localization technologies for connected vehicles [36].

provide, it also enables both product and process innovation and finally brings remarkable social benefits. As a matter of fact, three main classes of 5G network functionalities are envisaged to meet requirements of rather different application scenarios: enhanced mobile broadband (eMB); massive machine type communications (mMTC); and ultra-reliable low latency communications (URLLC). The synergy between broadband wireless and broadband photonic technologies, along with softwarization of network architectures and cloud-edge computing, devise novel and interesting perspectives for adaptive resource allocation through network slicing.

The 5G Action Plan for Europe, undertaken by the European Commission (EU), is likely the largest research and development program in the world, with the 5G Infrastructure Public Private Partnership (5GPPP) coordinating the efforts of research institutions and industries. In this frame the EU recommended starting with at least a 5G trial per country by the end of 2018 in order to stimulate development of services and novel business models. Italy was proactive, with, in 2017, the Ministry of Economic Development launching a tender to design, develop and experiment with 5G pre-commercial trials in 5 cities (Milano, Prato, L'Aquila, Bari, Matera). The network infrastructure roll-out was almost completed by the network operators in all cities in the spring 2019 and in many cases are currently experimenting in the 3.7-3.8 GHz band. Furthermore, other trials were started in other cities (e.g. Roma, Torino) after frequency bands for commercial deployments were assigned at the end of 2018.

Being driven by network operators, and involving telecom manufacturers and other industries related to vertical domains, the 5G trials have also involved the whole Italian academic telecommunications community. In particular, more than 1000 faculties and researchers are working together under the coordinating action of the Italian Inter-University Consortium for Telecommunications (CNIT) on several 5G related projects. In this frame CNIT promoted and coordinated the large dissemination initiative (https://www.5gitaly.eu) that was held in Rome from 4 to 6 December 2018 and produced an eBook [35], which is available and continuously updated as the standard evolves, the research activities progress, and the trials advance. After the success of the first edition, considering the coordinated efforts by the whole Italian telecommunications community, the next edition is planned for December 2019.

3.4 Commission D: Electronics and Photonics

As the wireless technology becomes increasingly more pervasive to our lives, International Symposium on Signals, Systems and Electronics (ISSSE) becomes one of the most important meetings for URSI that is emphasizing the telecommunication. ISSSE series was jointly organized by Commissions C (Signals and Systems) and D (Electronics and Photonics). The first meeting was held in Erlangen, Germany in 1989, followed by Paris in 1992 and San Francisco in 1995, the fourth event was organized in Pisa, Italy. The Symposium was intended to develop three main areas of DSP-

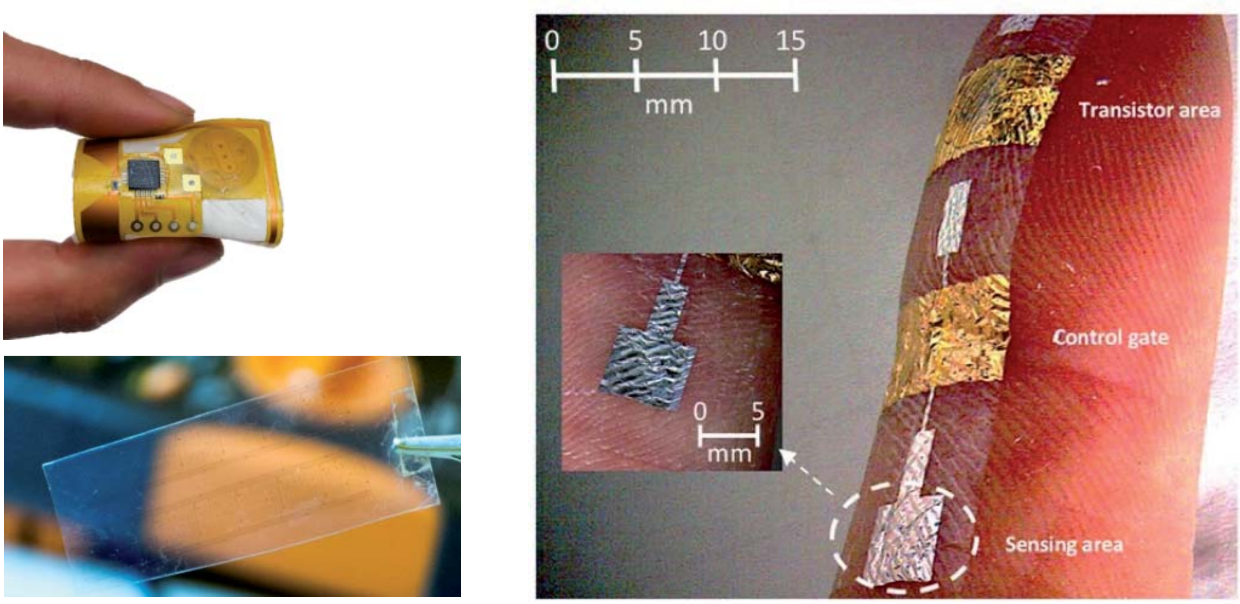


Figure 11. (a) SECOND SKIN, Università di Roma Tor Vergata; (b) Printed and Molecular Electronics, IIT; (c) Tattoo Electronics, University of Cagliari.

based Communication Equipment and Systems, VLSI design and Components, and Microwave Theory and Techniques. The Conference Chairman, Professor Luise, was successful in raising a considerable amount of sponsor funds from Italian telecommunication companies and from the University of Pisa. The conference was well organized and carried out in a relaxed and congenial atmosphere. There were ample occasions of technical exchange at coffee breaks and on-site luncheons for all participants. An excellent banquet was organized at a local restaurant with excellent Italian cuisine. The last two ISSSE were incorporated within AT-RASC [36].

From a scientific point of view, we notice that the pioneering research of Materials and Chemical engineers, mostly driven by the last 5-10 years' work of Prof. J. Rogers in USA, has led to a new kind of Electronics [37], made by ultra-thin and stretchable elastomeric membranes patterned with electrodes and sensors, memories, batteries, solar cells, and even displays by means of inkjet printing, screen printing and laser induced forward transfer. Devices become therefore suitable to a conformable application onto fabrics and even on the human skin, like plasters or tattoos. The resulting Epidermal or Skin Electronics is going to potentially revolutionize the way sensors are embedded with objects in the era of Internet of Things and in the forthcoming 5G communications. This new paradigm is quickly spreading outside the original Materials community toward Communication and Electromagnetics [38-43] Electronics and Photonics [44-46], thus leading to a new fascinating research topic within the Commission D.

Open technological challenges concern the robustness of the circuit vs. bending and stretching, the adhesion of components over thin films, the communication performance in presence of the human body, the repeatability of the sensing results and the large area manufacturing. Thanks to its intimate nature, the Skin Electronics will benefit from a tight cross-fertilization among several backgrounds of URSI commissions but also stimulates novel interactions with Materials and Chemistry scientists.

There are currently several active teams in Italy with different and complementary backgrounds spanning from solid state technology for flexible substrates to skin antennas and sensors and soft robotics. Next, without any presumption of completeness, a summary of some hot topics and the corresponding research teams (see Figure 11):

- SECOND SKIN: Epidermal Antennas for Radiofrequency Identification and Sensing, Università di Roma Tor Vergata (ref. Prof. Gaetano Marrocco), www.pervasive.ing.uniroma2.it: Optimal skin flexible antennas in the UHF band coupled with sensors and electronics to monitor body temperature, sweat, pH, breath and to recover/augment human senses. Manufacturing over ultra-thin stretchable substrates. Communication models involving the human body. Clinical trials, application to wellness and to the monitoring of personnel in harsh environments.

- Printed and Molecular Electronics, Italian Institute of Technology IIT at Politecnico di Milano (ref. Dr. Mario Caironi), https://www.iit.it/people/mario-caironi: Investigations of the opto-electronic properties of solution-processable semiconductors, in particular conjugated organic materials, with focus on their printability. Organic thermoelectrics and Edible Electronics.

- Tattoo Electronics, University of Cagliari (ref. Prof. Annalisa Bonfiglio), http://sites.unica.it/dealab/: Organic Electronics: knowledge and applications based on large area technologies applied on unconventional substrates. Organic Bioelectronics aiming at the development of multimodal sensing systems for biomonitoring applications.

3.5 Commission E: Electromagnetic Environment and Interference

Several reports (from 1990) and proceedings (from 2002) of the URSI flagship conferences represent a fundamental information source for the contribution of Italian radio scientists to Commission E, which became significant in 2002, after the appointment of Prof. Flavio Canavero (Politecnico di Torino) as Vice-Chair, during the XXVII URSI GASS in Maastricht, while the Chair of Commission E was Pierre Degauque (Université de Lille, France) [47]. Three years later, during the New Delhi XXVIII URSI GASS Prof. Canavero was appointed Chair of Commission E and Prof. Christos Christopoulos (University of Nottingham, United Kingdom) succeeded as Vice-Chair [48].

Under the Chairmanship of Prof. Canavero, the terms of reference of Commission E were changed with the official introduction of "electromagnetic compatibility" (EMC) [48], and they were finally consolidated in the present form in 2008 during the Chicago XXIX URSI GASS [49]. Indeed, before 2005, EMC appeared in the terms of reference only through a note stating that "many of the subjects mentioned are treated under the common title of Electromagnetic Compatibility". Several EMC symposia were sponsored by URSI in those years: EMC Zurich, EMC Wroclaw, EMC Roma (later EMC Europe), as well as IEEE and non-IEEE sponsored EMC symposia in the western and eastern world. The Chairs and Vice-Chairs of Commission E were organizers of numerous oral sessions at those conferences. Hence, by introducing EMC in the terms of reference, a direct connection was established between the scientific activity of URSI Commission E and the international EMC community. This was an important step forward in broadening the scientific interests of Commission E, which were, until then, limited to radio noise of natural origin eventually extended to man-made noise, mitigation of interference to equipment (not necessarily radio equipment) and the limitation of non-intentional electromagnetic emission. Actually, many papers presented in the above-mentioned conferences were notable examples of this extension of scope to the peculiar technical aspects of EMC, like the modeling of conducted and radiated emission/susceptibility phenomena. Among them, it is worth mentioning [50] as a specific contribution from the Italian URSI community, dealing with the experimental characterization and modeling of the bulk current injection (BCI) probe and the related test setup for conducted immunity.

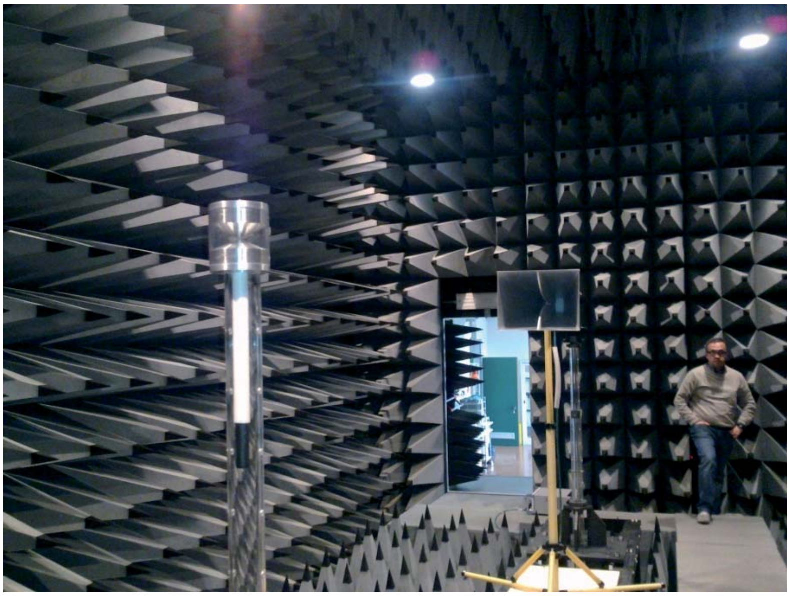


Figure 12. Calibration of a reference source of electromagnetic fields for inter-laboratory comparisons of EMC measurements in the anechoic chamber of the Italian National Metrological Institute (INRIM).

A co-author of that work, Prof. Sergio Pignari (Politecnico di Milano, Italy), was later invited by Commission E to write a "Review of Radio Science" paper on the role of statistics in EMC [51], an emerging topic within the community that showed many potential applications in the following years, up until the present day. For instance, the minutes of Commission E meetings of the 2011 Istanbul URSI GASS [52] mention Topic 3 "Complex Systems" and Topic 7 "Numerical Modeling of Complex and Large Systems," both implying the use of statistical techniques. During the same GASS, Prof. Pignari and Prof. Luk Arnaut (Queen Mary University of London, United Kingdom) organized the session "Stochastic Techniques in EMC," a subject that attracted (and it is still attracting) the interest of many researchers. Papers presented in this session by Italian attendees covered computationally efficient modeling techniques for interconnects and complex systems [53], and some were extended for publication in Radio Science [54]. Prof. Canavero also co-chaired with Dr. Christopher Holloway (NIST, United States of America), the session "EMC Interactions in Complex Systems," during which Prof. Christopoulos presented a paper about complexity in EMC modeling [55]. In the same vein of research, we can identify the contribution of Prof. Gabriele Gradoni (University of Nottingham, United Kingdom, presently Early Career Representative of commission E) and Prof. Ramiro Serra (Technical University of Eindhoven, The Netherlands, co-chair with Arnaut and Pignari of the commission E working group "Stochastic Techniques in EMC"), in the field of wave chaos modeling and mode stirred reverberation chambers, respectively.

Prof. C. Carobbi, currently chair of Commission E in the Italian URSI-CNR Committee (see Figure 7), contributed to the 2017 Montreal URSI GASS, AT-RASC 2018 in Gran Canaria and AP-RASC 2019 in New Delhi, by chairing sessions of Commission E during the last two conferences. He also contributed to papers dealing with EMC measurements and evaluation of EMC measurement uncertainty, emphasizing, inter alia, the importance of rigorous assessment of measurement reproducibility through inter-laboratory comparisons (Figure 12). During the 2017 URSI GASS a scientific collaboration was started among Prof. Carobbi, Prof. Sébastien Lalléchère (Université Clermont Auvergne, France) and Prof. Arnaut on the topic of uncertainty quantification of measurement and computational modeling in EMC, which produced a series of two review papers [56-57].

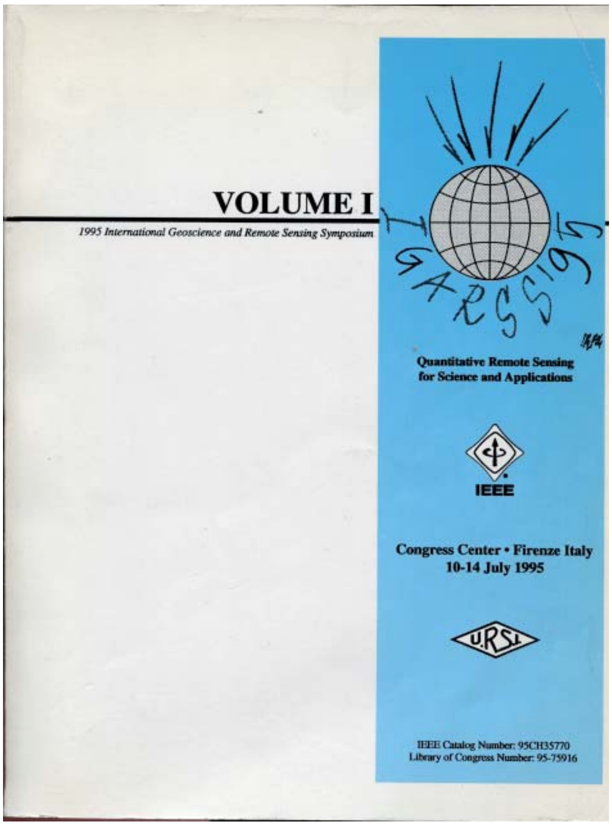
3.6 Commission F: Wave Propagation and Remote Sensing

The Italian contribution, over the years, to electromagnetic wave propagation in the troposphere at microwave frequencies is of undeniable importance for the research in this field. In the sixties, Francesco Carassa, director of the Telecommunication laboratory at Politecnico di Milano, designed a SHF satellite experiment to materialize his vision of the future of telecommunication. This has provided the research community with a tool for field-testing theoretical results on propagation impairments during adverse weather conditions. At the end of 1974, after a long and rocky period, the Carassa project got a new kick and the geostationary satellite SIRIO (Satellite Italiano di RicercaIndustriale e Operativa), developed under the First Italian space private public partnership between CNR and Compagnia Industriale Aerospaziale, was launched in August 1977. Although it was designed for a lifetime of 2 years, thanks to a precise manoeuvre to reach the final geostationary orbit, SIRIO operated for more than 10 years and allowed the most important research teams in the world (from USA to China) to investigate electromagnetic propagation at 12 and 18 GHz.

In 1991, the recently established Italian Space Agency (ASI) launched another advanced Italian gigahertz satellite, the ITALSAT F1, which allowed experimentations at different frequencies from 18 to 40 and 50 GHz. The data collected during this experimental campaign in many sites, spread all over Europe, are unique and still used for the development of channel models and the design of propagation impairment mitigation techniques. The ASI mission to anticipate the use of millimeter waves, although it is not yet considered for commercial applications, is still continuing. Indeed, within the ASI Q/V band program, a telecommunication and propagation experimental payload was developed in Italy in collaboration with the European Space Agency (ESA) and it placed on the Alphasat satellite. The Alphasat-Aldo Paraboni Payload was designed to study and test the potential of Q/V band frequencies. The experimentation is still ongoing and almost all the European research groups active in the propagation field are participating as a network.

The scientific contributions proposed by many Italian and foreign universities, as well as public/private research bodies involved in the space research, made possible thanks to those experiments, are numerous. Moreover, many of the papers are presented at URSI GAs and various URSI Commission F Open Symposia, where people involved in propagation and remote sensing meet, exchange their ideas and organize joint activities. The active participation in URSI by the Italian propagation community is exemplified in [58-62].

Remote Sensing is a relatively new discipline. Research in this field was stimulated by URSI after the Microwave Signatures Symposium, held in Berne, in 1974, and hence, before Commission F was renamed "Wave Propagation and Remote Sensing" (1978). At that time the Microwave Remote Sensing community in Italy was almost non-existent at the international level, and only two individuals from Italy attended that meeting as observers, as well as the following



VOLUME I

1995 International Geoscience and Remote Sensing Symposium

IGARSS'95

Quantitative Remote Sensing for Science and Applications

IEEE

Congress Center • Firenze Italy
10-14 July 1995

U.R.S.I.

IEEE Catalog Number: 95CH35770
Library of Congress Number: 95-75916

Figure 13. Cover page of the first volume of the 1995 International Geoscience and Remote Sensing Symposium Proceedings.

one in Kansas (1981). We had to wait a few more years before a significant interest in this discipline developed among Italian researchers, initially in the optical field, but then also in microwaves. An important motivation came from the Earth Observation programs promoted by national and international space agencies, firstly ASI, ESA and NASA. The European SAR 580 airborne campaign, organized by the Joint Research Center (JRC) in 1981 was the first opportunity for European scientists to evaluate the potential of data collected with a Synthetic Aperture Radar (SAR) on a few test sites, some of them in Italy. At that time digital processing was still in its infancy, and the optically processed SAR images were distributed on long strips of film. The programs of Earth Observation by ESA, with the satellites ERS followed by ENVISAT and SENTINEL, and the SIRC/XSAR mission of NASA/DLR/ASI (1994) to fly an L, C and X band SAR on a shuttle, have made possible a significant consolidation of knowledge for the monitoring, at high spatial resolution, of the Earth's surface. These sensors also contributed to the realization of one of the most important ASI projects: The Cosmo Skymed, a constellation of 4 small satellites (launched between June 2007 and November 2010) equipped with X-band SAR, orbiting in order to allow the use of repeat-pass interferometry.

In parallel with the high-resolution SAR missions, mostly oriented to the monitoring of ocean and land surfaces at regional and local scale, the potential of medium and low-resolution sensors for the retrieval of surface and atmosphere parameters at global scale was exploited in several experiments with ground-based, airborne, and satellite sensors. The most popular satellite sensors for these purposes were the multi-frequency SSM/I and AMSR-E/2 microwave radiometers and the two L-band SMOS and SMAP focused on the retrieval of soil moisture. Important results are expected from the ASI PRISMA, a medium-resolution hyperspectral imaging system launched by ASI in March 2019 and focused on the delivery of pre-operational hyper-spectral products.

Stimulated by these missions, the Italian Remote sensing community is now among the strongest and most productive in the world. Its contributions to URSI Commission F are highlighted by the participation in all the URSI conferences, also with Tutorials and Invited Papers, as well as by the organization of two important events such as IGARSS'95 (Figure 13) and Microwave Signatures 2010, both in Florence [e.g. 63-67]. The Italian scientists who alternate as Official members of the Commission F are noted in Figure 7.

3.7 Commission G: Ionospheric Radio and Propagation

Within the Italian scientific community, the study of ionospheric variability, i.e., how the physical parameters describing the ionosphere vary with time, depending on the present conditions of the Sun-Earth interaction and of our planet herself [68], has, in the past, taken great advantage from radio science, in particular from active and passive radio sounding [69, 70]. As the electromagnetic waves crossing the ionosphere are altered, depending on the local state of the medium, information about the latter can be inferred by collecting electromagnetic signals sounding the ionosphere. The use of the trans-ionospheric signals of satellites for positioning and navigation (the GNSS) provide the opportunity for both wide-area mappings of the ionization density (one of the crucial ionospheric proxies) [71], and small-scale structure studies [72, 73]; while the use of radio-occultations from low-orbiting satellites (LEOs) make it possible to monitor the local vertical ionization density profiles [74].

The great challenge of ionospheric variability, and the great opportunity for radio science in this branch, is the study of the actual predictability of the Earth's ionospheric state: this challenge is not just a technical issue because of the intrinsic complexity of the system [75]; it also raises the issue about how deterministic the Earth's ionosphere is as a physical system. Indeed, the ionosphere is a space-extended system with a huge number of degrees of freedom, that interact in non-linear ways; moreover, the ionosphere is open, as far as both matter and energy are concerned. This really puts the ionosphere on the border between chaos and probabilistic systems: it is theoretically challenging, and definitely uncertain, establishing to what extent the ionosphere is predictable, and to try to make predictions. Still, it is necessary for applications, and urgent from a fundamental science point of view.

Ionospheric modeling is a wide field of research that has received important contributions from the Italian scientific community [76]. The biggest problem was always modeling ionospheric plasma irregularities that cause severe and apparently stochastic disturbances to trans-ionospheric radio signals, namely radio scintillation [77]. New data analysis and mathematical tools from the science of complexity will be of great help in the quest for ionospheric predictability [78] (Figure 14). Recently, the constellations of GNSS satellites have increased their space-time coverage, creating a huge amount of data for unprecedentedly rich monitoring. Moreover, the near future is going to be the era of big data manipulation, hyper-fast computers and networks, and this will be a great chance, for the URSI community, to work on the most challenging points of Earth's ionospheric dynamics.

3.8 Commission H: Waves in Plasmas

Since a plasma is a collection of electrically charged particles (usually in disordered motion), and therefore unavoidably coupled to the electromagnetic (EM) field, the theme of EM waves in plasmas encompasses a large variety of aspects, ranging from astrophysical phenomena to laboratory devices and technological applications [79].

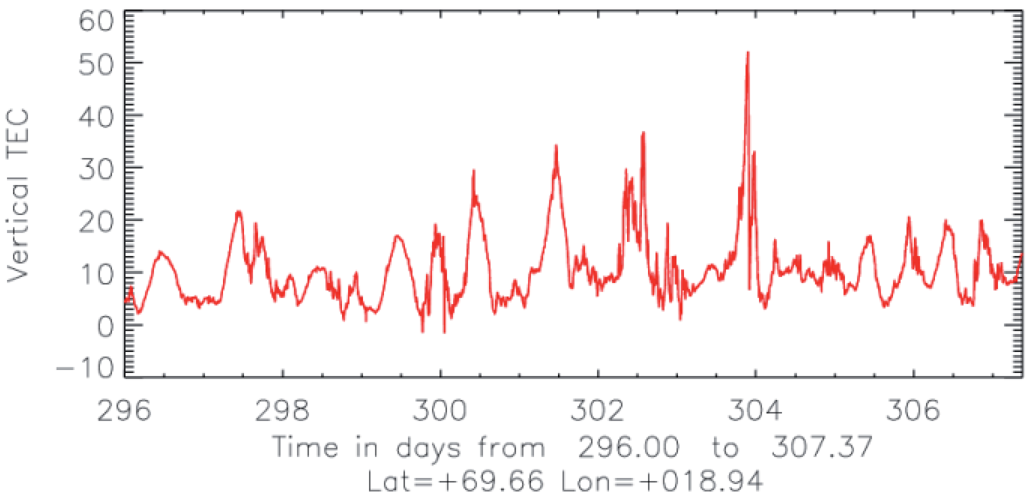


Figure 14. Plot representing the vertical total electron content (TEC) above the GPS station at Tromsø, between days 296 and 308, 2003, i.e., during a geomagnetically active period (from [78]). The irregular time series plot highlights how the complexity of ionospheric physical phenomena turns into apparent unpredictable behaviour of ionospheric proxies.

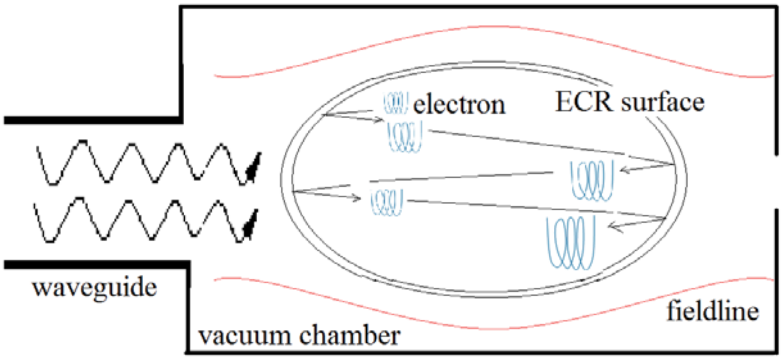


Figure 15. The electron cyclotron resonance (ECR) ion source is an example of EM waves and a plasma device in the laboratory. Using a nonuniform magnetic field (due to a magnet, not shown) the electrons, confined by the field and waves, can gain energy from waves at a resonant frequency; and they can then ionize heavy elements multiple times.

Even if a plasma is commonly associated with an arc, that is an electric discharge between metallic objects (electrodes), sometimes sharpened, electromagnetic waves are often a more convenient method to energize a plasma: the contactless transmission of power avoids the consumption of electrodes and leads to more stable plasma conditions (see applications later). Conversely plasmas and particle beams (collections of charges with ordered motions) can be a source of EM waves, which may be a natural effect (when a beam impinges on a plasma, giving the so called two-stream instability), or a desired effect (as in electron tubes), or a problem (fusion plasmas are cooled also by instabilities [79]).

As a first instance of interest to the Italian URSI Commission H, the complicate phenomena of the solar wind [80] (one stream) impinging on a planetary magnetic field and upper atmosphere (plasmas known as ionosphere and Van Allen belts) involve several wave generation processes, with the name "space weather" to encompass most of the EM disturbances in the space [81], that is the space EM environment. Observation devices include both Earth-based radio-telescopes [82] and satellites, either in geostationary orbit or in Low Earth Orbit (LEO). Conversely, since nowadays geostationary and LEO satellites have out-paced natural ionosphere EM wave reflection as relays of long-distance communications, the description of space weather is also of technological importance. Satellite propulsion by ion and plasma thrusters [83] is *also* actively developed in Italy.

As regards to laboratory devices, first of all, most high power microwave generators are based on electron-beam instabilities; to cite a few: the klystron [84] where a beam is bunched in the longitudinal direction; the similar Travelling Wave Tube [85]; the gyrotron where the azimuthal velocity of electrons (spiralling around a magnetic field, with the so-called cyclotron frequency) is the bunched variable; and others. Optimization of beam/wave interaction and of tube efficiency is actively pursued by the accelerator physics community [86] and by the fusion community [87]. The Italian plasma physics community is deeply involved with fusion research, where EM waves in plasma plays an important role, both for observation and for plasma heating. Microwave emission of plasma gives important information on plasma temperature; microwave propagation into plasma measures the plasma density; and 170 GHz microwaves can contribute to fusion plasma heating [87].

Another class of devices encompasses radiofrequency and collective accelerators [88, 89] and the related particle traps. Ion sources (for accelerators) greatly benefit from the contactless heating with EM waves. In Italy, we have several examples of 2 to 30 GHz microwave used in plasma ion sources (Figure15), mainly using the Electron Cyclotron Resonance (Catania, Legnaro, Milano, Pavia) [90]; and of heating plasma with 1 to 13 MHz radiofrequency, mainly with inductive coupling (Padova) [91]. These sources find applications in nuclear physics, medical adrotherapy, the semiconductor industry, and research for injecting particle beams into fusion reactors [91].

3.9 Commission J: Radio Astronomy

While radio astronomy began in 1933 with the serendipitous discovery, by Karl Jansky, of natural radio signals coming from space [92] it was only in the late fifties that Italian astronomers started to look at the Universe at radio wavelengths. The first attempts were conducted with dishes up to 10 m diameter built in Medicina (close to Bologna) and at the Arcetri Astrophysical Observatory for solar radio astronomy. In 1960, the Physics Institute of the Bologna University, directed by

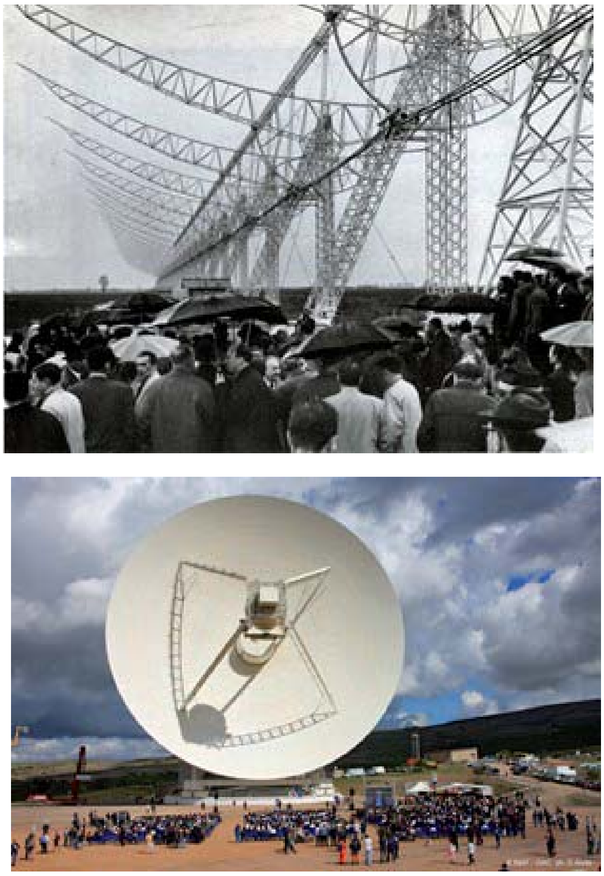


Figure 16. Inaugural ceremonies of: (a) The Northern Cross radio telescope, in October 1964, and (b) The Sardinia Radio Telescope, in September 2013.

Prof. G. Puppi, began the construction, in Medicina, of the Northern Cross, a huge interferometer consisting of parabolic cylinders distributed along two perpendicular arms. After an initial phase, the instrument was rearranged in its present configuration, with the two arms being 640 m and 576 m long and an overall collecting area of about 30 000 m^2. An interesting activity report was given at the 1966 URSI GA, where Prof. G. Righini reviewed the status of the Northern Cross, with the East-West arm operating regularly since the inauguration in 1964 (Figure16(a)), while the North-South foreseen to be commissioned in 1966 [93]. This instrument was mainly designed to perform radio surveys and it allowed the production of popular catalogues called B1, B2 and B3.

In later years, with antenna engineers developing large reflector antennas for telecommunication systems, the times were right to use such reflectors for scientific purposes, as well. Under the umbrella of the Institute of Radio Astronomy, two 32 m radio telescopes were inaugurated in Medicina and Noto (Siracusa) respectively in 1983 and 1988. They were subsequently used for observations up to 23 GHz (43 GHz for Noto) both in single dish mode and as participants in interferometric experiments within European and worldwide networks. Apart from constant upgrades at the two antennas, no other major infrastructure was built for 25 years, although smaller antennas were installed by the Trieste Astronomical Observatory for solar observations as an ante litteram Space Weather monitor.

It was in 2013, after the establishment of the National Institute for Astrophysics (INAF) in the early years of 2000, that the original idea to have a network of three Italian large radio telescopes was successfully completed, thanks to the advent of the Sardinia Radio Telescope (SRT) (Figure16(b)). This fully-steerable, wheel-and-track dish, 64 m in diameter, was designed to operate in the frequency range from 300 MHz to 100 GHz and beyond [94]. A significant contribution to the SRT project was made by Prof. G. Tofani [95] and Dr. R. Ambrosini who have chaired the Italian URSI Committee Commission J since its establishment until 2014 (see Figure 7).

The Italian reflector antennas are flexible instruments able to contribute to different branches of astrophysical research: compact objects, spectral lines of molecules associated with star formation, radio galaxies, interstellar masers, pulsars and much more. Furthermore, INAF envisages using SRT, Medicina, and Noto single-dish radio telescopes for solar radio imaging in the K band and above for Solar Radio Weather monitoring [96]. Recently, the 20-million-euro PON project entitled "Enhancement of the SRT for the study of the Universe at high radio frequencies" was funded and it will fully exploit the technical characteristics of SRT up to 100 GHz.

Besides national projects, INAF is currently involved in the development of the next generation of radio-astronomy infrastructures such as the Atacama Large Millimeter Array (ALMA), now hosting one of its Regional Centres in Bologna, and the Square Kilometer Array (SKA) project, with the Italian team presently taking part in the design of different elements that will constitute the final radio telescope. In particular, it is worthwhile mentioning how much the experience gathered in developing and operating the Northern Cross has contributed to forming a technical team who is now playing a primary role in the Low Frequency Aperture Array (LFAA) system of SKA [97].

In recent years, the Medicina observatory has participated in a wider range of projects, such as LOFAR (LOw Frequency ARray) with one station planned to be installed there. In line with this renovation phase, the Northern Cross, now 55 years old, is beginning a second life as ESA has funded a partial re-engineering of the instrument to join the European Space Surveillance and Tracking (EUSST) network for monitoring space debris.

3.10 Commission K: Electromagnetics in Biology and Medicine

Commission K is the youngest among URSI Commissions, as it was created during the Prague XXIII GA, in 1990 [98], due to the increasing interest and activities in the field of bioelectromagnetics. Since the beginning, the interdisciplinary character and the cooperation with other international organizations were particular attributes of this Commission.

The Italian national Commission K inherits similar features, promoting research on the biological effects of electromagnetic (EM) fields and waves, and their uses in diagnostic and therapeutic medicine. In particular, it has always cooperated with international organizations, such as EU COST Actions, the European Bio-Electromagnetics Association (EBEA), the Bioelectromagnetics Society (BEMS), the European Association of Antennas and Propagation (EurAAP), and was strongly involved in the European Framework Programs since the late 90's. At a national level, the close interaction with the national Inter-university Research Center for Interactions between Electro-magnetic Fields and Biosystem (ICEmB) is worth mentioning since researchers of this community have played important roles as member of the International Commission on Non-Ionizing Radiation Protection (ICNIRP), as part of the Electromagnetic Field project of the World Health Organization (WHO) and as external experts of the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR). Moreover, the national Commission contributed to URSI with two Chairs of the International Commission K, Paolo Bernardi (1993-1996), who was one of the promoters of the Commission itself, and Guglielmo D'Inzeo (2008-2011).

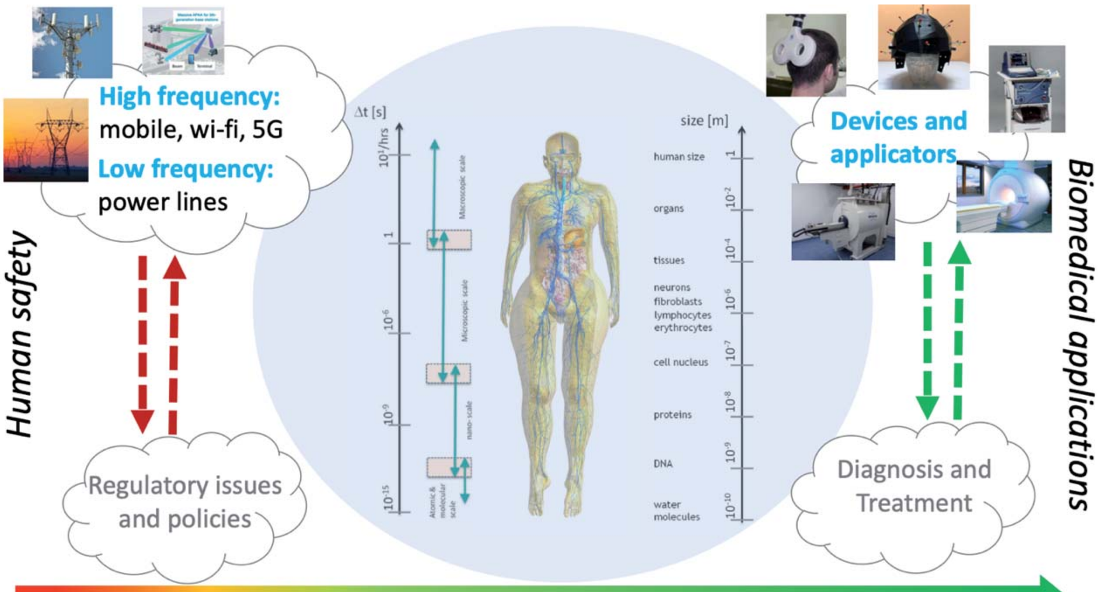


Figure 17. Schematics of a multiscale approach to the study of the interaction of electromagnetic fields and human systems either for safety assessment or for biomedical applications.

Figure 18. Logo of the URSI GASS 2020 showing the skyline of some of the main monuments in Rome.

During the first years, the national Commission K had a central role on the risk assessment for wireless communication, reinforcing a unique body of knowledge on the mechanisms of interaction [99], exploring the plethora of induced biological effects [100-102], developing advanced computational methodologies and dosimetric modeling [103], defining guidelines and regulatory limits [104], and exploiting more and more accurate measurement techniques [105, 106]. Notably, the outcomes of these research activities nowadays provide important milestones to face the challenges posed by the upcoming introduction of the 5G technology.

In subsequent years, the activities were focused on methodological approaches towards the multiscale-problem underlying the interaction of EM fields and human living systems. Whatever the source of the field (either coming from communications systems or from devices for biomedical applications) the interaction problem involves processes with length scales ranging from molecules to the whole organism, and with time scales going from tens of nanoseconds for ionic transport to many years of the human life (Figure 17). Therefore, a single mathematical model cannot describe such a variety of processes covering a factor of 10^9 in the spatial scale and 10^{17} in the timescale [107]. A suitable solution is the development of a hierarchy of models valid in a limited range of spatial and temporal scales and linked together through suitable parameters.

More recently, a huge effort was addressed to develop innovative medical devices, which exploit known mechanisms of EM field interaction the with the human body to achieve a therapeutic goal, guide a treatment, or diagnose a disease. Interestingly, as these aspects involve the same EM technologies, their study can lead to a novel generation of theragnostic devices. In this respect, researchers of national Commission K have developed ad-hoc approaches for the design of imaging systems [108], EM sensors [109], and smart nano-systems [110], as well as for the accurate characterization of the electromagnetic properties of human tissue [111, 112]. As far as therapeutic applications are concerned, the activities of the national Commission K are related to electroporation and electrochemotherapy [113], electrical and magnetic stimulation of the nervous system [114, 115], applications of pulsed EM fields (PEMFs) for acute ischemia stroke [116] and for anti-inflammatory diseases [117], microwave hyperthermia [118] and thermal ablation therapies [119]. Whereas, the diagnostic applications include microwave imaging for diagnosis of brain strokes [120], breast cancer [121], contrast enhanced microwave imaging for early stage tumour diagnosis [122], microwave imaging for treatment monitoring [123], and electrical property tomography via magnetic resonance imaging for both treatment planning and diagnosis [124].

4. Conclusion

The previous sections provide, without any presumption of completeness, a mix of historical facts, past, present and future research activities, and prominent personalities to highlight the remarkable contribution, over the years, of Italian radio scientists towards the URSI mission. The Italian URSI Committee was recently awarded the honour of hosting the coming URSI General Assembly and Scientific Symposium (GASS). This will be the third URSI GASS organized on the Italian territory and furthermore will coincide with the centenary anniversary of the establishment of URSI. Indeed, the

XXXIII GASS will take place in the prestigious Sapienza University Campus in Rome from August 29 to September 5, 2020 (see Figure 18). It is expected that URSI GASS 2020, in the Eternal City, will enjoy great success with outstanding participation by top-level researchers from all over the world. The guiding theme of the GASS2020, in Rome, will be centred on 100 years of Radio Science, with exhibitors, stand, movies, and panels dedicated to radio-frequency electromagnetic propagation and related applications. The Italian URSI Committee is looking forward to welcoming you in the Eternal City for this unmissable appointment. Please refer to the GASS 2020 website for further details: https://www.ursi2020.org/. [Note: Since this was written, GASS2020 was postponed until 2021, to be held in the same location at approximately the same dates in 2021.]

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Japan National Committee of URSI

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1. The Science Council of Japan and URSI

Kazuya Kobayashi and Satoshi Yagitani

In January 1949, the Science Council of Japan (SCJ) was founded, as a special organization of the Cabinet Office to represent the country's scientists both domestically and internationally, under the jurisdiction of the Prime Minister. Its role is to deliberate on and realize important science matters independently from the government, promote communication of scientific research, and improve its efficiency.

SCJ consists of 210 Council Members and some 2,000 Members, elected as representatives of the approximately 850,000 scientists nationwide. It conducts activities from a universal perspective and a comprehensive and multifaceted point of view, taking advantage of the fact that it is comprised of scientists from a broad-range of fields spanning over humanities and social sciences, life sciences, and physical sciences and engineering. SCJ's key activities are the following:

- Direct recommendations of opinions by Japanese scientists to the government and society.
- Contribute to academic promotion in local communities and enhancement of academic societies.
- Deepen mutual understanding of science through dialogue with civil society.
- Promote international academic exchanges as a leading science academy in Japan.

The SCJ organization comprises a General Assembly, three sections (Section I: Humanities and Social Sciences; Section II: Life Sciences; Section III: Physical Sciences and Engineering), an Executive Board, Administrative Committees for Operation, 30 Specialty Committees (depending on the categorization into 30 academic disciplines), and issue centered committees, and auxiliary committees. The details of the organization of SCJ are depicted in Figure 1.

One of the 30 Specialty Committees is the Specialty Committee on Electrical and Electronic Engineering, to which the Japan National Committee of URSI (JNC-URSI) belongs, [1, 2].

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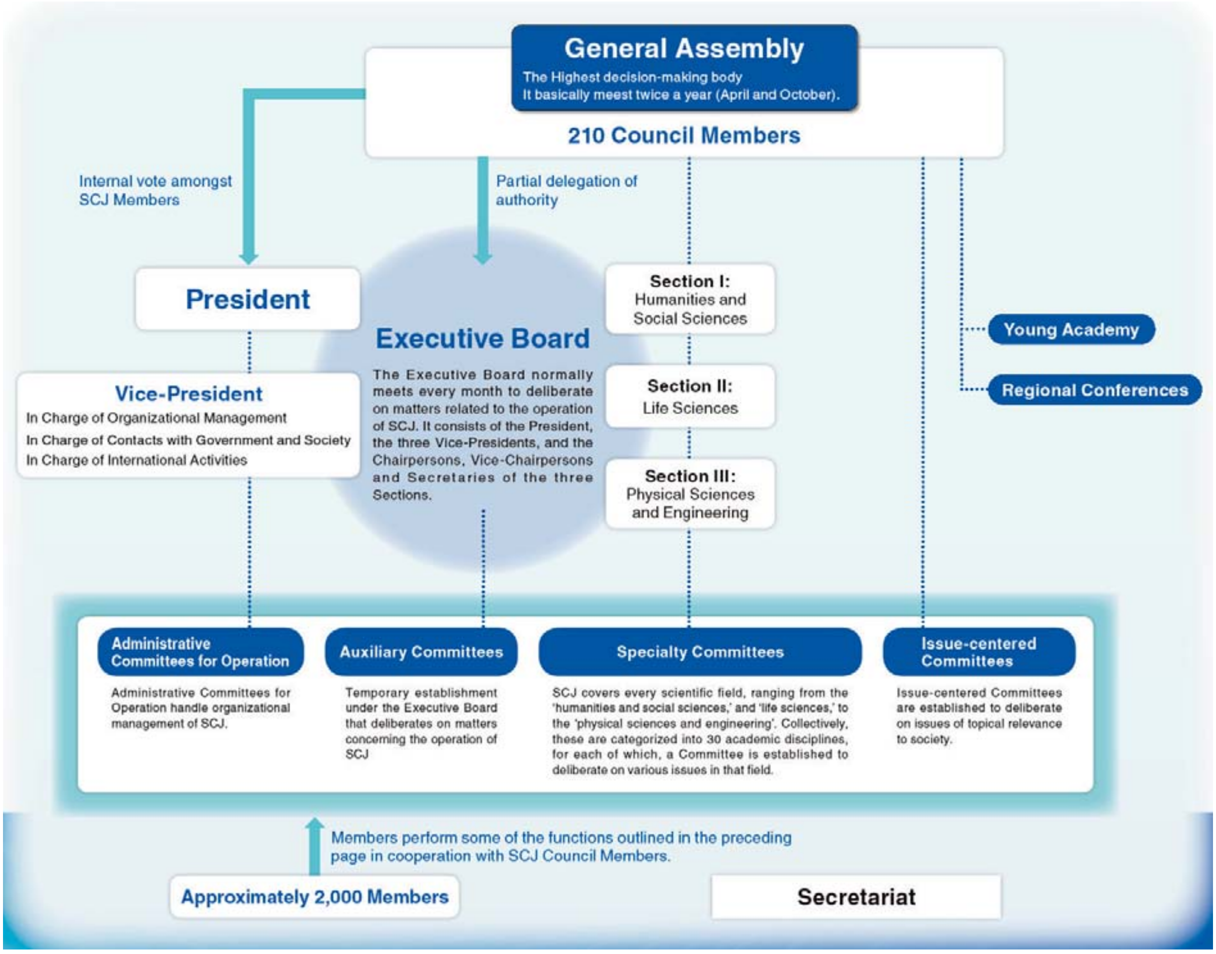

The Highest decision-making body
It basically meest twice a year (April and October).

The Executive Board normally meets every month to deliberate on matters related to the operation of SCJ. It consists of the President, the three Vice-Presidents, and the Chairpersons, Vice-Chairpersons and Secretaries of the three Sections.

Administrative Committees for Operation handle organizational management of SCJ.

Temporary establishment under the Executive Board that deliberates on matters concerning the operation of SCJ

SCJ covers every scientific field, ranging from the 'humanities and social sciences,' and 'life sciences,' to the 'physical sciences and engineering'. Collectively, these are categorized into 30 academic disciplines, for each of which, a Committee is established to deliberate on various issues in that field.

Issue-centered Committees are established to deliberate on issues of topical relevance to society.

Members perform some of the functions outlined in the preceding page in cooperation with SCJ Council Members.

Figure 1. The organization of the Science Council of Japan (SCJ).

2. Japan National Committee of URSI

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After URSI's foundation in 1919, the first URSI General Assembly (GA) was held in July 1922 in Brussels, Belgium. By this time four URSI Member Committees had been officially formed in Belgium, France, United Kingdom, and USA. In 1922 a further five URSI Member Committees adhered to URSI being Australia, Spain, Italy, Japan, and the Netherlands, [1].

The Japanese National Committee of URSI (JNC-URSI) was officially established in 1922 and when the second URSI GA was held in October 1927 in Washington, D.C., USA, Japan contributed for the first time with Dr. Tsutomu Minohara, Dr. Eitaro Yokoyama, Dr. Toyokichi Nakagami, and Dr. Sannosuke Inada attending as the official delegates [2].

Radio science research and related URSI activities in Japan are conducted under the leadership of JNC-URSI, which currently consists of about 200 official members nationwide. As a consequence of its importance it was placed under the supervision of the Science Council of Japan (SCJ) in 1949 when SCJ was founded by the Government of Japan. Since 1993, when the XXIVth URSI General Assembly was held in Kyoto, Japan, JNC-URSI has also adhered to The Institute of Electronics, Information and Communication Engineers (IEICE).

Table 1. Presidents, Secretaries, and Assistant Secretaries of the Japan National Committee of URSI (1949 to present).

SCJ-term	Period	President Secretary Assistant Secretary	SCJ-term	Period	President Secretary Assistant Secretaries
1st Term	1949-1951	Yusuke Hagihara	14th Term	1988-1991	Takanori Okoshi
		---			Tomohiro Oguchi Masato Ishiguro Nobuo Matuura
		---			---
2nd Term	1951-1954	Yusuke Hagihara	15th Term	1991-1994	Saburo Adachi
		Takeshi Nagata Toshihusa Sakamoto Takeo Hatanaka			Matsuichi Yamada Tomohiro Oguchi Tasuku Teshirogi
		---			---
3rd Term	1954-1957	Yusuke Hagihara	16th Term	1994-1997	Yoji Furuhama
		Toshihusa Sakamoto Takeo Seki			Yoshio Hosoya Tasuku Teshirogi Isamu Nagano
		---			---
4th Term	1957-1960	Issac Koga	17th Term	1997-2000	Yoji Furuhama
		Takeo Hatanaka Toshihusa Sakamoto Takeo Seki			Yoshio Hosoya Kazuo Sakai Masao Taki
		---			---
5th Term	1960-1963	Issac Koga	18th Term	2000-2003	Hiroshi Matsumoto
		Takeo Hatanaka Yuichiro Aono Hisanao Hatakeyama Sogo Okamura			Yoshio Hosoya Masao Taki Kazuya Kobayashi
		---			---
6th Term	1963-1966	Atsushi Kimpara	19th Term	2003-2005	Hiroshi Matsumoto
		Yuichiro Aono Sogo Okamura Masashi Miyaji Yasuo Taki			Yoshiharu Omura Masao Taki Kazuya Kobayashi
		---			---
7th Term	1966-1969	Atsushi Kimpara	20th Term	2005-2008	Hiroshi Matsumoto
		Mochinori Goto Hideo Hirose Sogo Okamura Yasuo Taki Tatsuzo Obayashi			Kazuya Kobayashi
		---			Masao Taki Yoshiharu Omura
8th Term	1969-1972	Atsushi Kimpara	21st Term	2008-2011	Kazuya Kobayashi
		Mochinori Goto Hideo Hirose Sogo Okamura Yasuo Taki Tatsuzo Obayashi			Tsuneki Yamasaki
		---			Jun-ichi Takada Satoshi Yagitani
9th Term	1972-1975	Atsushi Kimpara	22nd Term	2011-2014	Kazuya Kobayashi
		Masahide Kamiyama Yoshihide Kozai Tatsuzo Obayashi Yasuo Taki			Satoshi Yagitani
		---			Jun-ichi Takada Tsuneki Yamasaki
10th Term	1975-1978	Atsushi Kimpara	23rd Term	2014-2017	Kazuya Kobayashi
		Kenji Akabane Tatsuzo Obayashi Bunichi Oguchi Yoshihide Kozai			Satoshi Yagitani
		---			Jun-ichi Takada Tsuneki Yamasaki
11th Term	1978-1981	Sogo Okamura	24th Term	2017-2020	Satoshi Yagitani
		Kenji Akabane Takanori Okoshi Masaya Yamauchi Shigeru Yumi Hiroshi Yokoi			Shinichiro Ohnuki
		---			Yasuhide Hobara Keigo Ishisaka
12th Term	1981-1985	Haruo Tanaka	25th Term	2020-2023	Satoshi Yagitani
		Takanori Okoshi Tomohiro Oguchi Yoshihide Kozai Masaki Morimoto Hisayoshi Yanai			*(to be elected)*
		---			*(to be elected)*
13th Term	1985-1988	Takanori Okoshi			
		Nobuo Matuura Masaki Morimoto Yukio Hayakawa			

Table 2. Present URSI Officials elected from Japan.

Period	Name	Position
Board of Officers		
2017-present	Makoto Ando	President
Secretariat		
2015-present	Kazuya Kobayashi	Assistant Secretary-General (AP-RASC)
Commission Officers (Chairs, Vice-Chairs, Early Career Representatives)		
2014-present	Yasuhiro Koyama	Chair, Commission A
2017-present	Kazuya Kobayashi	Chair, Commission B
2017-present	Naoki Shinohara	Vice-Chair, Commission D
2017-present	Koichi Ito	Vice-Chair, Commission K
2017-present	Motoharu Sasaki	ECR, Commission F
2017-present	Kensuke Sasaki	ECR, Commission K
Standing Committees		
2017-present	Makoto Ando	Member, Standing Committee on Publications
2015-present	Kazuya Kobayashi	Chair, AP-RASC Standing Committee
2015-present	Makoto Ando	Member, AP-RASC Standing Committee
2018-present	Satoshi Yagitani	Member, AP-RASC Standing Committee
2017-present	Makoto Ando	Member, Standing Committee on Member Committees

JNC-URSI has made significant contributions to various URSI activities since it was established in 1922. In addition to the research and developments Japan has also contributed to URSI management. In particular Japanese scientists, have and are currently serving, as URSI Officials including Honorary President, President, Vice-President, Assistant Secretary-General, Chairs and Vice-Chairs of Commissions, and members of several Standing Committees.

JNC-URSI is a standing committee of SCJ, but this is reviewed and approved by the SCJ Executive Board at the beginning of each SCJ term. SCJ is now in its 25th term (three years from October 1, 2020 to September 30, 2023), and the JNC-URSI's purpose and agenda are currently:

Purpose of installation

The JNC-URSI is installed under the Special Committee of Electrical and Electronic Engineering in SCJ Section III, for the purpose that, on behalf of researchers and engineers in the field of radio science in Japan, JNC-URSI actively participates in various activities conducted by the URSI Headquarters, contributes to international collaboration on radio science, and promotes and strengthens radio-science-related activities in Japan.

Agenda items

JNC-URSI deliberates on the following items and takes the necessary actions:
i) Collaboration with the URSI Headquarters from various aspects.
ii) Promotion and strengthening of domestic radio-science-related activities.
iii) Preparation and operation of the XXXVth URSI General Assembly and Scientific Symposium to be held in August 2023 in Sapporo.

A list of Presidents, Secretaries, and Assistant Secretaries of the JNC-URSI from the 1st to 25th SCJ-terms is provided in Table 1. A list of Japanese URSI Officials are shown in Tables 2 and 3.

Table 3. Past URSI Officials elected from Japan.

Period	Name	Position
Honorary Presidents		
1981-1983	Issac Koga	Honorary President
	Presidents	
1999-2002	Hiroshi Matsumoto	President
1963-1966	Issac Koga	President
Vice-Presidents		
2011-2017	Makoto Ando	Vice-President
1995-1999	Hiroshi Matsumoto	Vice-President
1990-1994	Takanori Okoshi	Vice-President
1981-1987	Sogo Okamura	Vice-President
1957-1962	Issac Koga	Vice-President
1928-1946	Hantaro Nagaoka	Vice-President
Chairs of Commissions		
2011-2014	Masao Taki	Chair, Commission K
2008-2011	Takashi Ohira	Chair, Commission C
2008-2011	Yoshiharu Omura	Chair, Commission H
2002-2005	Makoto Ando	Chair, Commission B
2002-2005	Masami Akaike	Chair, Commission C
2002-2005	Makoto Inoue	Chair, Commission J
1999-2002	Yoji Furuhama	Chair, Commission F
1999-2002	Shoogo Ueno	Chair, Commission K
1996-1999	Masashi Hayakawa	Chair, Commission E
1987-1989	Takanori Okoshi	Chair, Commission D
1987-1989	Hiroshi Kikuchi	Chair, Commission E
1987-1989	Hiroshi Matsumoto	Chair, Commission H
1978-1980	Sogo Okamura	Chair, Commission A
1978-1980	Haruo Tanaka	Chair, Commission J

2.1 References

1. URSI History: URSI origins, http://www.ursi.org/ursi_history.php#tab-origins.
2. I. Koga, "On Forthcoming General Assembly of URSI," *The Journal of the Institute of Electrical Communication Engineers of Japan*, **46**, 1, January 1963, pp. 1-10 (in Japanese).

3. URSI Conferences Held in Japan

Kazuya Kobayashi and Satoshi Yagitani

3.1 URSI General Assemblies

The URSI General Assembly (GA) and subsequently URSI General Assembly and Scientific Symposium (GASS) have been held at intervals of three years to review current research trends, present new discoveries, and make plans for the future research and special projects in all areas of radio science. The URSI GA has been held twice in Japan. The first was the 14th GA held in Tokyo in 1963 and the second was the 24th GA held in Kyoto in 1993. The 35th GA is planned to be held again in Japan in 2023 (30 years after the Kyoto GA), and its venue city will be Sapporo [1]. The GAs held in the past are listed on the URSI website [2].

The XIVth (14th) GA was held September 9-20, 1963 in the Shinagawa Prince Hotel, Tokyo, [3, 4]. Table 4 shows the number of delegates in terms of URSI Member Committees, totaling 477. Table 5 shows the number of participants per participant category. As seen from this table, the grand total of participants including all the categories was 841. The number of URSI Member Committees was 28 before the 1963 GA (see the list of URSI Member Committees in Table 4), but this increased to 32 as a result of approved membership applications from Argentina, Ghana, Kenya, and China CIE.

Table 4. The number of delegates per URSI Member Committee at GA 1963 in Tokyo.

URSI Member Committee	Number of delegates
Australia	10
Austria	0
Belgium	4
Canada	12
Czechoslovakia	1
Denmark	1
Finland	1
France	39
Germany	15
Greece	1
India	3
Italy	11
Japan	166
Morocco	0
Netherlands	6
New Zealand	2
Norway	1
Peru	1
Poland	1
Portugal	0
Spain	1
Sweden	11
Switzerland	3
South Africa	3
United Kingdom	18
USA	144
USSR	21
Yugoslavia	1
TOTAL	**477**

Table 5. The number of participants per participant category at GA 1963 in Tokyo.

Participant category	Overseas	Japan
Delegate	311	166
Guest observer	4	8
Observer appointed by LOC Japan	0	189
Accompanying person	103	60
Subtotal	418	423
Grand Total	**841**	

Table 6. The numbers of submitted, accepted, and presented papers per Commission at GA 1993 in Kyoto.

Commission	Submitted	Accepted	Presented
A	64	62	62
B	262	150	143
C	145	128	127
D	112	93	91
E	132	103	102
F	132	116	111
G	224	209	207
H	249	248	245
J	145	143	139
K	117	88	87
YS	18	18	17
TOTAL	**1600**	**1358**	**1331**

Table 7. The number of registrants per country/region at GA 1993 in Kyoto. The numbers in parentheses denote the number of registrants who did not show up onsite.

Country/region	Regular	Student	Subtotal	Accompanying persons	Total
ARGENTINA	1	1	2	1	3
AUSTRALIA	25	3	28	5	33
AUSTRIA	2	1	3	0	3
BELARUS	0	1	1	0	1
BELGIUM	15	3	18	1	19
BRAZIL	5	0	5	1	6
BULGARIA	2	2	4	0	4
CANADA	22	2	24	3	27
CHINA-CIE(BEIJING)	13	11(1)	24(1)	0	24(1)
CHINA-SRS(TAIPEI)	6	3	9	2	11
CYPRUS	0	1	1	0	1
CZECH REP.	2	3	5	0	5
DENMARK	8	2	10	0	10
EGYPT	3	1	4	0	4
FINLAND	6	2	8	1	9
FRANCE	62	7(1)	69(1)	8	77(1)
GERMANY	46(2)	7	53(2)	6	59(2)
GREECE	2	1	3	0	3
HON GKONG	1	2	3	0	3
HUNGARY	5	2	7	0	7
INDIA	6	7	13	0	13
IRELAND	1	1	2	0	2
ISRAEL	10	0	10	2	12
ITALY	31	1	32	8	40
JAPAN	395(4)	85(1)	480(5)	7	487(5)
MALAYSIA	1	1	2	0	2
NETHERLANDS	14	2	16	0	16
NEW ZEALAND	4	0	4	0	4
NIGERIA	1	2(1)	3(1)	0	3(1)
NORWAY	7(1)	2	9(1)	0	9(1)
PERU	1	0	1	0	1
POLAND	6	1	7	0	7
PORTUGAL	1	0	1	0	1
RUSSIA	31	18	49	1	50
SINGAPORE	0	2	2	0	2
SOUTH AFRICA	5	1	6	2	8
SPAIN	2	2	4	0	4
SRILNKA	0	1	1	0	1
SWEDEN	33	1	34	6	40
SWITZERLAND	5	1	6	1	7
THAILAND	2	0	2	0	2
TURKEY	4	1	5	0	5
UK	43	3	46	13	59
UKRAINE	1	5	6	0	6
USA	207(1)	11	218(1)	43	261(1)
UZBEKISTAN	0	1	1	0	1
GRAND TOTAL	1037	204	1241	111	1352

The XXIVth (24th) GA was held August 23-September 3, 1993 at the Kyoto International Conference Center, Kyoto [5, 6]. The numbers of submitted, accepted, and presented papers were 1600, 1358, and 1331, respectively. The detailed paper submission statistics in terms of Commissions are provided in Table 6. The total number of registrants was 1241 (regular: 1037, student: 204). In addition, a total of 113 students were selected as recipients of the Young Scientist Award (YSA), from among 204 applicants. The detailed registration statistics are provided in Table 7.

Figure 2. The Sapporo Convention Center (GASS 2023 venue).

The XXXVth (35th) GASS will be held August 19-26, 2023 at the Sapporo Convention Center, Sapporo (see Figure 2), https://www.sora-scc.jp/eng/.

Sapporo is the fifth largest city in Japan by population, and the largest city of the northernmost Hokkaido Prefecture. Sapporo is particularly known outside Japan for having hosted the 1972 Winter Olympics, the first ever held in Asia. Annually, over 13 million tourists visit Sapporo from other parts of Japan and abroad. According to TripAdvisor's 2013 World's Top 10 Destinations on the Rise rankings, Sapporo is second in Asia and seventh worldwide. Meanwhile, Hokkaido was named the Best in Asia in 2017 by Lonely Planet. Summers in Sapporo are generally warm but importantly not humid, and are very comfortable. The average high/low temperatures in Sapporo in July and August are 24.9 °C/17.3 °C and 26.4

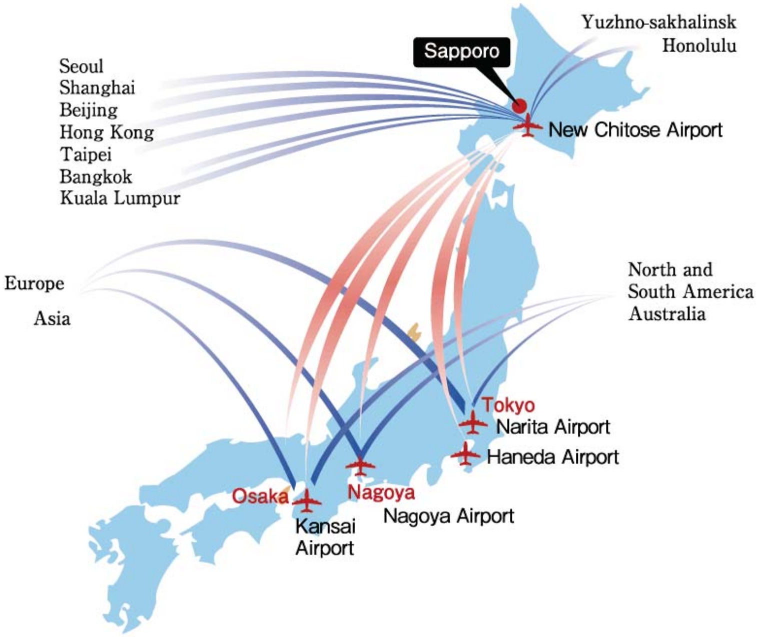

Figure 3. Flight connections to Sapporo.

°C/19.1 °C, respectively. The Sapporo area is served by one of the busiest airports in Japan – New Chitose Airport, which can be easily reached directly from major cities in Asia. New Chitose Airport also provides over 70 flights connecting to Tokyo/Narita and Tokyo/Haneda. The Sapporo New Chitose – Tokyo Haneda route has been the busiest air route in the world since 2006, with more than 10 million passengers carried per year (see Figure 3 for flight connections to Sapporo). Various useful information on travel to Japan and to Sapporo is available on the websites of the Japan National Tourism Organization (JNTO) [7] and the City of Sapporo [8].

JNC-URSI has appointed Convention Linkage, Inc. http://www.c-linkage.co.jp/en/ as the professional conference organizer (PCO). We have also set up the GASS 2023 Preparation Committee, and started to make various local arrangements. It is expected that all the Committees for running GASS 2023 will be formed by October 2021.

3.2 URSI Asia-Pacific Radio Science Conferences

The JNC-URSI has made significant contributions to regional URSI activities in the Asia-Pacific area. One of the JNC-URSI's most important activities is the organization of the Asia-Pacific Radio Science Conference (AP-RASC) which is held every three years. Like other URSI meetings, the objective of AP-RASC is to review current research trends, present new discoveries, and make plans for future research and special projects in all areas of radio science, especially where international cooperation is desirable. A particular emphasis was initially placed on promoting various URSI activities in the Asia-Pacific area.

Figure 4. The AP-RASC 2010 Opening Ceremony. Top (from left): K. Kobayashi, AP-RASC 2010 General Chair; F. Lefeuvre, President of URSI; T. Ishii, Governor of Toyama Prefecture; H. Matsumoto, Past President of URSI. Middle: Venue of Opening Ceremony. Bottom (from left): K. Kobayashi, AP-RASC 2010 Conference Chair; H. Matsumoto, Past President of URSI; T. Ishii, Governor of Toyama Prefecture; E. Takami, Interpreter; P. Lagasse, Secretary-General of URSI; P. Wilkinson, Vice-President of URSI; F. Lefeuvre, President of URSI.

Figure 5. The Young Scientist Reception (SPC finalists and YSA recipients were invited to join).

Figure 6. The welcome address, conference dinner, and special entertainment at the AP-RASC 2010 Banquet. Top (from left): K. Kobayashi, AP-RASC 2010 General Chair; M. Mori, Mayor of Toyama City; P. Wilkinson, Vice-President of URSI; P. Lagasse, Secretary-General of URSI. Bottom (from left): Conference Dinner; Piano Performance by K. Kobayashi, AP-RASC 2010 General Chair.

Figure 7. The awards ceremony at the AP-RASC 2010 Banquet: (a) AP-RASC 2010 Student Paper Competition; (b) AP-RASC 2010 Young Scientist Award).

AP-RASC was established based on the initiatives of the JNC-URSI, and was held for the first time in Tokyo, Japan during August 1-4, 2001. It was a great success with 601 papers and 704 participants from 34 countries/regions [9]. The third AP-RASC (AP-RASC 2010) was held in Toyama, Japan on September 22-26, 2010; it was also successful, with 605 registered participants and 529 papers from 31 countries/regions [10]. Figures 4-7 show photographs taken at some of the conference events. The meeting had a very strong young scientist program consisting of the Student Paper Competition (SPC) and the Young Scientist Award (YSA), which had a great impact to the worldwide URSI community.

In 2016, AP-RASC was renamed as the URSI Asia-Pacific Radio Science Conference (URSI AP-RASC), and became an URSI Flagship Meeting. At present, there exist three URSI Flagship Meetings that include the URSI GASS, the URSI Atlantic Radio Science Conference (URSI AT-RASC), and URSI AP-RASC. Since URSI is currently involved in organization of the URSI AP-RASC from various aspects, the conference has been expanding and attracting more international participants. Data on the past AP-RASC conferences are shown in Table 8.

Table 8. Past AP-RASC Conferences.

Name of Conference	Dates	Venue	Statistics
(1st) AP-RASC 2001	August 1-4, 2001	Korakuen Campus, Chuo University, Tokyo, Japan	601 papers; 704 participants from 34 countries/regions
(2nd) AP-RASC 2004	August 24-27, 2004	Qingdao, China	not known
(3rd) AP-RASC 2010	September 22-26, 2010	Toyama International Conference Center, Toyama, Japan	566 papers; 605 registrants from 33 countries/regions
(4th) AP-RASC 2013	September 3-7, 2013	Howard International House, Taipei, Taiwan	618 papers; 576 registrants from 28 countries/regions
(5th) URSI AP-RASC 2016	August 21-25, 2016	Grand Hilton Seoul, Seoul, South Korea	687 papers; 789 registrants from 31 countries/regions
(6th) URSI AP-RASC 2019	March 9-15, 2019	India Habitat Centre, New Delhi, India	952 papers; 686 registrants from 31 countries/regions

3.3 URSI - Japan Radio Science Meetings

The URSI-JRSM, organized by JNC-URSI, provides a regional scientific forum for radio scientists and engineers in Japan and the Asian region with similar objectives to the international meetings. A particular emphasis is placed on enhancing the visibility of URSI in Asia and encouraging young scientists to contribute to various URSI activities. The URSI-JRSM covers a wide range of topics in radio science specified by the 10 URSI Commissions, A-K.

The first URSI-JRSM was held in Tokyo, Japan, on September 8, 2014 [14]. A one-day program was organized as plenary sessions with three keynote lectures and ten invited talks from the URSI Commissions A-K by outstanding researchers from Japan and Asia. The meeting was successful with 204 participants.

The second URSI-JRSM was also held in Tokyo, Japan on September 3-4, 2015 [15], where scientific sessions were composed of plenary sessions with two keynote lectures, two special lectures and ten invited talks, and a poster session of contributed papers. The meeting was successful with 132 participants, and 74 papers (14 oral and 60 poster) being presented. The Student Paper Competition (SPC) was organized for full-time university students in a degree program and was financially supported by URSI. Among a total of 13 applicants for the SPC, three finalists were selected and awarded the first, second and third prizes. The papers by the three SPC awardees were published in the Special Section on URSI-JRSM 2015 Student Paper Competition in the March 2016 issue of the Radio Science Bulletin (RSB) [16]. A total of 13 papers, consisting of nine papers based on the keynote lectures, special lectures and invited talks, and four papers based on poster presentations at URSI-JRSM 2015 were published in a Special Issue of the 2015 URSI-Japan Radio Science Meeting in Radio Science [17].

The third URSI-JRSM was again held in Tokyo, Japan on September 5-6, 2019 [18]. The scientific programs consisted of plenary sessions with one keynote lecture and ten invited lectures by the ten URSI Commissions. Oral and poster sessions were arranged by each Commission for invited and contributed papers, with a total of 75 oral and 78 poster presentations. A number of the topics in the oral sessions addressed the history and perspective of radio science research in Japan, on the centennial anniversary of URSI. The meeting was successful with a total of 232 scientists and engineers attending from three countries. A SPC was organized again and the papers by the three awardees (first, second and third prizes) among seven applicants were published in the URSI-JRSM 2019 Student Paper Competition Special Issue in the March 2020 issue of the RSB [19]. A collection of papers from URSI-JRSM 2019 are planned to be published in the Special Issue of the 2019 URSI-Japan Radio Science Meeting in Radio Science in 2021.

Figures 8-10 show some photos taken at URSI-JRSM 2014, 2015 and 2019, respectively.

Figure 8. The URSI-JRSM 2014 Opening Ceremony: (a) Welcome address by K. Kobayashi, URSI-JRSM 2014 General Chair. Keynote Lectures: (b) D. Guha, Commission B Chair, India National Committee of URSI; (c) L.-C. Lee, President, China (SRS) National Committee of URSI; (d) S. Ueno, Past Chair, URSI Commission K.

Figure 9. (a) Special Lecture by M. Ando, Vice-President, URSI, and (b) Poster Session, at URSI-JRSM 2015.

Figure 10. (a) Student Paper Competition, and (b) banquet at URSI-JRSM 2019.

3.4 References

1. Future URSI Meetings: GASS, http://www.ursi.org/events.php?gass=on.

2. List of General Assemblies, http://www.ursi.org/ursi_general_assemblies.php.

3. I. Koga, "On Forthcoming General Assembly of URSI," *The Journal of the Institute of Electrical Communication Engineers of Japan*, **46**, 1, January 1963, pp. 1-10 (in Japanese).

4. I. Koga, "Looking Back upon XIVth General Assembly of URSI," *The Journal of the Institute of Electrical Communication Engineers of Japan*, **47**, 1, January 1963, pp. 8-28 (in Japanese).

5. URSI GA 1993 Organizing Committee, *Report on the XXIVth URSI General Assembly*, January 1994 (in Japanese).

6. T. Okoshi and S. Adachi, "Report of the 24th General Assembly of the International Union of Radio Science (URSI)," *The Journal of the Institute of Electronics, Information and Communication Engineers*, **77**, 1, January 1994, pp. 36-41 (in Japanese).

7. Travel Japan - Japan National Tourism Organization (JNTO), https://www.japan.travel/en/us/.

8. Tourism Sapporo Global Site, http://www2.city.sapporo.jp/global/english/sightseeing/.

9. AP-RASC 2001 Final Program.
http://www.ursi.jp/assets/files/ap-rasc01/AP-RASC'01%20final%20program.pdf.

10. AP-RASC 2010 Homepage, http://www.ursi.jp/assets/files/ap-rasc10/index.html.

11. URSI-JRSM 2014 Homepage, http://www.ursi.jp/conference/jrsm2014/.

12. URSI-JRSM 2015 Homepage, http://www.ursi.jp/conference/jrsm2015/.

13. K. Kobayashi and S. Yagitani, "Introduction to the Special Section on URSI-JRSM 2015 Student Paper Competition," *The Radio Science Bulletin*, **356**, March 2016, pp. 11-12.

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16. K. Kobayashi and S. Yagitani, "Introduction to the Special Section on URSI-JRSM 2015 Student Paper Competition," *The Radio Science Bulletin*, **356**, March 2016, pp. 11-12.

17. K. Kobayashi and S. Yagitani, "Introduction to Special Issue of the 2015 URSI-Japan Radio Science Meeting," *Radio Science*, **52**, 4, March 2017, pp. 430-431.

18. URSI-JRSM 2019 homepage, http://www.ursi.jp/conference/jrsm2019/.

19. S. Yagitani and S. Ohnuki, "Introduction to the URSI-JRSM 2019 Student Paper Competition Special Issue," *The Radio Science Bulletin*, **372**, March 2020, pp. 10-11.

4. JNC-URSI Report

Satoshi Yagitani and Kazuya Kobayashi

An important activity of JNC-URSI is to publish the URSI National Report every three years on the occasion of the URSI GASS. This report provides an extensive summary of radio science research in Japan for the triennium between the two successive GASS. The National Reports published after 1993 are archived and available on the JNC-URSI website [1]. The JNC-URSI National Reports were distributed at the URSI General Assemblies (GA) in Kyoto, Japan (1993), Lille, France (1996), Toronto, Canada (1999), Maastricht, The Netherlands (2002), New Delhi, India (2005), and Chicago, USA (2008), and for the URSI GASS in Istanbul, Turkey (2011), Beijing, China (2014), and Montreal, Canada (2017).

4.1 References

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Table 9. Financial support for the YSA at GA/GASS.

Year	GA/GASS	Location	Amount of support (USD)
2002	27th GA	Maastricht, Netherlands	4,000
2005	28th GA	New Delhi, India	6,000
2008	29th GA	Chicago, Illinois, USA	6,000
2011	30th GASS	Istanbul, Turkey	6,000
2014	31st GASS	Beijing, China CIE	5,000
2017	32nd GASS	Montreal, Canada	2,000
2020/2021	33rd/34th GASS	Rome, Italy	2,000

5. Issac Koga Gold Medal

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Professor Issac Koga was born in Saga, Japan on December 5, 1899. He received the degrees of Bachelor of Engineering and Doctor of Engineering from Tokyo Imperial University (later renamed as the University of Tokyo) in 1923 and 1930, respectively. He joined the Electrotechnical Research Institute of Tokyo Municipality in 1923. In 1929 he became Associate Professor, and later Professor in the Electrical Engineering Department of the Tokyo University of Engineering (later renamed as Tokyo Institute of Technology). He moved to the Faculty of Engineering, Tokyo Imperial University in 1946, and served as the Dean of Engineering from 1958 to 1960. In 1960, he was granted the title of Professor Emeritus from The University of Tokyo and Tokyo Institute of Technology, and joined the Research Laboratories of Kokusai Denshin Denwa Co. (now KDDI Corporation). He passed away on September 2, 1982.

Figure 11. (a) Professor Issac Koga (1899-1982) and (b) his invention of a temperature-insensitive quartz oscillation plate.

Figure 12. Memorial stamp of URSI GA 1963 in Tokyo.

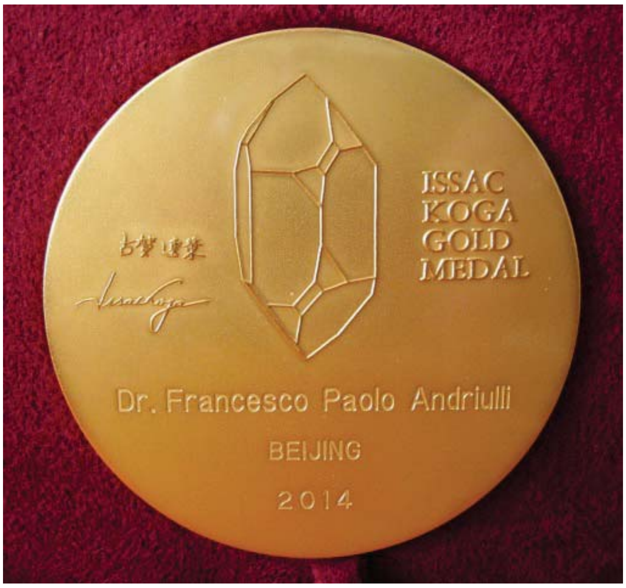


Figure 13. Issac Koga Gold Medal.

Professor Koga devoted himself to the research on frequency standards and piezoelectric crystals (Figure 11). The most famous of his inventions is a piezoelectric crystal unit with zero frequency temperature coefficient, which has been widely used for various applications. The IEEE milestone plaque presented to Tokyo Institute of Technology in 2017, states:

Invention of a Temperature-Insensitive Quartz Oscillation Plate, 1933
In April 1933, Issac Koga of the Tokyo Institute of Technology reported cutting angles that produced quartz crystal pates having a zero-temperature coefficient of frequency. These angles, 54° 45' and 137° 59', he named R_1 and R_2 cuts. Temperature-insensitive quartz crystals were used at first for radio transmitters and later for clocks, and have proven indispensable to all radio communication systems and much of information electronics.

Professor Koga became a member of URSI Commission I in 1934, and served as Vice-President of URSI from 1957 to 1963. He was elected President for the period 1963-1966, and remained a member of the Board as Past President until 1969. The title of Honorary President was conferred on him at the General Assembly in Washington, D.C. in 1981. When the 14th General Assembly of URSI was held in Tokyo in 1963, he was Chairman of the Organizing Committee, and it was thanks to his great efforts that this event is regarded as one of most successful General Assemblies in the history of URSI (Figure 12).

The Isaac Koga Gold Medal (Figure 13) was established in 1982 commemorating Professor Koga's long-time distinguished services to URSI. The Isaac Koga Gold Medal is awarded to a young scientist who has made an outstanding contribution to any of the branches of science covered by the URSI Commissions. Candidates must not be older than 35 on September 30 of the year preceding the URSI GASS. The award is for career achievements of the candidate with evidence of significant contributions within the most recent six-year period. The Issac Koga Gold Medal is presented by the Japan National Committee of URSI on the occasion of URSI GASS.

6. Contribution to the URSI Young Scientists Program

Tsuneki Yamasaki and Kazuya Kobayashi

The JNC-URSI understands that one of the key activities of URSI is to attract and encourage more young scientists to join various URSI events including GASS. Therefore, it has contributed to the funding of the Young Scientist Award (YSA) at every GA/GASS since 2002, starting when financial support from ICSU and UNESCO terminated. Japan's financial contribution to the YSA at the GASS is shown in Table 9.

7. Large Research Project Plan Selected by the Science Council of Japan

Kazuya Kobayashi and Satoshi Yagitani

SCJ has accepted a JNC-URSI proposal (as described below) to be part of the SCJ Master Plan 2020 on Large Research Projects [1]. It is one of 146 such projects, and although the result does not mean that the project is funded, the master plan serves as a pool of ideas for future research.

The radio spectrum use is administered by ITU in the form of Radio Regulations at the international level, and various services are allocated to the fragmented spectra. Coexistence conditions are described in its Recommendations. On the other hand, CISPR regulates unwanted radio emissions from electric/electronic equipment through standards. Both parties issue regulations and recommendations to facilitate coexistence, but negotiations are led by different stakeholders which results in inconsistent conditions and outcomes. For example, (1), digital communication systems are robust against the interference from other systems, but this is not necessarily considered within the coexistence criteria which were established in the analog era. (2), the number of new types of equipment with unwanted emission is increasing, but the inclusion of such sources into the standards lags behind. (3), passive services such as for radio astronomy or earth exploration are very sensitive and strong protection is needed, while subsurface radar or wireless power transfer requires high power.

The project plan is entitled, Regulatory science center for the harmonization and coexistence of scientific and commercial radio spectrum use (Figure 14). The goal of the project is to experimentally derive objective coexistence conditions among radio spectrum users for various applications including scientific use such as radio astronomy, earth exploration satellites and ground penetrating radar, and commercial use such as mobile communications and wireless power transfer. The JNC-URSI, research community will contribute to the studies. Regulatory science will be employed as a norm to determine the coexistence conditions among different usages by quantifying the risk and the benefit tradeoff, together with uncertainty and costs. The center will be equipped with test facilities so that experimental investigations are possible. The center will be run by a neutral institution such as a university, serving the national and international researchers and stakeholders.

7.1 References

1. “Recommendation: SCJ 24th-term Master Plan on Large Academic Research Projects (Master Plan 2020),” Subcommittee on Research Plan and Funding, Committee of Scientists, Science Council of Japan, January 2020 (in Japanese).

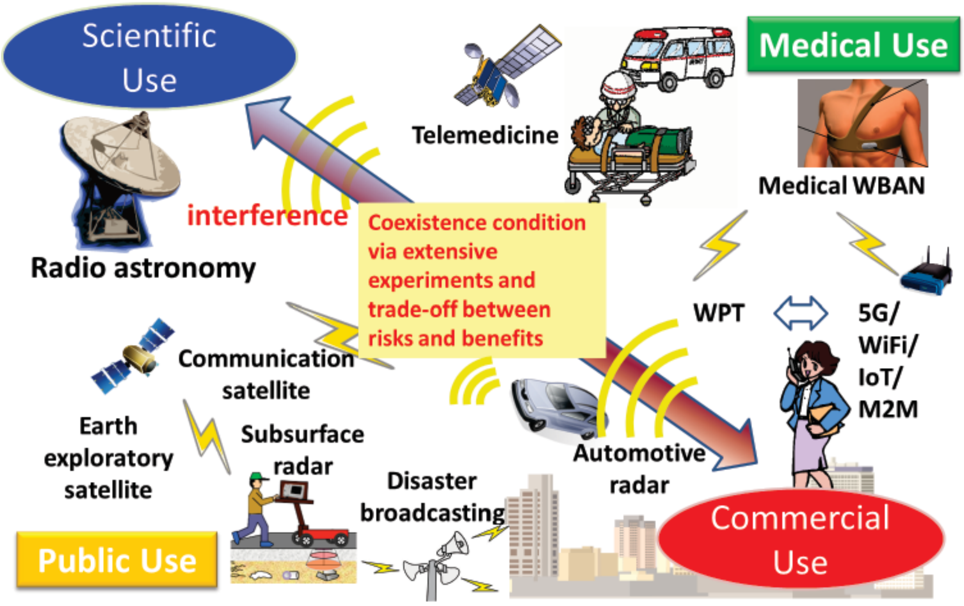


Figure 14. The regulatory science center for the harmonization and coexistence of scientific and commercial radio spectrum use.

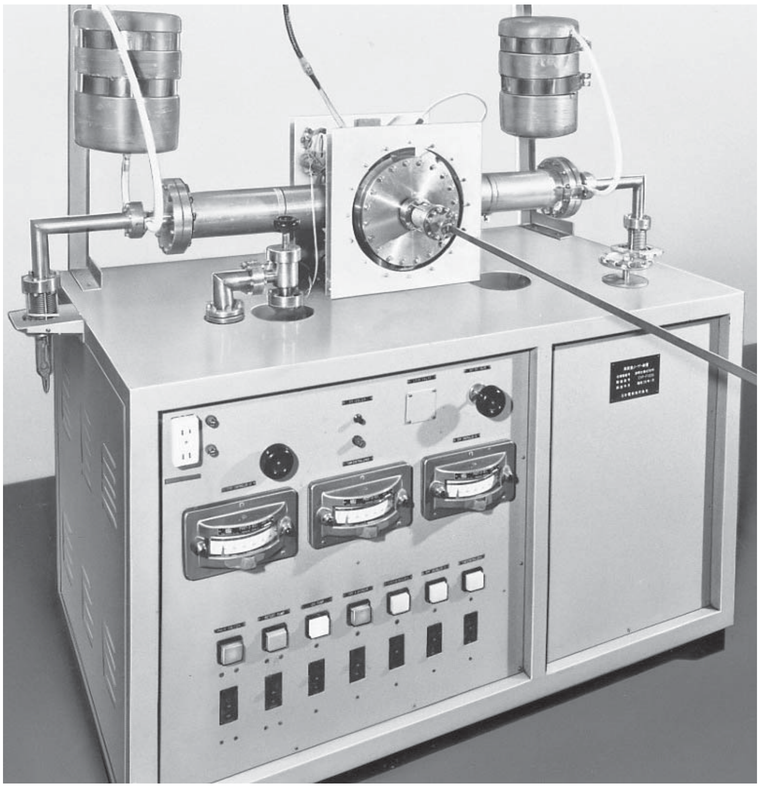
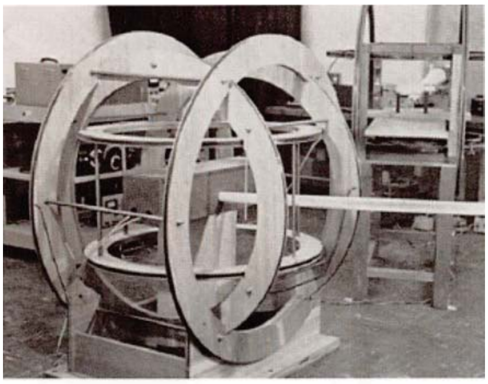


Figure 15. A double-beam type NH3 maser (3-2 line), which reached a stability of 1e-10 in 1960 [Section 8.1.1: 1].



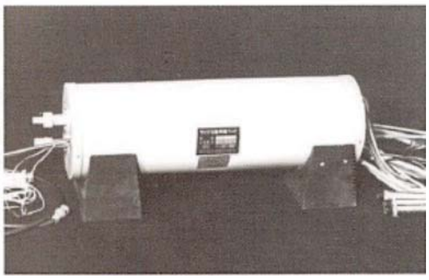


Figure 16. The gas cell-type atomic frequency standard (1963) [Section 8.1.1: 2]. Research work on an atomic frequency standard started at the NRLM with the aim of revising the definition of the second. The apparatus detects the microwave resonance frequency of the Rb atom by its change in transmitted light subjected to optical pumping.

8. Japanese URSI Commissions

8.1 Commission A

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Together with others, the institutes National Institute of Information and Communications Technology NICT1), National Institute of Advanced Industrial Science and Technology AIST2), Institute of Physical and Chemical Research RIKEN3), and the University of Tokyo4), Kyoto University, Tokyo Institute of Technology, Tokyo Metropolitan University, the University of Electro-Communications, and Yokohama National University have contributed to Commission A in Japan. The following lists a number of URSI Commission A events that have taken place in Japan. In this section, the superscripts assigned in the first sentence of this paragraph are used to identify the organization at which the work discussed was performed.

1920s. Finished comparing the meter bar with the Cd red-line wavelength standard2). First international frequency comparison between NICT and PTB with a light emitting quartz resonator by Loewe Radio Co. with a coincidence level of 1E-61).

1950s. Obtained a frequency reproducibility level of ±2E-10 using an ammonia (NH_3) maser (3-3 line) frequency standard, regulating the standard radio frequency1), (Figure 15).

Figure 17. The left and right systems are sequentially developed hydrogen masers. The center system is a compact hydrogen maser developed as an engineering model for a quasi-zenith satellite. This photo was taken in 1990 [Section 8.1.1: 1].

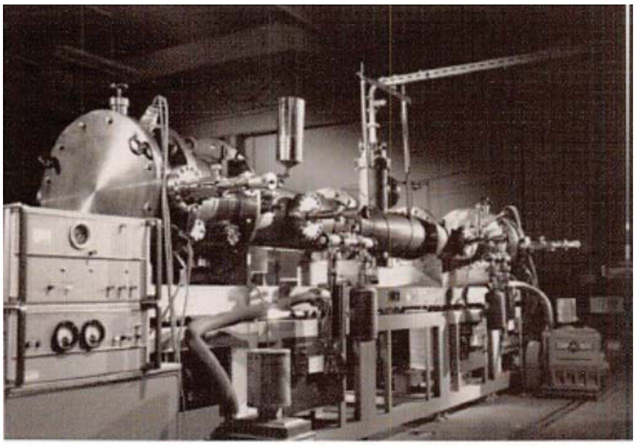

Figure 18. The cesium beam primary atomic frequency standard [Section 8.1.1: 2], the first frequency standard (NRLM-I) completed in Japan. It detects microwave resonance frequency by magnetic resonance.

1960s. First oscillation of a He-Ne gas laser in Japan[2)]. Started study in Rb gas cell FSs[2)], (Figure 16). World-third oscillation of the H-Maser after the US and Switzerland[1)], (Figure 17).

1970s. Started study on Cs beam FS[2)], (Figure 18). Started operation of the Cs beam FS (NRLM-I)[2)]. World-first two way satellite intercontinental time comparison between Kashima ground station and Rasman ground station of NASA via ATS-1 satellite, demonstrating the Sagnac effect with a 10 ns accuracy[1)]. Succeeded in two-way satellite time comparison using domestic communication satellite with a 1 ns precision[1)]. Started operation of Cs beam FS (NRLM-II)[2)], (Figure 19). Reported the measurement of hydrogen Rydberg constant[2)]. Developed a measuring device for amplitude probability distribution (APD) for electromagnetic noise[1)]. Design and construction of a 633-nm iodine (I_2) stabilized He-Ne laser based on the CIPM recommendation[2)].

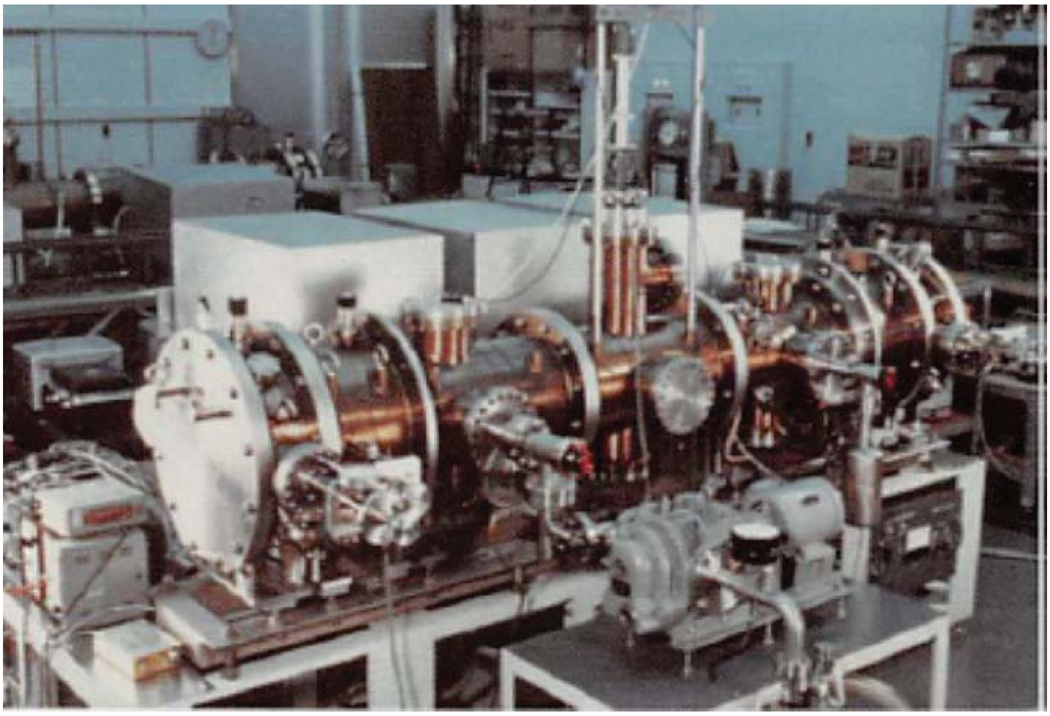

Figure 19. The cesium beam atomic frequency standard (NRLM-II) [Section 8.1.1: 2]. By improving on the results of the fundamental experiments on the NRLM-I, an accuracy of 2 × 10^{-13} was attained. A series of results were reported to the Consultative Committee on the Definition of the Second.

Figure 20. An interferometer for calibrating an optical distance meter (2001) [Section 8.1.1: 2]. This interferometer was installed in the tunnel for optical measurements (total length: 300 m) that was built on relocation to Tsukuba in 1979. It is an apparatus for direct calibration of an optical distance meter with the light wavelength standard as a reference using a 100 m traveling stage.

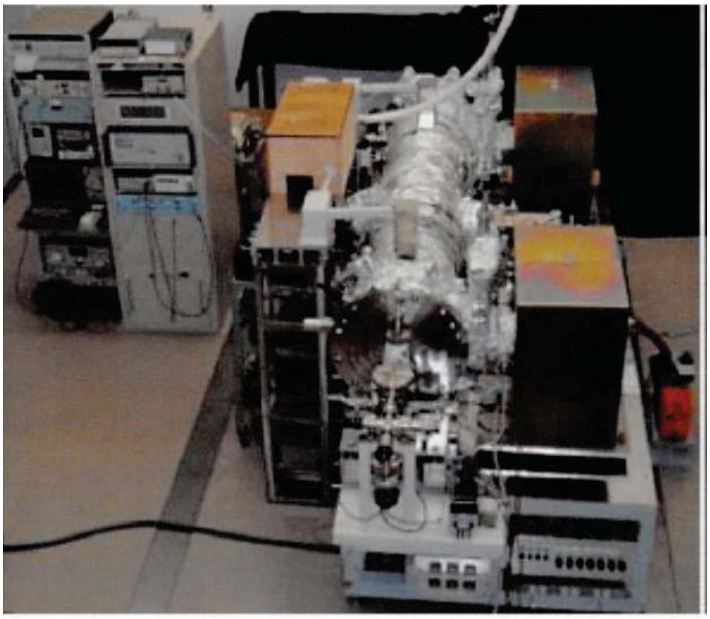

Figure 22. An optically pumped Cs frequency standard (NRLM-4) [Section 8.1.1: 2]. The selection of atomic state was by laser pumping, and the uncertainty of the standard frequency was 2.9 × 10^{-14}. It was compared with TAI almost monthly from 1997 to 1998.

1980s. Completed the optical tunnel facility$^{2)}$ (Figure 20). Started a Japan-US joint VLBI experiment, succeeded in measuring the motion of the Pacific plate for the first time ever$^{1)}$, (Figure 21). Completed the first domestic GPS receiver for time comparison and started international time comparison, contributing to the determination of TAI for the first time$^{1)}$. Started developing a neutral Ca optical FS$^{2)}$. Constructed an optical pumping Cs beam FS (NRLM-4)$^{2)}$ (Figure 22). Started study on Yb^+ ion trap for an optical FS$^{2)}$.

1990s. Developed a site validation method for measuring 30 to 1000 MHz interference (normalized site attenuation measurement method)$^{1)}$. Started research on radio wave safety$^{1)}$. Measurement method of specific absorption rate (SAR), calibration of probe for SAR measurement, human body model, etc$^{1)}$, (Figure 23). Reconstruction of antenna calibration

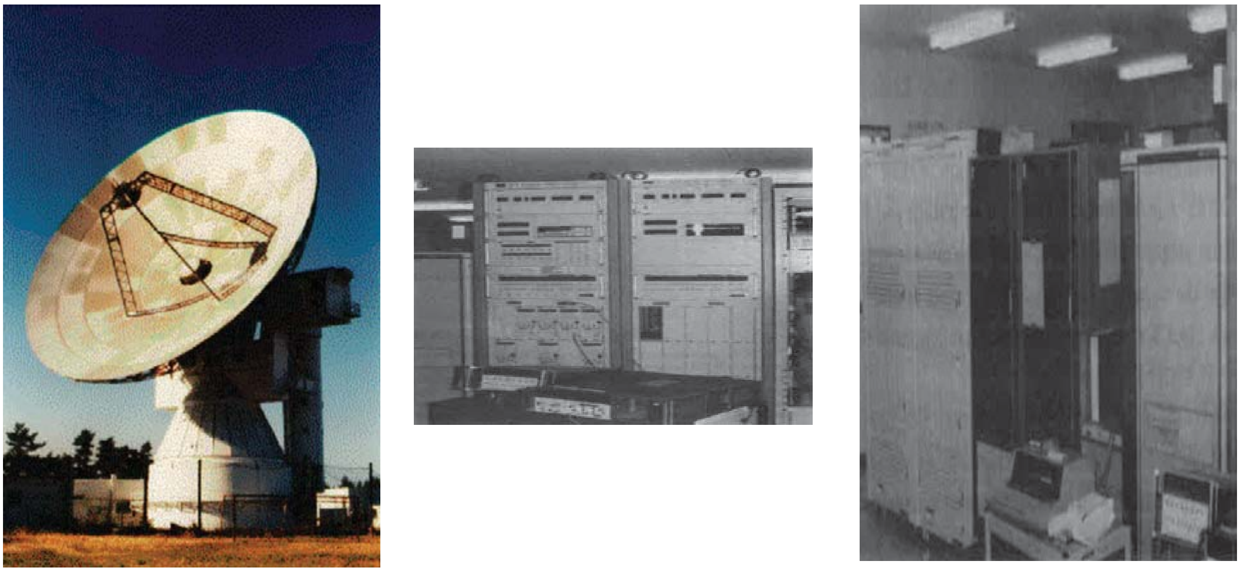

Figure 21. (a) 26 m VLBI Antenna at Kashima used for the first Japan-US joint VLBI experiment in 1983, (b) K3 data acquisition terminal at the Kashima VLBI Station, (c) K3 correlation processor (photo by NICT).

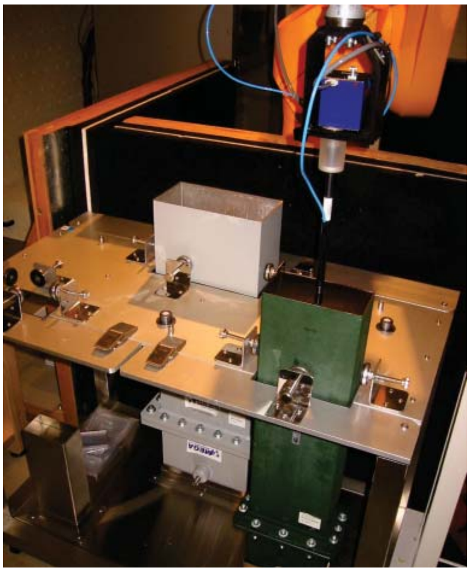

Figure 23. The calibration system of a SAR probe (photo by NICT).

Figure 25. The optically pumped Cs PFS (CRL-O1), which was jointly developed by NIST and NICT (CRL at that time) (photo by NICT).

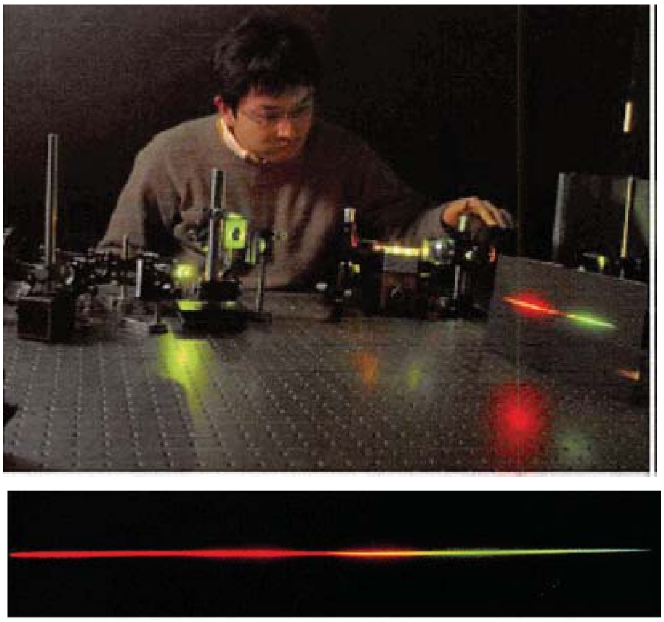

Figure 24. Measurement of optical frequency using a femtosecond mode-locked laser (2000) [Section 8.1.1: 2]. By combining a femtosecond laser and a photonic crystal fiber, light with an equal frequency interval can be generated over a wide spectrum range from green to near infrared. This is called an "optical frequency comb," and can be regarded as a bundle of several million stabilized, continuously oscillating lasers. Using this "optical ruler" made it possible to measure optical frequencies (or wavelength in *vacuo*) to an accuracy of 12 or more digits. Robust fiber-based optical frequency comb combined with UTC (NMIJ) was designated as the national primary length standard in 2009.

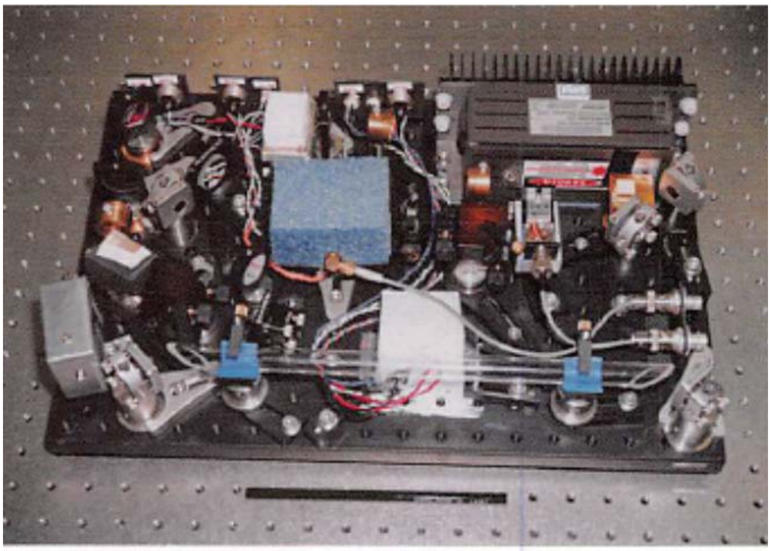

Figure 26. The optical frequency (wavelength) standard based on the 532 nm wavelength (1997) [Section 8.1.1: 2]. This is a standard achieved with the Nd:YAG laser stabilized by the hyperfine transitions of molecular iodine. It is characterized by high accuracy, small size, and portability, and can be used in international comparisons. It has extremely high stability and reproducibility, making it the most important target for measurement when the optical frequency was measured at AIST. The measured result was employed in the CIPM list of approved radiations together with the US and German results in 2001, and it greatly contributed to improving the international length standard.

Figure 27. Preparation of the antenna factor standard for dipole antennas (2002) [Section 8.1.1: 2]. An open-area test site for the frequency range of 30–1000 MHz. Antenna properties are determined by measuring the propagation attenuation between two dipole antennas set up on the ground plane. The institute participated in an international comparison in 2002.

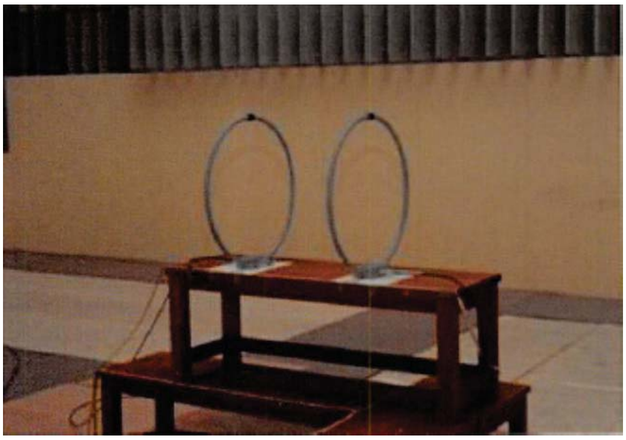

Figure 28. Preparation of loop and monopole antenna in the long-wave region (2002) [Section 8.1.1: 2]. Antenna factors of loop antennas are measured using the three-antenna method as a standard antenna on magnetic field below 30 MHz. The institute participated in the international comparison held in 2002.

technique for 30 to 1000 MHz interference wave measurement1). Demonstrated agreement with 0.3 dB or less by comparison with NPL, UK1). Started the frequency comparison with TAI by NRLM-42). Conducted world's first international comparison with the developed portable I_2 stabilized Nd:YAG laser2). Started research on optical frequency measurement (absolute frequency measurement, AFM) with mode-locked laser2) (Figure 24).

2000s. Report on the accuracy of the optically pumped Cs Primary Frequency Standard (PFS) (CRL-O1) to BIPM1), (Figure 25). AFM of I_2 stabilized Nd:YAG laser contributed to the recommended frequency value by the CIPM2), (Figure 26). Data reporting to BIPM by two-way satellite time comparison method2). Started technical development of real-time remote frequency calibration system2). Started supplying antenna factor standards2), (Figure 27). Proposal for an optical lattice clock (OLC)4). Started supplying standards of 30 MHz or less using micro antenna such as loop antenna and monopole antenna2), (Figure 28). Started data reporting to BIPM by GPS carrier phase automatic transmission2). AFMs of acetylene stabilized semiconductor lasers contributed to the recommended frequency by the CIPM2), (Figure 29). First observation of the Sr clock transition in optical lattice4). First operation of the Sr OLC and the first AFM of the Sr clock

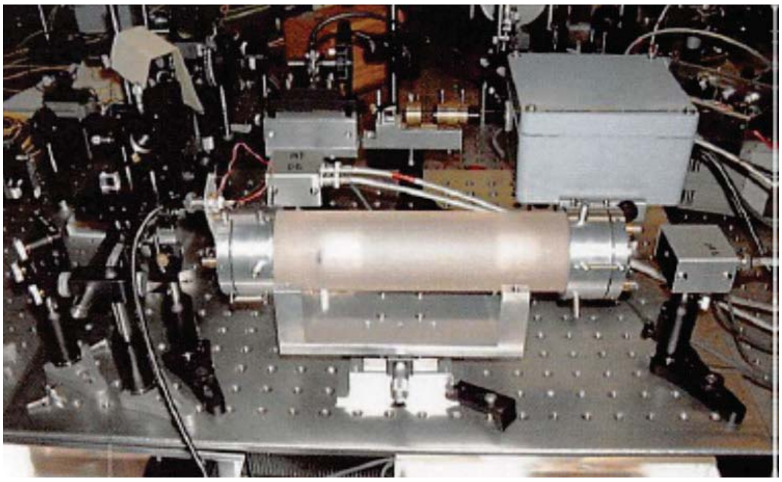

Figure 29. An optical frequency (wavelength) standard for the optical communication band (2001) [Section 8.1.1: 2]. By stabilizing the optical frequency (wavelength) on an extended cavity laser diode, an accurate optical frequency standard for the optical communication band of the wavelength of 1.5 μm was achieved using the saturated absorption of vibrational-rotational transition of acetylene molecules as a reference. It was developed in cooperation with the University of Electro-Communications based on the pioneering work done at the Tokyo Institute of Technology. It serves to supply the high accuracy optical frequency (wavelength) standard used in the wavelength-division multiplex (WDM) system.

Figure 30. A cesium atomic fountain standard (2003). An atomic fountain frequency standard was developed in which laser-cooled cesium atoms are launched upward towards to a microwave cavity. Various factors causing frequency shifts were eliminated and the uncertainty of the primary frequency standard was reduced to the order of 10^{-15} (photo by AIST)

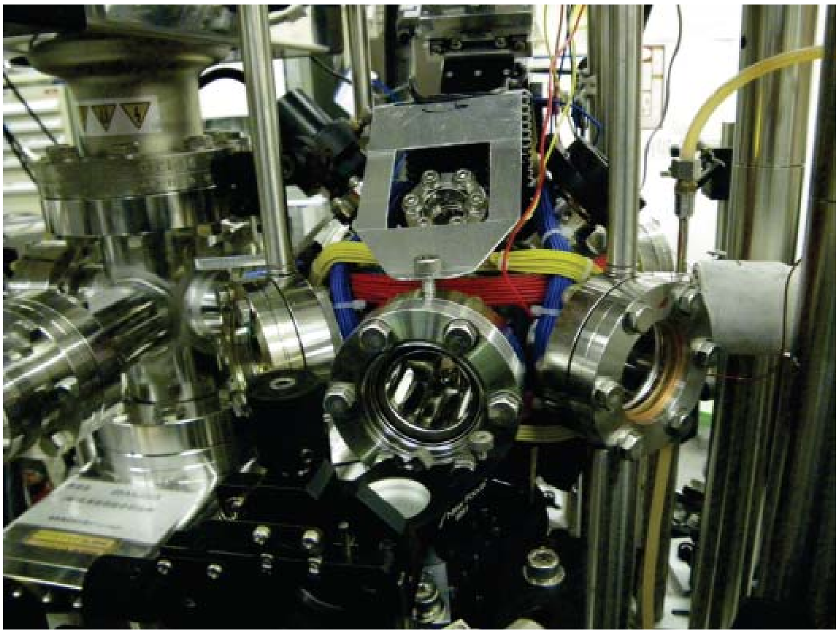

Figure 31. A ytterbium optical lattice clock (2009). The first absolute frequency measurement of the $^1S_0$-$^3P_0$ clock transition in ^{171}Yb was attainted. Improved absolute frequency measurement in 2012 led to the adoption of Yb OLC on the secondary representation of the second (photo by AIST).

transition[2,4]. Completed the Cs fountain PFS (NMIJ-F1), started calibrating TAI[2], (Figure 30). Started developing an Yb OLC[2], (Figure 31). Sr OLC listed on the secondary representation of the second[4]. Following new recommendations for a new FS, the NICT atomic fountain Cs FS (NICT-CsF1) has become the first PFS that has been reviewed and certified by the Consultative Committee for Time and Frequency (CCTF) Working Group on Primary and Secondary Frequency Standards (WGPSFS)[1], (Figure 32). Started developing Cs fountain PFS (NMIJ-F2)[2]. First AFM of the Sr OLC with an inter-city coherent optical fiber link (OFL)[2]. Determined the absolute frequency of the Ca^+ single ion clock with 1.7E-14 accuracy[1], (Figure 33). Reconstruction of magnetic field standard (loop antenna) below 30 MHz Started joint research with AIST[1], (Figure 34). First AFM of the Yb OLC[2].

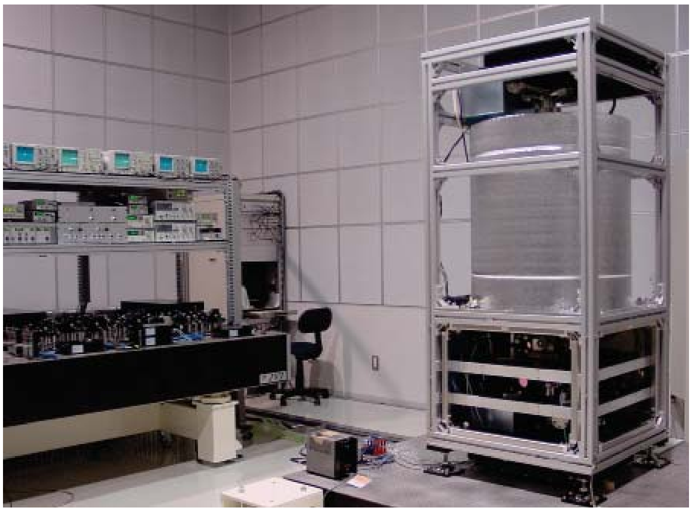

Figure 32. The cesium atomic fountain primary frequency standard NICT-CsF1 (photo by NICT).

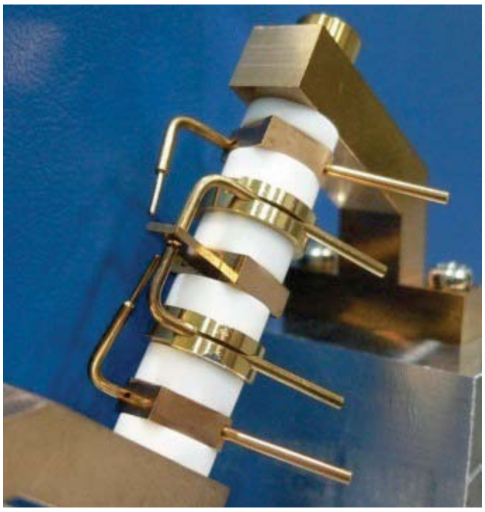

Figure 33. The electrodes for a Paul trap of a single $^{40}Ca^+$ ion. The frequency of the $^2S_{1/2}$ – $^2D_{5/2}$ transition of the ion was measured (photo by NICT).

Figure 34. The magnetic field standard (loop antenna) for the frequency range below 30 MHz (photo by NICT).

2010s. First remote comparison of Sr OLCs between UT and NICT with an OFL, confirming the coincidence with a 16-digit level uncertainty1,4), (Figure 35). Development of power standard over 110 GHz, started joint research with AIST1). Yb OLC listed on the secondary representation of the second2). Development of power standard (calorie meter) of 110-170 GHz frequency band1). Compared 2 Sr OLCs with 18-digit level3,4), (Figure 36). Frequency ratio measurement of Sr and Hg OLCs with a 17-digit level uncertainty3). Remote comparison of Sr OLCs between UT and RIKEN with an 18-digit level uncertainty3,4). Frequency ratio measurement of Sr and Yb OLCs with a 17-digit level uncertainty3). NICT Sr OLC (NICT-Sr1) validated by WGPFSF as a secondary FS, contributed to the first calibration of the most recent TAI1), (Figure 37). Development of power standard (calorie meter) of 220-330 GHz frequency band1), (Figure 38).

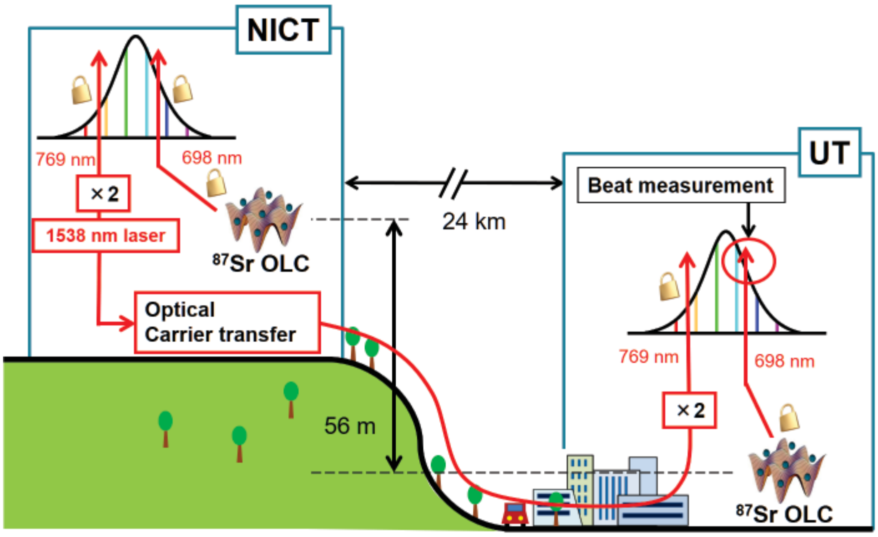

Figure 35. A signal of the ^{87}Sr OLC at NICT was transferred to UT to measure the frequency difference between ^{87}Sr OLCs at NICT and UT using an optical fiber link, which is the first demonstration to confirm the frequency coincidence with a 16-digit level uncertainty [from *Appl. Phys. Express*, 4, 082203].

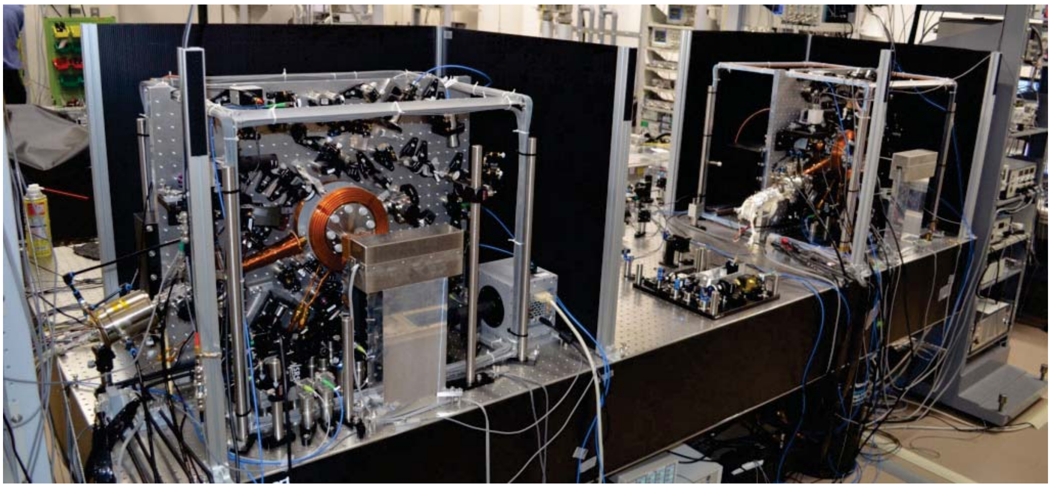

Figure 36. Two cryogenic Sr optical lattice clocks showed good agreement with 18-digit accuracy (photo by RIKEN).

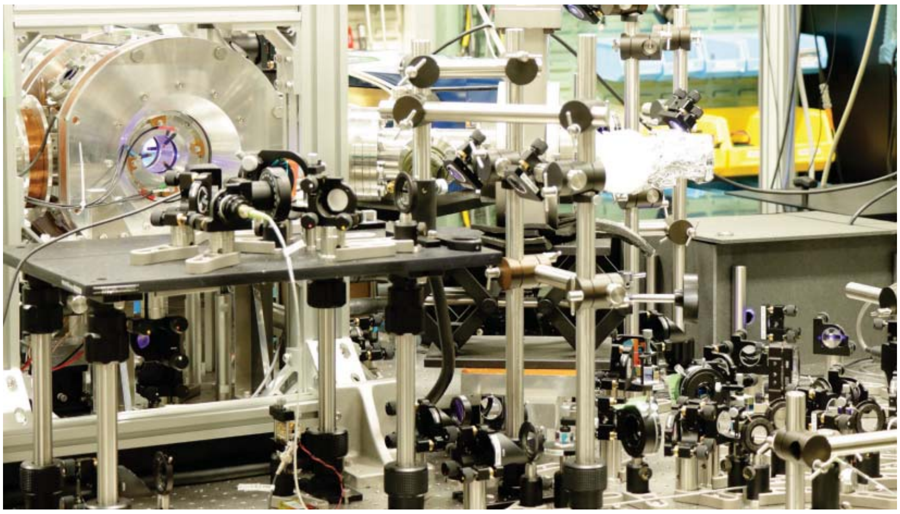

Figure 37. A part of NICT-Sr1 system, which was validated by WGPSFS as a secondary FS and contributed to the first calibration of the most resent TAI (photo by NICT).

Figure 38. An RF power standard (calorimeter) for the frequency range from 220 to 330 GHz (photo by AIST).

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8.2 Commission B

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The JNC Commission B Committee is composed of about twenty leading researchers in the fields of electromagnetic theory, antennas and wave propagation, from university, national and industrial research institutions. The objective of this committee is to encourage and promote international and domestic activities in electromagnetic wave science and its applications, such as antennas, microwave components, measurements and the prediction of wave propagation. To achieve these objectives, the JNC Commission B Committee cooperates closely with International Commission B and academic societies in Japan. The latter include the technical committee on electromagnetic theory and the technical committee on antennas and propagation in the Institute of Electronics, Information and Communication Engineers (IEICE) and the Institute of Electrical Engineers of Japan (IEEJ). Active cooperation and participation in the organization of the GASS, AP-RASC, AT-RASC, URSI-Japan Radio Science Meeting (JRSM), and EMT symposium are primary missions of Japan National Commission B. The national report at 3-years interval is an important task.

The investigation of radio wave science and engineering, including electromagnetic theory, antennas and their related fields has a long history in Japan. Japanese Commission B members have conducted outstanding research, some of which have been realized to serve the public. The invention of the Yagi-Uda antenna and the self-complementary antenna are both worthy of special mention. In 1995, the IEEE dedicated an Electrical Engineering Milestone entitled "Directive Short-Wave Antenna" to Tohoku University, Japan for the outstanding achievement of Professors Yagi and Uda. This was the first Milestone awarded to the Asia region. The IEEE awarded a further Milestone to the same university for the "Discovery of the Principle of Self-Complementarity in Antennas and the Mushiake Relationship, 1948" in 2017. This principle is the basis for many very-wide-bandwidth antenna designs, with applications that include television reception, wireless broadband, radio astronomy, and cellular telephony. Prof. Inagaki has developed improved circuit theory for analyzing linear antennas.

Antennas were developed for solving specific applications. One wavelength circular-loop antennas were originally investigated and developed by Professors Adachi and Mushiake, and later modified to a twin-loop antenna and installed on Tokyo Tower for broadcasting. Tokyo Tower was selected for a further IEEE Milestone in 2011. Various kinds of aperture antennas were put to practical use for terrestrial microwave relay links from the 1950s to the 1980s. The reflector antennas for earth stations, radio telescopes, and for satellites were also investigated nearly simultaneously. A 20 m Cassegrain antenna was dedicated as an IEEE milestone in 2009 for "The First Transpacific Reception of a Television Signal via Satellite, 1963." Some original technologies were established for planar antennas, such as microstrip antennas and the radial slot-line antenna that was invented by Prof. Goto. Various cellular base-station and vehicular antennas were developed as well, and their investigation still continues to this day for 5G and Beyond 5G.

Japan National Commission B continually encourages the development of telecommunication technologies using the knowledge of radio science, including metamaterials, computational electromagnetics and electromagnetic theory.

8.3 Commission C

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The members of Japan Commission C hold open workshops three or four times per year to stimulate research work since 2003.

The work of Professors Yagi and Prof. Uda is of seminal importance. Not only did they invent the Yagi-Uda antenna but they studied V/UHF radio systems [1, 2] in detail. To do this they used split-anode magnetrons and succeeded in making communication experiments at a distance of 50 km on 65 MHz and 30 km on 600 MHz. The magnetron tubes, used today for microwave ovens, were simultaneously invented by Prof. Okabe in the same campus of Tohoku University.

A remarkable development was the development of the "Wireless Telephone" which was demonstrated at World Expo '70 in Osaka (Figure 39) [3], thereby demonstrating the feasibility of portable and personal telephones. In the field of multiantenna signal processing the direction-constrained minimizing power algorithm (DCMP) for adaptive arrays [4] has been widely applied [5]. In the field of RF and microwave circuits and devices, the invention of the high electron mobility field effect transistor (HEMT) [6] is important. For digital mobile communications, Gaussian Minimum Shift Keying (GMSK) [7] and π/4-DQPSK [8] are famous modulations with the former adopted for GSM, the first digital cellular system in Europe and latter adopted by the USA and Japan. Self-adjusting feed-forward techniques to compensate for the non-linearity of RF power amplifiers [9] patented in 1988 is also useful and remarkable work for cellular system base stations. Space division multiplexing (SDM), including Multiple Input Multiple output (MIMO), has actively been studied. The paper on SDM by Dr. Yoshino et. al. [10] is the first paper showing that SDM can be realized with multiple antennas and interference cancellation [11].

Figure 39. A wireless Telephone demonstrated at Expo '70 (source: https://commons.wikimedia.org/wiki/File:EXPO_%2770_Wireless_Telephone.JPG).

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8.4 Commission D

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Prof. Koichi Shimoda, who was author of “Nonlinear Spectroscopy of Molecules” and “Introduction to Laser Physics,” was awarded the Japan Academy Prize in 1980 for studies on laser physics and laser spectroscopy, the Order of the Sacred Treasure, Gold and Silver Star in 1990, and Persons of Cultural Merit in 2008. He was a member of the committee from 1963 to 1985.

Prof. Fumio Inaba, in the field of optoelectronics and laser applications, translated “Introduction to Quantum Mechanics for Electrical Engineers” by P. A. Lindsay and served as chair of Japan Commission D from 1985 to 1991.

Prof. Takanori Okoshi, author of “Three-Dimensional Imaging Techniques,” “Optical Fibers,” “Planar Circuits for Microwaves and Lightwaves” and “Coherent Optical Fiber Communications,” was awarded the IEEE Morris N. Liebmann Memorial Award in 1988, the Fujiwara Award in 1991 and the Japan Academy Prize in 1993 for research on coherent optical fiber communications. He was a member of the committee from 1981 to 1987, a member of Commission D from 1988 to 1991, and served as chair of the committee from 1985 to 1991.

Prof. Kunio Tada in the field of optoelectronics, translated “Optical Electronics” by Amnon Yariv and served as chair of Japan Commission D from 1991 to 1997.

Prof. Kenichi Iga, author of “Fundamentals of Micro-optics,” “Fundamentals of Laser Optics,” and “Process Technology for Semiconductor Lasers,” was awarded the Medal with Purple Ribbon in 2001, The Rank Prize in 2002 for the invention of vertical cavity surface emitting lasers (VCSELs), the IEEE Daniel E. Noble Award in 2003, Fujiwara Award in 2003, the Bower Award and Prize for Achievement in Science in 2013 for the conception and development of the VCSEL and its multiple applications to optoelectronics, the Order of the Sacred Treasure, Gold and Silver Star in 2018 and served as chair of Japan Commission D from 1997 to 2000. VCSEL, the initial idea and typical structure of which are shown in Figs. 40a and b, has the advantages of small size, low power consumption, ease of one- and two-dimensional arrays and

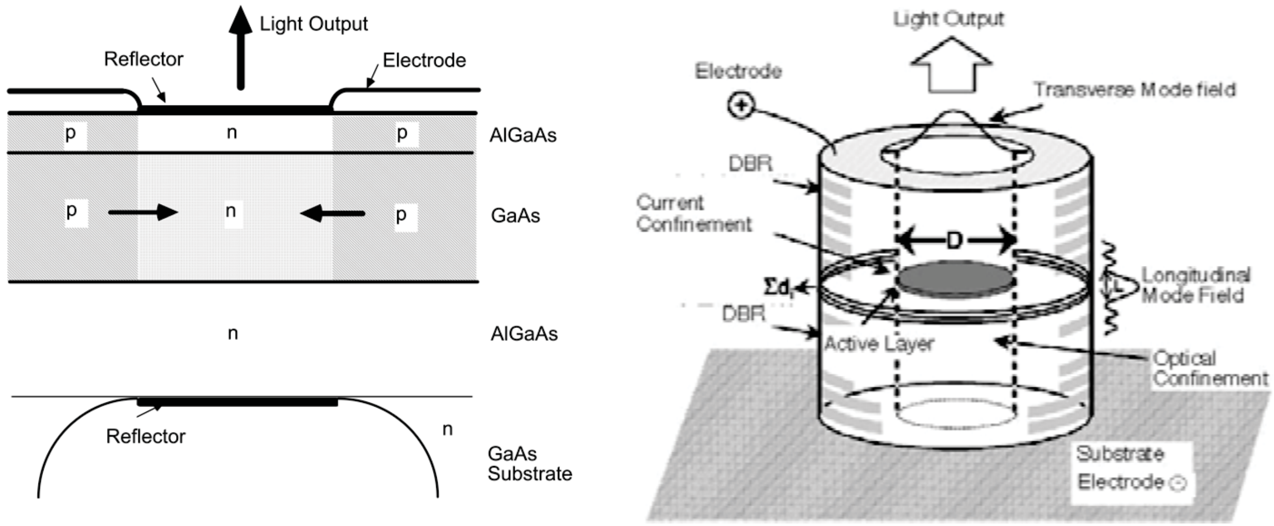

Figure 40. A VCSEL (vertical cavity surface emitting laser) [Section 8.4.1: 1]: (a) Initial idea, and (b) typical structure.

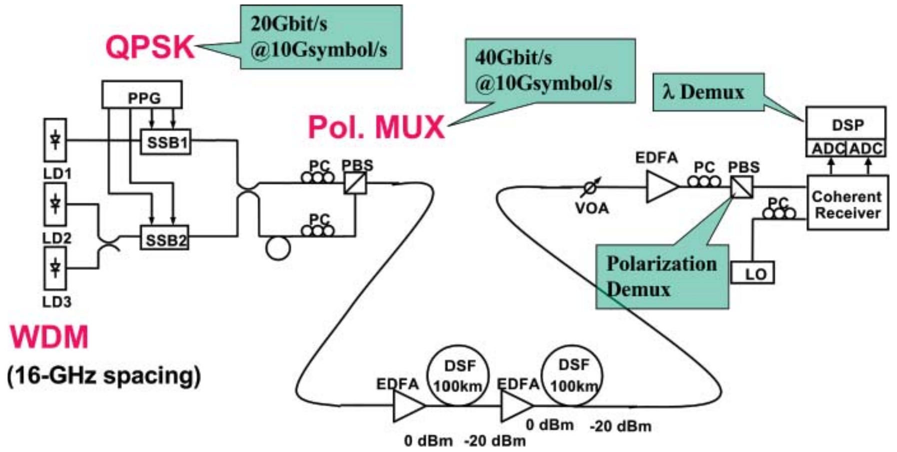

Figure 41. A digital coherent optical communication system [Section 8.4.1: 2] (courtesy of Prof. K. Kikuchi).

is suitable for mass production. Because of those advantages, VCSEL is used as the light source in many applications such as the laser printer, for sensors such as the laser mouse and for communications such as in local area networks, data center networks, etc. As a remarkable application, 3-dimentional face recognition system for mobile phone was realized by using VCSELs very recently.

Prof. Masayuki Izutsu, an author of "Encyclopedic Handbook of Integrated Optics" edited by Kenichi Iga and Yasuo Kokubun, served as chair of Japan Commission D from 2000 to 2005.

Dr. Hiroyo Ogawa, in the field of optical/millimeter-wave systems, contributed standardization activities at IEC and IEEE, served as chair of Japan Commission D from 2005 to 2008.

Prof. Tadao Nagatsuma ,in the field of THz technology, served as chair of Japan Commission D from 2008 to 2014.

Prof. Katsutoshi Tsukamoto, in the field of wireless communication and microwave photonics, served as chair of Japan Commission D from 2014 to 2017.

Prof. Hiroyuki Toda, in the field of optical communication and microwave photonics, has been chair of Japan Commission D since 2017.

The intrinsic advantage of coherent optical communications with optical heterodyne or homodyne detection, invented by Prof. T. Okoshi, is shot-noise-limited high receiver sensitivity by the use of highly pure semiconductor lasers. This technique was not applied in real systems mainly because of the invention of optical fiber amplifiers.

Prof. K. Kikuchi, edited the National Report, Commission D (Nov. 1995 - Oct. 1998), demonstrated digital coherent optical communication by the use of digital signal processing (DSP), as shown in Figure 41. In the system, wavelength demultiplexing, hitherto performed in the optical domain, was performed in electrical domain using DSP, and a spectral efficiency of 2.5 bit/s/Hz was obtained. Using this technique, a lot of functions such as data demodulation, dispersion (including polarization mode) and even nonlinearity compensations can be performed using large scale integration DSP without the use of highly pure semiconductor lasers. Nowadays, digital coherent technique is indispensable for high capacity transmission systems [3].

Convergence of Electronics and Photonics is very important for high-speed signal processing, large capacity transmission, and so on. As an example, Figure 42 shows the world's first 120 GHz band experimental radio station, where photonics technologies were efficiently employed to generate and modulate 120 GHz carrier signals in the transmitter. The system was developed at NTT, where Dr. T. Nagatsuma has led the research project since 2000 [4]. The 120 GHz band wireless link, with a data rate of over 10 Gbits^{-1}, was used for at the 2008 Beijing Olympic Games to deliver uncompressed high-definition TV signals in the Stadium. On January 30, 2014, the Ministry of Internal Affairs and Communications (MIC) of Japan officially revised the radio regulations to allocate the band from 116 GHz to 134 GHz for the 120 GHz band wireless link for broadcasting services. This pioneering work has stimulated THz wireless communications research throughout the world, and currently a 300 GHz band link with a data rate of over 100 Gbit/s has been demonstrated.

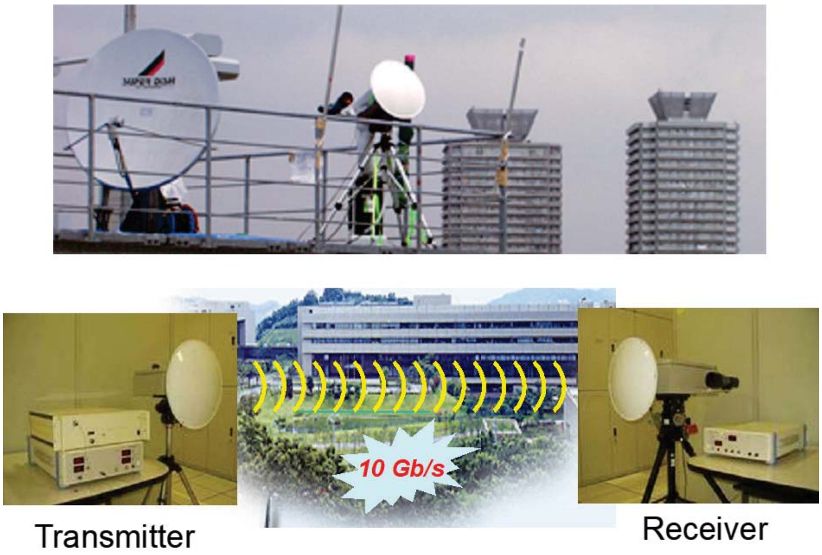

Figure 42. The world's first 120 GHz band experimental radio station (in 2005).

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8.5 Commission E

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8.5.1 Atmospheric (Sferics) Due to Lightening Discharges

The Japanese Commission E has made significant contributions to the investigation of sferics initially in the VLF/ELF bands and later at HF/VHF. These include (1) the establishment of a VLF network in Japan, which monitored lightning discharges in one of the major global lightning chimneys (south-east Asia), (2) the study of low-latitude whistling atmospherics (or whistlers) with the use of a VLF network in Japan, (3) the discovery of some unusual peculiarities of Japanese winter lightning in the Sea of Japan, with lower cloud height and an extremely high rate of positive lightning discharges.

The Japanese contribution to the study of mesospheric optical emissions (transient luminous emissions (TLEs)) in the context of a possible association with positive lightning discharges is significant in the general study of TLE generation. This is because Japanese winter lightning plays an important role. The studies use VLF sub-ionospheric data of the associated ionospheric perturbations due to energetic particle precipitation and EM (electromagnetic) and QE (quasi-electrostatic field) heating associated with the TLE body. Recently many field campaigns have been conducted by Japanese groups to elaborate on lightning physical properties by using modern technological systems such as digital interferometers, VLF/LF interferometers and ELF observations.

Studies related to the mitigation of meteorological hazards using radio observations is also a very active area among Japanese groups. The use of total lightning (sum of cloud-to-ground and in-cloud discharges) detection networks with information from newly developed phased-array VHF radars is one of the very promising tools to detect precursor phenomena of extreme weather such as tornadoes and heavy rainfall. Damage to the power grid and re-usable energy systems, due to the energetic lightning, is a serious issue for low- and mid-latitude latitudes. Lightning charge moment changes have been deduced from ELF sferics, which will be useful for real-time monitoring and mitigation of future lightning damage.

8.5.2 Electromagnetic Phenomena Associated with Seismic Activities

Japanese groups have made a significant contribution to this science field, exploring the possibility of earthquake prediction using EM effects. In 1982 a Japanese group, in collaboration with a Russian group found a precursor anomaly in the noise intensity in the LF band. This is pioneering work in the field of seismo-electromagnetics and initiated further work on precursory radio noise in different frequency ranges from DC/ULF to VHF.

A Japanese group succeeded in finding convincing evidence for the presence of a lower ionospheric perturbation just prior to the Kobe earthquake, but recognized that the causal link is unknown. Japanese groups also made extensive studies of lithospheric ULF emissions. Just after the Kobe earthquake, a Japanese group performed the frontier project with the former NASDA team, suggesting the possibility of earthquake prediction using EM effects not only in the lithosphere, but also in the atmosphere and ionosphere. These investigations included extensive global VLF/LF studies, upper ionospheric anomaly detection using VHF techniques, a French satellite experiment, ULF network observations and others. Japan

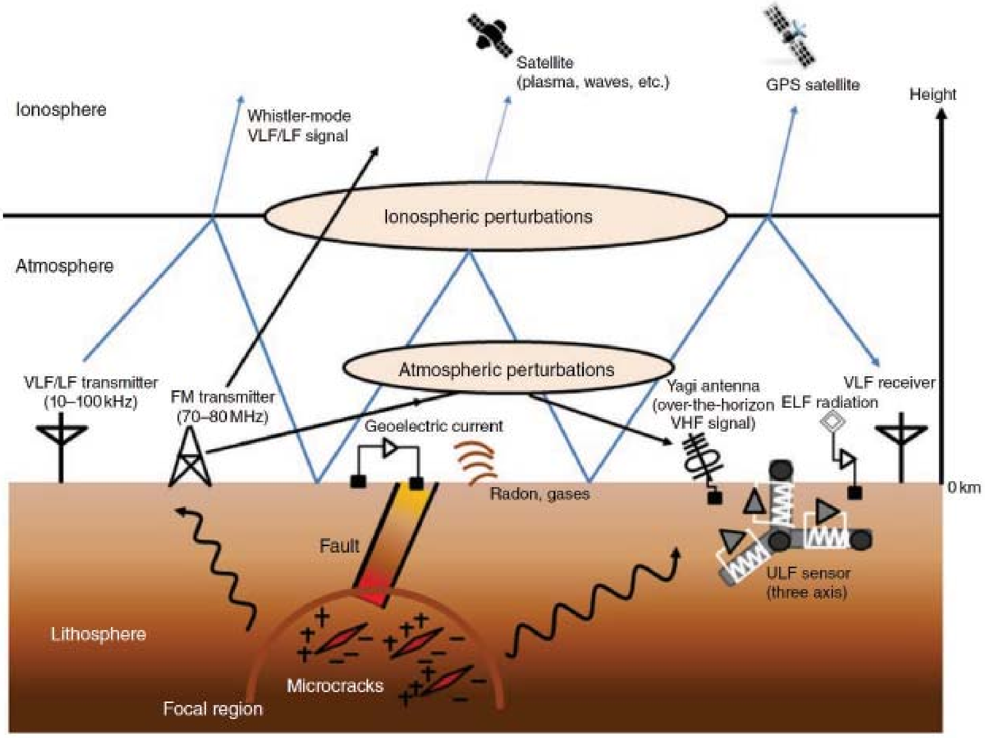

Figure 43. Electromagnetic phenomena in possible association with seismic activities and different techniques to measure those electromagnetic effects.

continues to lead this new science field, by conducting different kinds of continuous observations in the DC/ULF, VLF/LF and VHF bands (Figure 43). Recently, multi-parameter analysis and advanced signal processing techniques based on big data (e.g. machine learning in artificial intelligence) have been recognized as promising approaches to shed light on the generation mechanisms and to develop accurate detection earthquake precursors.

8.5.3 Man-Made Noise and Interference Issues

In the mid-1990s Japanese groups joined this Commission E activity. In the early days, the main topics were (1) coupling of external electromagnetic waves (such as lightning discharges) to transmission lines, and (2) measurement systems to estimate the interference. Japanese groups organized many sessions on these subjects in the URSI GASS. The coupling problem was extensively studied with the use of EM analysis. Different kinds of analysis methods in the study of man-made noise have been proposed by Japanese groups, including APD (amplitude probability distribution) etc.

Recent advances in power electronics has generated new types of interference in industry, cities, automotive and consumer power control systems. Smart grid and smart power systems as well as the information system, shall be supported by either wired or wireless communication (most of them are adopting digital modulation, and the same for TV broadcastings). With this environmental change of RF, new technologies have been developed in Japan, such as APD to statistically estimate the RF interference because APDs are strongly correlated with digital communication performance, and some are applied in international standards of EMC (Electromagnetic Compatibility). This redirection of EMC research is expected to continue, given the major technological and social changes associated with the Internet, the Internet of Things, wireless power transfer for electric vehicles, information security etc.

8.6 Commission F

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8.6.1 Radio Wave Propagation Models

Wireless communication has developed significantly in the last 100 years and it is important to understand the characteristics of radio wave propagation that degrades communication quality. However, since various radio wave propagation phenomena are strongly connected with radio meteorology such as rainfall, environmental factors such as urban structures, and system factors, their understanding and modeling are usually very difficult. In the following we introduce four Japanese pioneers who had struggled to elucidate natural phenomena and have created radio wave propagation models and concepts useful for developing communication systems.

Dr. Minoru Nakagami developed the key probability distributions, namely, Nakagami-n distribution (now, called as Nakagami-Rice distribution) and Nakagami-m distribution, Both distributions are highly effective in describing multipath propagation in mobile communications. These models were established in 1940–1950s for the study of ionospheric propagation.

In the 1960s, Dr. Yoshihisa Okumura established a mobile propagation model composed of three factors, namely, path-length, long-term variations and short-term variations. This approach is still used for the design of mobile communication systems. The so-called "Okumura curve" derived from extensive propagation measurements has provided useful knowledge for system design.

In the 1980s Dr. Fumio Ikegami established the APS Trinity connecting the antenna (A), propagation (P) and systems (S) for realizing wideband mobile communications. He passionately encouraged young research engineers to use the APS Trinity paradigm. Various technologies such as CDMA, OFDM, MIMO and phased array systems developed in Japan have been affected by his philosophy.

In the 1970s, Dr. Kazuo Morita modeled the rain attenuation in terrestrial wireless communication systems. After a long investigation concerning the probability distribution and spatial correlation characteristics of rainfall rate in Japan, a straightforward theoretic attenuation model was developed. Based on the model, many successors have studied and improved the model prediction accuracy and extended its function. The result has been an accurate prediction model which has been adopted as the standard calculation model for wireless system design in Japan.

Other topics and pioneers, are described in [1, 2].

8.6.2 Weather Radars

The contribution of Japan to the development of weather radar is significant, including 1) polarimetric observations, 2) application of higher frequencies, 3) utilization of various platforms, and 4) fast scanning technology [3].

Here we focus on 3) and 4), especially on the spaceborne radar and ground-based phased array radar. The precipitation radar (PR) onboard the Tropical Rainfall Measuring Mission (TRMM) satellite is the world's first spaceborne precipitation radar. To overcome the constraints of spaceborne system a high frequency (Ku-band), electronic scanning system was introduced, bringing advantages of antenna size and sensitivity. Electrical scanning was realized by controlling the phase independently on each of 128 slotted waveguides antennas.

One concern for a Ku band radar is attenuation due to precipitation. The path integrated attenuation, estimated from the ground (sea) surface echo, is utilized as a boundary condition to retrieve the attenuation corrected radar reflectivity factor profile, and this method can provide the model parameter of drop size distribution at the same time. TRMM/PR provided accurate global precipitation and characteristics of global precipitation (such as diurnal cycle and extreme precipitation events) for the first time. It is also used for inter-comparison/calibration of ground-based radars because of its un-biased global observation. TRMM had been in operation for about 17 years, and its follow-on mission GPM (Global Precipitation Measurement) core observatory, that is equipped with a dual-frequency radar system by adding a Ka-band radar, was launched in 2014. GPM seeks to realize more accurate precipitation estimations and to contribute to the estimation of cloud physical quantities. NASA/JPL launched a W-band cloud profiling radar (CloudSat) in 2006. CloudSat is the first spaceborne radar to reveal the 3D structure of global clouds, which is important for the quantitative evaluation of the effects of clouds on the radiation balance of the Earth. The cloud profiling radar (CPR) onboard the EarthCARE satellite (to be launched in 2021), which is a joint mission between Europe and Japan, is the first spaceborne Doppler radar, and it is expected to contribute to cloud and precipitation research.

Ground-based phased array weather radar has been studied since the 2000s, mainly in Japan and the United States. In the US, two-dimensional phased array weather radars and one-dimensional array systems for high-speed scanning in the vertical (or horizontal) direction has been developed. In Japan, the combination of electronic scanning in the vertical (elevation) direction and mechanical scanning in the horizontal (azimuth) direction has been adopted in the Phased Array Weather Radar (PAWR), which is suitable for operational observations. PAWR makes possible observations out to a range of 60 km and up to 15 km in height without a gap, in 30 seconds. The heritage of this system is technology cultivated in TRMM/PR. As of 2019, six phased array meteorological radars have been developed in Japan, one of which is the multi-parameter phased-array meteorological radar (MP-PAWR) that enables dual polarization observation. Since PAWR and MP-PAWR can observe the three-dimensional structure of the precipitation system in 30 seconds, they are useful for detailed observation of cumulonimbus clouds that cause localized heavy rainfall, and for the observation of isolated precipitation systems that have been difficult to observe by conventional radars. MP-PAWR and PAWR are expected to open new fields in meteorological research.

It should be noted that these developments are dependent on basic technologies such as semiconductor devises, and progress in the signal processing systems.

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8.7 Commission G

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Japan has a long history of studies of radio wave propagation through ionosphere, and studies of the ionosphere. The importance of radio-wave telecommunications was clear to the Japanese government from the early years of URSI and it is well known that radio-wave communications supported the success of the Japan Sea battle during Russo-Japanese War of 1904.

Hiraiso Observatory was the first radio observatory in Japan and was opened in 1915 [1]. The observatory was the cradle of the radio technology in Japan. Ionospheric observations started in 1932, including studies of the relationship between solar activity and ionospheric disturbances. The observatory became part of the Radio Research Laboratory (RRL) established in 1952, and led to the radio-propagation alert service, and the space weather forecast services by the National Institute of Information and Communications Technology (NICT).

We should note the intense observation efforts of the ionosphere by Japan before the World War II (WWII) period. The ionospheric observation network was deployed in wide areas including Southeast Asia and Western Pacific in support of the Japan military expansion in those regions [2]. The data led to a better understanding of the fundamental behaviors of the ionosphere, i.e., the plasma density distribution obeys the geomagnetic latitudes rather than the geographic latitudes [3]. The most important scientific achievement from these efforts was the finding of the equatorial ionospheric anomaly (EIA) which was later named by Appleton [3][4].

Ionospheric studies by Japanese scientists continued after WWII. In this period, the theoretical framework for the electromagnetic and/or fluid dynamic behaviors of the ionosphere and the upper atmosphere was established [4]. Important contributions included understanding the equatorial ionosphere in quiet times (i.e., EIA formation and equatorial enhancement of conductivity), the tidal wind system in the ionosphere/upper atmosphere (i.e., Sq current system and atmospheric tidal theory), and the formation of the F2 layer including ionospheric disturbances [4]. These efforts continued in Antarctic expeditions and rocket experiments during IGY (1957–1958).

Later development of the research field is too much for this short article. Here we touch on some important observations of the ionosphere by using radio waves. The University of Electro-Communications (UEC) established Sugadaira Space Radio Observatory in 1975 [5]. The main instrument was the HF Doppler (HFD) system (which technique is an invention by Japan). HFD was used for the study of faint variations of the ionosphere that can be generated by the atmospheric waves or even by the seismic motion of the Earth’s surface.

Radar observations of the atmosphere/ionosphere is another important contribution to the research field by Japan. Kyoto University developed the MU radar (MUR) at Shigaraki, Japan in 1984 [6]. MUR was the world’s first atmospheric radar with an active phased-array antenna system. In recognition the URSI Appleton Prize was given to S. Kato in 1987 and an IEEE Milestone was awarded in 2015. The efforts continued to the establishment of the Equatorial Atmosphere Radar

(EAR) right over the geographic equator at Sumatra Island, Indonesia. These radars contributed to studies of dynamical vertical coupling of the atmosphere and the ionosphere.

Super Dual Auroral Radar Network (SuperDARN) is the international HF radar network started in 1995. The National Institute of Polar Research (NIPR) was a founder member and started Syowa South radar in 1995 in Antarctica with Syowa East radar added in 1997 [7]. NICT started King Salmon radar in Alaska in 2001, and Nagoya University established Hokkaido East radar (2006) and Hokkaido West radar (2014). All of these contributed much to the ionospheric study in the middle- to high-latitude regions.

Global Navigation Satellite Systems (GNSS) are a great innovation for global positioning and navigation. GNSS is also widely used for environmental studies, especially the total electron content (TEC) of the ionosphere. Japan has deployed the GNSS Earth Observation Network System (GEONET) that consists of about 1300 GPS receivers. In 1998, Japanese scientists started to show the horizontal distribution of TEC based on the GEONET data [8]. The technique is very effective to study wave structures in the ionosphere.

We acknowledge that this article is based on several review papers and presentations in 2019 URSI-Japan Radio Science Meeting, Commission-G History Session. Below are the references to them.

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8.8 Commission H

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Plasma wave measurements provide many scientific clues to plasma dynamics in the magnetosphere, solar wind and the other regions in the solar system. Japan has made plasma wave measurements for nearly 50 years since the DENPA satellite was launched in 1972. Since GEOTAIL discovered that intense broadband electrostatic noise (BEN) consists of electrostatic solitary waves (ESW) [1], the importance of electromagnetic measurements has been well recognized. Notably, the plasma wave instruments (VLF and PWS) and radiation monitor (RDM) aboard the AKEBONO have collected data for 26 years (1989–2015) and contributed important scientific ouputs concerning the long-term changes of plasma wave activity and of the Van Allen belt [2, and the references therein].

The plasma sounder technique in Japan was established on board the JIKIKEN in 1978, and was applied to the topside sounding experiments by the OHZORA, and AKEBONO. The technique was also implemented in NOZOMI for Mars exploration and was further applied to the sub-surface Lunar Radar Sounder (LRS) on board the KAGUYA lunar orbiter [3].

Comparisons of spacecraft observations and computer simulations have taken place. Kimura [4] developed a three-dimensional ray tracing program taking account of the effect of ions. Kimura [5] reviewed the ray tracing, to stress its significance in the discovery of the magnetosphere and for the modeling of the plasmasphere combined with the direction finding of the plasma waves. A variety of simulation codes, such as particle-in-cell (PIC), MHD and hybrid were also developed and applied to investigate wave-particle interactions. The generation mechanism of ESW discovered by the GEOTAIL [6], the generation processes of chorus and ion cyclotron (EMIC) triggered emissions and related particle acceleration and precipitation processes caused by non-linear wave-particle interactions in the inner-magnetosphere [7–10, and references therein] were investigated by the computer simulations. Computer simulations were also applied to the study of the interaction between plasma and spacecraft [11].

Geomagnetic pulsations at ULF/ELF range are a specific plasma waves in geospace. Terada [12] discovered Pi2 pulsations associated with magnetospheric substorms, which is one of the pioneer works for geomagnetic pulsations. Kato and Saito [13] and Saito [14] [15] categorized the geomagnetic pulsations, into Pc and Pi pulsations. These categories were endorsed by IAGA in 1963 and 1973, and have been used as the standard classifications since that time. Japanese researchers have continued to contribute to studies of geomagnetic pulsations and have developed ground-based magnetometer chains [e.g., 16–18]. Recently, Nosé et al. [19] proposed the Wp-index related to low-latitude Pi2 pulsations, which has been used as a standard index to identify the onset of substorms.

We should also note that Commission H in Japan significantly contributed to the development of microwave energy transmission techniques as one of applications of radio waves in space. Matsumoto [20] presented an excellent review paper on the microwave power transmission from space and the related nonlinear plasma effects. The paper covers not only a brief history of the development of technology and scientific research related to the transmission of electrical energy via radio waves, but also various kinds of experiments related to the microwave energy transmission and associated theoretical and numerical studies.

The activities of Japanese Commission H contribute much wider research fields and the achievements are highly valued in URSI. Prof. H. Matsumoto won the Booker Gold Medal in 2008 for his outstanding contributions to the understanding of nonlinear plasma wave processes, promotion of computer simulations in space plasma physics, and international leadership in plasma wave research. He also contributed to the URSI activities as Chair of Commission H in 1987–1989, Vice President in 1995–1999 and President of URSI in 1999–2002, respectively. Prof. Y. Omura won the Appleton Prize in 2017 for his significant contributions to nonlinear wave-particle interaction theory, simulations of chorus and ion cyclotron emissions and the associated acceleration and precipitation of relativistic electrons in the radiation belts. He also contributed to the URSI activities as Chair of Commission H in 2008–2011.

Finally, we summarize recent plasma research activities and projects in Japanese Commission H.

BepiColombo/MIO (https://global.jaxa.jp/projects/sas/bepi/). BepiColombo is a Mercury exploration project jointly planned by JAXA and the European Space Agency (ESA), launched in 2018. The plasma wave investigation (PWI) [21] aboard the MIO spacecraft, will observe electric field, plasma waves, and radio waves around Mercury after its arrival in 2025.

ARASE (http://ergsc.isee.nagoya-u.ac.jp/index.shtml.en). The Arase was launched in 2016 to study acceleration and loss mechanisms of relativistic electrons in the inner magnetosphere of the Earth. The Plasma Wave Experiment (PWE) [22] has measured DC electric field and plasma waves covering wide frequency range from DC to 10 MHz for E-field and from a few Hz to 100 kHz for B-field. The Software-Wave Particle Interaction Analyzer (SWPIA) [23] is equipped to realize direct measurements of interactions between energetic electrons and whistler-mode chorus.

PWING Project (http://www.isee.nagoya-u.ac.jp/dimr/PWING/en/). The PWING project operates eight ground-based stations at subauroral latitudes using induction magnetometers, riometers, VLF/ELF receivers, and all-sky airglow/aurora imagers and EMCCD cameras to investigate the process of dynamical variation of the particles and waves in the

Earth's inner magnetosphere. Conjugate measurements of particles and waves with Arase and the Van Allen Probes has been intensively conducted.

JUICE (http://sci.esa.int/juice/) JUICE (JUpiter ICy moons Explorer) is the L-class mission of ESA, planned for launch in 2022 and arrival at Jupiter in 2029. It will make detailed observations of the Jovian system including Ganymede, Calisto and Europa, and finally be on the orbit around Ganymede. The Japanese members will mainly contribute to the development of High Frequency part (RWI-Preamp and HF-Receiver) in the Radio and Plasma Wave Investigation aboard the spacecraft.

Ground-based observations of solar and planetary radio waves (http://ariel.gp.tohoku.ac.jp/jupiter/). Ground-based observation of solar and planetary radio waves is performed using IPRT (Iitate Planetary Radio Telescope) and an HF antenna array. The primary purpose of the telescope are to investigate the dynamic behavior of Jupiter's synchrotron radiation and solar radio emissions in the low-frequency range. In addition to this, IPRT has capability to observe weak radio sources in the low frequency range such as pulsars.

Hisaki spacecraft (http://global.jaxa.jp/projects/sat/sprint_a/) Hisaki satellite with the EUV spectrometer (Extreme Ultraviolet Spectroscope for Exospheric Dynamics: EXCEED) is the UV/EUV space telescope dedicated to planetary sciences. Hisaki has provided continuous observations of Jovian system in UV aurora total flux and EUV Io torus plasma distributions and plasma diagnostics, which connected the solar wind information and ground-based radio observations.

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8.9 Commission J

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Radio astronomy in Japan began in the late 1940s and early 1950s at the Tokyo Astronomical Observatory (now the National Astronomical Observatory of Japan), Osaka University, the Radio Research Institute, and Nagoya University. The research began with solar radio emission which is strong and easy to observe, and gradually evolved into radio observations of object beyond the solar system.

In the field of solar radio observation, various and pioneering radio telescopes were constructed in various parts of Japan from the 1950s to the 1960s. The Solar-Terrestrial Environment Laboratory of Nagoya University constructed a 3.75 GHz solar radio interferometer (1967), and the Tokyo Astronomical Observatory of the University of Tokyo constructed a 160 MHz solar radio interferometer (1970). The Nobeyama Radio Heliograph was constructed in 1992, and real-time radio solar images are obtained at 17/34 GHz.

In the field of astronomical radio observation, the 6 m millimeter-wave telescope was constructed in 1970. This was the catalyst for leading the Japanese radio astronomy to millimeter waves. In parallel with the construction of the 6 m telescope, a 45 m large radio telescope plan was conceived, and construction began in 1978 as the Nobeyama 45m radio telescope. Nobeyama 45 m was completed in 1982 and was said to be the first large-scale equipment in the field of basic science made in Japan. The telescope is still the world's top-class sensitivity millimeter-wave telescope. With the 45 m radio telescope, various studies on interstellar molecules such as carbon monoxide molecules in the inter stellar space and star formation process have been carried out, which is now a feature of Japanese radio astronomy. In 1993, it was discovered that there was a black hole with large mass in the center of the galaxy NGC4258, which attracted worldwide attention.

At the Nobeyama Radio Observatory, a millimeter-wave interferometer consisting of five 10 m-diameter telescopes was also constructed. The 45 m telescope and millimeter-wave interferometer have raised the level of radio astronomy in Japan to the highest echelons. The millimeter-wave interferometer ended its operation in the 2000s, and the scientific research and technology cultivated were handed over to ALMA, a large-scale international joint research. The Atacama Large Millimeter / submillimeter Array (ALMA) is the world's largest millimeter-wave radio interferometer consisting of 66 millimeter-wave radio telescopes built in the Atacama Desert in Chile, with the participation of countries from all over the world including Japan. It is currently the most active radio telescope, and many researchers have used ALMA to achieve excellent results.

On the other hand, in the 1990s, VSOP, the world's first space VLBI, was realized. This performed VLBI observations between the artificial satellite HALCA, equipped with a deployable antenna with a diameter of 8 m launched by the Institute of Space and Astronautical Science (ISAS), and radio telescopes on the ground. The satellite was launched in 1997 and carried out VLBI observations with radio telescopes around the world until 2005, when the operation of the satellite ended. In order for terrestrial telescopes and artificial satellites to cooperate, it is necessary to have a structure in which radio telescopes from all over the world cooperate, and for that purpose, the Global VLBI Working Group (GVWG) was formed within URSI to support its operation. This achievement was reported by leader Hirabayashi at the Plenary Talk of the URSI General Assembly held in 2005, New Delhi. In the 2000s, the National Astronomical Observatory of Japan built an array of four VLBI telescopes (VERA) for astrometric observation in Japan. VERA is still observing and has developed into an East Asian VLBI observation network in collaboration with South Korea and China. In addition to the National Astronomical Observatory, a VLBI observation network (JVN) of universities organized by Kagoshima University, Ibaraki University, Yamaguchi University, etc. has been constructed and is still undertaking research.

The role played by the Nagoya University group in Japanese radio astronomy is very important. In cooperation with the Nobeyama 45 m and millimeter-wave interferometer, they built a millimeter-wave telescope with a diameter of 4 m on their own, and their research has been highly acclaimed internationally. In addition, a research group at the University of Tokyo built a submillimeter-wave telescope on the summit of Mt. Fuji to conduct pioneering research. The Waseda University group has built and is operating a unique interferometer consisting of eight radio telescopes with a diameter of 20 m in Nasu.

Japan's radio astronomy, which began with the observation of solar radio emission after the World War II, has reached some of the world's leading levels and is still developing strongly. Professor Tanaka (1978-80) and Professor Inoue (2003-05) chaired Commission J of URSI.

8.10 Commission K

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URSI Japan, Commission K research on Electromagnetics in Biology and Medicine has been growing since the 1980's, when human exposure to radiofrequency radiation safety guidelines were under development regarding by Ministry of Posts and Telecommunications (currently Ministry of Internal Affairs and Communications, MIC). The establishment of Commission K at the 23rd General Assembly (GA) in Prague in 1990 was a timely for research in this field in Japan, especially since the Kyoto GA in 1993 was the first opportunity for Commission K to organize sessions. Since this event, Japanese URSI-K has been very active and has played a central role in the academic activities in this field in Japan.

The first chair of Japanese URSI-K was Prof. Masao Saito of the University of Tokyo (1990-1993). He organized Japanese URSI-K as a scientific group covering both medical applications and safety issues of electromagnetic fields. Prof. Shoogo Ueno took over the chair for Japanese URSI-K in 1993. He served as the Vice Chair of URSI Commission K in 1996–1999 and as the Chair in 1999–2002. Japanese URSI-K have been contributing to the international URSI-K after Prof. Shoogo Ueno. Prof. Masao Taki of Tokyo Metropolitan University served as the Vice Chair in 2008–2011 and as the Chair in 2011–2014. Prof. Koichi Ito of Chiba University is now serving as the Vice Chair since 2017. Dr. Kensuke Sasaki was elected as the Early Career Representative in 2017.

One of the driving forces for Japanese URSI-K derived from the national project of the MIC promoting research on biological effects of electromagnetic fields (EMFs) and assessment methods for EMF safety. The national project started in 1997 and is still on going. Prof. Shoogo Ueno served as the first chair of the committee to promote the project from 1997–2007. The funding of this national project promoted the activity in this field and eventually the activity of Japanese URSI-K.

Japanese URSI-K is officially a part of the Science Council of Japan (SCJ). In addition to the official activities for SCJ, the members have organized another scientific group for more extensive activities than those of SCJ. This group is named Research Group on Electromagnetics in Biology and Medicine. This group hosts a symposium once and holds two or three meetings a year for discussion of matters for SCJ. The group also plays a role of a voluntary local organization for Bioelectromagnetics Society. The activity of this group enhances the activity of Japanese URSI-K. The chair of Japanese URSI-K holds the chair of this group and currently Prof. Jianqing Wang of Nagoya Institute of Technology is the chair.

9. Summary and Future Prospects

Satoshi Yagitani and Kazuya Kobayashi

The Japan National Committee of URSI (JNC-URSI) has taken the lead in conducting radio science research in Japan since its establishment in 1922. It has also conducted various national and international URSI activities under the auspices of the Science Council of Japan (SCJ) (since 1949) and The Institute of Electronics, Information and Communication Engineers (IEICE) (since 1993). The JNC-URSI has made significant contributions to various activities of URSI with several Japanese scientists serving as URSI Officials. Another important contribution of the JNC-URSI is the establishment of the triennial "Asia-Pacific Radio Science Conference" (AP-RASC) in 2001, which was substantially expanded as one of the URSI Flagship Meetings from 2016. Recently the "URSI-Japan Radio Science Meeting" (URSI-JRSM) was initiated to provide a regional scientific forum for radio scientists and engineers in Japan and the Asia region. It should be mentioned that following the 14th General Assembly of URSI in Tokyo, Japan in 1963 and the 24th General Assembly of URSI in

Kyoto, Japan in 1993, both of which were led to a great success, the 35th General Assembly and Scientific Symposium (GASS 2023) will be held in Sapporo, Japan in 2023.

In the coming decades, the JNC-URSI will continue to coordinate the radio science community in Japan, and contribute to various URSI activities, including research and supporting international activities. It is particularly important to attract and encourage young scientists to participate actively in the URSI community, through the international and domestic URSI conferences, as these young scientists will lead the next generation of radio science research in Japan and in the world.

Highlights of Radio Science in the Netherlands

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1. Introduction

The first General Assembly of URSI was held in July, 1922, in Brussels. At that time, only four Member Committees (MCs) were officially formed: Belgium, France, United Kingdom and the USA. However, several MCs joined URSI during the same year, including the Dutch MC. A striking development in subsequent years was the emergence of radio astronomy. The beginning of this new science was reported first at a meeting of the US MC in 1932 by Karl Jansky. During an investigation on atmospheric interference in communication systems, he recognized that noise-like signals were being emitted from the plane of our Galaxy, their strength being greatest from the Galactic center. This discovery had a profound impact on radio science in The Netherlands.

Well before URSI was founded, radio science already played a key role in long-distance radio-communication systems. Over time, radio-communication systems made an ever-increasing impact on society. In the mid-1980s, the desire emerged to have a wireless means to connect devices to a Local Area Network. This ultimately led to the Wi-Fi standard we know today. Interestingly, a group a radio engineers in Nieuwegein, The Netherlands, played a key role in these developments.

In parallel with the establishment of URSI, radio industry developed in the Netherlands in the third decennium of the 20th century. On the national level, the Nederlands Radio Genootschap (The Netherlands Radio Society, NRG, later NERG with E for electronics) was formed, May 1920; an austere society with Nobel Prize laureates Prof. H.A. Lorentz, Prof. P. Zeeman and Prof. J.D. van der Waals among its members. The goal was to enhance interaction between academia and industry on all aspects of radio, and it was quite successful.

These highlights of radio science and engineering are presented in some detail in this contribution. At the end of this contribution, we briefly touch upon the Dutch involvement and its efforts in the global URSI organization.

2. Radio Astronomy

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2.1 The Birth of Dutch Radio Astronomy

After the Second World War (WW2), radio astronomy, one of the new, technique-driven sciences spawned by wartime developments, became established in a number of countries including The Netherlands. In most countries, the discipline was developed and shaped by engineers. In the Netherlands, however, the situation was different. There, radio astronomy was in the hands of astronomers (in close cooperation with engineers and technicians). The problems being tackled in The Netherlands were first astronomical, then technical. The whole story began, however, a decade before WW2.

Around 1930, there was increasing interest in the use of radio frequencies for communication. One of the main players, the Bell Telephone Laboratories in New Jersey, asked their research engineer, Karl Jansky, to investigate the interference environment in the short-wave band around 20 MHz. In particular, Jansky was to look at frequency bands where naturally-occurring radio waves were weak, since this background radiation would be a limiting factor in determining whether faint communication signals could be detected at large distances. Jansky constructed an antenna suitable for scanning the horizon at about 15 m wavelength. The working of his instrument has been described thoroughly in several publications [1].

Jansky was both a good radio engineer, and a careful scientist. He detected "static" from local and distant thunder storms, much as expected. He also found atmospherics from unknown sources, including one type, which was always present, and followed a consistent daily pattern. It eventually became clear that the diurnal cycle adhered to timing, not of 24^h duration, but lasting 23^h56^m: the temporal pattern was sidereal, not solar. The most intense radio static came from the direction of the stellar constellation Sagittarius, which was interesting as it is the location of the center of the Milky Way. The nature of the radiation – the process by which it was produced – was a complete mystery; the Galaxy we see consists of stars and glowing gas clouds. Could the radio waves also have their origin in stars? Since the sun is a star, one might then expect a radio signal to reach us from the sun. However, in fact, none of the antenna records showed a hint of solar radio emission.

Having completed his investigation of radio static, Bell Laboratories assigned Jansky to other research, and the detection of extraterrestrial radio emission was not followed up. Although there were several proposals to continue studies of this radio emission from space, none of them received funding (at the height of the great depression, this was not too surprising). The field was open to anyone with time, a large space (Jansky's antenna spanned some 30 m), an interest in radio equipment and a bit of money. In Wheaton, Illinois, there was such a person: Grote Reber. He had the discipline of an engineer and the curiosity of a scientist. The backyard of his mother's house (also his residence) was just large enough for his project: the construction of a 9 m parabolic reflector and its supporting struts. In his spare time, Reber constructed a steel reflector that could be steered in elevation: a meridian-transit radio telescope. With his instrument (and after overcoming initial difficulties), Reber eventually confirmed the existence of Jansky's radio emission from the Milky Way, and began making the first maps of the radio sky at declinations $>-45^o$. His first astronomical publication on radio emission appeared in June 1940; Reber continued his measurements throughout the war. With the 1940 publication, the story took an unexpected twist.

Prof. Jan Oort, of Leiden University Observatory, was keenly interested in understanding our Galaxy, having studied it for nearly 20 years. From the motions of stars near the sun, Oort had shown how the kinematics could be unraveled. What one really needed, however, was information on the motion of stars near the galactic center, but obtaining this seemed all but impossible. Research in the 1930s had shown that the disk of the Milky Way was filled with dust particles that obscure its more distant reaches, and in particular mask the vital center, around which everything spins. Seeing through this dusty fog seemed impossible. An important clue to overcoming the obstacle was contained, surprisingly, in Reber's article, but it would only reach Oort by a circuitous path.

In May 1940, the Netherlands was invaded by Germany, and a number of American science publishers, with postal delivery in Europe were uncertain and suspended the dispatch of their periodicals. By autumn, Oort expressed his concern about the delayed deliveries to his former colleague Bart Bok (then working in America), who looked into the matter. An agreement was reached that would ensure scientific publications (like important astronomical journals) were sent to major European institutions despite the war. By December, the June issue with Reber's article had reached Oort. There are several facts that indicate the information about radio emissions from the Galaxy had an immediate impact. Oort sent the article to H. Rinia, a senior Philips engineer who had done some consulting work for Leiden Observatory. In his reaction, Rinia notes that the radio waves will penetrate atmospheric clouds as well (making observations of galaxies at radio wavelengths possible, even from the cloudy Dutch environment).

After this flurry of activity and interest in the possibilities offered by radio research of galaxies, several years of relative silence follow. While the trigger was Reber's 1940 article, it is unclear to what extent Dutch astronomers were aware of Jansky's work (most of which was published in engineering journals). There are hints in a 1977 interview that Oort might have heard of it before 1940. He spent most of 1939 visiting observatories in the U.S., and Jansky's discovery might well have come up in discussions. There is, however, no hard evidence that Oort was aware of it, and it seems that if he was, it did not make much of an impression on him.

There the matter rested for most of the war years. Oort pursued the problem of interstellar dust, its production and destruction. He got Henk van de Hulst, then a student of Prof. Marcel Minnaert, to participate in this research, and to that end he arranged an extended visit to Leiden in the first quarter of 1944. Minnaert (who was politically left wing) was taken hostage (as were other prominent Dutch citizens) from 1942 to 1944. Oort left Leiden for most of the war years, to

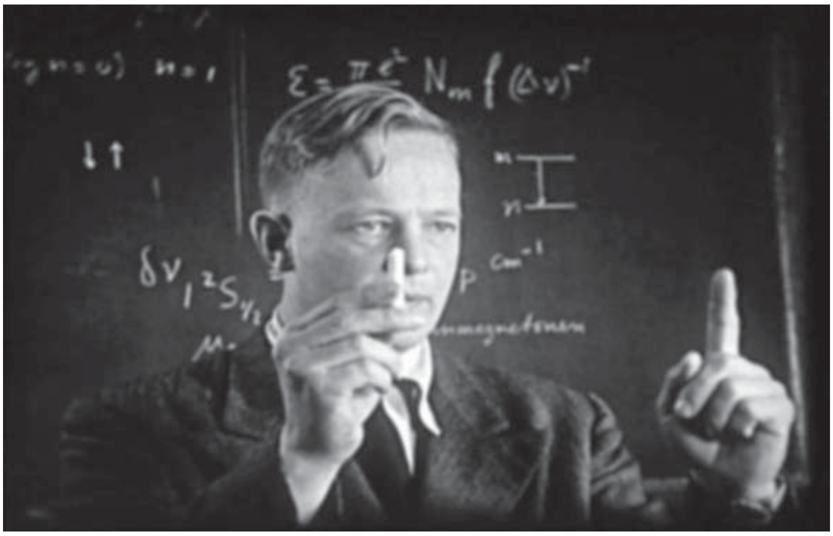

Figure 1. Van de Hulst explaining the 21-cm hydrogen line.

avoid a similar fate. From his undercover address he would regularly cycle the 100+ km to Leiden, to keep contact with colleagues and on astronomical developments. He kept busy researching a planned book on the Galaxy, a work which never saw the light of day. One can only imagine that sometime, while thinking about the book, the possible use of radio astronomy in galaxy studies may have occurred to him.

In the planning for Van de Hulst's 1944 visit, no mention is made of radio. It only came up after the visit had already begun. In Van de Hulst's own words:

> In the spring of 1944 Oort said to me: "We should have a colloquium on the paper by Reber; would you like to study it? And, by the way, radio astronomy can really become very important if there were at least one line in the radio spectrum."

That hypothesized line was, of course, the 21-cm HI transition, the likely detection of which was predicted by Van de Hulst at the April meeting. The 1944 colloquium in Leiden had as its title, *Radiogolven uit het Wereldruim* (Radio waves from space), and Oort had arranged for two speakers to discuss Reber's results. Dr Cornelis Bakker (a physicist with the Philips NatLab.) reviewed radio techniques. Van de Hulst considered the origin of continuum radio emission, then possible lines: recombination, and that of neutral hydrogen at 21 cm. Figure 1 shows Van de Hulst explaining the HI line.

The existence of a hyperfine transition in atomic hydrogen was already known, but its physical properties were rather uncertain. Moreover, the conditions in interstellar space were unclear: the line might appear in absorption or in emission. On top of that, hydrogen might be in molecular form (H_2), rendering it undetectable by radio. In view of all these uncertainties, Van de Hulst was cautious in what he said.

Oort, never one to let things stagnate, wrote to Bakker just four days after the Leiden Colloquium, thanking him for his contribution and asking whether Philips could build a receiver for the radio antenna reflector that was already taking shape in his mind. In his reply Bakker said that while there was interest at Philips, little could be done before the end of the war.

2.2 First Detection of the HI Line

What was needed to look for the 21-cm HI line? The antenna, which was only the most visible component required, would in Oort's original plan be constructed by the Observatory workshop. He may have reasoned that if Reber could construct a 10 m dish with his own labor and funding, then the Observatory would surely be able to build something larger using its manpower, and public funding. This was rather optimistic, and a year later he was in contact with a civil engineering firm. Oort may not have realized that it would be almost as difficult to acquire a sufficiently low-noise receiver: 21 cm was an extremely short wavelength at the time (Bakker indicated that Philips could build low-noise amplifiers only for wavelengths of 30 cm and longer). Finally, there was the problem of finding an excellent radio engineer, as Reber had strongly advised in correspondence.

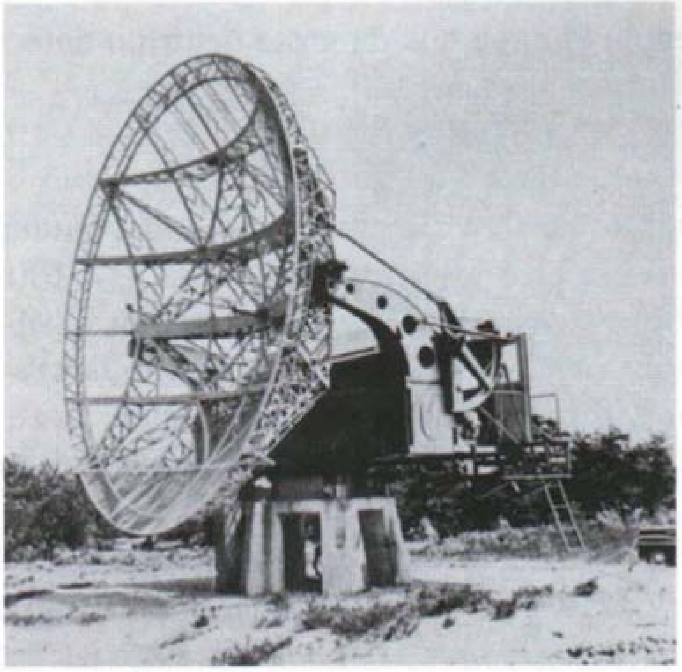

Figure 2. The Kootwijk Würzburg 7.5-m radar antenna, which observed HI (photo taken in 1951).

Despite the challenges, Oort and others began serious efforts to carry out radio astronomical research from the Netherlands. In 1946 or 1947, Ir. A. H. de Voogt, head of the Post Office Radio Division, appropriated a number of abandoned German Würzburg radar dishes and set up the country's first radio astronomy observatory near Kootwijk. He, Minnaert and Dr. Jaap Houtgast also helped to form a working group to study the ionosphere and radio emissions from the sun; by 1947, Oort was also involved in the discussions.

The Leiden physicist, Cornelis Gorter, who had made laboratory experiments with microwaves, was also interested in detecting the 21 cm line, and apparently began an independent project in 1946. By 1948, he had an engineering student from Delft, H. Ho, working on the problem. Meanwhile, De Voogt had suggested that Oort might use one of the Würzburg antennas for the 21 cm line search, and Gorter's and Oort's efforts were merged. Oort and Minnaert set up a Foundation for Radio Astronomy, which included representatives from Philips, the Meteorological Institute (KNMI) and the Post Office and later evolved into the Netherlands Institute for Radio Astronomy (ASTRON). Ho became its first employee and 1949 saw test observations being made on the borrowed Würzburg radar at Kootwijk, shown in Figure 2.

In 1950, another team was also looking for the line. Harold Ewen and Prof. Edward Purcell at Harvard had heard about Van de Hulst's prediction at a conference in 1949. Both had radar experience and came up with a simple solution to the antenna problem: a horn. Their equipment was similar to that of the Dutch, based upon a super-heterodyne receiver, with one important innovation: frequency switching was used to remove amplifier drift. In addition, certain electronic components, which Ewen had access to, were probably of higher quality. The line was detected on Easter weekend, 1951.

With the newly employed engineer, Lex Muller, the Dutch team detected the line just 6 weeks after Ewen and Purcell, and the results were published simultaneously. For Ewen it meant the completion of his Ph.D. thesis; he and Purcell did not follow up their detection. For Oort and his team, it was only the beginning of systematic studies, first of the Milky Way, and later of other galaxies.

2.3 Radio Telescopes in Dwingeloo and Westerbork

While the Foundation was working towards the detection of the 21 cm HI line, plans were already made for a 25 m class radio telescope to investigate the characteristics of atomic hydrogen in the Milky Way. Once the line was detected, some of the manpower could be switched to the 25 m effort. Observations with the 7.5 m Würzburg at Kootwijk continued, and a survey of the visible sky was made in 1952-1953. The data were reduced and interpreted under Van de Hulst's

Figure 3. Her Majesty Queen Juliana and Prof. Oort at the opening of the 25-m Dwingeloo Telescope in April 1956.

Figure 4. The Westerbork Synthesis Radio Telescope in full operation, 1978 (image courtesy of ASTRON).

guidance with the help of several students, and in collaboration with Muller and Oort (1954). By 1951, the 25 m antenna project was contracted to the civil engineering firm Werkspoor, and at the end of 1953 a site was chosen near the village of Dwingeloo. Construction began in 1954, and the Dwingeloo Telescope was opened by Her Majesty Queen Juliana in April, 1956, see Figure 3.

Oort once again used a two-track approach by starting the next large telescope project during the latter stages of its predecessor (in this case, the Dwingeloo Telescope). Always aware that angular resolution at radio wavelengths (around 1 arcmin hoped for) would usually be inferior to that of optical telescopes (where 1 arcsecond was possible), the plan was to build an array of some 5 km overall size, in collaboration with Belgium (and Luxembourg). The array would be in the form of a cross (or T), building on several successful radio telescopes in Australia, Canada and the US. It became the Benelux Cross Antenna Project (BCAP), to be constructed near the Belgian/Dutch border. The details of the project were described by E. Raimond [2]. In the end, Belgium withdrew from the project, and the instrument was modified, to become the Westerbork Synthesis Radio Telescope (WSRT, see Figure 4).

Opened in 1970, the WSRT originally consisted of ten fixed 25 m parabolic dishes at 144 m intervals on an east-west baseline. Two mobile 25 m antennas moved on a 300 m long track at the eastern end of the fixed-telescope array. At its initial observing frequency of 1415 MHz the telescope had an angular resolution of 25 arcseconds. To further improve the resolution, two additional movable antennas were constructed in the mid-1970s and placed on a second track east of the array, nearly doubling the baseline. In its almost fifty-year existence, receivers, feed systems, hardware and software have been vastly refined and improved, to keep the telescope at the forefront of radio astronomy. What was originally an analogue instrument is now fully digital. Improvements in instantaneous sensitivity (at L-band the system temperature has gone down by an order of magnitude) and increases in bandwidth mean that for 21 cm continuum observations, overall sensitivity has improved by over two orders of magnitude since the early observations in 1970.

2.4 Discovering the Low-Frequency Universe

At the end of the nineties and stimulated by studies in the US and of the European Space Agency, a new, low-frequency telescope started its early developing phase. This approach was based on the paradigm shift of using tens of thousands of low-cost antennas supported by massive signal processing and data-handling techniques. These efforts led

Figure 5. An Aerial photograph of the core of the Low Frequency Array (LOFAR) telescope near Exloo, The Netherlands (image courtesy of ASTRON).

to the Low Frequency Array [3] with its core in the Netherlands, shown on an aerial photograph in Figure 5. It started its first operations towards the first decade of this millennium to become International LOFAR Telescope in 2010. Operating in the 30 – 250 MHz frequency range (excluding the FM radio band), stations are located in 8 European countries with further extensions awaiting.

LOFAR stimulated the need to invest in High Performance Computing and Massive Data pipelining, archiving and algorithmic technologies. Together with another low-frequency telescope in Australia (the Murchison Widefield Array (MWA) [4]), LOFAR serves as a science and technology reference point for the low frequency part of the to-be-built international Square Kilometre Array telescope; e.g., with respect to calibrating the effect of the ionosphere. Because of the accumulated experience and improved understanding of the Sun-Earth system, including the effects of the ionosphere, LOFAR is now also engaged in space weather experiments besides its main focus on radio astronomical observations.

3. The Birth of Wi-Fi

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In the mid-1980s, NCR, a US based company, which specialized in terminals for financial institutions and retailers, wanted to meet their customers' needs. Retail customers wanted to connect their cash registers to the back-office computers without cables so that they did not need to route new cabling in case the floorplan changed. NCR[1] Corporate R&D decided to fund its R&D lab in Nieuwegein, The Netherlands, to perform the feasibility study because the computer-to-terminal protocol knowledge for Local Area Networks and radio technology was available at the lab.

At that time, office and business communication systems used wired Local Area Network technology carrying data rates exceeding 1 megabit per second (1 Mbit/s). No commercial wireless technology was available that approached that speed. To reach that goal, sufficient easily accessible radio bandwidth was needed. In 1985, the spectrum regulator for non-federal users in the US, the Federal Communications Commission (FCC), permitted the use for communications in three bands, without requiring an end-user license for the use of a radio transmitter, provided the radio used spread spectrum. Silicon circuits were only available in commercially viable prices for the lowest of the three bands (900 MHz)

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[1] In 1991 NCR was acquired by AT&T, in 1996 AT&T split into three parts and the corporate name changed into Lucent Technologies. In 2001 Lucent Technologies sold some of their business units and the corporate name was changed into Agere Systems.

Figure 6. The first prototype of a WaveLAN card (image courtesy of Vic Hayes).

so that was the band to be used in the 1985-1995 timeframe. The general feeling was that for the spreading some 125 to 255 bits sequence would be required. However, a member of the team found out that using an 11-bit Barker sequence, a speed of 2 Mbit/s could be achieved. This was a nearly a 10-fold increase over competing systems. The technique was realized in a commercial product called WaveLAN, which was publicly demonstrated for the first time in 1990 (Figure 6).

This breakthrough led to establishing the IEEE 802.11 standardization working group, which, for more than 10 years, was chaired by a member of the NCR-team. Apart from these achievements, the team contributed to improvement of the radio network by introducing several new features to the collision and MAC protocols. Once a standard was fixed (1997), Steve Jobs of Apple Computer decided to add wireless communications to Mac iBooks (1997). His requirement was that the retail price would be below $100[2]. WaveLAN was the only contender accepting the challenge and won the contract to supply the PC cards (Figure 7). After the launch at MacWorld on June 21st, 1999 the industry was shocked and the breakthrough was a fact.

In 1999, the so-called Wi-Fi Alliance was erected and established a certification mark called Wi-Fi for certified products conforming to the IEEE 802.11 standard. The Wi-Fi Alliance drives global Wi-Fi adoption and evolution through thought leadership, spectrum advocacy, and industry-wide collaboration. It helps ensure that Wi-Fi devices and networks provide users the interoperability, security, and reliability they have come to expect. Moreover, the Alliance organizes testing of Wi-Fi products by one of their independent Authorized Test Laboratories[3]. WaveLAN overcame many hurdles that empowered Wi-Fi later on. In the course of time, the 802.11 standard was extended many times. Initially the lower 2.4 GHz band was most widely used. Nowadays this band is becoming overcrowded and a switch to the higher 5 GHz band is on its way, enabled by the availability of silicon chips for these frequencies. In the near future even higher frequency bands will be assigned for those services, such as the 60 GHz band, enabling data rates over 10 Gbit/s.

Presently, the ubiquitous Wi-Fi technology is used to wirelessly connect all types of mobile devices to each other, and to the internet, and it operates in businesses, hotels, stations, restaurants, shops, public buildings, residences, in trains, and even in airplanes. This technology brings ease of access to information, supporting both the workforce as well as those seeking entertainment. In November 2018, the IEEE approved a so-called Milestone Award to WaveLAN, as the precursor of Wi-Fi. The corresponding bronze plaque, shown in Figure 8, is situated in the town hall of Nieuwegein.

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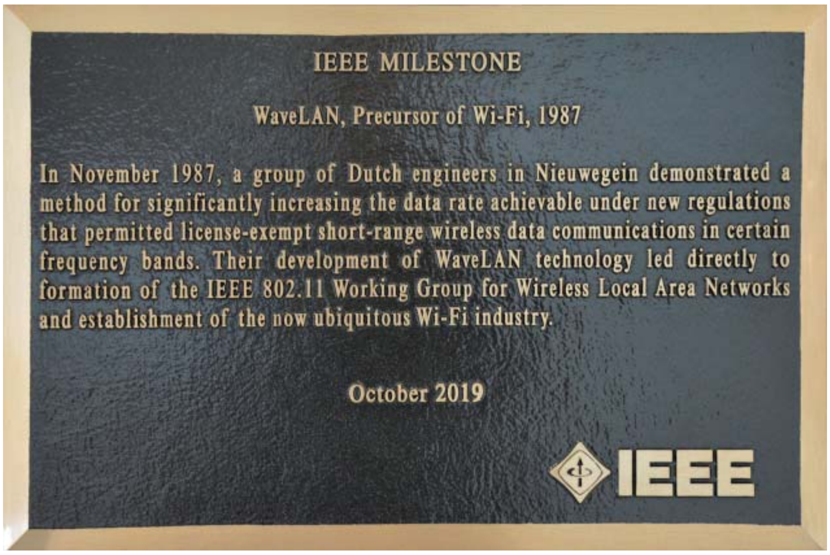
[2] The price point at the time of request was $500 for a 2 Mbit/s device. The device presented by NCR operated up to 10 Mbit/s.

[3] See the Wi-Fi Alliance site: https://www.wi-fi.org/

Figure 7. The Wi-Fi card in the 1997 Apple MacBook (left, image courtesy of Vic Hayes and Frans Florentinus) and the Apple Radio Access Point (RAP, right, image courtesy of Vic Hayes).



IEEE MILESTONE

WaveLAN, Precursor of Wi-Fi, 1987

In November 1987, a group of Dutch engineers in Nieuwegein demonstrated a method for significantly increasing the data rate achievable under new regulations that permitted license-exempt short-range wireless data communications in certain frequency bands. Their development of WaveLAN technology led directly to formation of the IEEE 802.11 Working Group for Wireless Local Area Networks and establishment of the now ubiquitous Wi-Fi industry.

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Figure 8. The bronze IEEE Milestone Award plaque for WaveLAN situated in the town hall of Nieuwegein (image courtesy of Wim van Etten).

4. Collaborations on EMC

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A key study area in radio science, of interest to industry, is the reliable operation of communication channels and control systems. In modern terminology: electromagnetic compatibility, or EMC. In the Netherlands, industry carried out much of the work in this area, for example at the research labs of Philips, Hollandse Signaalapparaten (now Thales), NLR, TNO and Dutch PTT, and in the military.

Over time, the world witnessed an ever-increasing penetration of electronics into society. The 1989 EU EMC directive stipulates that all electric and electronic equipment to be sold in the Common Market meets specific standards in the emission of, and immunity from, electromagnetic interference. In 1992, national legislation came into force in the member states, allowing a four-year transition period for the industry to adapt. As could have been expected, a large back-log became apparent in 1996 as many enterprises waited because of other pressing business.

Figure 9. A window sensor for the lightning magnetic field, considered as a thick slotted antenna. In the setup shown the flux capturing area is of the order of a2 where a is the long axis of the window for a horizontal current density in the fuselage. With the wire vertical, it is sensitive to a vertical current density, although with different sensitivity.

In the Netherlands, as well as in other countries, there were early initiatives to enhance general EMC awareness and knowledge. Dr. J. Goedbloed (then at Philips Natlab) started an in-house course in the 1980s with a few co-workers from different Philips branches. Because various components were manufactured at different Philips sites, Goedbloed realized that the need for EMC knowledge had to be spread, and because external parties were often involved, the spread should cover other manufacturers as well. With the foundation of PATO (Post Academisch Technisch Onderwijs - Post Academic Technical Education; now PAO; Postacademisch Onderwijs - Postgraduate Education), Goedbloed started a 5-day post-academic EMC course in 1984, to be held in November, assisted by several researchers from other industries, universities and organizations. To his great surprise and satisfaction, that course was over-subscribed (more than 100 participants) for many years in succession. It still runs yearly and its founding fathers still contribute, be it on a reduced scale.

Connections between equipment usually require cabling for power and communication. Apart from equipment manufacturers, installer firms could benefit from guidelines to assure EMC in large installations. Work that started in the 1980s finally led to the IEC document 61000-5-2 for Installation and Mitigation Guidelines. The topic “Earthing” was mostly written by P. Guillery from EdF, based on the grounding approach for nuclear power plants in France. The second part “Cabling and Wiring” was mostly based on recent research at Eindhoven University of Technology (TU/e). The IEC document was finally published in 1997 after the committee partners produced their own versions for local use. As a consequence of the IEC document, the EMC approach spread widely and contributed to the safety of installations worldwide; e.g., such as power plants, natural gas liquefiers, and ships. A recent, large-scale example is the fusion reactor ITER (originally, the International Thermonuclear Experimental Reactor), currently being built in Cadarache, France. The installation incorporates a general, common-grounding network to protect against lightning, power shorts and other potential failures involving large ground currents. The tested and reliable approach deviates strongly from the “single point grounding” approach advocated elsewhere.

Another successful application of EMC principles was in the EU-subsidized ILDAS project (ildas.nlr.nl). The acronym stands for In-Flight Lightning Damage Assessment System. The system, developed by 12 partners, detects the lightning current distribution over an aircraft. Reliable magnetic field sensors using a window-fitting sensor were proposed and developed by TU/e (see Figure 9) and the first data acquisition stages were developed by TU/e and NLR. The ILDAS is currently employed in factory test flights following the sensor layout shown in Figure 10. During the last few years, lightning research married with high-energy physics, and X-ray sensors, were brought together, which simultaneously detects the high-energy radiation of the lightning current. It is amazing that thundercloud electrostatic fields can accelerate electrons up to 100 MeV under atmospheric conditions. Collision of those energetic electrons with air molecules generate hard radiation.

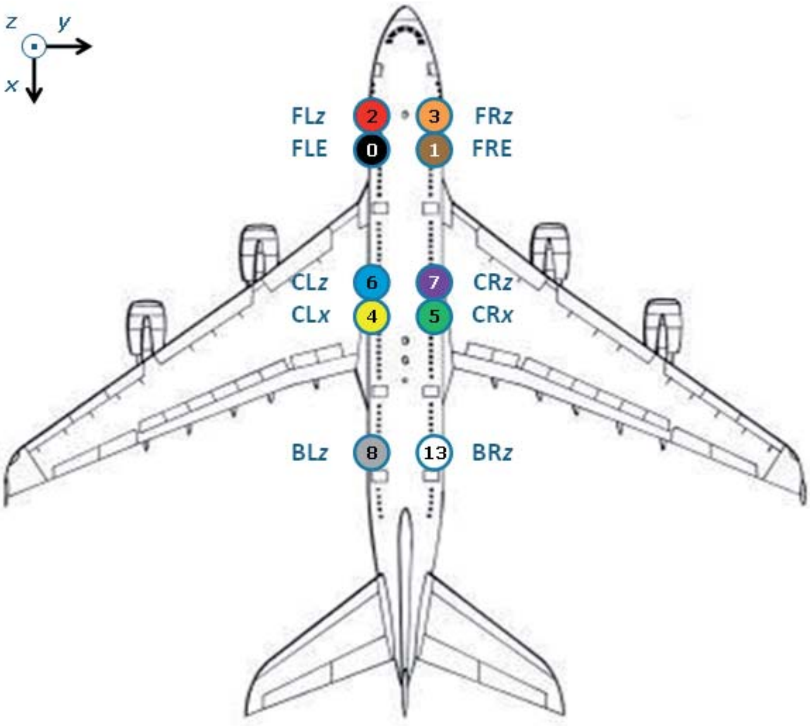

Figure 10. Position of the window sensors for the local magnetic field on an A350 aircraft.

The EMC techniques developed can also be applied on the small scale, to control electrical current flow and minimize undesired voltages in any circuit, no matter what the size. This makes EMC applicable over many specialized branches of electrical engineering. For instance, it is of little use to talk about EMC of power engineering when the installation is controlled by fast computers communicating via ethernet or wireless. Education remains of utmost importance. At the TU/e we started a general EMC course in 1988. The emphasis was on general physical and mathematical principles, rather than norms and regulations. The University of Twente followed a decade later. Several Dutch polytechnic schools have EMC in their electronics curriculum. The challenge is to give every electrical engineer the necessary basic EMC background, rather than rely on a consultant after manufacturing a device.

5. Activities of the Dutch Member Committee

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The Dutch Member Committee was one of the first Committees to join URSI. Prof. Balthasar van der Pol (see Figure 11), who was one of the founding members of the NRG, was a pioneer of radio science and one of the most prominent members of the Dutch Member Committee. During the second Assembly of URSI, in 1927, he called attention to the need for a separate Commission for such subjects as the general theory of triodes, new developments in the general theory of complex functions, modulation theory, and the theory of oscillations of linear and non-linear systems. Each of these topics was to become of foremost importance in the ensuing five years. The formation of a new Commission, on Radio Physics, in accordance with Prof. Van der Pol's recommendation, certainly contributed to the growth of interest and research in those fields. He served URSI for over 30 years and was an Honorary President from 1952 until he passed away in 1959. Wishing to leave a tangible testimony of her husband's devotion, Mrs. Van der Pol, with the unanimous agreement and gratefulness of the Board of Officers, gave URSI the possibility to award, at each General Assembly, the Van der Pol Gold Medal to a scientist whose researches have advanced one of the fields of URSI activity. Among the recipients of this URSI

Figure 11. Prof. Balthasar van der Pol (image courtesy Eric Berkers)

Award was another prominent Dutch radio scientist, Prof. A. T. De Hoop "for fundamental contributions to the theory of radiation and scattering of waves."

As testified by the historical overview in this contribution, radio astronomy has played (and is still playing) a dominant role in Dutch radio science. This is not only reflected by eminent Dutch scientists like Prof. I. de Pater, who was awarded the John Howard Dellinger Medal at the URSI General Assembly in 1984 for "work on noise of planetary origin, the magnetosphere of Jupiter, and shock waves in the magnetosphere of the Earth," but also by the list of Dutch members on the Board of Officers and Dutch chairs of URSI scientific Commissions, many of whom are affiliated with the Commission on Radio Astronomy. It is also reflected in the interest of the Dutch Member Committee in spectrum management and associated policy making organizations, not only at local level, but also internationally with representation at IUCAF (Inter-Union Commission on Frequency Allocation for Radio Astronomy & Space Science) and CRAF (Committee on Radio Astronomy Frequencies) meetings.

Spectrum management is just one issue that is of interest to both science and industry. Such joint interests are reflected in the membership of the Dutch Member Committee, which includes members from academia, (non)-governmental organizations, and industry. It is also reflected in collaborations with organizations like the Royal Institute of Engineers (KIvI) and the IEEE Benelux section in the organization of joint meetings of interest to the local community of scientists and engineers. Its members also participate in societal discussions in which radio science plays a key role, such as the impact of EM fields on human health. The involvement of several members in space weather research initiated the case for what is now the acting URSI EJGH-Inter-Commission Working Group on Space Situational Awareness.

The active members of the Dutch Member Committee value it most for the networking opportunities it provides. The main local event is the annual meeting with its Belgian counterpart: the URSI Benelux forum. This provides a platform for young scientists, such as Master and PhD students, to present their work. At the broader international level, a dedicated 2-day URSI BEJ workshop was organized in conjunction with IEEE-Africon, in 2013, supporting international science and engineering collaborations in Africa and, last but not least, the Dutch Member Committee has hosted the URSI General Assembly twice: in 1954, in The Hague; and in 2002, in Maastricht.

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New Zealand URSI-Related Research

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1. Introduction: New Zealand Research Institutions

The URSI-related research in New Zealand performed by government agencies was, prior to ~ 1995, carried out by the Department of Scientific and Industrial Research (DSIR), later to become NIWA (National Institute of Water and Atmospheric Research). The original universities (all founded in the 19th century and all except Otago, originally colleges of London University) that carried out URSI type programmes were (in geographical order from south to north): The University of Otago (in Dunedin), The University of Canterbury (Christchurch), Victoria University of Wellington, The University of Auckland, and the Auckland University of Technology (AUT) (founded in its present form in 2000).

Figure 1. Sir Ernest Rutherford (r) discussing ionospheric topics with Dr. J. A Ratcliffe, Cavendish Laboratory ~ 1935 (photograph by C. E. Wynn-Williams, courtesy of AIP Emilio Segrè Visual Archives).

The section of DSIR devoted to radio type research was the Physics and Engineering Laboratory, PEL (originally the Dominion Physical Laboratory, based at Lower Hutt near Wellington). In Christchurch there was the Geophysical Observatory (GO), which around 1970 joined PEL and became PELGO. A further section of DSIR was established near the small township of Lauder, some 120 km NW of Dunedin. It was from Lauder that the radar stations (at Bluff and Slope Point) on New Zealand's south east coast were operated.

In this account the research programme at each of the institutions will be covered, for clarity, in separate sections in order of the institution's operations base from south to north over the geography New Zealand.

2. Early Days: 1920 to 1950

This chapter opens with the URSI contribution of the renowned New Zealand researcher Sir Ernest Rutherford. Well known for his Nobel Prize for Chemistry, Sir Ernest Rutherford in 1920 (and so nearly coincident with the formation of URSI) became a foundation member of the UK Radio Research Board, and when in the United Kingdom (UK) organized early investigations in radio and ionospheric research (Figure 1) [1-3].

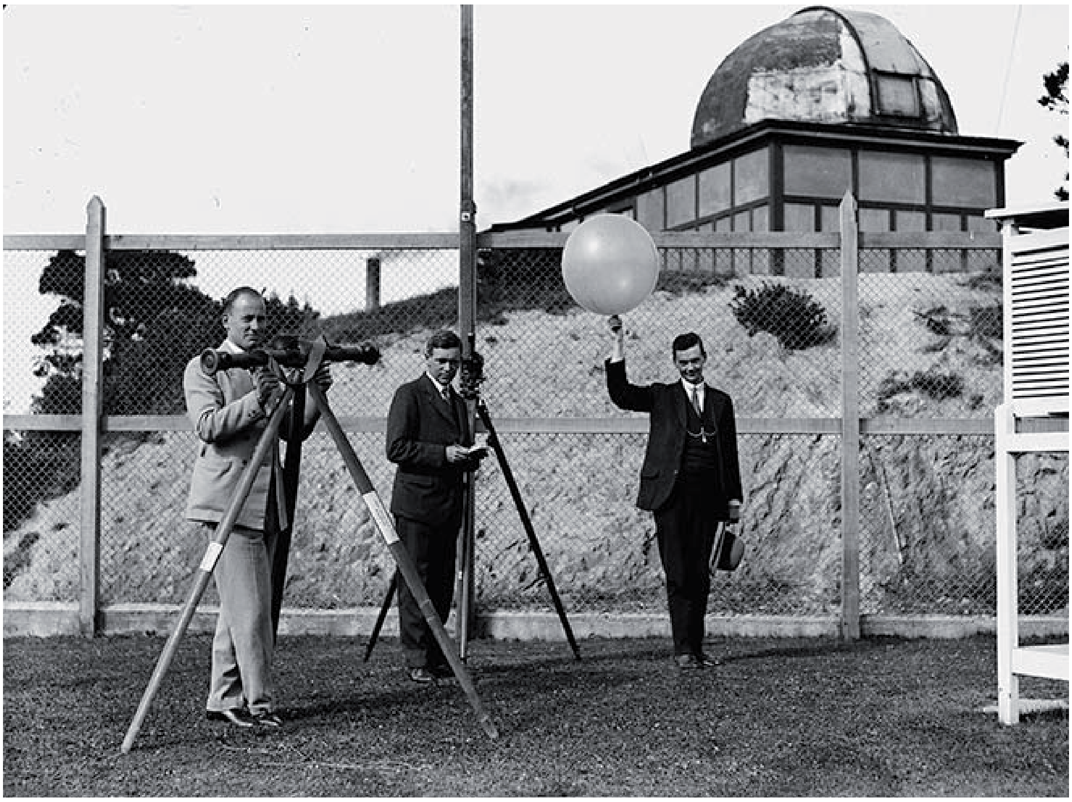

Figure 2. Dr. M. A. F. Barnett OBE (l) was director 1939-1962 of the New Zealand Meteorological Office (later Service) in Wellington ~ 1950 (source: New Zealand Meteorological Service).

The origins of radio public broadcasting in New Zealand can be traced to November 1921, when Robert Jack, Professor of Physics at Otago University produced voice and music from a transmitter built in the University's Physics Department.

A student in that Department was Miles Barnett (who had done design work on the transmitter) and who, with Sir Ernest Rutherford's encouragement, travelled to the Cavendish Laboratory, Cambridge, and in April 1924 enrolled with Edward Appleton as his research supervisor. Their work led to the recognition of the ionospheric F layer [4]. On returning to New Zealand Barnett, Figure 2, worked at the new DSIR engaged in radio propagation research, with a paper on observations during an eclipse [5], and subsequently became Director of the NZ Meteorological Office.

The first New Zealand based researcher was Percy Burbidge (a student of Sir Ernest Rutherford's) who, at Auckland University, started research on the field strength and direction of arrival of radio signals and atmospherics. An early student on this project was George Munro who produced the first NZ publication on ionospheric propagation [6] – he estimated the height of the ionosphere from the dawn-dusk changes in absorption of 500 kHz spark transmissions between Wellington and Auckland.

Fred White, a graduate of Victoria University, worked in the Cavendish Laboratory UK, with J. A. Ratcliffe, on ground-wave attenuation and in 1932 he joined Appleton at King's College. In 1937, White moved to the University of Canterbury, Christchurch, and established a radio propagation programme with support from Sir Ernest Rutherford and with the technical expertise of C.J. Banwell. John Banwell, Figure 3, had earlier designed mobile radio communication equipment to aid communication after the devastating 1931 Napier earthquake. An ionosonde was operating at Christchurch by October 1937 [7].

White studied the behaviour of the ionosphere using data on aurorae, radio fadeouts and magnetic storms, available from the adjacent Magnetic Observatory in Christchurch. He assembled observations of the southern Aurora logged by early navigators to the Antarctic, beginning with Cook in 1773, and later expeditions that had wintered on the continent in the 20th century, White was able to establish the position for the auroral zone. White also measured the critical frequencies of the F2-region and confirmed the anomalous diurnal and seasonal variations of the F2-region ionisation. He also made a series of fixed frequency measurements of the total absorption of waves reflected from the F-region and worked on the dispersion of radio echoes from the ionosphere.

Figure 3. John Banwell ~ 1940 (source: Trevor Hunt).

Figure 4. Dr. Elizabeth Alexander (source: Mary Harris).

George Peddie, at Victoria University, constructed a manually-tuned, pulse ionosonde and reported [8] virtual height measurements from June 1935 to December 1936. At Auckland University in the same year (1935) [9] Kreielsheimer and Brown (1937) had begun pulse height measurements. Collaborative measurements from the two manually-tuned ionosondes from October 1937 to April 1939 were published by White and colleagues [7].

Banwell worked in war-time Britain joining Ratcliffe's group at the British radar programme at the Air Ministry Research Establishment, renamed the Telecommunications Research Establishment (TRE) in 1940. One of the important projects on which Banwell was working in early 1940 was a transmission-line transmit-receive switch to avoid the problems of having two separate antennas for radar operations [10].

During WW2, the coastal defence operations NZ radar network had experienced problems due to two effects - anomalous tropospheric propagation, and solar noise. The leader of Radio Development Laboratory (RDL) Operational Research Section (ORS) was Dr Elizabeth Alexander, Figure 4, who was responsible for further research on these two

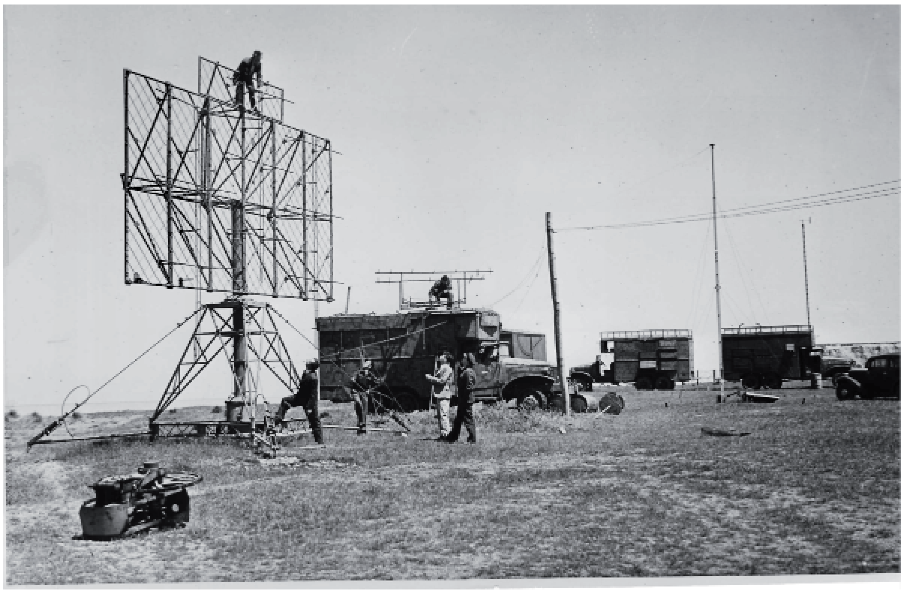

Figure 5. The Canterbury Project transmitting equipment installed at Wakanui beach (source: Martin Unwin).

important topics [11]. A radar propagation study using multiple frequencies ("The Canterbury Project") was set up on the Canterbury Plains with the operation centered at Ashburton aerodrome, transmit equipment at Wakanui beach (Figure 5), and multiple receive antennas at ground level, in aircraft, and on off-shore ships, to monitor how the local terrain could produce wind patterns responsible for ducting of radio waves [12, 13].

The other significant scientific study by Alexander [14] was based on observations at a Royal New Zealand Air Force (RNZAF) coastal radar station situated on Norfolk Island (~1000 km north west of mainland New Zealand). A solar source was obtained for increased radio noise at sunrise and sunset at one of the NZ stations by following the sun with a Yagi antenna leading to further investigations in October 1945 and reported by Alan Maxwell of Auckland University [15].

In the UK, Appleton recommended that the NZ DSIR carry out further ionospheric sounding (Ellyett, [16]). Ellyett also measured meteor atmospheric speeds at Jodrell Bank in the UK [17]. An Ionosphere Laboratory, directed by Ellyett, was set up within the Defence Development Section of DSIR in Christchurch and by the end of the war ionosondes were sited in NZ and at five islands in the wartime Pacific. The Ionosphere Laboratory and its network of ionosondes continued as the Christchurch Geophysical Observatory of DSIR (GO).

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Figure 6. The original International Geophysical Year (IGY) team at Awarua, Invercargill, before the move to Central Otago. (l-r, rear) Mike Gadsden, Bill Ireland, Bob Unwin; (front) Maurie Poletti, Des Rowles, Colin Lewis, Alex Ayton (source: DSIR).

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3. DSIR PEL – The Bluff Hill and Slope Point Radars

In 1957 a rotatable 55 MHz radar for auroral work, which was led by Bob Unwin (see Figure 6), was installed on Bluff Hill (Figure 7) near Invercargill (~47° south) on the southern coast of the South Island of New Zealand. Following his leadership of the Canterbury Project (see section 2) Unwin was prominent in guiding the radar research programme

Figure 7. The Bluff Hill radar (1957) (source: DSIR).

Figure 8. The Bluff Hill radar interior (1957) (source: DSIR).

Figure 9. The 55.3 MHz co-linear array for the Slope Point auroral radar (with Paul Johnston) ~ 1970 (source: DSIR).

over the following years. The site chosen overlooked the sea so that interference lobes enabled a precise measurement of the auroral echo heights [1]. The latitude was also important in permitting an association between the echoing regions and the geomagnetic field to be gained [2]. It was also proposed [3] that the site provided an opportunity to employ crossed-beam dual auroral radars to determine the ionospheric electric field in the auroral region.

The Bluff station, Figure 7, 8 was moved some 50 km east to Slope Point in 1963 and employed a 69 MHz rhombic antenna and later a 55.3 MHz co-linear array (Figure 9). The operation was managed from the Lauder DSIR station with the radar work continuing until 1985. The work was dedicated to studies of the aurora by radar with some representative work being: balloon flights with X-ray detectors simultaneous with radar signatures supported the two-stream instability theory mechanism as a process for diffuse echo formation [4]; patterns of auroral activity compared with records at the conjugate station at Anchorage in Alaska showed close association [5]; the association of wave and particle phenomena

Figure 10. The multi-frequency Unwin Radar at Awarua, near Invercargill (source: P. Wilkinson).

linked to convection electric fields and whistler measurements of convection activity during auroral substorms [6]; the examination of the ion-acoustic instability and drift-gradient instability mechanisms and their relation to micro-pulsations [3]; comparisons of pulsating radio aurora with absorption and magnetic data as influenced by hydromagnetic wave activity [7]; the recording of radio aurorae produced by shaped charge barium release observed at magnetically conjugate locations [8]; work on the characteristic pattern of radio auroral echoes at conjugate locations associated with the onset and initial development of the expansive phase of polar substorms [9]; the Doppler radar probing of the aurora [10]; the relation of diffuse radio aurora to proton and electron precipitation observed via the Isis 2 satellite [11]; studies of the height characteristics of Diffuse radar aurora associated with the eastward electrojet [12]; the relation of geomagnetic pulsations to radar auroral radar signatures in opposite hemispheres [13]; the investigation of the signature of gravity waves propagating in an ionospheric sporadic-*E* layer [14]; observations of Auroral radar ULF pulsations and the spatial characteristics of resonant toroidal mode oscillations [15]; and observations by satellite, auroral radar and magnetometer of transient ULF pulsations [16]. A compendium of progress in auroral sciences was presented [17].

The Slope Point radar ceased operation in 1985. During the rationalization of New Zealand DSIR science in the last decade of the 20th century, ionospheric research was curtailed and the radio aurora research was succeeded by the Unwin radar, operating between 8 and 22 MHz, Figure 10, and situated at geographic 46.51°S 168.38°E, near Invercargill, with a programme operated by the University of La Trobe in Melbourne Australia. The Unwin Radar is one of a pair of radars that, together with its counterpart, at Bruny Island in Tasmania, form the Tasman International Geospace Environment Radar (TIGER), which is part of the Super Dual Auroral Radar Network (SUPERDARN), an international network of radars for studying the upper atmosphere and ionosphere.

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4. University of Otago, Physics Department

Professor R. L. (Dick) Dowden, Figure 11, served as Vice President of URSI from 1987-1993.

Two URSI conferences have been held: URSI Conference on "Wave Induced Particle Precipitation and Wave Particle Interactions," held in Dunedin, New Zealand, 5-11 February 1989 and hosted by Prof. Richard ("Dick") Dowden; and "Waves in space plasmas" a Conference held in Hawaii, 7-11 February 1983, organized by R. L. Dowden and B. J. Fraser. Highlights of the conference were published in *Space Science Reviews*, **39**, 1984, pp. 227-253.

An extensive program, from the 1960s, of research mainly involved VLF propagation and included work on: the investigation of ionospheric sounder echoes caused by backscatter from sea waves (which led to the suggestion of sea scatter radar to probe types of sea state [1]); studies of radio emissions from Jupiter employed a polarimeter to suppress artificial transmissions [2]; the first accepted explanation for the mechanism for the generation of whistler mode chorus generated by radiation belt electrons [3, 4]; observations and elucidation of many features of the dynamic spectral shape and characteristics of whistlers [5-12]; a program was initiated for the ground reception of non-ducted whistlers [13]; carried out the first recordings of whistler mode signals remote from the conjugate point of a VLF transmitter [14, 15]; work on the VLF generation by modulation of the auroral electrojet by an ionospheric heater [16, 17]; the design of a RF heating beam scanning system which was used at the Ionospheric Heating facility at Tromsø in Norway [18-20]; identified phase perturbations termed phase Trimpis in association with whistlers [21, 22]; carried out a program on the identification and interpretation of VLF perturbations caused by red sprites [23-27]; operated a real-time global network (WWLLN) of VLF receivers to monitor lightning activity using Otago-designed and built instruments [28-34].

Figure 11. Professor R. L. ("Dick") Dowden carrying out tests at the Unwin Radar ~ 2010 (gratefully acknowledge Otago Daily Times newspaper).

In their work the Otago Group designed several specialized experimental facilities: earlier, Dowden had designed a modified tape recorder [35] he later termed termed "Dynagraph" for the analysis of VLF dynamic spectra; the "OMSK" and later the "OmniPAL" VLF receivers used for Trimpi studies as well as AbsPAL and UltraMSK receivers (see, for example [31, 36]); the development of TOGA which is at the main component of the global real-time World Wide Lightning Location Network (WWLLN) [29].

An extended series of studies carried out employing the amplitude and phase characteristics of VLF transmissions to further understand whistler mode see for example [37] and taking part in AARDDVARK (Antarctic-Arctic Radiation-belt Dynamic Deposition VLF Atmospheric Research Konsortia). Otago also hosts an Eötvös University Automatic Whistler Detector (AWD) system.

Also, studies carried out devoted to the lower ionosphere - VLF probing of the D region [38, 39] and a body of work employing satellite X-ray measurements on the influence of major solar flares on the structure of D region [40, 41].

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5. DSIR Geophysical Observatory (GO), Christchurch

The Geophysical Observatory (GO) was operated by DSIR from about 1950 to around 1992. It focussed on radio ionospheric modeling work (e.g., Geoff King (Figure 12), Harvey Cummack, Justin Cooper), on the radio Aurora (Bob Unwin, see Figure 6), and ionogram scaling (e.g., Arnold Stanbury), as well as the operation and analysis of geomagnetic observations (e.g., Lester Thomlinson).

The Christchurch ionosonde started life as an experimental endeavour at the University (at that time College) of Canterbury Physics Department by Fred White (see Section 2) and was located 1937-1941 on the University grounds and also at localities near Christchurch, Belfast and Lincoln. In the 1940s, the radar was installed on the coast at Godley Head (possibly in late 1942) and operated and maintained there with ionogram scaling by GO until 1987 when the operation was taken over by the University of Canterbury (see section 6). Thus, Christchurch had an operational ionosonde from January 1938 to June 2014.

An important role of the GO was the overall operation and maintenance of several vertical ionosonde radars with scaling carried out in Christchurch (e.g., P. J. A. “Paddy” Morris and Jean Bullen). The individual ionosondes were located, with dates, at the following locations: Auckland 1967 - 78; Campbell Island 1944 - 1985; Cape Hallett 1957 - 1964; Christchurch 1938 - 2014; Kermadec Island 1943 - 1972; Raoul Is 1943 - 1972; Rarotonga 1945 - 1980; Scott Base 1957 - 2020. The Scott Base facility is still (Oct 2020) in operation (automatic scaling) and operated by Antarctica New Zealand (and the Bureau of Meteorology, Sydney). The scaled ionograms for the network were communicated to the then Ionospheric Prediction Service (IPS) Sydney and also lodged with the World Data Centre B, UK. All ionosondes film records before ~ 1989 were stored in controlled conditions by the New Zealand Film Archives, in Wellington.

Figure 12. Dr. G. A. M. King at Scott Base ~ 1960 (source: Antarctica New Zealand).

The GO built up a skilled and experienced personnel devoted to ionogram scaling. Staff also cooperated with the Australian group and, for instance, Paddy Morris, GO, attended the IPS Operators’ Conference, Sydney, 28 February - 2 March, 1984.

An important role of the research operation was devoted to the interpretation and analyses of ionograms and theoretical work on the behaviour of the ionospheric regions. Early work was devoted to the major science event of the IGY, commencing 1956.

The atmospheric nuclear tests of 1958 and 1962 in the Pacific were monitored with multiple instruments - recordings via ionosonde, radio links, optical and seismic sensors [1-5].

Work was devoted to a wide range of topics: the modelling of the behaviour of the ionospheric regions and control by thermal, magnetic, physical, and chemical influences; ionospheric layer reflection processes, ray tracing, and geometrical effects; electron production function; the effect on ionogram traces of, for example, the causes of spread traces, and the influence of gravity waves on the ionization, and the consequences for ionogram interpretation [6 - 14]; modelling of multiple ion species in meteoric ionization [15]; and studies the importance of standardizing ionogram scaling [16]. Much work was carried out on ionospheric morphological studies; the short-term (hours) deviation of recorded parameters; diffusion effects; tilted surfaces giving rise to spread-F; range and frequency spreading; and ionization production and recombination processes [17-30]. Also, there was an extended programme of work on the interpretation of the auroral radar observations carried out by the Bluff and Slope Point radars [31-35], and a review of the progress in the field of the radio aurora [36] up to the end of the sixties.

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6. The University of Canterbury, Physics Department: Christchurch

Post-war research in the University Physics department included a significant contribution from techniques based on pre-war radiophysics, including radar (being developed in secret in many laboratories around the world), and ionosphere sounding with its technique of pulsed transmissions.

Figure 13. Dr. John B. Gregory ~ 1962 (source: the University of Canterbury).***

Figure 14. The layout of the Rolleston Field Station ~ 1960 (source: the University of Canterbury). Key: (1) Omnidirectional crossed dipoles for all-sky meteor radiant survey; (2) Broadside array for meteor radiant determination; (3) Broadside rotating (360 deg) array (first installed 1951); (4) Eight Yagi antennas for meteor radiant determination; (5) Receiver and recording building for 69 MHz; (6) COL 200 MHz radar originally at Wigram RNZAF base; (7) Housing for the 69 MHz GL Mk 2 transmitter; (8) Yagis for meteor radiant determination; (9) Broadside array for meteor radiants; (10) Broadside 1.75 MHz TX array for partial reflection radar; (11) The 1.75 MHz circular polarisation receiving array.

6.1 The Atmospheric Radar at Rolleston

John Gregory (Figure 13) had worked with radar in the RNZAF during the war. This had given him the expertise to build a high-power, ionospheric sounder with a high-gain antenna on a fixed frequency of 1.75 MHz. It was installed at the Rolleston field station (44° S) of the University of Canterbury (Figure 14, 15). He found reflections from heights of 95, 85, 75, 67 and 55 km [1 - 5].

Gregory was interested in the winter anomaly in ionospheric absorption, which had been reported by Appleton in 1937 [6]. The relevant region was the D-region [7, pp. 58-70], below the E-Region, and labelled the "middle atmosphere" by Watt in papers [8, 9] that were the cover story for the development of British radar at Orfordness and Bawdsey. There

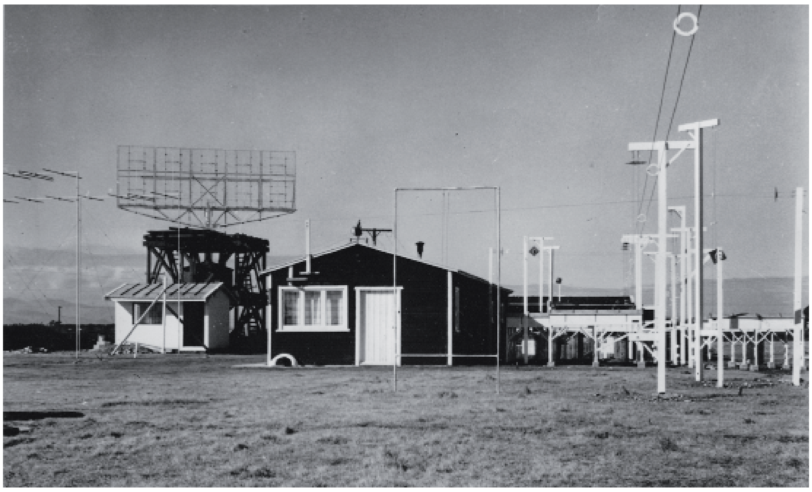

Figure. 15. Rolleston Field Station: (l-r) part of the 69 MHz meteor radiant array, GL2 rotating antenna for the meteor programme, main building housing the 69 MHz receiving-recording and winds (source: the University of Canterbury).

Figure 16. The Stratospheric-Tropospheric radar at Birdlings Flat (source: the University of Canterbury).

was increasing evidence that the winter anomaly was caused by dynamical events in the neutral atmosphere and also an association of enhanced absorption on certain winter days with echoes from low heights [10].

Due to the favorable geography it was possible for Seed [11, 12] to make radar observations of the Aurora Australis from Rolleston.

6.2 Atmospheric Radars at Birdling's Flat

In 1961, Gregory established a new site at Birdling's Flat (south of Christchurch) with equipment similar to his original (1.75 MHz) radar at Rolleston for the measurement of atmospheric electron densities [1 - 5, 13-21]. At first, electron densities were measured using the technique developed by Gardner and Pawsey [11, 14-16]. Later on, more sophisticated techniques were used [22-25].

Figure 17. Dr. Clif Ellyett ~ 1960 (source: the Royal Society of New Zealand).

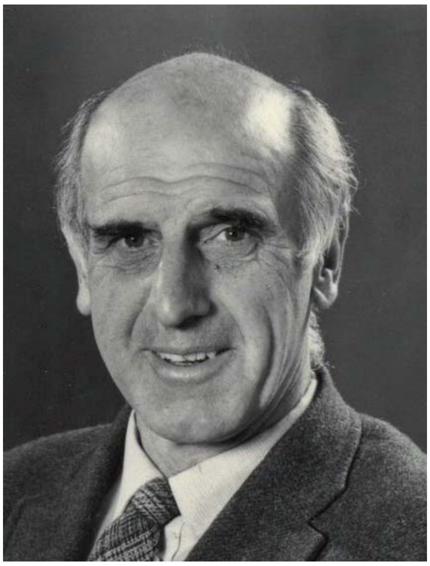

Figure 18. Dr. Bob Bennett (source: the University of Canterbury).

Figure 19. Meteor radar transmitters at the Birdlings Flat site (source: the University of Canterbury).

Fraser [26-28] installed a spaced-receiver array to investigate whether winds at the reflection height could be measured from the partial reflections like the technique used earlier on the total reflections [29]. This proved to be correct [7].

In the following years more spaced antenna partial reflection wind radars were established around the world, supplementing the meteor wind radars already in operation. There began "campaigns" at many sites to yield reference datasets for global-scale winds and atmospheric tides; comparison with reference atmospheres [30-35]; and joint satellite observations [36-39].

Other features of the mesosphere (D-region) studied were: the statistical properties of the partial reflection echoes [40, 41]; ionospheric/stratospheric coupling [42-44]; the height of airglow [45]; spatial correlation of winds [46], and 2- and 5-day waves in the mesosphere [47, 48].

Other radar techniques were established at Birdlings Flat [49-53] and a dedicated 42.5 MHz Stratospheric-Tropospheric radar (Figure 16) was constructed [54-56].

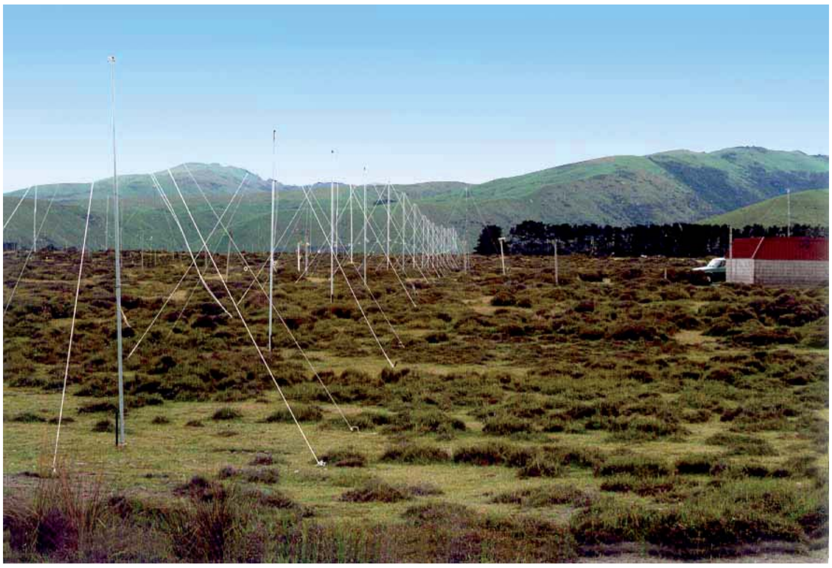

Figure 20. The 27 MHz collinear transmitter array at Birdlings Flat for meteor trajectory and orbit mapping ~ 1995 (source: the University of Canterbury).

Work was carried out on the analysis of long-term ionosonde data (for example [57]) and on a triple ionosonde array study of the dynamics of sporadic E [58].

6.3 Radar Meteor Programme

At the Rolleston Field Station, at the commencement of experimental work in 1951, Clif Ellyett (Figure 17) had begun the development of a meteor radar, using a GL MkII 69 MHz unit, to investigate meteor astronomy, assisted by colleagues Roth, Bennett and Keay.

The meteor programme was extended by Jack Baggaley and Bob Bennett (Figure 18) with work including: the meteoric ionization control by the geomagnetic field [59], the life of meteoric plasma [60]; the effects of meteoroid ionization of the propagation of LF [61], and the modeling of radio wave reflections from meteoric ionization columns [62].

A radar system was operated (1989-2005) at the Birdlings Flat site for the tracking of meteors to determine the atmospheric trajectories and hence the orbits of interplanetary meteoroids. The 27 MHz radar system employed 100 kW pulse transmitters (Figure 19) and orthogonal narrow beam co-axial antenna arrays oriented NS and EW with the transmitter arrays (Figure 20) (400 m long) having different electrical lengths from the receiver arrays to reduce side-lobes of the overall system. Two remote sites, ~ 8 km distant, equipped with similar receiving arrays, with UHF communication links, provided the required in-atmosphere meteor velocities [63].

Figure 21. The Christchurch ionosonde when operating from Eyrewell, 1990 (source: the University of Canterbury).

6.4 Ionosonde

In 1987, with the closure of the DSIR PELGO, the University of Canterbury took over the operation and maintenance of the Christchurch ionosonde when it was relocated (Figure 21) to Eyrewell Forest, ~30 km north of Christchurch. The IPS-42 ionosonde was replaced from Aug 1994 to Oct 2011 by an IPS-4D; and in May 2012 to Jan 2014 an IPS 5D; then from Jan 2014 to May 2014 a CADI. Land closure forced the termination of the installation in May 2014.

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Figure 22. A general view of Scott Base, Antarctica (source: Antarctica New Zealand).

Figure 23. The Scott Base ionosonde mast (source: the University of Canterbury).

7. The University of Canterbury, Physics Department: Scott Base

Following the success of the Canterbury based radars for measuring ionization and neutral-atmosphere winds below the E-region (lower thermosphere and mesosphere), similar radars employing the partial reflection mode were installed over two periods at Scott Base (latitude 78° S) (Figure 22) with work on motions of time-scales from gravity waves to mean winds. An ionosonde (Figure 23, 24, 25) was operated at Scott Base under the New Zealand Antarctica programme from 1957 to the present, with Canterbury University providing close monitoring together with the Bureau of Meteorology, Sydney, from 1993.

The first Antarctic study at Scott Base was undertaken by John Gregory during and after the period of the IGY [1-4]. A further extended program was initiated in 1982 to the present [5-8] where work was devoted to delineation the mean winds [9-12]; tides [13-17]; gravity waves and other atmospheric oscillations [14, 18-21]; planetary waves [22-24], and mesospheric dynamics [25, 26].

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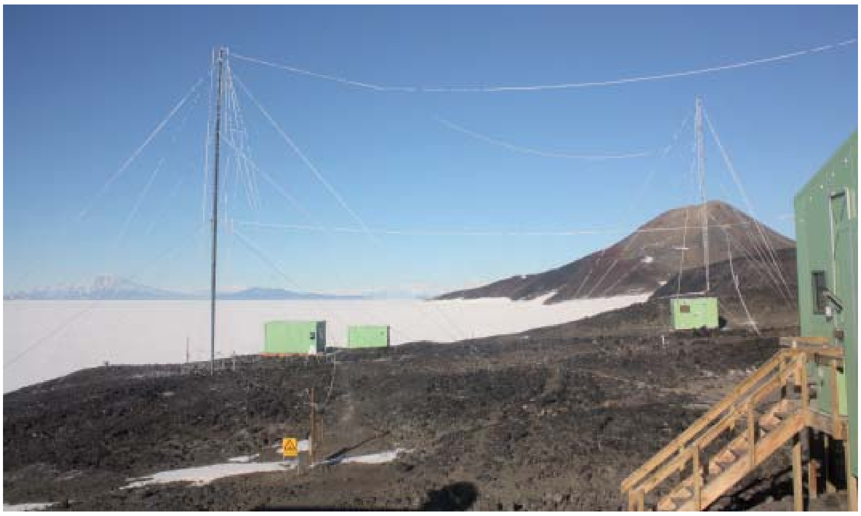

Figure 24. The Scott Base ionosonde mast (l) and winds radar mast (r) (source: the University of Canterbury).

Figure 25. The Scott Base ionosonde (source: the University of Canterbury).

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8. DSIR Physical Engineering Laboratory, Wellington

Within the DSIR, the Dominion Physical Laboratory was founded in 1939 and renamed as Physical Engineering Laboratory (PEL) in 1964. The PEL headquarters were at Gracefield, Lower Hutt, in the Wellington region. Observational operations and recordings were made and were available from field sites at Gracefield, Bluff, Slope Point, Lauder, and Scott Base and Halley Bay (British Antarctic Survey) in the Antarctic. Historically, PEL carried out a broad spectrum of ionospheric, auroral, and magnetospheric research. In addition to the radars operated near Invercargill (see section 3), riometers were operated at Lauder, Campbell Island and Scott base.

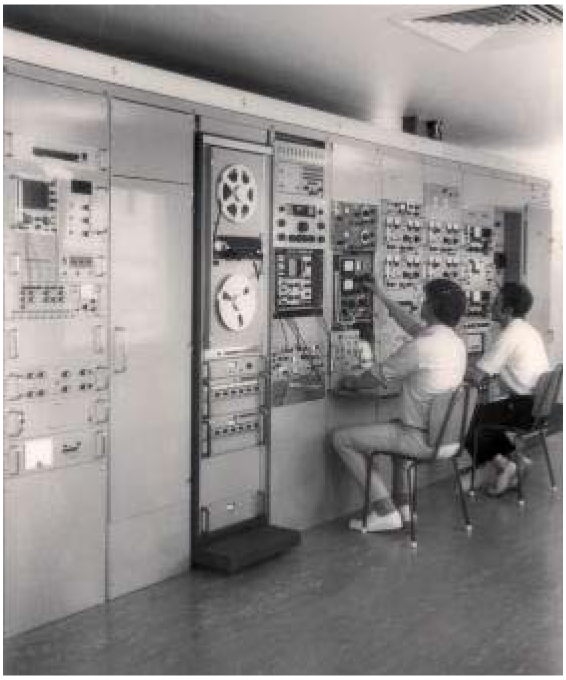

Figure 26. The Alouette/ISIS ground station at Lauder with personnel Pat Holm (l) and Alan Creswell (source: DSIR).

The Lauder station was the principal observational site. A telemetry system was operated monitoring beacon transmissions from the Alouette/ISIS satellite programme (1969-~1985, Figure 26), In addition, several conventional instruments were operated: a riometer, operating at 40 MHz, from 1962 and later 30 MHz; a magnetometer; HF radio propagation - measuring azimuth of arrival; Whistler recording; VLF propagation; and the station hosted an all sky camera, multiple bandpass photometers, and a high dispersion grating spectrometer and a polarimeter.

Much work was devoted to whistler and chorus [1-9]. The department also monitored the effects of high-altitude explosion tests [4, 10].

Recognizing the difficulties of constructing radio antennas at VLF, due to inefficiency arising from the physical dimensions of practical radiators, work was carried out on making use of geographical km-size features to aid in the construction of a loop antenna [11, 12]. In earlier experiments, the heating facility at Ramfjordmoen, near Tromso, Norway, was used to modulate the auroral electrojet at frequencies in the ELF/VLF range, and used it as an antenna to successfully excite the Earth-ionosphere waveguide. The results were modelled [13-16] using wave-guide mode theory. Further studies were carried out generating ELF and VLF radio waves in the ionosphere, using powerful HF transmitters as ionospheric heaters, and diagnostic facilities like EISCAT incoherent scatter radars [17-22].

The Earth's magnetosphere is highly structured, both in the magnetic field and its plasma characteristics, which influences the propagation of plasma waves, especially ultra-low-frequency (ULF, mHz) waves. With further work, these waves may then be used as diagnostics of the magnetospheric system [23].

Several other topics dealt with were: e.g., topside ionosphere changes during magnetic storms [24]; the analysis of ground-based magnetic field data and fixed-frequency VLF signals propagating in the whistler mode, and magnetospheric hydromagnetic waves [25-28]; comparisons were made between magnetic disturbances in the magnetosphere and those recorded at ground level and monitoring ground VLF signal from powerful transmitters propagating in the whistler mode over ionospheric ducts and recorded at the ground. Some of these recordings were characterized by large oscillations in the Doppler shift of the ducted signal, revealing the action of electric fields on micropulsation events [29-33]; and investigation of the magnetic perturbations associated with standing Alfvén waves in the coupled magnetosphere-ionosphere system [34-36].

Sea-surface Doppler microwave resonant Bragg scattering observations were made of short surface gravity waves [37, 38].

Using scintillation observed on VHF signals from the beacon satellites, recorded at multiple stations, ionospheric irregularities were identified [39-45]. The distribution of small-scale irregularities observed from high-latitude ground stations was mapped and their geomagnetic control in the Antarctic ionosphere demonstrated [46-48]. Recording both amplitude and phase information of scintillation records from beacon satellites (yielding a hologram) were used to deduce irregularity dimensions [49-50].

In 1992, the Crown Research Institutes Act was passed and the National Institute for Water and Atmospheric Research (NIWA) was created, with its head office in Auckland, as part of a government initiative to restructure the science sector. NIWA personnel largely came from the break-up of the DSIR, where PEL resided, and the Meteorological Service of the Ministry of Transport, and was later joined by other groups.

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9. University of Auckland, Physics Department

The idea of measuring the radio signals transmitted from the massive broadcasting system located at Rugby, UK, to New Zealand, on the opposite side of the globe, was first suggested, in 1938, by Lord Rutherford to his former student Percy Burbidge, the first Professor and Head of the Department of Physics in Auckland University College, that became the University of Auckland. Burbidge was able to secure funding from DSIR and prototype equipment was built but operations were stopped by the onset of war. In 1945, just before the end of the war, interest in the work was renewed by DSIR since radio waves reflected from the ionosphere were still the only method of communicating with Europe and America.

With the arrival of the United States Airforce, at Ardmore (some 30km south of Auckland), during the war, the equipment was moved from the pre-war RNZAF Seagrove Site to Ardmore to help set up reliable communications to the USA. This was in the aftermath of serious communications problems between Hawaii and the USA.

Radio research was guided strongly by Harry Whale (Figure 27) - his lifetime work at the Radio Research Centre (RRC) was seen as being critically important for New Zealand as, in the days before satellites, long-distance radio was key to keeping New Zealand in communication with the rest of the world. There was a problem in that there are (for example) no pathways between the UK and New Zealand that does not include a polar region, where ionospheric radio propagation is problematic, and was certainly not understood at the time. Any propagation path is complex, with multiple hops between the ionosphere and the surface, but this added complexity made the theoretical analysis of the problem intractable. The RRC was set up to investigate radio propagation models, including surface and ionospheric reflections, and measurements from these [1 - 8].

The RRC used three principal field stations at Ardmore, Seagrove, and Awarua (near Invercargill). Ardmore and Seagrove had rotating interferometers, [9] devised by Harry Whale, that allowed the arrival patterns of signals to be measured even when the signals were so weak as to be in the noise floor.

Under Harry's leadership the RRC was outstandingly successful, to the extent that Harry was in demand internationally for reasons other than long-distance radio propagation. He was, for example, invited to Goddard Space Centre, by Sir William Pickering, for work on why rockets passing through the ionosphere create absorbent holes such that all communication was lost and the rocket "disappeared" for a few precious seconds.

At the time of the atmospheric explosion tests in 1962 monitoring of the electrostatic potential near the ground was made [10].

John Titheridge (Figure 28) produced significant work on the ionospheric F region and exosphere [11-15], and recognised the possibilities of characterizing the ionosphere by detailed measurement of the radio signals from artificial satellites [16 - 18]. For real height analysis of ionograms, Titheridge devised the POLAN (POLynomial Analysis) program

Figure 27. Dr. Harry Whale, about 1990, holding a cake depicting a rotating interferometer (source: University of Auckland).

Figure 28. Dr. John Titheridge (source: David Titheridge)

[19] that employs polynomial real-height sections of any required degree and is able to fit any number of data points. This proved to be a very productive line of research that continued for many years and received world-wide recognition.

The other projects of the Radio Research Station expanded greatly and included the measuring and real time transmission of the dynamical performance of racing cars at nearby Pukekohe Motor Racing track thereby developing the technology that pioneered systems currently in use on Formula 1 racing cars.

Since 1990, the flat open agricultural site at the Ardmore research site has proved ideal for a variety of experiments in Geophysics, Atmospheric Science, Environmental Science, and Engineering. These include: weather radar; acoustic atmospheric sounding; trace greenhouse gas measurements; micro gravity mapping; soil conductivity measurements; ground penetrating radar; and seismic reflections. The weather radar initiative resulted in building several X-band radar systems [20-22], designed and constructed by the Physics Department, and deployed in several places in NZ and overseas. The best documented multi-radar imagery of the suspected but not measured seeder-feeder mechanism for orographic rainfall was obtained in the Southern Alps of NZ, as well as investigations of snow formation processes in the Snowy Mountains in Australia. The radar equipment has more recently been deployed in several different NZ cities to establish improved urban flash flood analysis and short-term forecasting named "AUSTIN". That radar equipment was purchased by Weather Radar New Zealand Ltd who continue to use and develop the radar system for urban flood forecasting and analysis.

Recently, two experimental glass houses and two former social state houses have been installed to facilitate a variety of experiments involving the use of solar hot water and solar voltaic panels to reduce greenhouse heating costs and improve the health status of the occupants of social housing. A recent new initiative by the Auckland University Electrical Engineering is installing radio-based smart electrical monitoring and control systems in the houses to make better use of New Zealand's electrical energy, including locally generated sustainable power sources.

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10. Auckland University of Technology (AUT): Radio Astronomy

Radio astronomy in New Zealand has links stretching back to the work of Elizabeth Alexander on solar radio emissions. In the 1940s a group of Royal New Zealand Air Force personnel were stationed on the Australian island of Norfolk Island. In March 1945 the sun was detected with the 200 MHz radar aerial on Mount Bates. The follow up work on these Type I bursts was organized by Dr Elizabeth Alexander, head of the Operations Research Section of the Radio Development Laboratory, Wellington [1].

In 1948, John Bolton and Gordon Stanley came to New Zealand as leaders of “The Cosmic Noise Expedition” to obtain rising and setting records of various radio astronomical sources at 100 MHz with the use of a sea-cliff interferometer brought from Sydney. Historical measurements made near Auckland (in Leigh and Piha) allowed, for the first time, the determination of accurate positions for several strong radio sources. Their optical counterparts were identified as a supernova

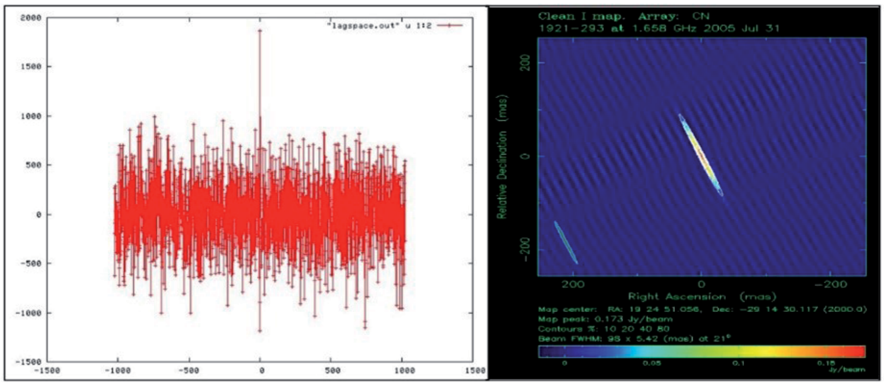

Figure 29. The first Trans-Tasman interferometer fringe (l) and image (r) (source: Sergei Gulyaev).

Figure 30. Jubilation by scientists from AUT University, Swinburne University and University of Tasmania following first fringes, demonstrating the success of the AUT VLBI system installed in the control room of the Mt. Pleasant Observatory near Hobart. This photo was taken by Prof. Steven Tingay soon after the sunrise on 26 August 2005

remnant, and external galaxies, and not "radio-stars," as previously had been assumed [2, 3]. This ground-breaking work is widely considered as the beginning of radio astronomy as science [4].

At the Auckland University of Technology (AUT), radio astronomy developments started in 2004, initially using an amateur radio telescope "BART-6": a 6-metre (in diameter) dish built by an amateur radio ham, Brent Addis, in Karaka. AUT Senior Lecturer, Tim Natusch, developed a receiving system and conducted VLBI observations, getting the first

Figure 31. Sir Ian Axford providing an inspirational speech at the ceremony of launch of the 12-m radio telescope at Warkworth (2008) (source: Sergei Gulyaev).

Figure 32. Finishing construction of the 12-m radio telescope at Warkworth, New Zealand, 2008 (source: AUT).

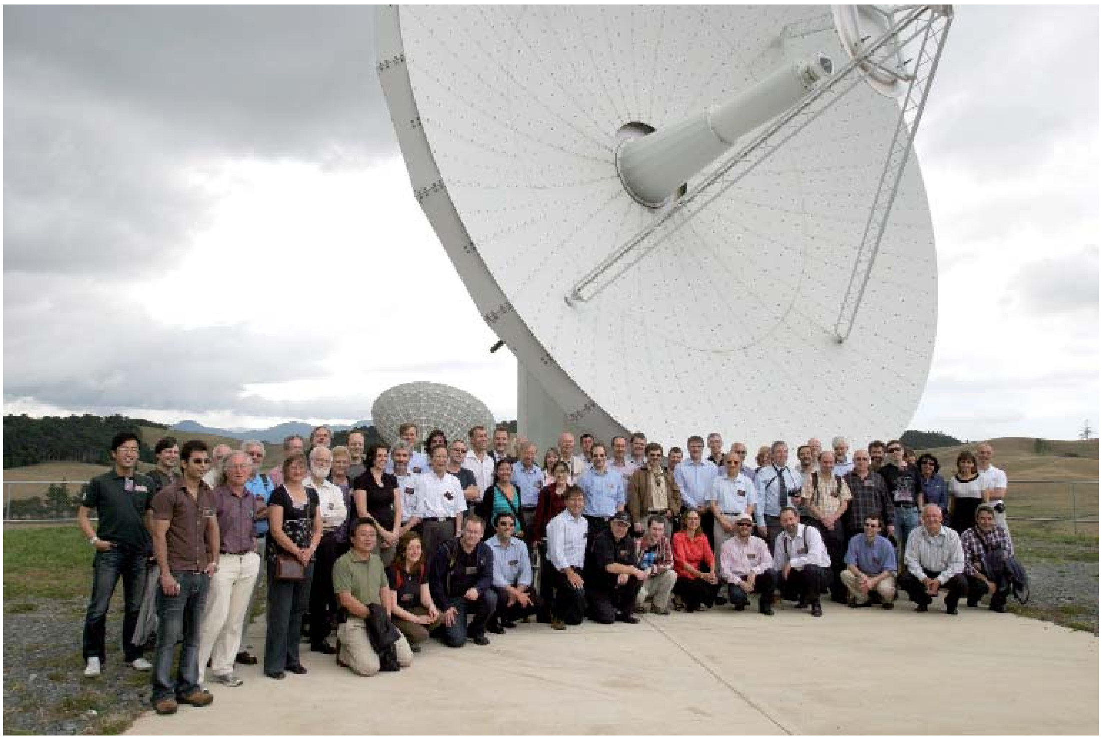

Figure 33. The 1st NZ SKA Conference in Auckland (February 2010). A group photo by the 12-m radio telescope (source AUT).

interferometry fringes (Figures 29 and 30) between BART-6 and radio telescopes in Australia and Japan [5]. The Centre for Radiophysics and Space Research (CRSR) was founded at AUT (Professor Sergei Gulyaev – Director, Sir Ian Axford – Patron, Tim Natusch – Deputy Director). In 2005, a joint Australia-New Zealand development towards participation in the Square Kilometre Array (SKA) project started, and the NZ SKA Committee (SKANZ) was formed with Professor Sir Ian Axford as the Chair (Figure 31).

Figure 34. First light of the 30-m radio telescope, Warkworth, 4 July 2014 (source: AUT).

In 2008, AUT purchased in the US, and installed at Warkworth, a 12-m radio telescope, the first professional radio telescope in New Zealand (Figure 32). The same year the Warkworth Radio Astronomical Observatory (WRAO) became a network station of the International VLBI Service for Astrometry and Geodesy (IVS). In 2010, the Institute for Radio Astronomy and Space Research (IRASR) was formed on the basis of the CRSR, and the first NZ SKA Conference took place in Auckland. The same year, Telecom NZ (currently Spark) provided its large (30 metres in diameter) telecommunications dish to AUT for conversion into a radio telescope (Figures 32 to 34).

Currently (Oct 2020), the AUT's Radio Astronomical Observatory operates 12-m and 30-m radio telescopes. New Zealand radio telescopes are capable of observing in L, S, C and X bands, they participate in global and regional VLBI observations, and work as a 2-dish interferometer. Research interests of IRASR staff include astronomical instrumentation, physics of galaxies and the interstellar media, radio spectroscopy, pulsars and neutron stars, planetary science, and space geodesy. New Zealand's radio telescopes are involved in a number of international projects and programs, including the SKA and IVS, they participate in radio astronomical observations of spacecraft and deep space missions of world-leading space agencies, such as NASA, ESA, SpaceX, JAXA, and took part in joint observations with the space radio telescope RadioAstron. IRASR staff supports the Astronomy and Space Science major of the Bachelor of Science programme at AUT.

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URSI Portuguese Member Committee: Contributions for the 100 years of URSI

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1. Introduction

URSI Portugal was created in the 1980s, and Joaquim Fernandes Patrício was the first representative of Portugal to attend the URSI General Assembly. At the time, he was the Director of Radiocommunications, at the Portuguese Post and Telecommunications Service, CTT, which was the former entity in charge of radio spectrum management in Portugal.

In 1981, he was formally appointed President of the Portuguese Committee of URSI, which was endorsed by the Ministry of Science and Higher Education. He held the position until 2003. The Committee logo is shown in Figure 1.

In 2003, URSI Portugal, which was then under the Minister of Science and Higher Education, transferred to ICP-ANACOM (Autoridade Nacional de Comunicações), which became the national institution adhering to URSI exercising responsibility for the National Committee and its specialized Committees, thus succeeding the GRICES, Office of International Relations for Science and Higher Education.

In 2004, the ICP-ANACOM's Board of Directors, appointed Maria Luísa Mendes, Director of Spectrum Management, Chairman of the Portuguese Committee of URSI and Helena Paula Prazeres, Consultant of that Directorate, Secretary of the Committee.

The Portuguese committee, over the years, is shown in Table 1.

In addition, since 2007, URSI Portugal also promotes a one-day workshop, where, each year, academia, industry and government bodies are brought together to explore radio activities, addressing different topics of interest to society. The full list of themes (in Portuguese) are presented below.

Table 1. The Portuguese Member Committee of URSI.

President	Engº Joaquim Fernandes Patricio Former Director of the Portuguese Radio Services (CTT-DSR)	Engª Maria Luísa Mendes Spectrum Management Director of ANACOM	
Secretary		Engª Helena Paula Prazeres ANACOM	
Commission A	Engº Armindo Custódio Mendonça Caetano Observatório Astronómico da Ajuda	Prof. Carlos Cardoso Fernandes Instituto Superior Técnico	Prof Nuno Borges Carvalho Instituto de Telecomunicações – Universidade de Aveiro
Commission B	Prof. Afonso M. Barbosa Instituto Superior Técnico (Instituto de Telecomunicações)	Prof. Custódio Peixeiro Instituto de Telecomunicações - Instituto Superior Técnico	
Commission C	Prof. José Nunes Leitão Instituto Superior Técnico (Instituto de Telecomunicações)	Prof. Antonio Rodrigues Instituto Superior Técnico (Instituto de Telecomunicações)	
Commission D	Prof. Francisco José Oliveira Restivo Faculdade de Engenharia (Depart. de Engenharia Electrotécnica e de Computadores) Universidade do Porto	Prof Leonel Sousa Instituto Superior Técnico (Instituto de Telecomunicações)	
Commission E	Engº Joaquim Fernandes Patricio Former Director of the Portuguese Radio Services (CTT-DSR)	Dr. José Pedro Borrego ANACOM Spectrum Control and Monitoring Centre of ANACOM	
Commission F	Prof. José Carlos da Silva Neves Instituto de Telecomunicações - Pólo de Aveiro Universidade de Aveiro – Campus Universitário		
Commission G	Prof. Carlos Cardoso Fernandes Instituto Superior Técnico	Capitão Tenente Eduardo Ludovico Bolas Marinha Portuguesa	Prof Pedro Renato Tavares Pinho - ISEL - Instituto Superior de Engenharia de Lisboa Instituto de Telecomunicações (IT-AV)
Commission H	Prof Armado Larcher E. Brinca Instituto Superior Técnico	Professora Maria Emília Manso Centro de Fusão Nuclear do IST	
Commission J	Engº António Amândio Sanches Magalhães Observatório Astronomico Manuel de Barros	Prof.. Luís Cupido Centro de Fusão Nuclear – Polo de Aveiro Instituto de Telecomunicações - Pólo de Aveiro	
Commission K	Dr. Joaquim Ribeiro Arenga	Prof. Pais Clemente Director of the Otorhinolaryngology Service Faculdade de Medicina do Porto Hospital S. João	

Figure 1. The URSI Portugal logo.

- 2018 - 12.º Congresso do Comité Português da URSI “Inteligência artificial e as ciências rádio”
- 2017 - 11.º Congresso do Comité Português da URSI “Novas tecnologias para a mobilidade”
- 2016 - 10.º Congresso do Comité Português da URSI “Comunicações em cenários de segurança e emergência”
- 2015 - 9.º Congresso do Comité Português da URSI – “5G e a Internet do futuro”
- 2014 - 8.º Congresso do Comité Português da URSI – “Drones e veículos autónomos: desafios do presente e do futuro”
- 2013 - 7.º Congresso do Comité Português da URSI – “Um mar sem fronteiras: desafios tecnológicos”2012 - 6.º Congresso do Comité Português da URSI – “Aplicações das ondas eletromagnéticas: da eficiência energética à bioengenharia”
- 2011 - 5.º Congresso do Comité Português da URSI “Detecção e medição de sinais rádio no futuro das radiocomunicações”
- 2010 - 4.º Congresso do Comité Português da URSI “Comunicações rádio pessoais: redes de curto alcance e RFID”
- 2009 - 3.º Congresso do Comité Português da URSI “Radiocomunicações: da Terra ao Universo”
- 2008 - 2.º Congresso do Comité Português da URSI “Compatibilidade Electromagnética e Novos Serviços de Radiocomunicações”
- 2007 - 1.º Seminário do Comité Português da URSI “Radiocomunicações - Novos paradigmas e impacto na saúde”

At these events an award is usually granted to Portuguese radio researchers to stimulate creativity and rigor in scientific radio research in Portugal. For such a purpose, the Portuguese Committee of URSI instituted the “URSI Portugal Research Prize” in 2009. Sponsored by ANACOM, the prize, worth four thousand euros, is now known as the “ANACOM - URSI Portugal Award”.

Seeking to encourage young authors, in 2011, ANACOM began sponsorship of the Best Student Paper Award, awarding five hundred euros to the best paper presented by a student, who is both the leading author of the paper and who makes an oral presentation of the scientific work at the annual Congress of the Portuguese Committee of URSI (Figure 2).

With the same objective, in 2015, ANACOM decided to establish the Best Student Poster Award, worth one thousand euros, to be awarded to the best poster presented by a student, who is both the poster’s first author and who presents the Poster during the Congress of the Portuguese Committee of URSI.

2. Radio-Telecommunication Milestones in Portugal

The Portuguese telegraphy network started in Portugal in 1853 and the public telephone networks of Lisbon and Porto were initiated in 1882 by The Edison Gower Bell Telephone Company of Europe Ltd [1]. In Portugal, the first experiments with wireless communications were conducted by the Engineering Regiment of the Portuguese Army in 1901. This led to the acquisition of 4 Telefunken stations in 1909 (2 fixed and 2 mobile) [2].

Figure 2. The workshop room and the prize award.

In 1925, Guglielmo Marconi and the Portuguese government signed a contract to create the "Companhia Portuguesa Radio Marconi (CPRM)" which had a monopoly of point-to-point radio-communication services in the Portuguese territories [3]. For seven decades, this company had the monopoly for intercontinental telecommunication services (ionospheric, transatlantic cables, and satellites).

On 1 March 1925, regular radio broadcast services started and, on 7 March 1957, television broadcast services (with black and white transmissions) started. Colour Television arrived 23 years later.

In 1974, CPRM satellite communications started. Terrestrial analogue mobile communications services (1G) were introduced in 1989, and the first GSM (2G) call was made on 17th May, 1992. Nowadays, 4G mobile communication networks are under deployment and 5G is envisaged for the near future.

3. Radio-Telecommunication in the University

Teaching telecommunication courses started in 1935 in Instituto Superior Técnico (IST), the engineering faculty of the Technical University of Lisbon. The first professor was António Manuel Bivar, an enthusiastic radio amateur, who was simultaneously the founder and first technical director of the Portuguese national broadcaster (Emissora Nacional). Courses started in the Military Academy in 1940, and in 1943, in IST, telecommunication courses were taught regularly by Paulo Brito Aranha. In IST, he was followed by José Correia Victorino, António Carvalho Fernandes and Manuel Abreu Faro [4]. Abreu Faro introduced modern telecommunication courses and taught them for almost four decades (1956-1994). In 1955, telecommunication teaching was initiated by Velez Grilo in the University of Porto. The other Portuguese universities started teaching telecommunications by the seventies or later. In 1974, the University of Aveiro created the first course on Electronic and Telecommunication Engineering, changing the panorama of telecommunication teaching in Portugal.

4. Radio-Telecommunication Research and Development Activities

There were no relevant telecommunication research and development activities in Portugal before 1950. In 1950, the Group of Studies on Automatic Switching (Grupo de Estudos de Comutação Automática) was created in Aveiro, a research group that had an important role in the development of the national telephone network and originated the "PT Inovação" R&D company in 1999. Starting in the seventies, some research and development activities were also carried out in other research centres at the Lisbon, Porto and Aveiro universities.

After 1950, there were also some MF and HF antenna development activities outside academy, mainly in telecommunication operators, such as CPRM, and radio broadcasters, such as Radio Free Europe [5].

Nowadays, the two main research and development institutions this area are Instituto de Engenharia de Sistema e Computadores (INESC) (founded in 1980) and Instituto de Telecomunicações (IT) (founded in 1992). These two institutions have a nationwide role, fostering cooperation between university and industry and gathering, presently, most of the researchers working in the URSI Commission B topics. The research topics carried out in these institutions can be obtained in their web pages (www.inesc.pt and www.it.pt).

5. Radio Propagation Activities

URSI commission G, in Portugal, promoted public awareness and understanding of specific radio science areas, which included applications and state-of-the-art technology that took advantage of ionospheric research.

The main objective was to stimulate curiosity; namely, to capture young talent to study these topics, and update interested communities, like the amateurs, who traditionally supported URSI in Portugal. Commission G has tried to fill a short-wave communications gap in the radio science community, by stimulating stakeholders to publicize on-going developments, project implementations and technology improvements.

Typically, published radio science research and funding are highly correlated with the economic interest in its associated spectrum. This is particularly evident in areas like 5G, where the massive numbers of potential users are paramount, explaining the associated number of papers, theses, patents, and budgets. Nevertheless, the beginning of the XXI century was a turning point for short-wave communications. Although far from being comparable to their higher sister bands, it still received an important boost from traditional Morse and basic telegraphy for long-range communications. Improved waveforms, support for IP services and, recently, wideband channels are some of the features that have resulted from a growing interest in alternative means to Satellite Communications (SATCOM) for providing Beyond Line-Of-Sight (BLOS) communications.

Lessons learned from the Iraqi war highlighted the western military dependence on SATCOM for planning and execution of operations, and its vulnerability to electronic warfare. On the other hand, growing interest in the Arctic Ocean, increasingly accessible due to climate change, exposed the inadequate high-latitude SATCOM coverage. Those are just two representative examples of important triggers that drove short-wave communications improvements in the HF band. Several USA military and NATO standards were developed to build up a full protocol stack that can provide support for IP-based services. From high-speed waveforms, which allow data rates up to 9.6 kbps in 3 kHz bandwidth channels, to datalink specific adaptations to the different IP clients, in the so called STANAG 5066, there are several examples of important technological advances that allow IP convergence and integration of services in federated radio networks.

Recently, WBHF (Wideband HF) communications were increasingly seen as the ultimate driver for a paradigm change in HF communications and a significant improvement in BLOS communications flexibility and capability. In the case of satellite jamming, or unavailability, it would be possible to rely on HF communications to support fundamental IP services with a remarkable user experience. Successful trials reported, with currently available products and prototypes, make WBHF a promising technology and the publicized data rates up to 120 kbps (or 240 kbps, for 48 kHz bandwidth) can potentially support service delivery that would not have been foreseen decades ago, and opens a door for WBHF to become a valid alternative to SATCOM.

Surprisingly enough, outside niche areas, some of these topics are not adequately recognized in radio communities. This is particularly the case in academia, where potential researchers could be attracted to enlarge studies, and produce theses and papers in these related areas. Technological developments are a simple and attractive way to promote awareness and understanding of this area, and stimulate interest in foundational studies like ionospheric physics (Figure 3).

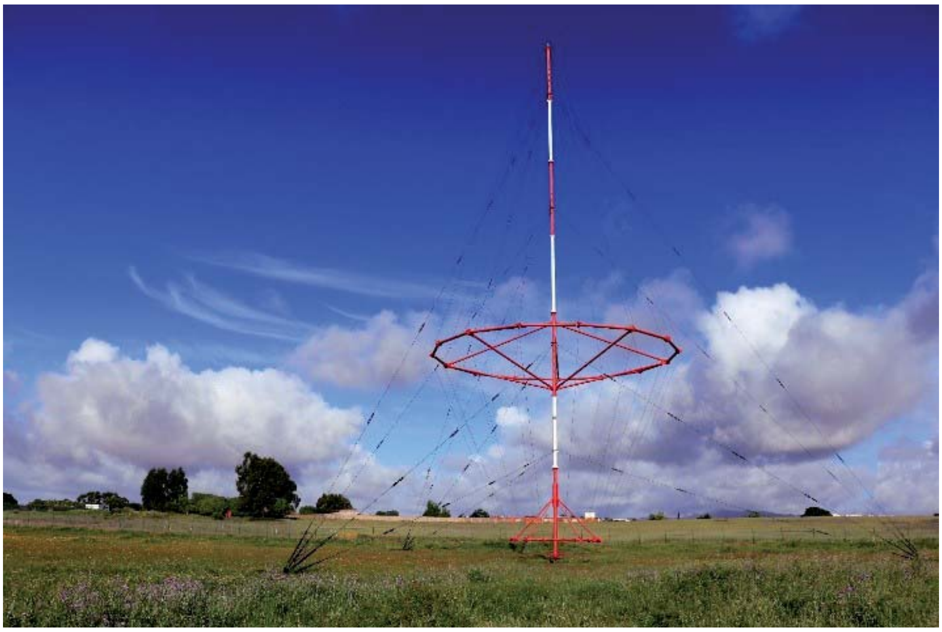

Figure 3. An HF Antenna in the ANACOM's farm in Barcarena, Portugal.

Essentially, this was the strategy that was followed by our Commission trying to overcome the reduced size of the radio community, the lack of research in this area and the difficulties in recruiting young talent to study these topics.

5.1 Developing Radio Propagation Initiatives

Given the constraints mentioned, the Commission G focus has mainly been on the diffusion of on-going developments, project implementations and technology improvements. Unfortunately, most of the stakeholders in this area follow military and government agencies, which reduces diversity. On the other hand, that can make it easier to collect and share information about new developments.

Recently, the Ministry of Defence developed two of the most relevant short-wave communications projects implemented in Portugal in recent decades. One was for civil application in the MF band, and encompassed two important components of the Global Maritime Distress and Safety System (GMDSS): the coverage of Sea area A2 (required for ships operating beyond 40 nautical miles range from shore); and the modernization of the NAVTEX system, a service for delivery of navigational and meteorological warnings and forecasts, as well as urgent maritime safety information, to ships. The objective was the modernization and automation of the safety system that was originally deployed to fulfil international obligations within the International Convention for the Safety of Life at Sea (SOLAS), increasing the coverage and quality of service for mariners.

The second project, developed for military purposes, included a transformation of all HF-based services delivered by Navy, to naval and Marines forces, and a complete refurbishment and modernization of shore-based naval communications systems in the mainland, Azores and Madeira. The so-called BRASS project, designed to support national and NATO communications, represented a significant improvement in the delivery of short-wave services introducing capabilities that enable IP convergence and a significant reduction of man-power to operate Navy's HF services.

Naturally, the intrinsic interest of these projects, reinforced by the enthusiastic dynamics of the marine community, due to on-going projects associated with initiatives such as the extension of the outer limits of the continental shelf, triggered the theme for 2013's Congress of the Portuguese Committee of URSI: "An ocean without borders: technological challenges" This was an opportunity to promote discussions on sea-related topics with direct impact on radio science and technology, namely marine policy, economy, and developments in areas such as communications, robotics, energy, transportation, etc., trying to link business opportunities with researchers and radio scientists. Likewise, many other areas of sea-based communications are trying to reduce dependency on satellites and move towards ad-hoc mesh and alternative means of achieving BLOS, particularly for sensor networks and the Internet of Things (IoT). There are plenty of applications where throughput is not the main driver, so it is important to promote opportunities for research and engineering to capture the radio community interest and the curiosity of new talent.

5.2 The Future of Radio Propagation Studies in Portugal

Currently, most of the research and development initiatives in the short-wave communications area are related to throughput improvement and IP convergence. Improvements in data compression in VLF, diversity of IP-based services using HF and the potential of WBHF are renewing and enhancing interest in this portion of the spectrum. Nevertheless, the main challenges are coming back to the foundations – physics: propagation modelling, and spectrum management.

The emerging Arctic interest, associated with a lack of adequate SATCOM coverage in high northern regions, has triggered several ionosphere modelling initiatives. Specifying the high-latitude effects of ionospheric and atmospheric disturbances (the effect of solar activity, magnetic storms, etc.,) are incompletely characterized. Unfortunately, high-latitude space-time variations are completely different from mid-latitudes, so none of the known models can be applied. There are plenty of research opportunities in this area, so we can expect a significant increase in published work in the upcoming years.

Furthermore, the importance on the HF band increases pressure on spectrum demand. State-of-the-art and current spectrum allocations only allow for data rates up to 9.6 kbps, per 3 kHz channel. The allocated bandwidth needs to be expanded to improve throughput. Proposed standards for WBHF aim to achieve higher data throughputs by either combining multiple 3 kHz channels – a non-contiguous approach – or by increasing the bandwidth of a single frequency channel, from 3 kHz to up to 48 kHz – a contiguous approach. Currently, there are no allocations for WBHF communications and this subject was never included in the World Radio-communications Conference agendas (WARC). On the other hand, given the characteristics of HF signal-propagation mechanisms, which not only impose international coordination on spectrum management, but also bandwidth constraints on the usable spectrum (as a function of time), there are additional physical constraints related to availability and interference. In addition to interference across international borders, there is a potential issue regarding the physical impracticality of finding enough bandwidth for all users, particularly due to the need for redundant channels for day-and-night usage to ensure continuous service. Clearly, the spectrum management challenges to operate WBHF based communications services calls for added flexible and efficient spectrum procedures and innovative methods to enforce them.

All in all, Commission G is dealing with a specific radio science niche that has reduced its footprint in Portugal during the last decades. Nevertheless, there are good reasons to be optimistic regarding the future, because short-waves are increasingly seen as the solution for high-resilient BLOS communications in demanding environments.

6. Portuguese Studies of Waves in Plasmas

The study of waves in plasmas in Portugal started in the sixties at the academic level with the main focus on wave propagation and reflection, mainly for ionosphere sounding purposes.

In the mid-sixties, the first Portuguese students (with degrees in Electrical Engineering) were sent abroad to get their PhD degrees in plasma science in prestigious institutions, such as, for example, Stanford University (USA) and FOM (Fundamental Research on Matter), Amsterdam (Netherlands). The studies covered space and laboratory plasmas in linear machines (Beam-Plasma Experiment and Q-machine, respectively). Upon return to Portugal, those scientists formed their research groups and expanded the interest in topics related to plasma waves, instabilities and diagnosis of plasmas. At Instituto Superior Técnico (IST), the engineering faculty of the Universidade Técnica de Lisboa (UTL), the topic Waves in Plasmas was included in one main course of the Electrical Engineering Department of IST [6-9].

In 1986, after Portugal joined the European Community (EU), Portugal had access to large EU projects in the area of Nuclear Fusion. The combined expertise in electrical engineering and plasma science was crucial to creating a group at IST in microwave diagnostics for fusion plasmas [10, 11].

6.1 Research in Waves in Plasmas and Contributions to URSI Portugal

Magnetosphere plasmas addressed topics such as wave instability theory; magneto heat waves and quasi-perpendicular shocks; cometary plasmas and instabilities; whistler cyclotron modes and resonance.

The research in low-temperature laboratory plasmas in linear machines, was mainly focused on basic research, for example nonlinear development of the electron and ion cyclotron instabilities in a beam-plasma experiment; the influence of lower hybrid oscillations; and plasma potential fluctuations with emissive probes.

In 1986, research emerged in the IST group, in collaboration of Universidade de Aveiro (UA), on reflectometry diagnostics (based on the radar principle) for hot plasmas in fusion devices. Advanced reflectometry systems were developed beyond the state-of-art for the largest EU fusion machines (tokamaks ASDEX, ASDEX Upgrade and JET) and led the EU representation to the international ITER project in microwave diagnostics. In 2011, it was demonstrated for the first time at the ASDEX Upgrade tokamak that the position of a fusion plasma could be controlled based on the data obtained from the microwave reflectometry systems.

This work was submitted to the 6th Congress of URSI Portugal in 2012, and was awarded the ANACOM-URSI Portugal Prize.

Several other contributions were made to URSI over the years, namely papers that are referenced in the Review of Radio Science [1990-1999] and papers submitted to the Congress of URSI Portugal, as well as invited talks.

7. Metrology Studies in URSI Portugal

Commission A is devoted to metrology studies and in Portugal most of the contributions for URSI explore radio essentials, mainly focused on wireless communications.

Some of the results obtained at the University of Aveiro were on the characterization of nonlinear aspects in radio transceivers, including the study and proposal of new techniques for the analysis of nonlinear distortion, including intermodulation, noise-power ratio and a new Portuguese proposal called “co-channel power ratio”, which evaluates the complete co-channel nonlinear distortion presented in a nonlinear device [12].

These developments were also later applied to mixed-signal components and to Analog-to-Digital Converters and vice versa, especially when those devices are used in software defined radio (SDR). The use of the so-called D-parameters [13] is a major step towards the full characterization of SDR transceivers.

More recently, the Portuguese team has also explored metrology aspects of space communications and wireless power transmission; a new field where URSI team members in Portugal are making proposals to ITU, in collaboration with other international teams.

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URSI Slovak National Committee

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1. Historical Note: Contribution to the Development of Wireless Telegraphy

Jozef Murgaš (1864-1929) was an inventor, artist, Slovak patriot, and botanist (Figure 1). In 1904, he invented the "Musical Tone System" of wireless telegraphy, enabling faster transmission of Morse code. Murgaš' invention was able to transmit two or more sounds 70 miles over land and 700 miles over water, whereas Marconi's invention could only transmit a single sound a short distance over water [1]. On November 23, 1905, he made a radio transmission between Wilkes-Barre and Scranton, Pennsylvania, USA, a distance of 20 miles, generating 50 WPM (words per minute) while Marconi's system could only generate 15 WPM. In 1905, President Theodore Roosevelt visited Murgaš in his laboratory, shown in Figure 1, and Murgaš was hired by the US Navy to improve wireless telegraphy. Guglielmo Marconi visited Murgaš on the advice of Thomas Edison, his last visit being in 1917, when, in failing health, he gave Marconi his patents and all the information he needed. Murgaš lacked funding and did not want his patents "to be lost to the human race."

Figure 1. Jozef Murgaš (1864-1929) and his laboratory in Wilkes-Barre, Pennsylvania, USA.

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Figure 2. The members of the Slovak National Committee of URSI.

Murgaš was active in the Slovak expatriates movement, wrote articles for their press, was one of the founders of the Slovak League in America, actively supported the creation of the state of Czechoslovakia, organized the collection of money (US$1,000,000) from American Slovaks for the creation of Czechoslovakia and was also a writer and a signatory of the Pittsburgh Agreement in 1918 between Czechs and Slovaks on establishing Czechoslovakia. As a respected personality, he gained the trust and support of the highest authorities in the USA for the establishment of Czechoslovakia. Among his other inventions was the spinning reel for the fishing rod [2-16].

2. URSI in Czechoslovakia 1948-1999

The Slovak national committee of URSI had its predecessor, the Czechoslovak Committee of URSI, which operated from 1948 up until 1999. The dissolution of Czechoslovakia, which took effect on 1 January 1993, was an event that saw the self-determined split of the federal republic of Czechoslovakia into the independent countries of the Czech Republic and Slovakia.

In October 2018 the Czech and Slovak National Committees of URSI organized in Prague a special Radio Science meeting with a student poster competition and a celebration of 70 years of URSI in Czechia and Slovakia.

3. Slovak National Committee of URSI

The Slovak National Committee of URSI was officially formed in 1999 as a logical result of the dissolution of Czechoslovakia, since both new countries wanted to have separate representation in URSI. Prof. Igor Baláž was responsible for nominating people for the national committee. He was known in Czechoslovakia as an expert in linear and nonlinear systems theory [17, 18]. The first President of the newly constituted Slovak National Committee of URSI was Dr. Ľubomír Šumichrast, an expert in electric circuits and electromagnetic field theory, and high-frequency and pulse electrodynamics. He developed new methods and algorithms for computer modeling of electromagnetic wave propagation in microwave and photonic frequency bands. In March 2013 Dr. Vladimír Štofanik replaced Prof. Igor Baláž in Commission F and he was constituted as the new President of the Slovak National Committee as well. Dr. Štofanik focused his research on frequency control and applications of dual-mode oscillators. His early contributions were presented at AP-RASC in 2001 in Tokyo, and at XXVII URSI General Assembly in 2002 in Mastricht, where he received one of the URSI Young Scientist Awards [19, 20].

In 2018, Prof. Kneppo and Dr. Šumichrast retired and two new members were nominated: Prof. René Harťanský, Commission A, and Dr. Elena Cocherová, Commission B. All members of the Slovak National Committee of URSI are shown in Figure 2.

3.1 International Conferences – Radioelektronika 1991-2019

Since constitution, the Slovak National Committee of URSI has helped to establish the quality and reputation of several international scientific conferences arising in Slovakia. Although the origin of the conference Radioelektronika was officially dated to 1991, thanks to Prof. Igor Baláž two successful predecessors were organized: the national conferences Radioelektronika ’86 and Radioelektronika ’89 in Bratislava, Czechoslovakia. The Czech and Slovak Committees of URSI supported the conference from beginning and helped to establish the high quality and reputation of this forum. Today, the Radioelektronika conference represent a well-established annual scientific forum in the European region for the presentation and discussion of the latest advances in the broad area of radio electronics, circuits theory and applications, signal processing, microwaves, and optoelectronics. Since 2007, all contributions presented at the conferences have been collected in the IEEE Xplore database [21]. Figure 3 shows the cover of the proceedings of 19th Radioelektronika 2009 conference organized in Bratislava, where 30 years of the conference were to be celebrated in April 2020.

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2009
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ISBN: 978-1-4244-3536-4
Library of congress: 2008911108
IEEE catalog number: CFP0985B-PRT

19th International Conference
Radioelektronika
2009

Czechoslovakia Section of IEEE

Radioengineering Society

Czech Electrotechnical Society Professional Group Microwave Engineering

Proceedings of 19th International Conference
Radioelektronika 2009

Department of Radio and Electronics
Bratislava Slovak University of Technology

April 22-23, 2009
Bratislava, Slovak Republic

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Figure 3. The cover of the Radioelektronika 2009 conference proceedings.


Figure 4. The front cover of the MEASUREMENT 2019 conference proceedings and of the *Measurement Science Review* journal.

3.2 International Conferences on Measurement – Measurement 1997-2019

Even the first measurement conference in 1997 had its successful predecessors: international workshops on the design of experiments, measurement theory, and measuring methods and systems, and the Emiscon conferences devoted to electronic measuring and information systems. Since its beginning, in 1997, the conference was organized by the Institute of Measurement Science, Slovak Academy of Sciences, in close cooperation with other academic and professional organizations; and it is supported by the Slovak National Committee of URSI as well. Prof. Ivan Frollo was Chair of most of the measurement conferences. The mission of the conference is continuing exchange of information among experienced specialists in measurement science, metrology, and selected areas of measurement technology, and also attracting young specialists and scientists to actively join this community. This is also the reason for the competition for the Young Investigator Award. Traditional general topics of the conference are: theoretical problems of measurement; measurement of physical quantities; and measurement in biomedicine [22]. The front cover of the Measurement 2019 conference proceedings is shown in Figure 4.

3.3 The International Journal: Measurement Science Review – From 2001

In 2001 the Institute of Measurement Science, Slovak Academy of Sciences, started publishing an Internet online edition of *Measurement Science Review* as an official journal of the Institute of Measurement Science as well as a journal of the International Conference Measurement (Figure 4). The Editor-in-Chief is Prof. Ivan Frollo. The aim of the journal is to publish papers from scientific disciplines covering measurement science with an orientation toward the theory of measurement, measurement of physical quantities, and measurement in biomedicine. The journal provides an environment for information exchange among scientists, engineers and industry people, as well as encouraging effective and coordinated research cooperation [23].

3.4 The 9th IEEE EUROCON Conference

In July 2001, the international conference 9th IEEE EUROCON was held in Bratislava (Figure 5). The program and organization committee chair of the conference was Prof. Peter Farkaš. He decided that the event would be co-organized by URSI in order to increase its visibility in the region. The organization was special because there was a gap of more than 12-years since the last EUROCON, which was held in Stockholm Sweden. Prof. Baldomir Zajc persuaded the Region 8 Committee to try to revive this event. He did try to find organizers in central Europe ready to take this risky undertaking. After some failures he met the chair, who agreed to help together with his small team. The task was not simple, but thanks to personal contacts of the chair some famous researchers agreed to be members of the program committee and to deliver keynote addresses and tutorials for free (Prof. Richard Blahut, Prof. Ramjee Prasad, Prof. Naoki Suehiro, Prof. Lajos Hanzo) [24, 25]. Thanks to these top-level scientists, the event attracted participants from 37 countries; 145 papers were presented in 25 sections. The most valuable impact, however, was on young participating students who were motivated by the distinguished speakers to create their own research in radio science. It had a direct impact on research in Slovakia. Two presentations inspired research on complementary codes, which soon resulted in the discovery of two and three dimensional complete complementary codes [26-28]. This research direction was followed at the Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava and later and it also brought further results [27-32].

Nowadays EUROCON is a flagship event of the IEEE Region 8 held every two years in a different country with participants from all over the world. It is a major international forum for the exchange of ideas, basic theory, design methodologies, techniques, and experimental results between academia, research institutions, and practitioners from industry. It has achieved a considerable success after its revival. It can therefore be concluded that the decision to involve URSI was correct. The Slovak National Committee of URSI was also involved in the organization of three SympoTIC conferences: in 2003 (Figure 5), 2004 and 2006 in Bratislava; and in 2017 and 2018 in the new emerging conference Electro-Mechanical Systems – Application in Industry.

IEEE Region 8
EUROCON'2001

INTERNATIONAL CONFERENCE ON
TRENDS IN COMMUNICATIONS

PROCEEDINGS

Volume 2/2

Bratislava, SLOVAKIA, 4 -7 July, 2001

Združenie
Jozefa Murgaša
pre podporu činnosti
IEEE na Slovensku

KINGSTON
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JOINT 1 WORKSHOP ON
MOBILE FUTURE
&
SYMPOSIUM ON
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Bratislava, SLOVAKIA, 26 -28 October, 2003

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Združenie
Jozefa Murgaša
pre podporu činnosti
IEEE na Slovensku

Figure 5. The front cover of the EUROCON 2001 conference proceedings and of the SympoTIC 2003 workshop proceedings.

Figure 6. Prof. Ramjee Prasad (left) and Prof. Lajos Hanzo (right) presenting during EUROCON 2001 in Bratislava.

3.5 In Memoriam: Karel Kudela (1946-2019)

Prof. Karel Kudela was one of the founders of the Space Physics Department at the Institute of Experimental Physics of the Slovak Academy of Sciences in Košice, which he led until 2011, and where he contributed to the work until his death. His research topics in the past five years focused primarily on the research of dynamics of low-energy cosmic rays and suprathermal cosmic particles. He acted as scientific coordinator in many physical experiments performed on satellites and in-ground measurements of cosmic radiation at the Observatory Lomnický štít. He contributed significantly to an improved understanding of the impact of solar activity on the cosmic-ray flux, the dynamics of the Earth's particle environment, and on the relationship between cosmic rays and space weather. One of his most important scientific achievements was the confirmation of solar neutron incidence on the Earth's surface as part of solar eruptions. He published more than 250 scientific papers and presented his results regularly at important international conferences. He served as a member of the scientific councils of several research institutions and several scientific committees for international meetings. He was a member of the IAA (International Academy of Astronautics). Being an excellent scientist, Karel contributed significantly to nurturing new generations of researchers at Pavol Josef Šafárik University in Košice, where he was responsible for the field of space physics within master's and doctoral study programs, lecturing courses of plasma physics, cosmic rays, energetic particles and the heliosphere, energetic particles and the magnetosphere, plasmas in space, and selected issues

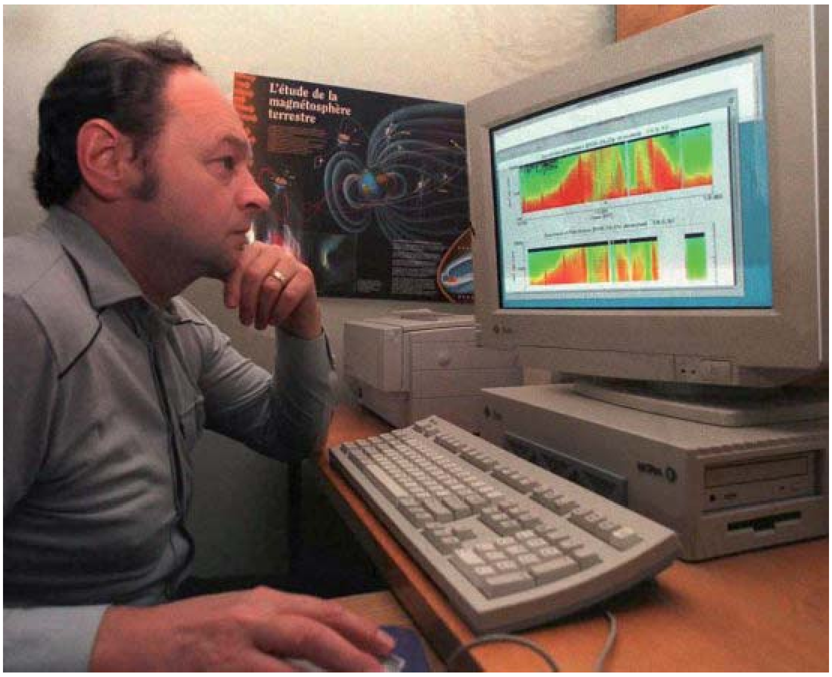

Figure 7. Prof. Karel Kudela analyzing data from the INTERBALL satellite.

Figure 8. Anton Hajduk (r) and Ján Štohl (l) working with Bertil Lindblad at the Astronomical Institute in Bratislava in 1975.

in cosmic physics. Figure 7 shows Prof. Kudela deep in the analysis of data from the INTERBALL satellite. Prof. Kudela collaborated with the Institute of Nuclear Physics of the Czech Academy of Sciences for a long time, but more intensively during the last several years, on the European project CRREAT focused on radiation effects in the atmosphere. We will remember Prof. Karel Kudela forever as a kind person, a hardworking devoted colleague, an inspiring teacher, and an excellent expert with an outstanding international reputation.

3.6 In Memoriam: Anton Hajduk (1933-2005)

Anton Hajduk, Professor of Astronomy and Astrophysics, was a scientist at the Astronomical Institute of the Slovak Academy of Sciences in Bratislava since 1961. Anton Hajduk began his career with radar meteor observations using the Ondřejov Observatory radar, and later closely cooperated with Bruce McIntosh, from the Springhill Meteor Observatory in Canada. Prof. Hajduk conducted further research into the dynamics and physics of meteoroids, the behavior of head echoes and ionospheric phenomena. He also worked in the area of the relations between cosmology and science and religion. Figure 8 shows Hajduk working with Ján Štohl and Bertil Lindblad at the Astronomical Institute in Bratislava. Hajduk cooperated closely with scientists from the Astronomical Observatory in Lund, Sheffield University, Institute of Astrophysics Dushanbe, Astronomical Institute Ondřejov, and established the Bologna-Modra-Lecce forward scatter

Figure 9. An illustration of Plasmabit and the plasma drilling process [34].

radar system together with scientists from the Instituto ISAO CNR Bologna in Italy. Apart from his remarkable scientific contribution to meteor astronomy (over 150 scientific papers), he lectured on radio astronomy and meteor astronomy at Comenius University in Bratislava, and on philosophical questions relating to cosmology at Trnava University. Hajduk gave more than 400 public lectures. He wrote seven astronomy-related books intended for the lay public and was coauthor and co-editor of the Encyclopedia of Astronomy (in Slovak). The International Astronomical Union acknowledged his scientific work by assigning the name Antonhajduk to the asteroid 1997 EN No 11657.

3.7 In Memoriam: Ján Dušan Skalný (1944-2008)

Prof. Ján Dušan Skalný will always be associated with the Comenius University in Bratislava, where he started his professional career as a researcher and scientist in 1966, in the Department of Experimental Physics. His original research was focused on the development of high-pressure discharges and it was a field in which he established an international reputation. In 1991, he was finally appointed Associated Professor and in 1998 to full professorship in Plasma Physics at Comenius University. From 1996 to 1999 he was Head of the Department of Plasma Physics at the Comenius University, and quickly sought to ensure that the department built ties with other international groups. He supervised many students focusing on high-pressure electrical discharges and molecular physics. His students were soon visiting several excellent laboratories abroad as Prof. Skalný sought to promote the careers of many young Slovak physicists. Since 2006, he was Head of the Research Unit of the Slovak Association to the EURATOM Fusion. Before the end of his life, he was appointed to the Leverhulme Professorship at the Open University, UK, and he was focused on cluster ions in atmospheric pressure discharges.

4. Plasmabit – The New Ground-Breaking Technology

Utilization of high-pressure pulsed discharges and plasmas are crucial in the novel plasma-based drilling technology developed in Slovakia [33]. Plasmabit, and the plasma-drilling process, are shown in Figure 9. Dr. Štofanik, President of the Slovak National Committee of URSI, nowadays leads research and development of unique embedded power electronics for the generation of high-energy pulsed plasma in extreme down-hole environment (high pressure and temperature). The current global energy mix expects a very low utilization of geothermal energy, since it is based on maintaining the current high cost of deep drilling. The novel plasma drilling technology has the potential to economically reach a depth of 8 km to 10 km and to get access to hot spots with temperatures higher than 300°C for high-efficiency electricity generation, as was presented at the XXXIInd URSI General Assembly in Montreal in 2017 [34].

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South Korea National Committee of URSI

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1. Introduction

The year 2022 is the 100th anniversary of URSI GASS; the first international conference organized by URSI was held in Belgium in 1922. The URSI headquarters asked the South Korea URSI committee to submit an article regarding the South Korea URSI committee's activities in the past, present, and future for the centenary book. However, there were few official records remaining regarding URSI activities in South Korea. After some discussion among the ex-presidents of the South Korea URSI Committee, it was decided to write a history of the South Korean URSI Committee based on the memory of those who have led the activities of the South Korean URSI committee. They are the former/present presidents and official members of South Korea URSI committee: Jung Woong Ra, Hyuckjae Lee, Hyo Joon Eom, Young Ki Cho, Sangwook Nam, Seong-Ook Park. This article is a summary of those words and memories recorded in the meeting held on July 2, 2019 in Daejeon KAIST (Korea Advanced Institute of Science and Technology) where they gathered together and recalled the past days (Figure 1). All the attendees understood the length of this article would be relatively short and the contents might be somewhat vague, due to their old memories, except for a few documents from the early stage of the South Korea URSI Committee.

2. Brief History of the South Korea URSI Committee and Its Activities

2.1 Before 1992

Dr. Jung Woong Ra had attended the URSI National Meetings and the URSI Conferences in the United States with his advisor, Professor L.B. Felsen, when he was a graduate student. With this experience, he recognized that URSI was an organizer of important technical meetings in the field of electromagnetic wave research. Therefore, his special interest in the URSI conferences continued even after he came to South Korea. Since he had attended URSI conferences frequently, and met many scientists and URSI headquarters officials over a long period of time, URSI officials recognized him as a representative radio scientist of South Korea even though his attendance was a personal activity not an official one.

2.2 1992 - 2012

In 1992, the URSI Secretary-General, Professor J. Van Bladel, suggested and recommended that South Korea should become a regular member of URSI. After some preparation, the South Korea URSI Committee became a category 2 official member of URSI in 1993 and started to receive copies of the quarterly Radio Science Bulletin from URSI.

Figure 1. The Daejeon KAIST meeting for preparing the 100th anniversary article.

Dr. Jung Woong Ra, who had actively participated in URSI conferences as an individual for a long time, naturally became the first President of the South Korea URSI Committee and exercised his right to vote as an URSI official member.

Right after being a member country of URSI, many specialists from various fields in radio science in South Korea were appointed as commission chairs and a South Korea URSI Committee with the official members for commissions was completed. However, all URSI-related activities of the South Korea URSI Committee had been done mainly by Professor Ra and Professor Eom. Table 1 identifies the official members of the South Korea URSI Committee from 1993 to the present.

The annual fee, of about USD 1,800, was paid for being an official member country of URSI. In many European countries, URSI membership fees were supported by the National Academy Fund. However, it was difficult to find such a fund in South Korea in those times. Fortunately, Dr. Hyuckjae Lee, of ETRI (Electronics and Telecommunications Research Institute) understood the importance of being an official member country of URSI and advised ETRI to pay the URSI membership fee for some period.

Table 1. List of Official Members of the South Korea URSI Committee

Year	President	Secretary	Official Members
1993 - 1996	Jung Woong Ra	Hyo Joon Eom	A (H.J.Lee), B (Y.K.Cho), C (S.W.Yun), D (S.Y.Shin), E (N.H.Myung), F (S.D.Choi), G (K.W.Min), H (S.Y.Kim), J (S.H.Cho), K (C. Park, Added in 1996)
1996 - 2002	Jung Woong Ra	Hyo Joon Eom	A (H.J.Lee), B (Y.K.Cho), C (S.W.Yun), D (S.Y.Shin), E (N.H.Myung), K (Y.M.Gimm, Added In 2000) Till 2000
			A (H.J.Lee), B (Y.K.Cho), K (Y.M.Gimm) In 2001
2002 - 2009	Hyo Joon Eom	Hai Young Lee	A (H.J.Lee), B (Y.K.Cho), K (Y.M.Gimm)
2009 - 2012	Young-Ki Cho	Hyuckjae Lee	A (H.J.Lee), B (Y.K.Cho), K (Y.M.Gimm)
2012 - Present	Sangwook Nam	Seong-Ook Park	A (J.H.Kim), B (S. Nam), C (J. Chun), D (J-S.Rieh), E (W. Nah), F (Y. Oh), G (S.-H. Bae), H (J. Choi), J (S.-T.Han), K (Y.-M. Gimm)

Figure 2. The AP-RASC Welcome Reception.

Figure 3. The AP-RASC Opening Ceremony.

Figure 4. The AP-RASC General Lecture.

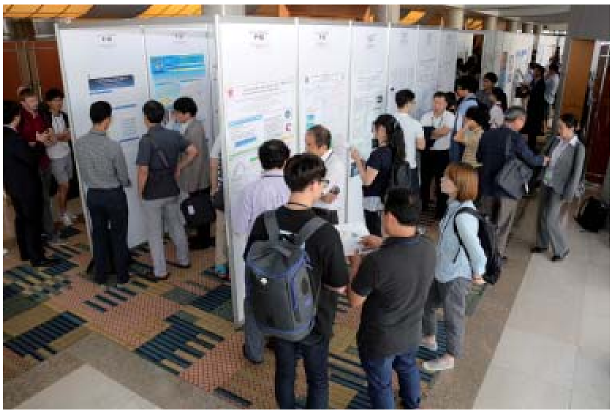

Figure 5. The AP-RASC Poster Session.

Figure 6. The AP-RASC Banquet (YSA).

Figure 7. The AP-RASC Banquet (SPC).

In 2002, Professor Hyo Joon Eom became the President of the South Korea URSI Committee and was appointed the official member, as shown in Table 1. In the same year, Professor Young-Ki Cho successfully persuaded KIEES (Korean Institute of Electromagnetic Engineering and Science) to pay the membership fee and subsequently the membership fee has been paid by KIEES.

In 2009, Professor Young-Ki Cho took over the presidency and maintained the same official members of the national committee to continue the URSI activities, such as attending GASS and voting as an official member. Especially, Professor Y.K. Chou has attended the triannual Symposium continually since EMTS 1995, held at St. Petersburg.

2.3 2012 - Present

In 2012, Professor Sangwook, Nam, was elected as the President of the South Korea URSI Committee and newly appointed the Commission chairs and organized the South Korean Committee as shown in Table 1. They have been active in participating in URSI activities such as attending URSI related academic events and voting in commission meetings.

In particular, at AP-RASC (Asia-Pacific Radio Science Conference), 2013, held at Taipei, they won the bid for hosting AP-RASC 2016 in South Korea and AP-RASC 2016 was a great success with more than 700 attendees from 34 countries (Figures 2 – 8). The summary of the conference is briefly described in section 3.

Figure 8. The AP-RASC Banquet.

Figure 9. Dinner after the URSI South Korea Works

In 2018, as an event of the South Korea URSI Committee alone, a small workshop on important topics in the field of radio science such as (1) Quantum Computing, (2) Time-modulated Antenna, and (3) Plasma in Atomic Fusion was held for the first time (Figure 9).

3. Summary of AP-RASC 2016

URSI AP-RASC 2016 was held from August 21 to 25, 2016, at the Grand Hilton Seoul Hotel, in South Korea. The conference was organized by the KIEES (Korean Institute of Electromagnetic Engineering and Science) and URSI. It was also co-organized by the National Radio Research Agency (RRA), ETRI, the Korea Astronomy and Space Science Institute (KASI), and the National Fusion Research Institute (NFRI). Also, it was technically sponsored by several academic organizations: IEICE (JAPAN), IEEE (USA), IEEE AP-S, IEEE AP-S Seoul Chapter, KICS (KOREA), IEIE (KOREA).

The total number of attendees was 756 from 34 countries. A total of 727 papers were submitted, and among them 687 papers were presented in 107 oral sessions and one poster session.

After the conference, the papers from the YSA (Young Scientist Award) were published in Radio Science in August 2017 - December 2017 issues as full papers and a special issue for SPC (Student Paper Contest) was published in Radio Science Bulletin, in June 2017. Also, one invited paper from the GL (General Lecture) was published in JEES (Journal of Electromagnetic Engineering and Science), in October 2017.

4. Future Plan and Vision

After becoming an official member country of URSI in 1993, the South Korea URSI Committee has continuously increased its activities. Recently, it successfully hosted AP-RASC, one of the URSI Flagship conferences, in 2016. It was the 23rd year after South Korea became an official member country of URSI, in 1993. After the conference, the South Korea URSI Committee prepared the “URSI AP-RASC FUND” from the surplus of the conference. Using this fund as seed money, we intend to strengthen URSI activities in the future in South Korea as follows:

- Construct a homepage of South Korea URSI Committee,
- Promote individual URSI membership,
- Support a national URSI workshop on important topics in radio science,
- Encourage South Korean researchers to attend URSI Conferences,
- Host several URSI Conferences in the future (e.g., EMTS, GASS etc.).

Through these activities, the South Korea URSI Committee intends to contribute to the promotion of international studies, research, applications, scientific exchange, and communication in the field of radio science, which is the basic mission of URSI.

URSI 100 Years: A Swedish Perspective

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Abstract

This paper presents some Swedish contributions to radio science over the last 100 years, with particular emphasis to activities close to the Swedish National Committee of URSI. The topics include the Grimeton World Heritage Site, Onsala Space Observatory, the EISCAT facility, a Swedish perspective on mobile communication and antenna engineering, and the recent column on Women in Radio Science appearing in the URSI Radio Science Bulletin.

1. Introduction

The Swedish National Committee of URSI (Svenska nationalkommittén för radiovetenskap, SNRV), was founded by the Swedish King on March 20, 1931. The history of Swedish radio science is not synonymous with SNRV, but they are largely intertwined, given that SNRV from the start has made an effort to act as the national network for Swedish radio scientists. Today, the committee has 20 regular members, and around 120 co-opted members, recognized for their activities in the field.

To celebrate the 75th anniversary of SNRV, a public seminar was held at the Royal Swedish Academy of Sciences (Kungliga vetenskapsakademien, KVA) in 2006, and the talks were later summarized in a book [1], edited by Prof. Gerhard Kristensson, who was then the Chair of SNRV. Much of the contents in this paper to celebrate the 100th anniversary of URSI comes from this effort to summarize the Swedish radio history, and I would like to explicitly mention the authors: Staffan Ström, Mats Bäckström, Åke Blomquist, Bengt Hultqvist, Roy Booth, and Carl-Henrik Walde, all of whom have made long standing contributions to SNRV. Also Jean van Bladel contributed to the book with a text on the URSI history. It is a pity to note that Ström, Blomquist, Hultqvist, Walde, and van Bladel, have passed away during the ten years that have passed since the book was finalized. We miss them dearly.

In addition, at the European Conference on Antenna and Propagation (EuCAP) in Göteborg 2013, a historical session covering Swedish antenna engineering history was organized. The papers presented at this session summarized, in a nice way, much of the antenna efforts laid down in Sweden. They have been extensively consulted as sources for this paper, and are cited accordingly below.

2. Selected Topics of Swedish Radio Science

The following subsections make no claim to be a complete review of radio science in Sweden during the last 100 years. They are rather the author's subjective selection of highlights, focusing on matters close to the activities of SNRV.

2.1 The History of SNRV

Following a request of the Royal Telegraphy Board, in 1928, the Swedish National Committee of Scientific Radio Telegraphy was formed by decision of His Royal Majesty on March 20, 1931. The first meeting was held on May 31, 1932. In

1944, the name was changed to the Swedish National Committee of Scientific Radio, and in 1966 the present day name, the Swedish National Committee of Radio Science (Svenska nationalkommittén för radiovetenskap, SNRV), was adopted. Internationally, the name is the Swedish National Committee of URSI. Nationally, SNRV is a committee within the Royal Swedish Academy of Sciences, KVA. The original purpose of SNRV can be seen through excerpts from the early statutes (author's translation):

"The Committee has the task of promoting Swedish scientific research and technological developments in the field of radio science, including through national conferences, and to convey Sweden's representation and research work in the international union, URSI, as well as suggesting to the Royal Majesty measures to promote its tasks."

The first members of SNRV were appointed on May 15, 1931, as representatives from the major stakeholder organizations: the Army, Navy, Air Force, Telegraph Agency, Meteorological-Hydrographic Institute, Royal Institute of Technology, Royal Swedish Academy of Sciences, and the Royal Swedish Academy of Engineering Sciences. Later on, representatives from more universities were added, and the presence of military representatives gradually diminished. To further strengthen the national network, the committee has been entitled to elect co-opted members without voting rights, who are considered useful for the committee.

Figure 1. The first Chair of SNRV, Prof. Henning Pleijel (1873-1962))photo from the Swedish National Archive (Riksarkivet).

The foundation of SNRV was strongly supported by its first Chair, Henning Pleijel (see Figure 1), whose career started at the Royal Telegraph Agency, and continued as Professor and Vice Chancellor of the Royal Institute of Technology, as well as Secretary of the Royal Swedish Academy of Sciences, Chair of the Nobel Committee of Physics, and many other honorable tasks in Swedish science [2]. A list of the SNRV Chairs is provided in Table 1.

The commission organization of SNRV closely mirrors that of URSI, as can be seen in Table 2. Major reorganizations were undertaken in 1948 and 1975, with some adjustments since then, the major one being the introduction of Commission K in 1990. The Chairs of the respective Commissions are members of the committee, which also includes additional members from the Royal Swedish Academy of Sciences and other recognized stakeholders in industry and the public sector, making a total of 20 members. The committee is elected for a period of three years, and regularly revises its list of co-opted members, currently comprising around 120 people.

Starting in 1949, one of the major recurring efforts of the committee has been to organize a series of national conferences called Conference on Radio Science (Radiovetenskaplig konferens, RVK). The meetings gathered around 100-200 attendees and 200-500 presentations; the peak being reached in the 80s. This was a venue for interaction on a national level, where young scientists were introduced to the scientific network, and preparations for the Swedish report to the URSI General Assembly were made. Following international trends in later years, several minor national conferences, with a narrower focus (for instance in antennas, electromagnetic computations, and RF electronics), have taken over the role of the RVK

Table 1: List of Swedish National Committee Chairs.

Chair	Tenure
Henning Pleijel	1931-1945
Håkan Sterky	1946-1969
Stig Lundquist	1970-1984
Peter Weissglas	1985-1993
Staffan Ström	1994-2005
Gerhard Kristensson	2006-2013
Asta Pellinen-Wannberg	2014-2017
Daniel Sjöberg	2018-

Table 2: History of commission organization of SNRV.

Commissions until 1948 I. Measurements methods and standardization II. Radio propagation III. Atmospheric disturbances IV. Liaison with operators, practitioners, and amateurs V. Radiophysics	Commissions from 1976 to the present A. Electromagnetic metrology including radio-properties of materials and (until 1990) biological action B. Fields and waves C. Signals and systems D. Electronics and photonics E. Electromagnetic environment and interference F. Wave phenomena in ionized media Wave propagation and remote sensing (from 1978) G. Ionospheric radio and propagation H. Waves in plasma J. Radio astronomy K. Electromagnetics in biology and medicine (from 1990)
Commissions until 1975 I. Radio normals and measurements II. Radio and troposphere III. Radio and ionosphere IV. Atmospheric radio interference V. Radio astronomy VI. Radio waves and circuits VII. Radio electronics	

conferences, which were discontinued after 2013. The present state of national conferences is to co-locate the smaller conferences under the name Swedish Microwave Days, which is organized biannually. There is also a biannual Nordic HF Conference organized on the small island of Fårö, famous for being the home of movie director Ingmar Bergman.

Håkan Sterky served as the Vice-President of URSI 1946-49, and Sweden arranged the URSI General Assembly, in 1948, in Stockholm, together with the CCIR Plenary Assembly (the Comité Consultatif International des Radiocommunications, CCIR, which became ITU-R in 1993). This meeting was the first time a Swede was elected as an URSI Commission Chair: Harald Norinder in Commission IV Atmospheric interference (1948-50). Several others have subsequently followed in various commissions: P. O. Lundbom (1972-74), F. Eklund (1975-77), B. Hultqvist (1978-80), S. Lundquist (1981-83), V. Scuka (1993-95), R. S. Booth (1996-99), and S. E. G Ström (1999-02). Since 1949, Sweden has hosted a few international Commission meetings, but has not yet organized another General Assembly although several bids have been made, each time as first runner-up.

Figure 2a. Ernst F. W. Alexanderson, 1878-1975 (photo from the Swedish National Archive (Riksarkivet).

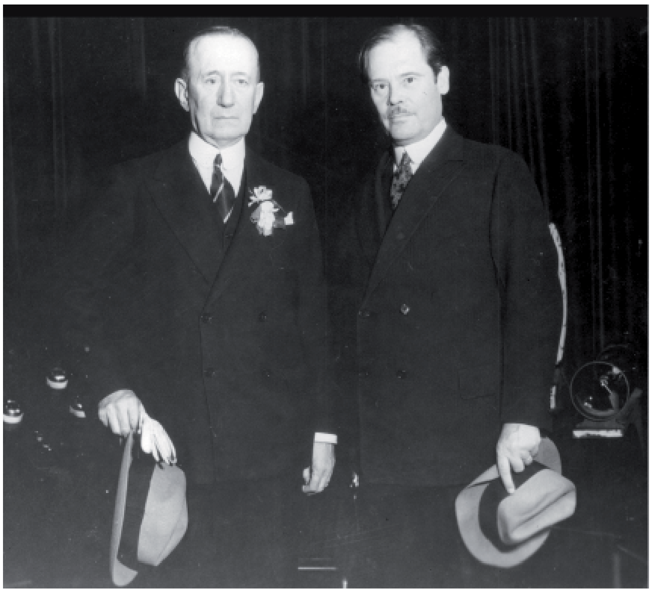

Figure 2b. Alexanderson together with Marconi at Schenectady, NY, in 1915 (photo from Tekniska museet).

Figure 3a. The Grimeton Station building and antenna towers (photo provided by Grimeton Museum).

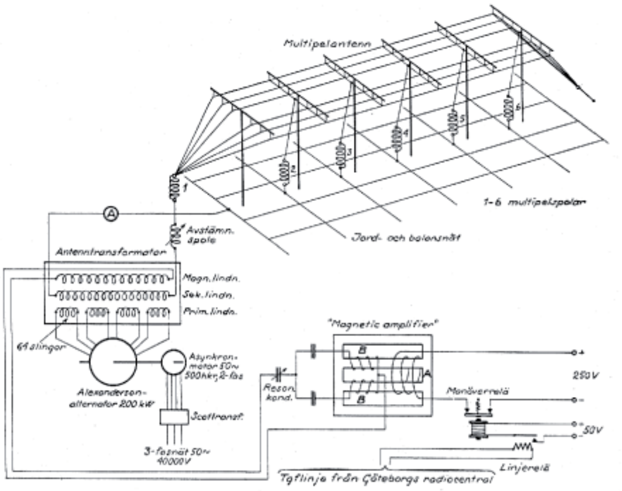

Figure 3b. The early principal schematic of the RF generation and antenna (Telegrafverkets handbok 1933).

2.2 World Heritage Site Grimeton SAQ

One of the pioneering radio engineering facilities from the pre-electronic era was conserved as a UNESCO World Heritage Site in 2004: the Grimeton Radio Station, close to Varberg on the Swedish west coast. This is a (still operational) VLF transmitter system, operating at 17.2 kHz, and based on the alternator designed by the prolific inventor Ernst F. W. Alexanderson (Figure 2). A detailed account of Grimeton can be found in [3], an extensive biography of Alexanderson is in [4], and the museum itself can be found online at https://grimeton.org.

Alexanderson spent most of his life working for General Electric and Radio Corporation of America. He was an extremely productive inventor, with at least 345 approved US patents (the last one awarded in 1973 at the age of 95). His understanding of the system aspects of radio communication is reflected by his statement: "*the problem of radio engineering is to establish the relation between kilowatts input and words output.*" He received the IRE Medal of Honor in 1919, and the American Institute of Electrical Engineers (AIEE) Edison Medal in 1944; two organizations that joined to form the Institute of Electronics and Electrical Engineers (IEEE) in 1963.

The Alexanderson alternator [5] produced high power continuous wave RF signals at a time when the competing technology was spark generators, and vacuum tube technology was not available. The alternator is based on a rotating steel disk with a slotted circumference moving between a series of narrow coils. This changes the magnetic flux through the coils resulting in an alternating current. Alexanderson managed to solve several engineering challenges in the design, required to handle rotation speeds of a 1.6 m steel disk at 2115 rpm at a distance of around 1 mm from the coils. He also solved important problems with the antenna, consisting of six 127 m tall towers, in particular with the grounding [6]. The efficiency of the antenna is around 10 %, which is quite good for such an electrically small antenna (compare the 127 m height and 2 km length with the wavelength of 17 km).

The location of the facility was chosen close to the city of Varberg on the west coast of Sweden, with a great-circle propagation path across the Atlantic to the US east coast, utilizing propagation over the sea water surface investigated by Sommerfeld, Zenneck, and others. The location also provided a stable power supply from an early hydro-electric power plant.

The Grimeton Station (Figure 3) has the call sign SAQ and was inaugurated on 2 July, 1925, by the Swedish King Gustaf V. A receiver station was built in Kungsbacka, some 54 km to the north, but the building is now residential and there are only a few isolators on the outside to be

Figure 4. Olof Rydbeck (1911-1999), founder of Onsala Space Observatory (photo from Riksarkivet).

Figure 5. Antennas at the Onsala site: the grey reflector in the center is the 25 m telescope from 1963, and the two white reflectors are the 13 m twin telescopes from 2017 (photo from OSO (under CC BY-NC-SA 2.0)).

seen today. During the 1920s, SAQ was part of a global Radio Corporation of America (RCA) network, operating with Morse code keying speed of typically 50 words per minute. The total information from Grimeton in 1936 was 1.8 million words, or around 10 megabytes [3]. The use for transatlantic wireless communication reduced as wired connections were made more available, but SAQ found new use in, for instance, communication with submarines, where the low frequency penetrated further under water.

At the end of the 20th century, following the de-regulation of the Swedish telephone state monopoly, Grimeton ended up in the private company Telia, which had the foresight to perform some crucial renovations of the towers. After some significant work by radio enthusiasts, including previous employees at the facility, it was possible to secure the station on the list of UNESCO World Heritage Sites on 2 July 2004, and it is now operated as a foundation and the site is open for visits. The Alexanderson Day is celebrated on the Sunday in June or July that is closest to 2 July. On this date, there is an open house at Grimeton, and a Morse message is transmitted from SAQ on 17.2 kHz. Please tune in for a piece of radio history!

2.3 Onsala Space Observatory

Onsala Space Observatory (OSO), founded by Olof Rydbeck, Figure 4, is a Swedish national facility for radio astronomy, providing scientists with several radio telescopes to study the Earth and the rest of the Universe, see [1, 7] and https://www.chalmers.se/en/researchinfrastructure/oso/. The facilities are located in Onsala, 45 km south of Göteborg, and on international sites like the Atacama desert in Chile. The Onsala site was established in the late 1940s when interference problems in Göteborg became too severe, and it was formally inaugurated in 1955. In the beginning, five 7.5 m German WWII radar antennas from Norway were used for observations of the 21 cm hydrogen line in our galaxy. In 1963, a 25.6 m telescope was erected, which is still in use today with instrumentation in the range 900 MHz – 7 GHz. The telescope was involved in the first transatlantic Very Long Baseline Interferometry (VLBI) experiment in 1968, achieving a resolution of 1 milli-arcsecond.

In 1976, a 20 m telescope was inaugurated, covering a range from 2.2 GHz to 116 GHz. It remained the largest millimeter-wave telescope in the world for about one decade, and is still in use for astronomical and geodetic VLBI studies. The success of the millimeter wave activities paved the way for establishing the 15 m Swedish-ESO Submillimeter Telescope (SEST) on the mountain La Silla in Chile at 2300 m altitude. It was completed in 1987, and was equipped with receivers in the range 70 GHz – 365 GHz. The need to focus resources on the Atacama Pathfinder Experiment (APEX) led to the closing of the facility in 2003. APEX is a 12 m submillimeter telescope in collaboration with the Max Planck Institut für Radioastronomie and the European Southern Observatory.

Figure 6. The EISCAT facility in Kiruna during an Aurora Borealis (photo: EISCAT [1]).

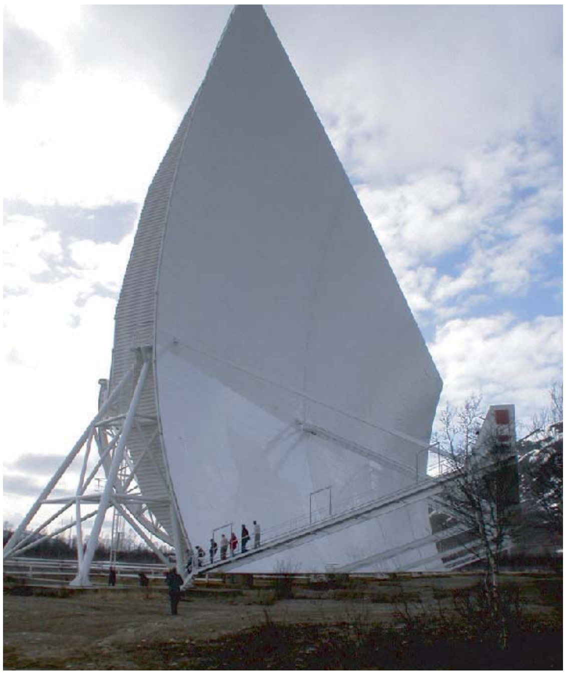

Figure 7. The EISCAT VHF antenna at Tromsø. The reflector is a parabolic cylinder rotating on a horizontal axis. For scale, note the people walking down the stair case (photo: EISCAT).

Several other facilities are provided through OSO, for instance the Swedish LOFAR (Low Frequency Array) station, the Odin satellite (the astronomy part of the mission ended in 2007, but aeronomy measurement continue), and OSO is participating in the development of the Square Kilometer Array (SKA). In 2017, a twin telescope for geodetic VLBI was inaugurated at the Onsala site, see Figure 5. The dishes are both 13.2 m, with broadband receivers covering 2 GHz – 14 GHz and 3 GHz – 18 GHz. The first observations have been made, and the facility is expected to be fully operational at the end of 2019.

The geodesy activities at Onsala have become more and more important, using observations of very distant objects in the universe to track movements of the Earth and its crustal motion. Another activity is a network of GPS stations called SWEPOS that was deployed in the 1990s. With the help of these stations the significant postglacial land-rise of the Swedish mainland has been tracked, which can be as much as 10 mm per year.

The APEX telescope was one of seven around the world participating in the 230 GHz VLBI imaging of a black hole, Messier 87, culminating in a series of publications in The Astrophysical Journal Letters in spring 2019 [8]. The work was a collaboration involving more than 200 researchers from 59 institutes in 20 countries, and had a tremendous impact in the world press.

2.4 European Incoherent Scatter Association, EISCAT

The European Incoherent Scatter Association, EISCAT, Figure 6, https://www.eiscat.se/, is an international facility installed at Tromsø and Longyearbyen at Svalbard in Norway, Kiruna in Sweden, and Sodankylä in Finland. It supports incoherent radar scattering experiments investigating phenomena in the atmosphere, ionosphere, and near-Earth space environment, in particular plasma physics. The plans started as a Nordic collaboration headed by Olav Holt from Norway, Bengt Hultqvist from Sweden, and Juhani Oksman from Finland [9]. They made a proposal at the 1969 URSI General Assembly, in Ottawa, for a radar facility in the auroral zone, which was accepted. After several years of political work, there was finally a decision to fund the project in December 1975, and EISCAT started as a not-for-profit organization seated in Sweden, supported by Finland, France, Norway, United Kingdom, Sweden, and West Germany.

The system basically consists of a transmitting and receiving station in Norway, and receiving stations in Sweden and Finland. The electrical design and evaluation of the VHF feed and reflector system in Tromsø, see Figure 7, was done by a young Per-Simon Kildal, at the time doing his PhD thesis at NTH Trondheim, who would later become a very productive

Figure 8. Östen Mäkitalo (1938-2011), father of the Nordic Mobile Telephone System (photo: Tekniska Museet).

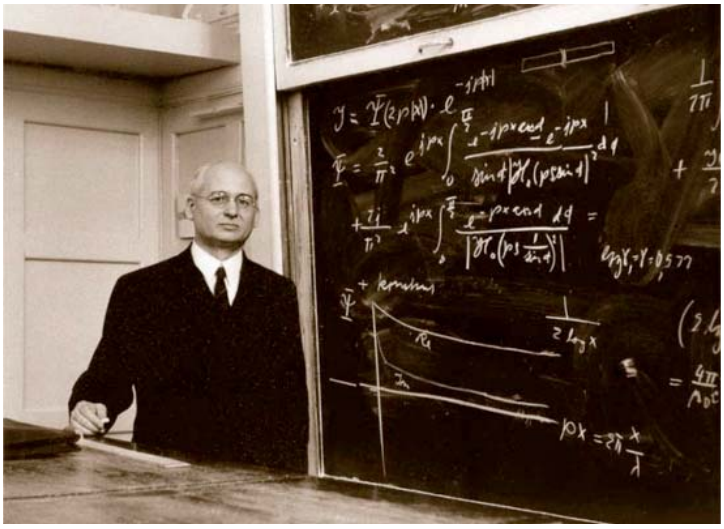

Figure 9. Erik Hallén (1899-1975) in front of a blackboard (unknown photographer).

antenna professor at Chalmers in Göteborg [10]. The first system became operational in 1981, having access to the entire 918 MHz – 948 MHz band. However, with the introduction of cellphone services significant interference and receiver non-linearity problems arose [11], requiring a significantly reduced bandwidth. Shifting the operations to 1410 MHz – 1427 MHz gave an extra 10 years of operation, but recently another shift to VHF band, 224 MHz had to be introduced.

The EISCAT facility has provided a means for studying the electrical field distribution around the aurora borealis, and the influx of electrons from the magnetosphere as well as the outflux of electrons from the ionosphere to the magnetosphere, proving that the ionosphere is an important source for the magnetospheric plasma. Another interesting entity is the Heating Facility in Ramfjordmoen, which can inject significant power (around 1.2 MW or over 1 GW equivalent radiated power) into the ionosphere at a few MHz, exciting plasma turbulence that can be studied with the incoherent radar.

A generation shift is being prepared with the introduction of EISCAT 3D. This is a concept where the traditional large reflector antennas are replaced by phased-array antenna fields. Five fields are planned, each consisting of around 10 000 crossed dipole antenna elements operating at 233 MHz. One field will act as the transmitter, and the others as the receivers. The system will be very flexible and able to track fast-moving objects, and allow volumetric imaging in a manner slow-moving large reflectors never can. It is expected to be operational in 2021.

2.5 Mobile Communication

Sweden is one of the pioneering countries in the development of mobile communication. Two local systems, MTA and MTB, were launched in the major cities in 1956 and 1965, but the big success came with the Nordic Mobile Telephony (NMT) system starting in 1981. The first steps were taken in 1967 in a study by Carl-Gösta Åsdahl at Swedish Telecom (Televerket, the Swedish State authority responsible for telecommunications in 1853-1993), which outlined the key systems to be developed. It was quickly realized that the task needed collaboration, and Sweden teamed up with the other Nordic countries. The first test system was launched in Saudi Arabia, but very soon Sweden, Norway, Denmark, Finland, and Iceland were in operation.

The NMT system was largely driven by governmental organizations like Televerket, but relied on a tight collaboration with industries like Ericsson and Nokia to come up with the necessary hardware. One particular change in operation compared to the fixed wire systems previously in operation, was that now the customers could own the terminal, and the specifications were open so that many manufacturers were able to participate. In an interview with Östen Mäkitalo, Figure 8, in 2008 [12], one of the pioneers and founding fathers of mobile telephony in Sweden, we find a telling remark about this era:

> According to Mäkitalo, some of the most important aspects of the work performed by Televerket in the field of mobile telephony has been the great degree of freedom and trust provided by the upper echelons of the company, as well as the fact that Televerket pushed the private sector into innovating new advanced technology by including non-existent technology in their product specifications to industry.

Figure 10. Asta Pellinen-Wannberg (1953-), Chair of SNRV 2014-2017 and Associate Editor of URSI Radio Science Bulletin column on Women in Radio Science (photo: Robert Cumming, shared under CC BY-SA-3.0).

In the same interview Mäkitalo talked about the "what if" questions that were going through the minds of the developers in the 70s:

> What if it [the mobile phone] could be made much smaller, what if it could be much cheaper, what if you would not need to know where the subscriber is but could be reached anywhere, then this would be the property of everybody.

We can see that all these "what ifs" have been fulfilled and surpassed. The early mobile phone systems were not so much driven by customer demand as by technology development and governmental organizations, but things have changed significantly with the massive customer base that is the result of the "what ifs."

The NMT system was based on analog technology, but the big promises from the digital realm were already clear at the start (for instance in mitigating fading dips), and the development of the new digital Groupe Spécial Mobile (GSM) system started in 1982 and was launched in 1992, mainly in a European context [13]. For the Nordic countries, it was important to stress the necessity of the system to provide a service to both cities and sparsely populated areas. Perhaps this contributed to the worldwide success of the system, which was followed by 3G, LTE, and currently 5G is being launched worldwide.

Starting in the 1980s, Sweden had its own development and manufacturing of mobile phone terminals through Ericsson. In 2001, this became a joint venture with Sony under the name SonyEricsson, and in 2012 it became a pure Sony enterprise. There is still a major development office in Lund, Sweden.

2.6 Antenna Engineering

Antenna engineering is an indispensable part of making radio science work, and as such it is important to mention a few Swedish contributions. Many antennas were certainly constructed in Sweden before the appointment of Erik Hallén (Figure 9) as Professor of Electromagnetic Theory at the Royal Institute of Technology in Stockholm in 1945 [14]. However, his work must surely be one of the milestones of the underlying theory. He focused on antenna theory, and is well-known internationally for his integral equation describing the current distribution on wire structures. Hallén would come to be a very influential teacher, and many people working on antennas in Sweden in the latter half of the 1900s either had him as a teacher, or were deeply influenced by his book [15]. Today, antenna engineering is taught at most of the major Swedish universities, many of which also participate in the European School of Antennas, which is a European collaboration organizing antenna related PhD courses.

As in most engineering activities, much of the antenna engineering is performed within commercial companies. In Sweden, two industrial groups stand out, having long-term activities developing antenna systems for telecommunication and aerospace purposes: Ericsson and Saab. Several of their achievements have been described in the overview papers [16, 17] from a historical session at the EuCAP'13, in Göteborg. It is worth mentioning that the space related activities, previously in different constellations at Ericsson and Saab, are now with the Swiss company RUAG Space AB, having several sites in Sweden.

There are several more or less specialized antenna companies in Sweden. Some of the more long-lived are Allgon [18] and Comhat/Arkivator [19], and their respective histories are described in the cited references. The mobile phone industry has generated an entire eco-system of companies, and with respect to antennas the author would like to mention in particular the terminal antenna designing company Lite-On-Mobile (previously Perlos/Moteco), and antenna characterization company Bluetest [20]. The latter company (as well as Comhat) was initiated by the late Prof. Per-Simon Kildal, at Chalmers University in Göteborg, who is recognized as one of the major antenna entrepreneurs in Sweden in the last few decades.

Table 3: List of columns of Women in Radio Science published so far.

Date of Column	Subject of Column
Sep 2015	Asta Pellinen-Wannberg, Sweden
Mar 2016	Sheila Kirkwood, Sweden
Jun 2016	Anthea Coster, USA
Sep 2016	Galina Ryabova, Russia
Dec 2016	Margaret Campbell-Brown, Canada
Mar 2017	Maria Hajdukova, Slovakia
Jun 2017	Yuka Sato, Japan
Sep 2017	Iwona Stanislawska, Poland
Dec 2017	Lee-Anne McKinnell, South Africa
Mar 2018	Jamesina Simpson, USA
Jun 2018	Ivana Kolmasova, Czechia
Sep 2018	Reflections from Asta after 3 years of the column
Dec 2018	Patricia Doherty, USA
Mar 2019	Tuija Pulkkinen, USA

2.7 Women in Radio Science Column

In Sweden, as in many other countries, the radio science field suffers from a severe gender imbalance. This already starts at an undergraduate level, where there are far too few female students in Electrical Engineering and similar programmes. The situation is a little bit better at PhD student level due to foreign recruitments, but there is still a long way to go to change the gender balance at higher academic positions like Professors and Associate Professors.

In order to highlight the female role models of the field, the Radio Science Bulletin has started a regular column on Women in Radio Science, and the first associate editor is Prof. Asta Pellinen-Wannberg, Chair of SNRV 2014-2017 (Figure 10). She has done a tremendous job identifying and describing a number of highly merited female radio scientists, and also helped organize sessions on the subject at the URSI flagship conferences. The Swedish community is very grateful to Asta and the Radio Science Bulletin for this effort, looks forward to it continuing. Table 3 lists the columns published so far.

3. Conclusions and Outlook

This paper has presented a number of Swedish contributions to radio science over the last 100 years. The Swedish National Committee of URSI is thriving, and several of its members have contributed vigorously to the international URSI organization throughout the years. In the years to come, we are looking forward to further developments in radio science as several exciting technologies where Swedish researchers are active, like Massive MIMO and millimeter wave radio, are put into commercial use in 5G mobile communication and a multitude of autonomous systems. We will also see the launch of large scientific facilities like EISCAT 3D, the synchrotron facility MAX IV (already in operation), and the European Spallation Source (ESS), where the latter two make use of RF fields and advanced control systems in accelerating charged particles close to the speed of light. Thus, radio science continues to be a fundamental part of science and engineering in Sweden and world-wide, with SNRV and URSI supporting the development. See you in the future!

4. Acknowledgments

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A Historical Perspective of URSI Activities in Turkey

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1. Introduction

Turkey has been a member of URSI since 1993 with the support of TUBITAK (The Scientific and Technological Research Council of Turkey), which is the leading agency for management, funding and conduct of research in Turkey. Since 1993, Turkey was represented in URSI by the National Committee whose objective is to encourage, promote and coordinate both national and international scientific activities in the field of radio science for the benefit of humanity. The organizational structure of the National Committee consists of the Executive Committee and the Supervisory Board, whose members are elected by the General Assembly, and includes institutional members. In addition, Scientific Commissions are established by the Board of Directors to carry out studies on scientific subjects. Prof. Mithat Idemen (1993 - 1996), Prof. Hamit Serbest (2000 - 2012) and Prof. Ayhan Altintas (2012 - 2018) served as the President of the National Committee in the past. Since 2018, Prof. Ozlem Ozgun has served as the President of the National Committee of URSI-Turkey.

For many years, numerous studies on radio science were conducted by researchers from various universities and institutions in Turkey. The purpose of this article is to provide a quick historical perspective of past and recent activities in Turkey about some topics of interest to URSI.

2. URSI-Turkey National Congresses

Every two years, since 2002, a national congress was held in different universities to bring together researchers working in URSI-related areas and to facilitate the exchange of ideas and information. Even though the congresses were of national nature and the presentations were in Turkish, plenary sessions were held in English by the international eminent radioscientists who were invited to bring up-to-date research topics to the attention of the audience with exciting presentations. Outstanding national radioscientists were also invited to cover a broad range of radioscience topics and to publicize research in Turkish universities. In order to encourage and motivate young scientists and students in URSI topics, a student paper contest was organized in each congress. Both URSI and the AP/MTT/EMC/ED Joint Chapter of the IEEE Turkey section (http://aeme.ieee.metu.edu.tr/) supported the organization of the student paper contests. As for the congresses, in 2016 and 2018 the student paper contest was supported by URSI and the Leopold B. Felsen fund. For the Felsen fund and IEEE Turkey section, the generous support of Prof. Levent Sevgi and Prof. Birsen Saka, respectively, is greatly appreciated.

The First URSI-Turkey National Congress was organized by the Istanbul Technical University (ITU), Istanbul, Turkey on September 18 - 20, 2002. The chair of the local organization committee was Prof. M. Gokmen. There were 120 presentations in the sessions of the congress.

The Second URSI-Turkey National Congress took place at Bilkent University, Ankara, Turkey, on September 8 - 10, 2004. The co-chairs of the local organization committee were Prof. A. Altintas and Prof. V.B. Erturk. There were about

Figure 1. The Fifth URSI-Turkey National Congress, held at METU-NCC, on August 25 - 27, 2010.

150 participants with 124 presentations. The outstanding invited speakers were: Prof. M. Ando (represented by Prof. J. Hirokawa), Prof. P. Russer, Prof. U.S. Inan, Prof. O. Breinbjerg, Prof. H. Ozaktas, Prof. Y. Tulunay, Prof. E. Ozbay, Prof. I. Aksun, Prof. M. Kuzuoglu, and Prof. E. Atalar. In addition, three short courses were delivered to young researchers by Prof. L. Sevgi, Prof. A. Altintas, and Prof. S. Topcu. There were two special sessions honoring Prof. M. Idemen, and Prof. A. Hizal. In the student paper contest, three students (O.S. Ergul, S. Onat, and A.E. Yilmaz) were awarded prizes.

The Third URSI-Turkey National Congress was held at Hacettepe University, Ankara, Turkey, on September 6 - 8, 2006. The chair of the local organization committee was Prof. E. Yazgan. There were 326 participants with 203 presentations. The outstanding invited speakers were: Prof. M. Swaminathan, Prof. L. Bertel, Prof. W. Keydel, Prof. A. Buyukaksoy, Prof. E. Ozbay, Prof. Y. Tulunay, Prof. I. Aksun, Prof. T. Akin, and Prof. A. Altintas. Seven students (K.O. Ozkan, E. Yigit, O. Ozgun, T. Malas, H. Yigitler, T.K.Yapar, and S. Deger) were awarded prizes in the student paper contest.

The Fourth URSI-Turkey National Congress took place at Akdeniz University, Antalya, Turkey on October 20 - 22, 2008. The co-chairs of the local organization committee were Prof. S. Ozen and Prof. S. Helhel. The plenary talks were given by Prof. K. Kobayashi and Prof. Y. Tulunay. There were more than 100 participants with 90 presentations. In the student paper contest, three students (H. Yuzer, N. Gokalp, and C.A. Tunc) were awarded prizes.

The Fifth URSI-Turkey National Congress was organized at Middle East Technical University (METU), Northern Cyprus Campus (NCC), Guzelyurt, Turkey on August 25 - 27, 2010 (Figure 1). The chair of the local organization committee was Prof. O. Ozgun. The plenary talks were given by Prof. R. Mittra, Prof. M. Kuzuoglu, Prof. I. Aksun, Prof. L. Sevgi, Prof. G.T. Sayan, Prof. E. Yazgan, Prof. N. Seyhan, and Prof. Y. Tulunay. Two special sessions were organized in the memory of Prof. M. Buyukdura and Prof. T. Ciftcibasi. There were about 150 participants with 138 presentations. In the student paper contest, awards were given to three students (M. Ural, D. Dogan, and O. Bayraktar).

The Sixth URSI-Turkey National Congress was held at Dogus University, Istanbul, Turkey on September 2 - 5, 2012 (Figure 2). The chair of the local organization committee was Prof. L. Sevgi. The plenary talks were given by Prof. P.Ya. Ufimtsev, Prof. C. Balanis, and Prof. L. Gurel. Short courses were delivered by Prof. P.Ya. Ufimtsev, Prof. O.A. Civi, Prof. G. D'Abreu, Prof. S.R. Rengarajan, and Prof. S.K. Koul. There were 77 presentations in the congress. Three students (O. Yurduseven, D.G. Tas, and G. Toroglu) were awarded prizes in the student paper contest.

Figure 2. The Sixth URSI-Turkey National Congress, held at Dogus University, Istanbul on September 2 - 5, 2012.

The Seventh URSI-Turkey National Congress took place at Firat University, Elazig, Turkey on August 28 - 30, 2014 (Figure 3). The chair of the local organization committee was Dr. A. Akbal. The invited speakers were Dr. M. Cetintas, Prof. E. Panayirci, Prof. I. Tekin, Prof. O. Arikan, Prof. M. Aydogdu, Prof. I. Unal, Prof. F.F. Ozeren, and Dr. H. Kalaycioglu. There were about 273 participants with 167 presentations. Three students (M. Kalfa, B. Ozbey, and O. Bayraktar) were awarded prizes in the student paper contest.

The Eighth URSI-Turkey National Congress was held at Middle East Technical University (METU), Ankara, Turkey on September 1 - 3, 2016 (Figure 4). The chair of the local organization committee was Prof. O.Aydin Civi. The plenary talks were given by Prof. Y. Antar, Prof. K. Kobayashi, Prof. A.I. Nosich, Prof. U. Inan, and Dr. U.C. Doyuran. There were 103 presentations in the congress. In the student paper contest, four students (B. Karaosmanoglu, H. Tuna, U.M. Gur, and K. Ustun) were awarded prizes.

The Ninth URSI-Turkey National Congress was organized at KTO Karatay University, Konya, Turkey on September 6 - 8, 2018 (Figure 5). The chair of the local organization committee was Dr. H. Acikgoz. The plenary talks were given by Prof. R. Mittra, Prof. J. Wiart, Prof. A. Alomainy, Prof. L. Sevgi, and Dr. M. Ciydem. There were about 117 participants with 95 presentations. Three students (G.Y. Altun, F. Mutlu, and E.K. Arici) were awarded prizes in the student paper contest.

The Tenth URSI-Turkey National Congress will be organized at Gebze Technical University, Kocaeli, Turkey on September 10 - 12, 2020. Detailed information about the national congress is available at the URSI-Turkey website: http://www.ursi.org.tr.

Figure 3. The Seventh URSI-Turkey National Congress, held at Firat University, Elazig on August 28-30, 2014.

3. URSI GASS 2011 in Turkey

The XXXth General Assembly and Scientific Symposium (GASS) of URSI was held at the Lufti Kirdar Convention & Exhibition Centre, Istanbul, Turkey, from 13 to 20 August 2011 (Figure 6). Prof. H. Serbest was the chairman of the organization committee. The scientific program coordinator was Prof. P.L.E. Uslenghi and the associate scientific program coordinator was Prof. H. Serbest. They were assisted by Dr. B. Yu, who handled the submission database. The opening ceremony was held on Sunday 14 August 2011 in the Anadolu Auditorium. The ceremony started with the Turkish national anthem, after which the Honorary Presidents, Officers of the URSI Board and primary speakers took their seats on stage. Prof. H. Serbest (President of the Turkish National Committee), Prof. F. Lefeuvre (President of URSI), Prof. M. Idemen (founding President of the Turkish National Committee), Prof. U. Shamir (President of the International Council of Scientific Unions), Prof. O. Altan (President of the International Society for Photogrammetry and Remote Sensing)

Figure 4. The Eighth URSI-Turkey National Congress, held at METU, Ankara on September 1 - 3, 2016.

Figure 5. The Ninth URSI-Turkey National Congress, held at KTO Karatay University, Konya on September 6 - 8, 2018.

and Prof. P. Lagasse (Secretary General of URSI) delivered their messages. Afterwards, the awards ceremony took place just after the opening of the GASS.

The scientific program consisted of 1299 papers (877 oral communications and 422 posters) with 1088 registrants from 54 countries. There were 97 young scientists from 33 countries. The program included 3 general lectures, 1 public lecture and 10 tutorials. Besides this, 4 workshops and 4 short courses were organized. The public lecture was entitled “Lightning-induced Effects in the Ionosphere and the Radiation Bel”. The general lectures, of interest to all participants, were entitled “SMOS: From requirements to results via Radio Science”, “The Radio Physics of Meteors: High Resolution Radar Methods offering new insights” and “Satellite Navigation: Present and Future”. In addition, each commission provided a tutorial lecture in its own sphere of interest. There were four short courses offered: “The uncountable number of degrees of freedom: complex media and metamaterials in electromagnetic” by Prof. A. Sihvola, “Let Darwin and the bees help improve your designs: nature inspired optimization techniques in engineering” by Prof. Y.R. Samii, “Metamaterials and applications” by Prof. A. Alu, and “Signal processing techniques for imaging of ionosphere using GPSTEC” by Prof. F. Arikan. A special session in honor of Prof. R. Kouyoumjian was organized by Prof. Altintas in the context of his ancestry coming from Istanbul (Figure 7).

Furthermore, the second International URSI Student Paper Competition was held. Ten finalists presented their papers orally in a special session at URSI GASS, competing for five monetary prizes. The competition was financially sponsored by the United States National Committee of URSI, and was co-chaired by Prof. S. C. Reising and Prof. B. Saka. The awards to the winners were presented at the GASS banquet.

Detailed information about the URSI GASS 2011 is available in [1]. It is also worthwhile to note that Prof. Altintas served as the Scientific Program Coordinator for the URSI GASS 2014, in Beijing, China.

4. Expertise in Microwave and Communication Engineering

Turkey’s activities on microwave and communication engineering can be traced back to the mid-1950s [2]. During 1956-1958, Prof. S. Sinman constructed the first radio broadcasting stations in Turkey. In 1970s, Prof. A. Ataman established the television laboratory in ITU and began the first television broadcasts in Turkey. In 1980s, two major telecommunication

Figure 6. The XXXth URSI GASS, held at the Lufti Kirdar Convention and Exhibition Centre, Istanbul, Turkey on August 13 - 20, 2011.

companies, Teletas and Netas, were established. Teletas developed the first X-band radio link in Turkey. The development of microwave systems in the Turkish military started in 1975 after the establishment of ASELSAN (Turkish Electronic Industry Corporation). ASELSAN [3] is the leading company manufacturing military microwave components and systems in Turkey, and is the 57th largest military electronics company in the world. In the early 1980s, TUBITAK Marmara Research Center (MAM) [4] developed the first C- and X-band radars. Another research center in TUBITAK is the Informatics and Information Security Research Center (BILGEM) [5], which works on information technology, information security and advanced electronics.

Research activities in Turkey in the area of microwaves, antennas, radiowave propagation, radar applications and communications are mainly conducted in preeminent universities in Turkey, such as METU, Bilkent University, Hacettepe University, ITU, Bogazici University, Sabanci University, Koc University, etc. There are numerous outstanding scientists working under the umbrella of electromagnetics and communications in Turkish universities. There are also various large-scale research centers in some universities, which host a wide range of research activities in these related areas. The Ayasli Research Center at METU [6] has specialized laboratories for conducting a wide spectrum of advanced research, ranging from micro-electronic design and prototyping, renewable and sustainable energy, medical electronics research and consumer electronics solutions to robotics, communications and networks, microwaves, antenna and radar systems. The METU MEMS Center [7] carries out research in the field of MicroElectroMechanical Systems (MEMS), and produces RF-MEMS and RF bio sensor chips for communication and medical applications. At Bilkent University, the Nanotechnology Research Center (NANOTAM) [8] and the National Nanotechnology Research Center (UNAM) focus on nanophotonics, nanoelectronics, metamaterials, and terahertz technology [9]. Sabanci University has the Nanotechnology Research and Application Center (SUNUM) [10] to conduct research activities in similar areas. At Bilkent University, the Communications and Spectrum Management Research Center (ISYAM) [11] conducted the project related to Radio and TV spectrum planning for Turkey and the National Frequency Management System, which includes the entire automation of all licensing and spectrum management activities of the Turkish Telecommunications Authority as well as spectrum engineering tools. Moreover, the National Resonance Research Center (UMRAM) [12] at Bilkent University conducts research on magnetic resonance imaging in medical applications.

Figure 7. The special session held in honor of Prof. R. Kouyoumjian, at the XXXth URSI GASS 2011 in Istanbul, Turkey.

It is evident that the research activities in Turkey in the field of microwave and communication engineering are more than these, and the high-quality research and number of publications is constantly increasing. Although it is not possible to mention each study conducted in Turkish universities and institutions in this short article, it might be worthwhile to mention some of the books recently published by prestigious publishers by Turkish scientists [13-18].

5. Expertise in Electromagnetic Metrology

The progress in the electromagnetic metrology field in Turkey is closely related with the history of the TUBITAK UME (National Metrology Institute) [19], which was established by TUBITAK in 1986 in order to respond to increasingly sophisticated measurement needed by society and industry. In the first years of UME, considerable efforts were devoted to the development of primary national wavelength standards. Experienced researchers from the former Soviet Union Republics and Turkish researchers jointly developed the iodine stabilized He-Ne laser (633 nm) in 1995. Meanwhile, the UME time and frequency standard system was established using three HP 5071 A Cesium atomic clocks and two GPS receivers. Absolute determination of the unit of a volt, at UME, using the Josephson Effect was achieved in 1997, after two years of development and installation work, Good results were obtained in the indirect comparison of 10 V Josephson array voltage standards between the UME and the BNM-LCIE (National Metrology of France). A Maxwell-Wien Bridge was constructed in 1998 as the first primary level measurement system to obtain the unit of inductance. Realization of Quantum Hall Resistance (QHR) standard and measurement system in 2001 was one of the key metrological milestones achieved at UME. One of the important projects carried out in the impedance measurement field was the development of a primary level inductive voltage divider calibration system. In the RF power measurement area, a coaxial-type total power radiometer was developed at UME. At the beginning of 2010s, generation of the low-level direct current was a hot topic and a programmable ultralow DC current source was developed at UME.

6. Expertise in Space and Remote Sensing Applications

The progress in space and remote sensing applications was carried out by universities and leading agencies such as TUBITAK Space Technologies Research Institute [20], Turkish Aerospace [21], ASELSAN [3], HAVELSAN [22], RST [23], etc. in Turkey. At ITU, the Research and Application Center for Satellite Communications and Remote Sensing (CSCRS) [24] conducts application oriented projects in remote sensing and satellite communications technologies.

During 2007-2012, the GOKTURK-1 and GOKTURK-2 satellite projects were conducted by the Turkish Aerospace and TUBITAK Space teams under the coordination of the Ministry of National Defense. The objective of these projects was to produce a satellite with an electro-optical payload in order to provide high resolution images from any location in the world for both military and civilian purposes such as forest control, illegal construction, crop management and casualty assessment after natural disasters. The satellite was placed in orbit in December, 2016, and started to supply the images it obtained. Furthermore, during 2013-2018, the ANKA project was realized by the Turkish Aerospace, under the coordination of Undersecretariat for Defense Industries. The aim was to develop a national unmanned aerial vehicle system to meet the requirements of the Turkish Armed Forces for reconnaissance, surveillance, target recognition and detection.

Ionospheric radio and propagation studies in Turkey were started by Prof. Y. Tulunay and her colleagues in the 1970s. In these years, they detected the dynamic relationship between the ionosphere and the magnetosphere and used the definition of “Main Ionospheric Trough” for the first time. Since the 1980s, scientists from different universities in Turkey have conducted research on ionospheric plasma parameters, electrical and thermal conductivity, reflection, refraction, absorption, diffusion, magneto-hydrodynamic waves, quasi-biennial oscillation (QBO), total electron content (TEC), critical frequency (foF2), maximum usable frequency (MUF), very low frequency (VLF) propagation in the D region and gravity waves. Currently, the scientists of IONOLAB (Ionospheric Research Laboratory) [25] in Hacettepe University continue to conduct research in this field. There are also scientists actively working in this area of research at Inonu and Elazig Universities.

7. Conclusions

On the 100th anniversary of URSI, the National Committee of URSI-Turkey is happy and proud to be a part of URSI. Today, the National Committee consists of many scientists working in a variety of fields, from theoretical and experimental electromagnetics to biomedical engineering, as well as engineers working in industrial companies producing components using a wide range of technologies, from classical electronics to modern nanotechnology. We believe that URSI activities and the existence of the National Committee of URSI-Turkey encourages scientists and engineers in Turkey to conduct more research and produce further knowledge in the field of radio science. The National Committee, established for this purpose and serving on a voluntary basis, would like to continue to carry out this mission, and continue to be a part of URSI in the next century.

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Radio Science in the UK, 1919-2019

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Abstract

The development of radio science in the United Kingdom (UK) in the hundred years since the founding of URSI is outlined here. Early research into the ionosphere by Appleton and colleagues experimentally confirmed the existence of a layer of conductive plasma in the earth's atmosphere, and observations of reflections from this layer prompted the invention of radar by Watson Watt and others. The availability of surplus radio equipment after the Second World War was a factor in the development of radio astronomy by Ryle's group in Cambridge and researchers lead by Lovell at Jodrell Bank. Other post-war developments included medical applications, waveguides, computational electromagnetics, novel antennas for electromagnetic compatibility and continued interest in wireless communications, ionospheric propagation and radio astronomy projects like the Square Kilometre Array. The UK's contribution has been enriched by the collaborative, international ethos of URSI.

1. Pre-URSI Period

Radio science began long before the founding of URSI in 1919, a key step being James Clerk Maxwell's theoretical prediction of electromagnetic (EM) waves in the 1860s, which was validated by Heinrich Hertz, Jagadish Chandra Bose, David Edward Hughes and Oliver Lodge towards the end of the century, and most famously by Guglielmo Marconi, whose experiments in the UK included the first radio communications with a ship from a transmitter on the Isle of Wight.

It is tempting to view the history of radio as "19th century physics leading to 20th century engineering," but that would be an oversimplification. The reality is that the line between engineering and applied physics is a blurred one, and the traffic between fundamental science and practical applications has been two-way. For example, we have the theoretical contribution of Oliver Heaviside (who also rewrote Maxwell's EM equations in their currently used form), and also Arthur Kennelly, independently predicting the Kennelly-Heaviside Layer. Practical experiments in the UK and elsewhere showed that this layer reflected radio waves, which lead to the realisation that EM pulses could be bounced off aircraft to determine their range and direction. Radar was a real-world application that had a great influence on the course of the Second World War and later found many peacetime uses. In the post-war period the availability of surplus radar equipment was a factor that enabled rapid developments in radio astronomy, where observations of distant emitters of radio waves gave us new scientific insights into the nature of the Universe.

Organisations like URSI have played an important role not just in fostering interactions between engineers and scientists, but also in promoting partnerships amongst researchers in many countries across the world. A glance at the lists

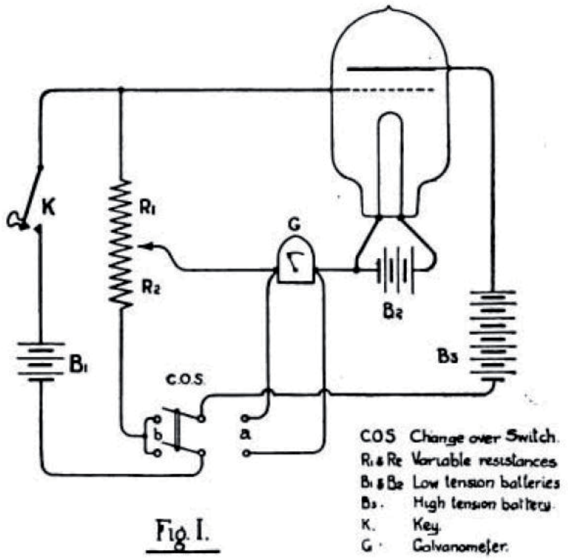


Figure 1. Appleton's slopemeter, used to obtain the wcurrent-voltage characteristics of triode valves (from [3]).

of prizes awarded by URSI [1] shows many who were based in the UK, but an Olympic-Games style medal table would hide the cooperative and international nature of science. Many of the "big names" in UK radio science were highly active in URSI and valued its promotion of scientific openness and global collaboration. It is notable that URSI was founded the year after the end of the First World War, and that internationalism and peaceful unity are embodied in its very name.

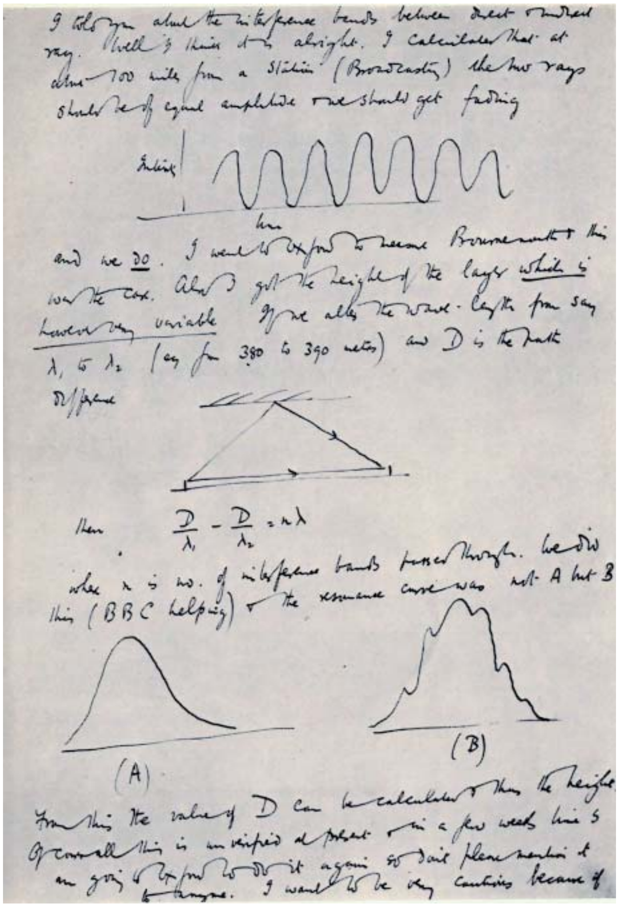
2. The Ionosphere

In the UK, a key figure for early research into Ionosphere is Sir Edward Victor Appleton, who was born in Bradford 1892 into a working-class family and became a professor at the age of 32 and Fellow of the Royal Society (FRS) at 35 [2]. Throughout his career he was a great supporter of URSI, serving as URSI President from 1934-52 and Honorary President from 1952-65. URSI's Appleton Prize is named after him, as is the Rutherford Appleton Laboratory in Harwell, Oxfordshire. Incidentally, Appleton was a life-long friend and colleague of the Dutch physicist and radio pioneer Balthasar van der Pol, another dedicated URSI supporter, after whom the URSI Van der Pol Gold Medal is named. As well as many other distinctions, Appleton was awarded the Nobel Prize for Physics in 1947.

Appleton studied at Cambridge University where he attended lectures by J. J. Thomson, Joseph Larmor and Oliver Lodge. After Cambridge he initially worked with Lawrence Bragg on X-ray crystallography but this work was interrupted by the First World War. He began to take an interest in radio while serving in the army as a Royal Engineer at Aldershot, where the early wireless equipment operated with spark gap sources and crystal detectors. During his service he helped to identify how enemy engineers were listening in on communications, a problem solved with a more secure system called the Fullerphone.

After the war Appleton went back to Cambridge with a position of assistant demonstrator under Ernest Rutherford, famous for splitting the atom, but found he preferred radio science to nuclear physics. Appleton's first paper was published in Wireless World in 1918 [3] where he describes a 'slopemeter,' an instrument for measuring the characteristics of three-electrode valves (Figure 1). These were triodes, the forerunner of the transistor, and used in the first RF amplifiers.

In the 1920s, Appleton and the New Zealand scientist M. A. F. Barnett in the UK, and also Gregory Breit and Merle Tuve in the USA, showed that radio waves can be reflected from ionised layers in atmosphere. Appleton was more aware than the others of the potential applications of this discovery. Key experiments performed in 1924 confirmed the hypothesis of Appleton and Barnett that fades in signal strength were due to variations in reflections from a conductive layer in the atmosphere, which had been postulated 20 or so years earlier by Heaviside and Kennelly [4]. They collaborated with the Electrical Laboratory at the University of Oxford on this research, and persuaded the British Broadcasting Company (later Corporation) to sweep the frequency of the BBC transmitter at Bournemouth, at a time after public broadcasting had finished for the night. A location was chosen where the sky wave and ground wave were of similar magnitude and therefore interfered either constructively or destructively depending on their phase shifts. As expected, sweeping the



I told you about the interference bands between direct & indirect ray. Well I think it's alright. I calculated that at about 100 miles from a station (Broadcasting) the two rays should be of equal amplitude & we should get fading

and we DO. I went to Oxford to measure Bournemouth this was the case. Also I got the height of the layer which is however very variable If we alter the wave-length from say λ_1 to λ_2 (say from 380 to 390 meters) and D is the path difference

then $\frac{D}{\lambda_1} - \frac{D}{\lambda_2} = n\lambda$

where n is no. of interference bands passed through. We did this (BBC helping) & the resonance curve was not A but B

From this the value of D can be calculated & thus the height. Of course all this is unverified at present & in a few weeks time I am going to Oxford to do it again so don't please mention it to anyone. I want to be very cautious because of

Figure 2. Experimental results in Appleton's notebook, showing interference between sky wave and ground wave as the transmitter frequency was swept, confirming the existence of the ionosphere (from [1]).

frequency caused an oscillatory variation in the combined signal strength (Figure 2).

Appleton and Barnett showed that their interference method was more successful than earlier attempts to observe the downward travelling ray with a directional antenna [5]. They also correctly hypothesised that interference was being observed from "single-hop" and "multi-hop" paths of rays reflected between ionosphere and ground as illustrated in Figure 3.

Appleton moved to Kings College London as professor to take up the Wheatstone Chair in 1924, and the ionosphere became his major and life-long interest. Appleton was an early advocate of academic collaboration with industry and with institutions like the BBC; he encouraged John Logie Baird to develop ultra-SW (i.e. UHF) transmissions of TV signals. He also saw the value of international relationships with researchers in the USA, Germany and elsewhere.

Collaboration between universities and government was important in early ionospheric research in the UK. The National Physical Laboratory (NPL) provided transmitters at Dogsthorpe near Peterborough. With an improved detector, the Eindhoven galvanometer, they showed that the height of the ionised layers changes at dawn, and also during a solar eclipse, so it must be influenced by the sun [6].

The Radio Research Station (1924-79) at Ditton Park, near Slough, Berkshire, England was the UK government research laboratory that pioneered regular observation of the ionosphere by ionosondes. It later became the Radio and Space Research Station (1965) and eventually merged with the Rutherford Laboratory. Appleton and radar pioneer Robert Watson-Watt (see next section) both worked there. The British physicist Mary Taylor (later Mary Taylor Slow) was perhaps the first woman to become a professional radio scientist; after studying at Girton College, Cambridge and the University of Göttingen, Germany she became a Scientific Officer at the Radio Research Station in 1929, where she published research on the Appleton-Hartree equation for EM propagation in a magnetised plasma [7].

Appleton's research has thus been useful in plasma physics generally as well as in the field of Antennas and Propagation. He named the layers of the ionisation in the atmosphere – initially the E-layer (E for Electric) and subsequently the D and F layers above and below it. However the word 'ionosphere' to describe the Heaviside-Kennelly layer seems to have been coined by Watson-Watt: in a letter to the Secretary of the Radio Research Board in November 1926 he wrote [2]

> We have in quite recent years seen the universal adoption of the term "stratosphere" in lieu of a previously well established misnomer "isothermal layer" and the adoption of the companion term "troposphere" for the "convection layer"...the term "ionosphere" for the region in which the main characteristic is large-scale ionisation with considerable mean free paths, appears appropriate as an addition to this series.

Appleton contributed to the International Polar Year 1932-3; a venture proposed by a sub-commission of URSI and lead by Danish physicist Dan Barfod la Cour, with the involvement of van der Pol and Watson-Watt. Activities included an expedition to Norway to investigate ionospheric propagation at high latitudes (Figure 4). Using SW and pulse transmitters near Tromsø, the researchers made the first observations of radio "black-outs" during magnetic storms [8].

Appleton's influence on the development of radar is described in the next section. Pulses, from improved pulse generators, were being bounced off the ionosphere, and this led on to a similar idea where the target is a moving aeroplane. Observers at the Halley Stewart laboratory at KCL in the early 1930's had noted "blips" on the response when the ionosonde beam directed upwards at the ionosphere was interrupted by passing planes.

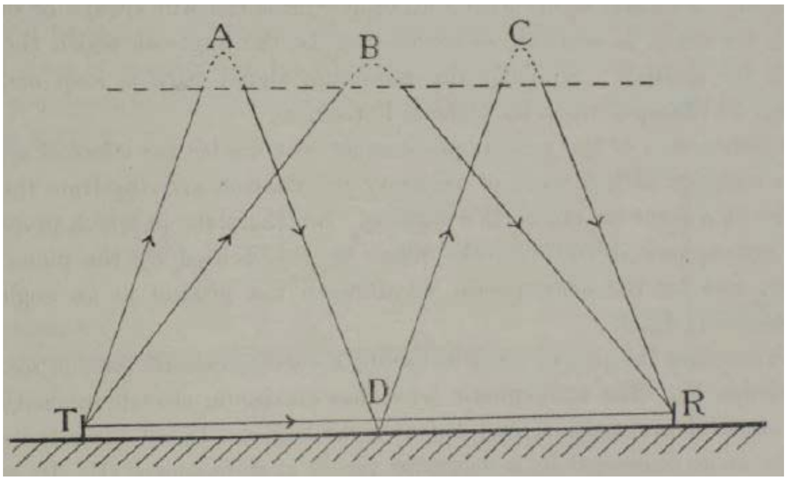


Figure 3. Appleton and Barnett postulated interference between rays reflected once and twice from the ionosphere (from [5]).

Other researchers in the UK joined the field. John Ashworth (or "Jack") Ratcliffe, an influential British radio physicist, was Appleton's student at Cambridge in 1923-4 and did much pioneering work on the ionosphere immediately prior to the Second World War. He served as URSI Honorary President from 1966-87, and continued his ionospheric research in the post-war period. He published observations on the spreading of radio frequencies by the Doppler effect, noting that this was analogous to broadening of spectral lines in the optical case [9].

William Henry Eccles was a British physicist and pioneer in the development of radio communication. He had assisted Marconi in his experiments, was an early advocate of the Kennelly-Heaviside Layer, and was involved in the early days of the BBC. He was URSI Vice-President 1921-34 and Honorary President 1934-66. Eccles-Larmor theory is named after him and the Northern-Irish Physicist Sir Joseph Larmor; it explains the mathematics of ionospheric propagation, including the plasma frequency [10].

Figure 4. Map showing that Tromsø (spelled Tromsö here) was well located for research into high-latitude propagation (from [8]).

Sir William John Granville Beynon was URSI President 1972-75 and Honorary President 1981-86; he published an account of URSI's involvement in the early research on the ionosphere [11]. After studying physics at the University of Swansea, he joined NPL in 1938 where he worked with Appleton on ionospheric propagation. After the war he returned to Swansea, and then in 1958 moved to what was then the University of Wales at Aberystwyth (now Aberystwyth University) where he carried out rocket-borne experiments in the 1970s. Like Appleton, Granville Beynon saw the value of international scientific cooperation. He played a key role on behalf of URSI in organising the International Quiet Sun Year 1964-65. Figures 5 and 6 are taken from a postgraduate brochure and show research into the ionosphere and satellite communications being undertaken at the Aberystwyth in the 1960s, under the guidance of Granville Beynon.

In more recent years, other UK scientists who contributed to ionospheric research include Henry Rishbeth [12], who received the Appleton Prize in 1981 for "Contributions to studies of the dynamics and structure of the ionosphere F region." At the University of Leicester, Tudor Jones carried research on the ionosphere, especially at the polar regions. He received the Appleton Prize in 1993 for "major contributions, individually and in scientific leadership, to the study of ionospheric physics, using radio and radar techniques." Michael Lockwood received URSI's Issac Koga Gold Medal in 1990 for "Study of non-thermal ionospheric plasma and ionospheric convection." Lockwood's work at the University of Reading in the 2000s contributed to the debate on solar versus anthropogenic influences on global warming.

Figure 5. Researchers at Aberystwyth, in the 1960s, using an automatic ionosphere sounder for measuring the height of reflection of radio waves.

3. Radar and Direction-Finding

Many countries were working on radar research in the 1930s. New devices were important in making progress, as well as advances in theoretical propagation calculations. The resonant cavity magnetron as shown in Figure 7 [13] was radically improved by physicists John Randall and Harry Boot in 1940 at the University of Birmingham [14], making smaller, higher frequency equipment possible. It was an improvement on the older klystron and is still used today in domestic microwave ovens.

Scottish engineer Robert Watson Watt was a regular participant at URSI meetings. He began his career at the Met Office (the UK's national weather service), where in the 1920s he used radio waves from lightning to track thunderstorms (Figure 8) [15]. In 1927 he was appointed superintendent of the Radio Research Station.

Figure 6. Equipment at Aberystwyth in the 1960s for recording radio signals from satellites.

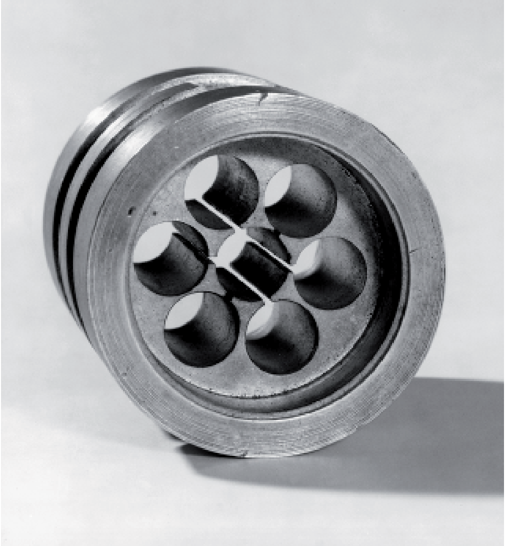


Figure 7. The anode block of the original cavity magnetron built in 1940 by Randal and Boot (from [13]).

High frequency direction finding (HF/DF or “Huff Duff”) was developed in the 1930s using Watson Watt’s principle. Based on two orthogonal loop antennas (Adcock antennas), connected to an early cathode-ray oscilloscope (CRO), with a slow phosphor and in x-y mode, it gave the angle of direction of incoming signals.

Research on ionosondes at the Radio Research Station, starting in 1932, eventually lead to the British “Chain Home” radar system that was used in the Second World War (Figure 9). In 1935 researchers at the RRS successfully detected reflections of a 6 MHz wave from a BBC short-wave transmitter in Daventry. They subsequently built a SW pulse system at Orfordness that generated pulse widths of only 25 µs.

The rivalry between Appleton and Watson Watt is well known, but both contributed greatly to radar’s success, and Appleton did acknowledge Watson Watt’s vision in developing a scientific principle into a practical radar.

Radar was deployed in the war, being crucial to the outcome of the Battle of Britain. The UK offered details of the newly-invented magnetron to the US in exchange for financial and industrial assistance. This gave the Allies better performance than Axis equipment. Airborne radars were being used by 1941, including ground mapping radars (H2S) that were developed by Alan Blumlein, who was killed in a plane crash during the H2S trial, and Bernard Lovell, more famous for his radio astronomy work. These were able to spot submarines from the radar reflection of their periscopes.

Another contributor to this field, from 1922 onwards, was Reginald Leslie Smith-Rose, an English physicist who worked at the National Physical Laboratory and was a world leader in radio direction-finding. He was the first director of the post-war Radio Research Organisation that was formed in 1948, and served as President of URSI from 1960-63.

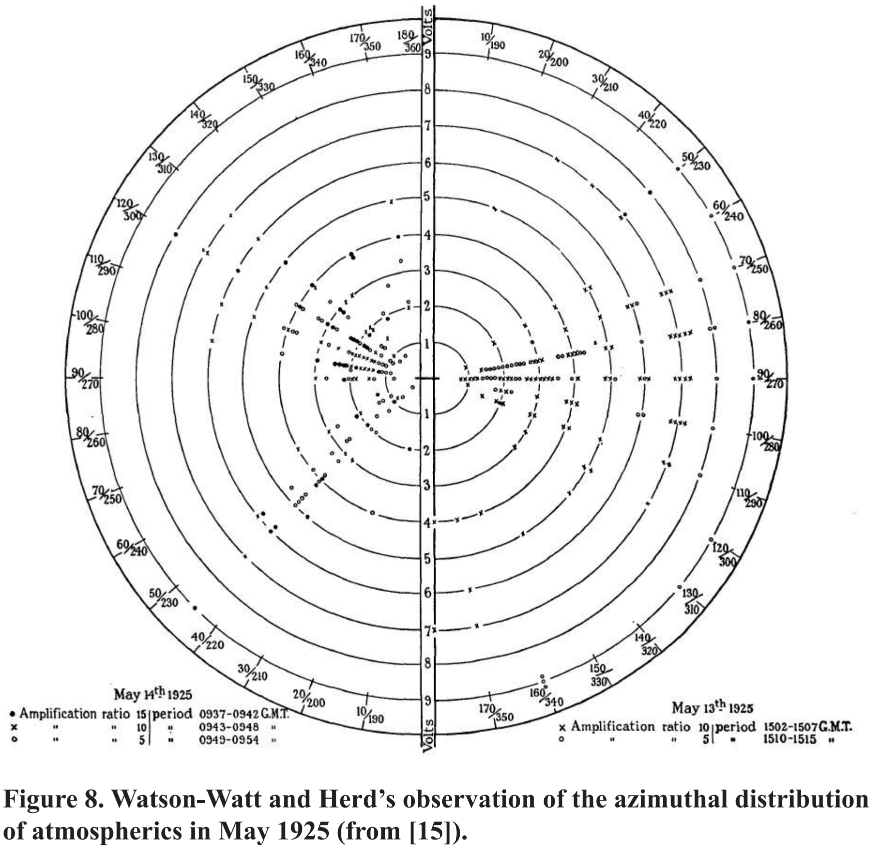


Figure 8. Watson-Watt and Herd’s observation of the azimuthal distribution of atmospherics in May 1925 (from [15]).

Figure 9. The last standing transmitter of the Chain Home network, at the site of the former RAF radar station at Stenigot, near Donington on Bain, Lincolnshire (from [14]).

URSI business during WW2 was minimal and the General Assembly (GA) did not restart until 1946, after a gap of 8 years. The Telecommunications Research Establishment (TRE) and the Radar Research and Development Establishment (RRDE) continued their research work at Malvern, Worcestershire, and in 1953 they were combined to form the UK's Radar Research Establishment.

Radar continued to be developed after the war, not just for military purposes, but for making all forms of transport safer (road vehicles as well as aircraft), and technological advances in radar have led to diverse applications including weather radar, ground penetrating radar (GPR) and radio astronomy.

4. Radio Astronomy

There had been unsuccessful attempts to detect RF emissions from the Sun in the 1890s. A proposal was made at the URSI GA of 1934 (by a commission headed by Appleton), for a global study of RF noise from stars, but this was not implemented [16].

Radio astronomy proper is generally considered to begin with the work of Karl Jansky in the US in the 1930s, which was taken up by Grote Reber in the early 1940s. However initial developments in radio astronomy in the UK, in research groups at Cambridge and Manchester, were more influenced by RDF and radar. Bernard Lovell's group at Manchester initially worked on meteors and the ionosphere, moving in the 1950s to develop interferometry techniques to study emissions from galaxies and discrete sources. Martin Ryle's group in Cambridge looked at solar emissions and observed what were then termed "radio stars", and subsequently commenced a programme of cataloguing and mapping.

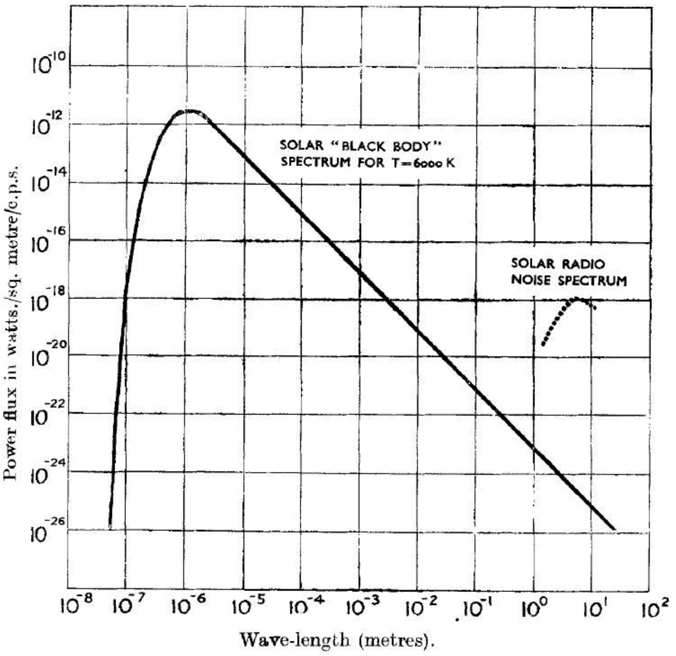


Figure 10. Appleton and Hey observed RF noise from the sun, and showed that it exceeded the solar black body spectrum (from [17]).

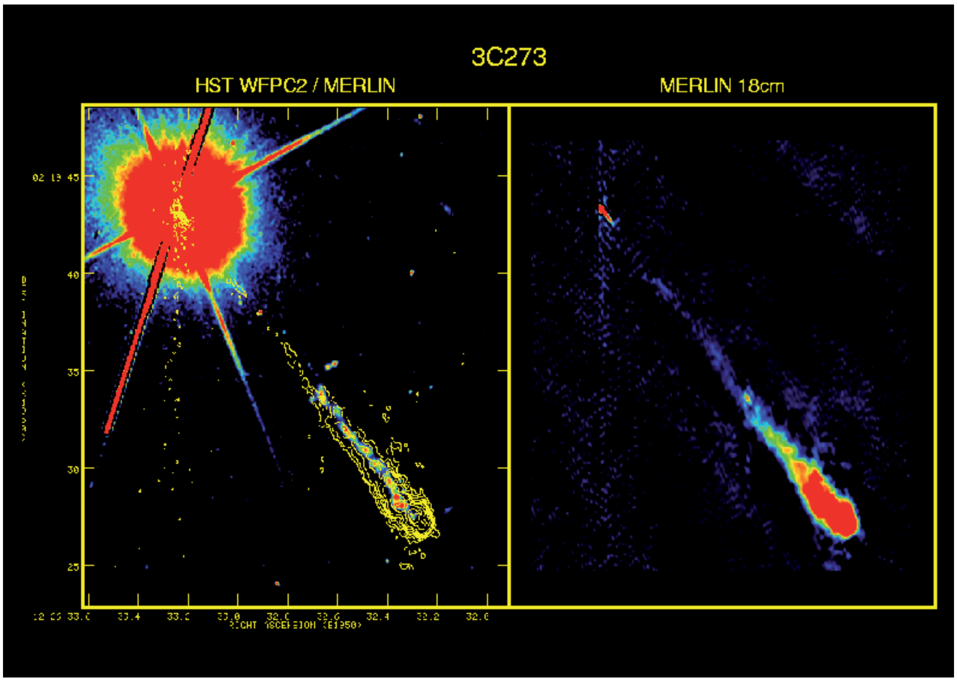


Figure 11. The 3C273 radio source (credit Jodrell Bank Centre for Astrophysics).

J. S. Hey had observed radio noise from the direction of the sun at radio stations on the British coast, in 1942. After the war, in 1946, Hey and Appleton showed that the power at peak times was much greater than could be explained by black body radiation in that band of the spectrum, and showed it was connected with solar flares and sun spot activity (Figure 10) [17]. Hey went on to work at the Royal Radar Establishment at Malvern, eventually becoming Head of Research there.

Ryle also worked initially on radio emissions from the sun [18]. After WW2 he lead the Cambridge radio astronomy group, and eventually founded the Mullard Radio Astronomy Observatory (MRAO) near Cambridge, in 1957. An advocate for the socially responsible use of science and technology, Ryle can be credited with key improvements in astronomical interferometry and aperture synthesis. Using slotted lines, stub tuners and hand-calculation of Fourier transforms, he and his group built the first multi-element interferometer in 1946, which operated at 175 MHz, and consisted of a broadside array of dipoles over a ground plane.

The Cambridge group published catalogues of astronomical radio sources. There have been ten of these to date, with the 3C and 4C catalogues in the 1950s being notable for their contribution of radio astronomy to debates in cosmology [19]. In particular, the "log N – log S, where N is the number of sources with flux density greater than S" relation seen in P. A. G. Scheuer's measurements of the radio source counts [20] provided strong evidence against the steady state theory and in favour of its rival, the big bang theory (which was further strengthened by observations of the cosmic microwave background). Scientific advances and technical developments were thus intertwined.

Radio astronomy at Cambridge continued its contribution to new discoveries in the 1960s. Optical follow-up of the radio source 3C273 (Figure 11) led to the discovery of quasars by Maarten Schmidt in 1963 [21]. A few years later, in 1967, Jocelyn Bell Burnell, a graduate student working with Antony Hewish, used the IPS array that was investigating interplanetary scintillation (Figure 12) to discover the first pulsar. Ryle received the Balthasar van der Pol Gold Medal in 1963 for "Application of the phase switching and aperture synthesis techniques to antennas for radio astronomy," while Hewish was awarded the John Howard Dellinger Medal by URSI in 1972 for "Advances in radio astronomy." Ryle and Hewish, but controversially not Bell Burnell, received the Nobel prize for physics in 1974.

Radio-astronomy at Manchester began with ex-army radar equipment, including Yagi antennas using the 4.2 m band (71 MHz), and a "large aerial" system [22]. Lovell's group then constructed a home-made paraboloid out of wire mesh, to provide a powerful instrument for its time. This had a narrow beam width that was slightly steerable, and was dubbed the "searchlight aerial." The famous 76-metre Lovell Telescope at Jodrell Bank (the location was originally the University of Manchester's botanical grounds) was conceived by Sir Bernard Lovell, and designed by him and engineer Sir Charles Husband. It was the largest radio telescope in the world when completed, in 1957, and tracked the USSR's Sputnik satellite later that year.

Figure 12. The IPS Array for investigating interplanetary scintillation, used to discover pulsars (credit Graham Woan, University of Glasgow).

Robert Hanbury Brown joined Lovell's group in Manchester, in 1949, where his work on airborne radar influenced Reber's research in the US on "cosmic static." In 1950, Hanbury Brown and his PhD student Cyril Hazard in Manchester used a 218 foot (66 m) paraboloid antenna, with a beam width of 2 degrees, the narrowest in the world at the time, to investigate the emissions at 159 MHz from the M31 nebula in the constellation Andromeda (Figure 13). This showed that M31 was an RF source [23].

Hanbury Brown's idea of an "intensity interferometer" was conceived in 1949 and confirmed (with British astronomer Richard Twiss) in 1954. Their concept was also applied to optical radiation and used to measure the angular diameter of Sirius – the first such measurement on a star [24]. Hanbury Brown also worked on plans to use the moon as a radio relay, although these were eventually rendered unnecessary by the development of artificial satellite communications. He moved to Australia in 1962 and continued his research there.

The Multi-Element Radio Linked Interferometer Network (MERLIN), an interferometer array of radio telescopes spread across England, is run from Jodrell Bank Observatory by the University of Manchester. The new radio telescope was finished in 1976, and the rest of the system built in the late 1970s.

The Laing-Garrington effect, an asymmetry in the polarisation of radio emissions from jets that emerge from a double radio source, was important in the development of unified schemes of active galactic nuclei (AGNs). It was discovered in 1988 by Robert Laing and Simon Garrington of the Jodrell Bank Observatory [25].

5. Post-World-War-Two Period

Wartime technologies evolved into other peaceful applications. The British science-fiction author Arthur C Clarke proposed satellite communications in 1945: in a letter to the editor of *Wireless World* he noted that a satellite in a 24-hour orbit [26]

> would remain stationary in the same spot and would be within optical range of nearly half the Earth's surface. Three repeater stations, 120 degrees apart in the correct orbit, could give television and microwave coverage to the entire planet.

This idea was subsequently taken up by many countries, and much sooner than the half century predicted by Clarke. A British satellite programme was started, with "Black Knight" rockets being tested on the Isle of Wight at a site near the Needles, not far from the location of Marconi's ship to shore transmissions at the turn of the century. Their successor, Black Arrow, launched the Prospero satellite from Woomera, Australia in 1971. Funding was then withdrawn as satellite communications were thought to have no commercial future, and interest moved on to other projects such as Concorde.

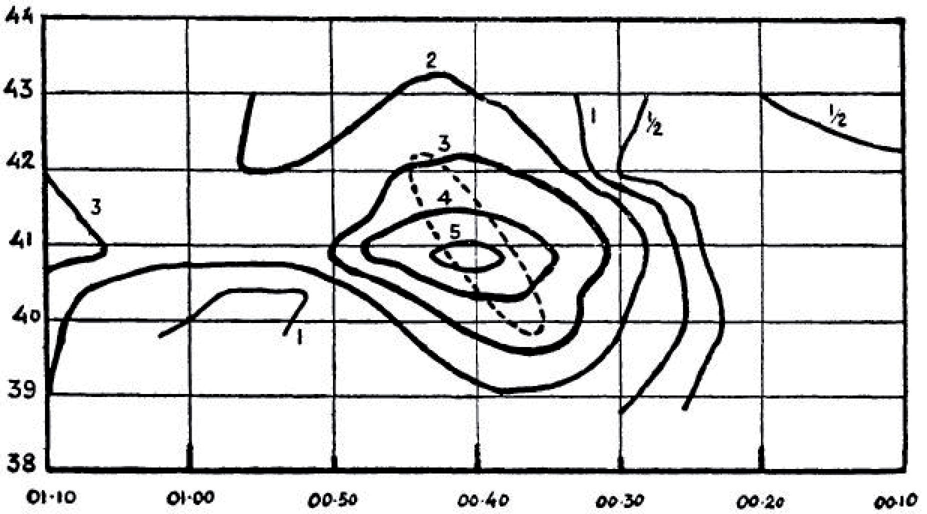


Figure 13. Hanbury Brown and Hazard's 1951 plot of contours of radio-frequency flux near the M31 source in Andromeda (dotted lines show a corresponding photo), obtained with a 2°beam at 159 MHz (from [23]).

Advances in EM theory were made in British universities. Professor Douglas Jones, a mathematician known for his work in electromagnetism, was appointed Chair of Mathematics at the University of Keele in 1957. He was the author of the key EM textbook *The Theory of Electromagnetism*, published in 1964 [27]. Jones was awarded the Balthasar van der Pol Gold Medal by URSI in 1981 for "Work on electromagnetic theory and, in particular, on the development of a number of analytical approaches."

Government laboratories such as NPL continued to play a role in radio science. E. H. Rayner at NPL served as Honorary President of URSI 1946-63. He had worked on the international comparison of radio frequency standards since the 1930s – an article in Nature from 1935 reports that a standard at NPL with "a frequency of 1000 cycles per second, the stability of which is better than one part in ten million" was used to modulate transmissions from three BBC stations, enabling frequency comparisons and also studies of fading [28].

There was renewed interest in the microwave region of the EM spectrum. Harold Barlow worked at University College London in the post-war period on problems involving guided-wave propagation, especially the development of circular waveguides (Figure 14) [29]. In 1969, Barlow was awarded the John Howard Dellinger Medal by URSI for "Development of waveguides; the characteristics of surface waves." A. L. Cullen, who was President of URSI 1987-90, started at UCL as Barlow's assistant and continued research at UCL into microwave and mm wave antennas.

Radio technologies found valuable uses in medicine. Magnetic resonance imaging (MRI) employs antennas in their near-field, typically at 64 MHz, to excite and sense resonances of the hydrogen nuclei in the human body in the presence of a strong magnetic field. Although nuclear magnetic resonance (NMR) spectroscopy had been known earlier, imaging systems were first developed in the 1970s by many researchers including Paul Lauterbur and Raymond Damadian. Peter Mansfield at the University of Nottingham introduced echo-planar imaging which speeded up the measurements, and John Mallard built a full-body MRI scanner at Aberdeen [30]. Lauterbur and Mansfield were awarded the 2003 Nobel Prize in Physiology or Medicine for their work on MRI.

Mallard suggested that differences in permittivity of body tissues could enable a radio frequency or microwave alternative to X-ray imaging, a promising area of application being the detection of breast cancer, where the high water content of tumours should provide high contrast to the surrounding healthy tissue [31]. This idea was taken up by researchers in several countries, including Alan Preece's group in Bristol [32]. Microwaves have also been used to treat cancers, with novel near-field antennas for hyperthermia therapy (known as applicators) being designed at Bristol [33] and also by Jeff Hand's group at Hammersmith Hospital and Imperial College London [34]. Parametric models of tissue dielectric properties were developed by Camellia Gabriel and colleagues which enabled detailed computational electromagnetic models to be created for simulating EMF exposure [35], while at the University of York (and elsewhere), an experimental technique allowed the absorption cross-section of the body to be measured directly in a reverberation chamber at microwave frequencies [36].

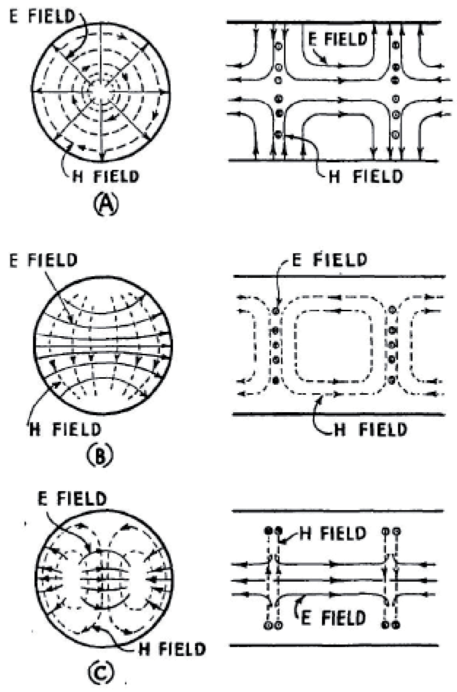


Figure 14. Barlow's 1947 illustration of the field patterns in a cylindrical waveguide, showing E01, H11 and E11 propagation modes (from [29]).

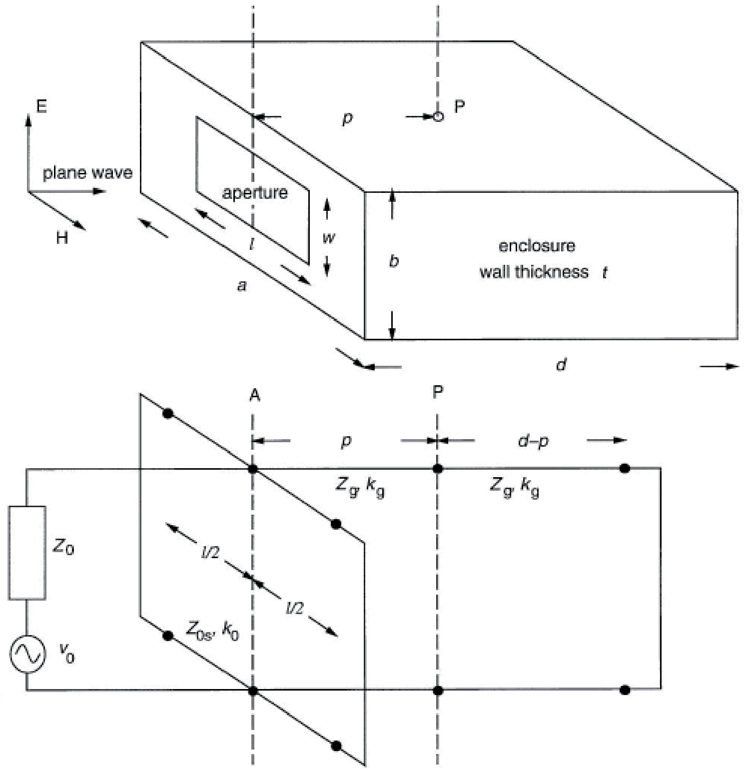


Figure 15. Intermediate level model of a rectangular enclosure with an aperture, introduced in 1998. The current and voltage at a given distance along the waveguide give, respectively, the electric and magnetic shielding effectiveness (from [39]).

The proliferation of electronic devices led to increased problems with radio frequency interference (RFI) and hence greater regulation, including the European Community Directive on Electromagnetic Compatibility 89/336/EEC. The need for industry to limit both emissions and susceptibility of products prompted research in 1990s in the UK and in other European Union countries into improved EMC test methods. A novel antenna design, the Bilog, enabled broadband frequency sweeps without the need to switch antennas; it combined features of bi-conical and log-periodic antennas, and was developed at the University of York by Andy Marvin and Stuart Porter [37].

There were also developments in computational electromagnetics, such as the Transmission Line Matrix method introduced by P. B. Johns and R. L. Beurle of the University of Nottingham in 1971 [38]. "Intermediate level modelling tools" that bridge the gap between analytical solutions and full-wave solvers, were introduced for EMC problems such as the design of EM shields. An example of these tools is the equivalent circuit of Figure 15 for an enclosure with an aperture, which is represented by a coplanar transmission line coupled to a shorted section of waveguide [39].

The UK Member Committee of URSI in its current form was set up in 1990, as a successor to the British National Committee, after the Royal Society in the UK reorganised the committees responsible for scientific unions. Its activities include the Festival of Radio Science (FRSci, previously National URSI Symposium), an annual one-day event aimed at PhD students and early-career researchers, with prizes for best oral presentations and posters.

An internal review of UK URSI in 1998 noted that UK radio scientists had a good level of participation at URSI conferences and at the GASS, with many elected to official positions such as commission chairs or editor of URSI journals. It also noted that the UK radio science community had particularly strong representation on Commissions B, F, G and H.

6. Twenty-First Century and Beyond

In this century, UK scientists and engineers have continued to contribute to URSI, presenting papers at the GASS and serving as commission chairs and in other posts. Paul Cannon of the University of Birmingham was President of URSI 2014-2017.

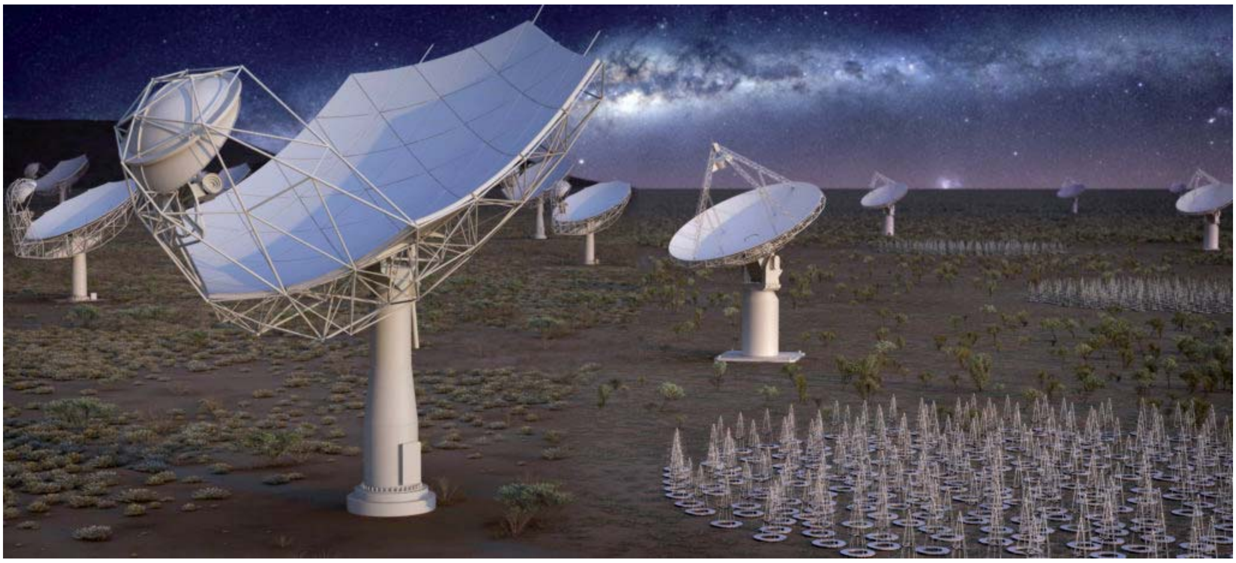


Figure 16. An artist's impression of the SKA (credit: SKA Organisation).

A glance at the programmes for the last few FRSci's shows that the UK still has an active interest in radio astronomy, including the Square Kilometer Array (SKA), and research continues on many aspects of ionospheric propagation. Another current topic of interest is mm-wave channels for 5G communications. There have been many papers on microwave and mm-wave devices such as dielectric resonators, amplifiers, switches and filters, and on antenna performance and the design of patch antennas and arrays. Propagation scenarios being studied include indoor, urban and vehicle-to-vehicle channels, while bio-medical applications include body-worn antennas, patient movement tracking and detection of breast cancer. Other topics have been wireless sensor networks, metamaterials and reverberation-chamber measurements for electromagnetic compatibility (EMC). Presenters have been mainly from universities, but also from companies like QinetiQ and research agencies such as NPL.

New research topics continue to arise, an example being Sir John Pendry's research at the Blackett Laboratory, Imperial College London on refractive indices and "perfect lenses," and associated work on metamaterials that have negative permittivity or permeability [40]. Pendry was awarded the John Howard Dellinger Medal by URSI for "outstanding advances in electromagnetic and optical metamaterials, the design of the perfect lens and transformation optics" in 2017.

The strong influence of the ionospheric plasma on radio signals is still important. Electron density enhancements and depletions in the ionosphere cover a wide range of spatial scale-sizes, and these structures and associated density gradients affect radio propagation and signal strength. Ionospheric imaging and modelling have played an important role in understanding and mapping the radio signal paths. Tomographic imaging [41, 42] has been used to identify large-scale ionospheric structure, including patches of enhanced density in the polar cap and blobs and troughs in the auroral and sub-auroral regions. Data assimilation allowed measured data to be combined with a background ionospheric model [43, 44], and modified Taylor diagrams have been used to assess such assimilative models [45]. An ionospheric data assimilation technique capable of resolving travelling ionospheric disturbances was presented by [46], which improved the accuracy of HF angles of arrival predictions. Statistical studies of large-scale ionospheric features have also been carried out. These include investigations of polar patches in the high-latitude plasma flow observed by the EISCAT Svalbard Radar [47] and the main ionospheric trough modelled by the Qinetiq Electron Density Assimilative Model [48]. Influences of geomagnetic storms and auroral precipitation on radio systems have also been studied, with [49] investigating the correlation between GPS phase radio scintillation and optical auroral emissions, and [50] examining the characteristics of sudden commencement absorption that accompanies a geomagnetic storm sudden commencement.

With the increasing dependency of society on modern technology, precision and safety are increasingly important for future operational systems. For example, improved nowcasting and forecasting of HF propagation is required for trans-polar airline routes [51]. The need for the quantification of space weather effects and their influence on the ionospheric plasma is therefore increasingly important, where severe perturbation of the ionospheric plasma can lead to signal degradation or loss. The plasmasphere is also affected by disturbed geomagnetic conditions and its coupling with the ionosphere and magnetosphere is also of interest for operational systems.

Recent advances in radio astronomy include the discovery of rotating radio transients (RRATs) in 2006 using the Lovell Telescope; these are thought to be intermittent pulsars. Jodrell Bank was selected as the permanent headquarters for the Square Kilometer Array (SKA) in 2015. On 7th July 2019, Jodrell Bank Observatory was awarded World Heritage Site status by UNESCO and added to that body's World Heritage List.

The SKA telescope, pictured in Figure 16, will provide a huge leap in radio astronomy capabilities when it comes on line in 2027. UK researchers are heavily involved with the design of the telescope and the definition of the science programme. Key areas where transformational discoveries are expected include: high precision timing of pulsars to test theories of General Relativity and detect very low frequency gravitational waves; exploration of the first stars in the Universe by studying highly redshifted neutral hydrogen emission; investigation of the recently discovered phenomenon of Fast Radio Bursts due to as yet unknown events at cosmological distances.

7. Conclusion

Science often progresses in unexpected directions, and those researchers who started investigating the ionosphere nearly a century ago might not have expected that the reflections they observed would lead to the concept of radar, or that the surplus of radar equipment after the war would assist in the development of radio astronomy. Although the main use of radio technology remains in wireless communications systems that connect people across the globe, it has also evolved into new applications that enable us to sense the smallest features of the body and to explore the furthest objects in the cosmos. This has been achieved by scientists, engineers and technologists in universities, companies and national laboratories, and the contribution of the UK researchers has been enhanced by their willingness to collaborate with those in other countries and to adopt the cooperative and internationalist ethos of URSI.

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One Hundred Years of Radio Science in the United States of America (1919-2019)

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1. Introduction

The International Union of Scientific Radio Telegraphy, later renamed the *Union Radio Scientifique Internationale (URSI)*, was founded in 1919 at the First General Assembly of the International Research Council. URSI held its first General Assembly in Brussels, Belgium, in July 1922, with official participation from four countries: Belgium, France, United Kingdom, and USA. The United States was thus involved with URSI from the very beginning of its activity, and has since contributed to the development of radio science with a prodigious panoply of scientific discoveries and organizational endeavors. A comprehensive description of such activities would require several tomes, hence only a sketchy survey of some of these activities is provided herein. The USA is a country of immigrants that has benefited from the influx of scientists from all over the world during the past one hundred years. Consequently, in addition to the outstanding contributions by locally born scientists, many of the discoveries that were made in the USA in all areas of radio science were by researchers educated elsewhere, who found in the USA a fertile ground for intellectual exchanges and financial support in a climate free from ideological constraints. A chronological overview of their discoveries is provided in the next section, which is followed by a description of the Nobel prizes awarded to US scientists for their pioneering work impacting radio science, and by a listing of the URSI awards received by US scientists.

The service provided to URSI by US scientists is recapped in three sections, covering the role of US scientists as URSI officials, the organization of URSI symposia, and URSI-related publications in the United States. Lastly, a history of the United States National Committee (USNC) of URSI and some predictions on radio-science activities in the USA over the next one hundred years conclude this survey.

2. Radio Science Milestones in the United States[1]

Scientific discoveries either directly related to radio science or impacting the development of radio science at a later time occurred in the USA long before URSI was established. The pioneering works of Benjamin Franklin, Antonio Meucci, Nikola Tesla, Alexander G. Bell, Samuel Morse, and Thomas A. Edison in the eighteenth and nineteenth centuries come to mind. The first demonstration of telegraphy was performed by Morse and Vail in 1838, and the first transcontinental telegraph line connecting the Atlantic and Pacific coasts of the USA was completed in 1861, followed by the first transmission of voice over electric wires in 1876. In 1884, the American Institute of Electrical Engineers (later to become the Institute of

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[1] Substantial information for this section was taken from https://ethw.org/Milestones:List_of_IEEE_Milestones.

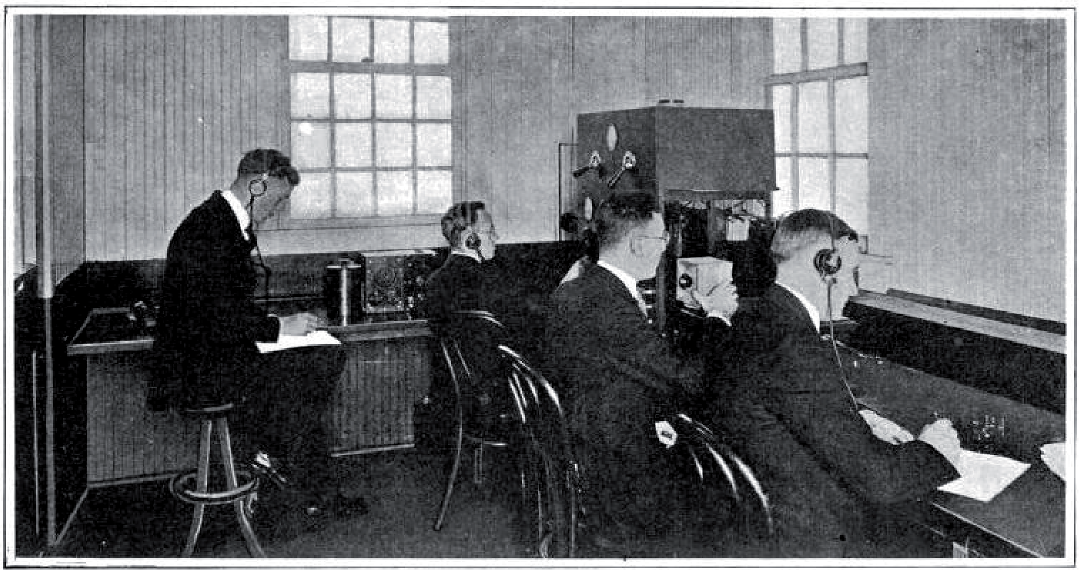

Figure 1. A photograph circa 1921 of the 9th floor of the KDKA transmission room [1].

Electrical and Electronic Engineers, the IEEE) held its first meeting in Philadelphia. A powerful source for transoceanic radio communications up to 100 kHz was the Alexanderson Radio Alternator, developed at Schenectady, NY, beginning in 1904, and perfected through the end of World War I. In December 1906, at Brent Rock, MA, Reginald A. Fessenden set up the first radio broadcast for music and entertainment, based on amplitude modulation of continuous electromagnetic waves.

The first twenty years of URSI's existence, from 1919 to 1939, spanned the period between the two World Wars, which saw significant development in radio science in the USA. The Westinghouse Radio Station KDKA (Figure 1) began transmitting from Pittsburgh, PA, in November 1920, with a power of 100 W on a 360-meter wavelength; it became a world pioneer in commercial radio broadcasting. The first one-way radio communication between a police station and its patrol cars began in Detroit, MI, in April 1928, and was followed by a two-way communication system five years later in Bayonne, NJ. November 1929 saw the first blind takeoff, flight, and landing of a biplane in Garden City, NY, using a combination of radio and aeronautical instrumentation. The first long-range shortwave voice transmission began in February 1934 from Byrd's Antarctic Expedition to New York. In 1937, Claude E. Shannon, while still a graduate student at MIT, developed the principles of digital circuit design, and John V. Atanasoff at Ames, IA, designed the first electronic digital computer, the prototype for which he built two years later with his student, Clifford E. Berry.

Figure 2. A photograph of Karl Jansky [2].

Perhaps the most significant research entity in the field of radio science to begin operations in this twenty-year period was the Bell Telephone Laboratories at Murray Hill, NJ, known simply as Bell Labs. Founded in 1925, it lost some importance after 1983, when the Bell System ran afoul of antitrust laws and was fragmented by judicial order. In its first six decades of life, Bell Labs was the world's pre-eminent research center in communication theory and networks, in solid-state and optical devices, in digital signal processing and computing, and in wireless and satellite communications. In 1932, Karl Jansky (Figure 2) at Bell Labs detected radiation coming from the Milky Way, using the first radio telescope ever built (Figure 3).

The ten-year period from 1939 to 1949, during and immediately after World War II, witnessed a frenetic development of radio science, mostly related to war efforts. A major center of these efforts was the MIT Radiation Laboratory, where a number of significant theoretical and experimental breakthroughs occurred. Much of this work is documented in the twenty-seven volume series

Figure 3. A replica of Karl Jansky's first radio telescope, now located at the National Radio Astronomy Observatory (NRAO) in Green Bank, West Virginia [3].

of books coauthored by some of the best scientists of that period in the field of microwave theory, components, devices, and propagation. The most important contribution of that research group was the development of radar, which played a decisive role in the outcome of the war, and without which modern air travel would be impossible. Another important milestone at the laboratory was the development of LORAN, the long-range navigation system that provided the first real-time positioning information.

In the civilian area, the contributions during that decade were equally impressive. Julius A. Stratton of MIT published his famous book on *Electromagnetic Theory* in 1941. The first FM police radio communication system began operation in Hartford, CT, in 1940. The world's first monochrome-compatible electronic color television system was developed at the RCA Laboratories in Princeton, NJ, between 1946 and 1950. Radar signals reflected from the moon were detected in January 1946 at Fort Monmouth, NJ, heralding the beginning of radio astronomy and space communications. The barcode was invented by Bernard Silver and Norman J. Woodland in Philadelphia in 1948. However, all these discoveries pale by comparison to three developments that have shaped the future not only of radio science, but of mankind: the transistor, communication theory, and the atomic clock.

Figure 4. A replica of the first point-contact transistor [4].

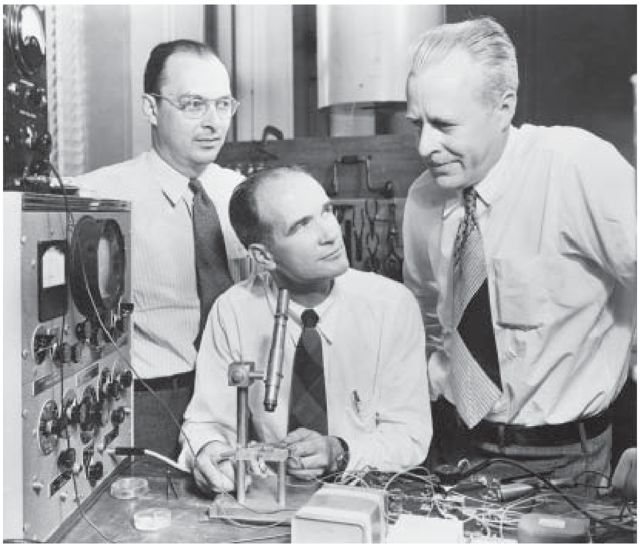

Figure 5. John A. Bardeen, William B. Shockley, and Walter H. Brattain [5].

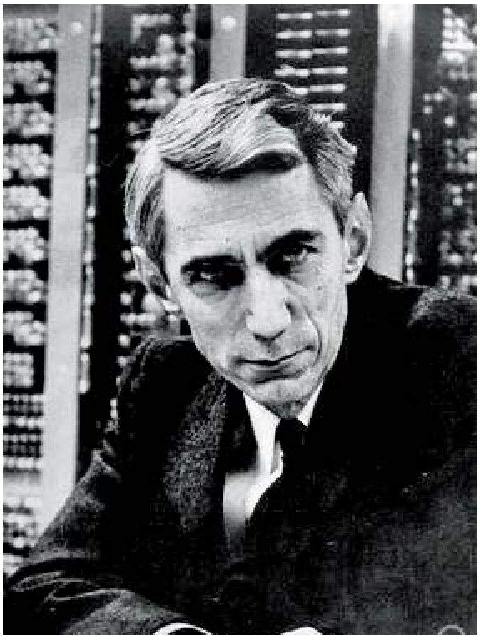

Figure 6. Claude E. Shannon, considered the "father of information theory" [6]

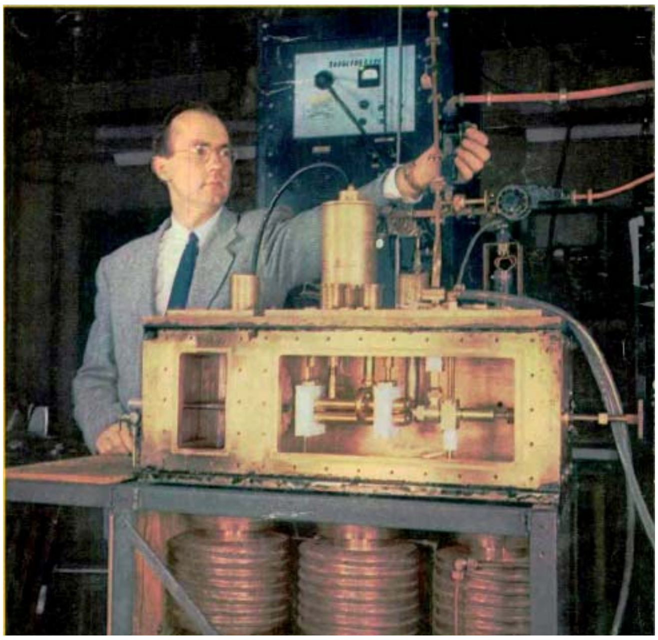

Figure 7. Charles H. Townes and the first prototype ammonia maser [7].

In November and December 1947, at Bell Labs, Walter H. Brattain and John A. Bardeen discovered the transistor effect and developed the point-contact germanium transistor (Figure 4). They worked under the direction of William B. Shockley, and the three scientists (Figure 5) came up the following year with a much more useful and efficient device, the junction transistor, which transformed the electronics industry and changed people's lives worldwide.

Claude E. Shannon (Figure 6), born in Petoskey, MI, and educated at the University of Michigan and at MIT, published a paper entitled "A Mathematical Theory of Communication" in the *Bell System Technical Journal* in 1948. That paper, republished as a book the following year, changed signal processing, information, and communication theories forever, and gained its author the name of "father of information theory."

In 1948, Harold Lyons at the National Bureau of Standards (later to be renamed National Institute of Science and Technology: NIST) used transitions of the ammonia molecule as a frequency source to build the first atomic clock. This quickly replaced the rotation of the Earth as a time reference, and was the first in a sequence of evermore precise atomic clocks that were fundamental in the development of novel technologies, such as the Global Positioning System.

Figure 8. James Van Allen [credit: NASA].

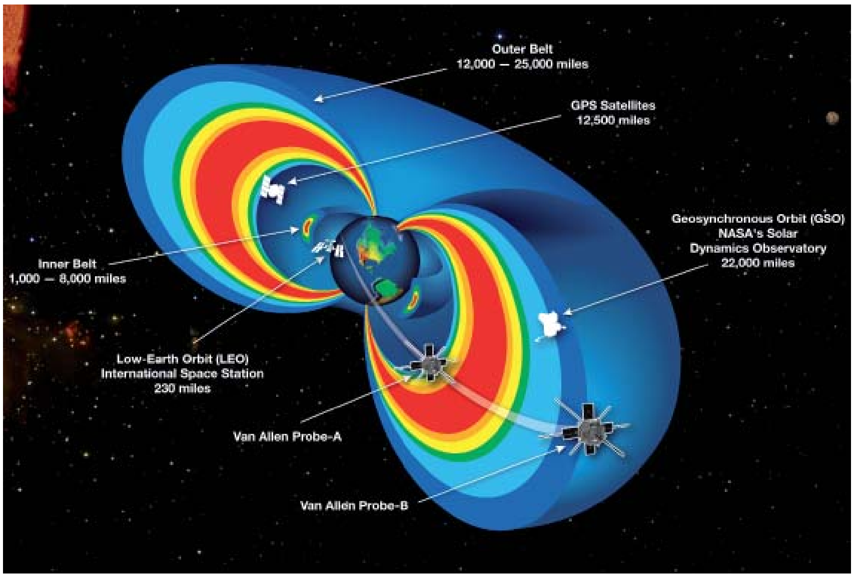

Figure 9. A model of the Van Allen radiation belts, also showing the Van Allen Probes missions [credit: NASA].

Figure 10. TIROS-1, the first meteorological satellite, on display at the Smithsonian [8].

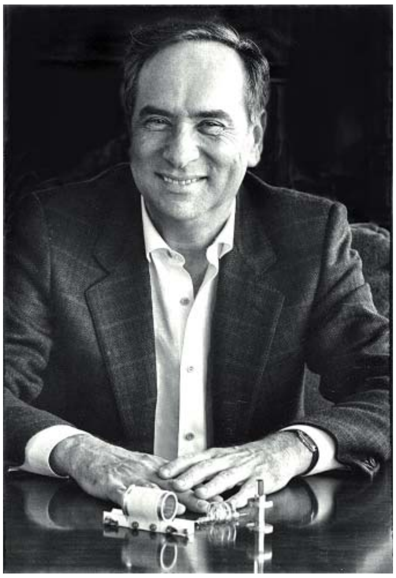

Figure 11. Theodore Maiman with the first laser [9].

The decade 1950-1960 saw explosive developments in semiconductor, optical, and computer technologies. The commercial manufacture of transistors began in Allentown, PA, in 1951. At Texas Instruments, Jack S. Kilby developed the first semiconductor integrated circuit in 1958. The following year, Jean A. Hoerni invented the planar process, which Robert N. Noyce applied to the integrated circuit, leading to a plethora of semiconductor products. From 1951 to 1958, the newly formed MIT Lincoln Laboratory developed a computerized air-defense system for the United States, which may be considered as the precursor to digital computer networks. The first maser was built by Charles H. Townes (Figure 7), James P. Gordon, and Herbert J. Zeiger at Columbia University, NY, in 1953. NASA was founded in 1958, and an era of space exploration was underway, leading to complex interactions among scientific disciplines and advances in radars, electronic instrumentation, robotics and controls, communications, and computers. James Van Allen (1914-2006) (Figure 8), a professor at the University of Iowa, discovered the radiation belts (Figure 9) that bear his name in 1958, thus opening up the field of magnetospheric research in space. NASA launched the first meteorological satellite, TIROS-1 (Figure 10), in April 1960. The following month, Theodore Maiman built the first laser (Figure 11) in Malibu, CA. This was followed by the first optical-fiber laser in 1961, and the first optical-fiber amplifier three years later, both built by Elias Snitzer in Southbridge, MA.

The development of radio science in the USA during the 1960s was propelled by significant financial government support in two directions: the arms race between the USA and the Soviet Union, and the race to be the first country to land a man on the moon. A number of university-associated laboratories sprung up to take advantage of research funding in radar and stealth technologies, antennas and arrays, microwaves and optics. Preeminent among these were the research groups at the Polytechnic Institute of Brooklyn, at the Radiation Laboratory of the University of Michigan, at the ElectroScience laboratory of the Ohio State University, and at the Antenna Laboratory of the University of Illinois. The culmination of the USA space program for that decade was the landing of a man on the Moon in July 1969, utilizing the Grumman Lunar Module.

The need for analytical and numerical tools for the evaluation of radar signatures of missiles, airplanes, ships, and land vehicles resulted in pioneering breakthroughs. On the analytical side, in

Figure 12. The Arecibo radio telescope in 2019 [10].

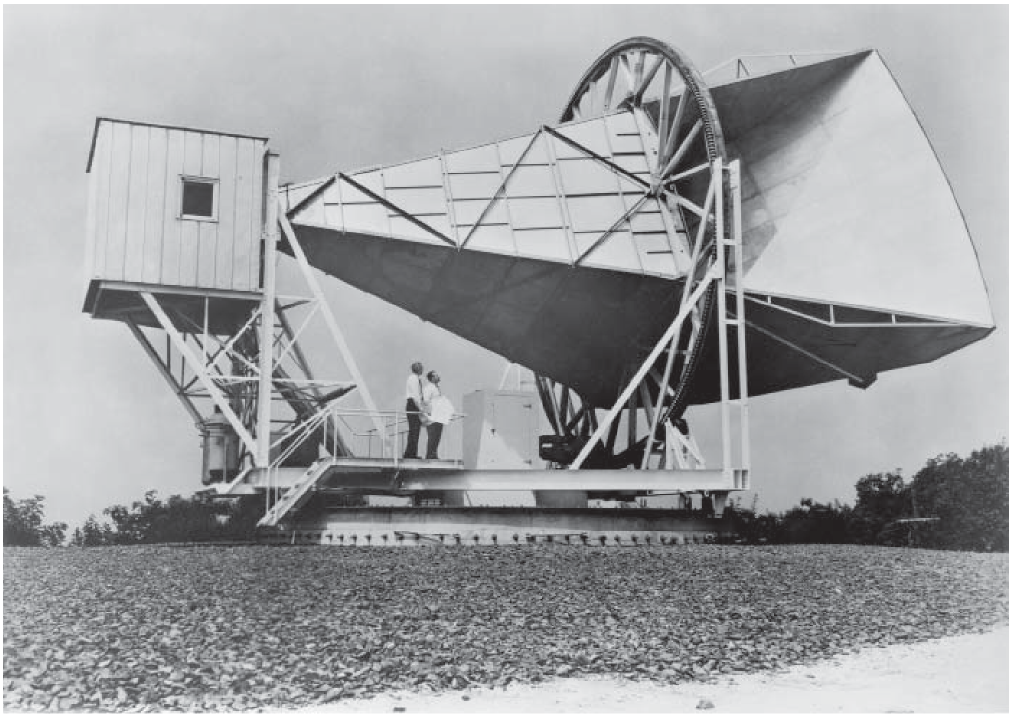

Figure 13. Penzias and Wilson standing on the 15 m Holmdel Horn Antenna with which they discovered the cosmic microwave background [credit: NASA].

the late 1950s and early 1960s, Joseph B. Keller developed the Geometrical Theory of Diffraction (GTD). This was later refined into various versions of the Uniform Theory of Diffraction (UTD) by many scientists in the USA and elsewhere, and found applications in other areas of radio science where high-frequency phenomena occur. On the numerical side, the advent of powerful digital computers provided the tools *necessary* for the implementation of two techniques that were developed in the 1960s and that remain of paramount importance to this day: in the frequency domain, the application of the Method of Moments (MoM) to electromagnetics, pioneered by Roger F. Harrington; in the time domain, the development of the Finite-Difference Time-Domain (FDTD) method, pioneered by Kane S. Yee.

The Arecibo Observatory (Figure 12) was completed in 1963 at Arecibo, Puerto Rico. The world's largest radio telescope, it incorporated advances in antenna design, electronics, signal processing, controls, and mechanical engineering, which allowed it to maintain a very accurate focus despite wind and temperature changes. It led to significant progress in atmospheric sciences, planetary studies, and radio astronomy. On December 1, 2020, the instrument platform of the observatory collapsed and the observatory ceased to function after fifty-seven years of radio-astronomical observations. A replacement of the observatory with an even better instrument at the same location is presently under planning; presumably, the new observatory will consist of a phased array of hundreds of smaller dishes, rather than one large dish.

The cosmic microwave background radiation was discovered by Arno A. Penzias and Robert W. Wilson in 1964 (Figure 13).

Collaboration between the University of California, Los Angeles, and the Stanford Research Institute let to the creation of ARPANET and subsequently the Internet in 1969.

The decade 1960-70 saw a push to utilize higher frequencies in the electromagnetic spectrum, resulting in theoretical developments and applications to integrated optics and optical electronics, in parallel with the development of integrated solid-state devices.

The twenty-year period from 1970 to 1990 was characterized by developments primarily in communications and computers. The first low-loss optical fiber was produced in Corning, NY, in 1970, and the first fiber-optic submarine cable was produced by AT&T Bell Laboratories, Middletown, NJ, and deployed between North America and Europe in 1988. The first real-time speech communication on packet networks occurred via ARPANET between the MIT Lincoln Laboratory and the University of Southern California in August 1974. The development of CDMA (code-division multiple-access) spread-spectrum technology for cellular communications was demonstrated by Qualcomm in November 1989.

Figure 14. The HP-35, the first hand-held scientific calculator [11].

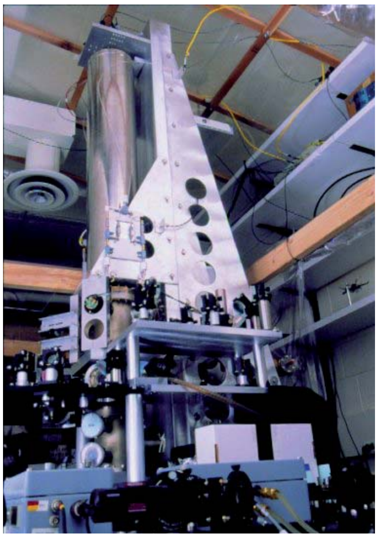

Figure 15. NIST-F1, a cesium-fountain atomic clock, which was the primary time standard in the United States [12].

In the area of computer development, the *SPICE* program was created at the University of California, Berkeley in 1970. The first handheld scientific calculator, the HP-35 (Figure 14), was introduced in Palo Alto, CA, in 1972. The *CP/M* microcomputer operating system, a foundation for the personal computer, was demonstrated by Gary A. Kildall in Pacific Grove, CA, in 1974. The first monolithic 16-bit digital-to-analog converter was built in 1981-1982 at Burr-Brown Research Corp., Tucson, AZ. The SPARC-RISC architecture was developed by Sun Microsystems, Santa Clara, CA, in 1987.

Two categories of the most expensive instruments developed by the United States and useful in advancing radio science are radio telescopes and satellites. As of December 2019, the USA had twenty-five radio telescopes operating on its soil and took active participation in telescopes located elsewhere, such as the ALMA project in Chile. As of December 2019, the USA also had 1,895 satellites in orbit, more than any other country.

The major activities of some if the URSI Commissions in the US during the past three decades are summarized in the following paragraphs. Some of the Commissions are lumped together, since many of their research activities overlap.

2.1 USNC-URSI Commission A

In the area of measurements and standards, the US National Institute of Standards and Technology (NIST) developed the first practical, stable, easy-to-use one-volt standard in 1985. In the late 1980s, major US advances in near-field antenna measurements enabled significant cost savings in the design and development of antennas. In 1993, Judah Levine of NIST developed the Internet Time Service, which enabled computer clocks around the world to be set to Universal Coordinated Time (UCT) over the Internet. In 1999, the primary time and frequency standard of the US became the NIST-F1 (Figure 15). It was replaced by the NIST-F2 in 2014. The optical frequency comb was invented in 2000. A quantum-logic clock was built by Till Rosenband (Figure 16) in 2005, and perfected over the next five years. Using a single trapped aluminum ion, it represented a significant improvement over fountain-based clocks. Quite recently, a very-wide-bandwidth, high-sensitivity room-temperature bolometer was developed by a group at MIT that uses the heating of electrons in graphene.

2.2 USNC-URSI Commissions B, C, D, and E

Major developments in the theory and applications of electromagnetic fields and waves have occurred in the areas of metamaterials, metasurfaces, photonic crystals, graphene-based devices, quantum optics, computational electromagnetics, signal processing, and antennas. Metamaterial research has gone from a theoretical curiosity in the 1990s and early 2000s to many practical applications, including cloaking devices, optical and microwave lenses with resolution beyond the classical diffraction limit, and significant enhancements to the performance of antennas. This includes both increasing the radiation efficiency and reducing the size of antennas. Metasurfaces, which are essentially two-dimensional metamaterials, have more recently extended these practical applications.

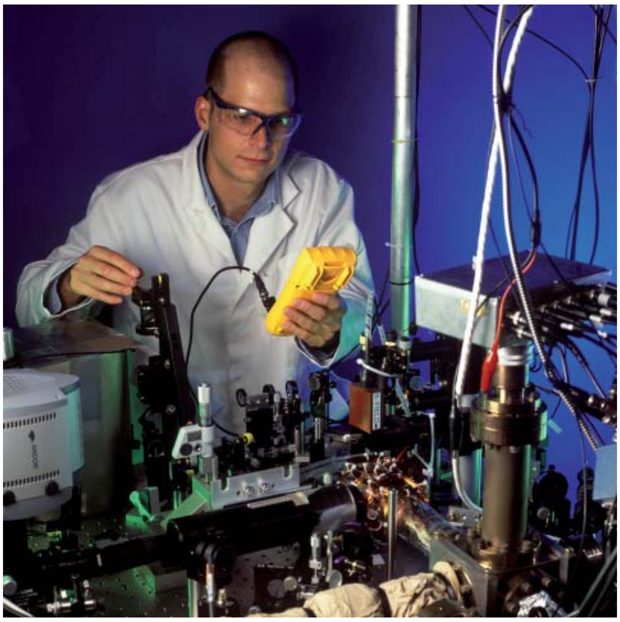

Figure 16. Till Rosenband and the NIST quantum-logic clock (credit: Geoffrey Wheeler [13]).

Computational electromagnetics has seen explosive growth, due both to developments in algorithms and to the low-cost widespread availability of multi-core computer systems. Algorithms such as the Multi-Level Fast Multipole Method (MLFMM) have made problems that were previously much too large to be practically solved quite tractable. Nature-based optimization methods, such as the genetic algorithm and particle-swarm optimization, combined with fast electromagnetic solvers, have made it possible to use simulation to design large, real-world systems, such as electrically large antennas, and optimizing the radar cross sections of ships and aircraft. The rise of petascale supercomputers has made it possible to model electrically large problems at super high resolution. Multi-physics solvers have also become common, simultaneously solving, for example, for electromagnetic radiation along with fluid forces, thermal effects, acoustics, and structural integrity.

2.3 USNC-URSI Commission F

The Commission members have been engaged in research related to a wide range of topics related to electromagnetic wave propagation phenomena, as well as active and passive microwave remote sensing of the Earth and planetary surfaces, subsurfaces, and atmospheres. Research in electromagnetic wave propagation included analytical, numerical, and experimental studies for understanding and predicting field intensity in the atmosphere with inhomogeneous interfaces and other natural environments, including vegetation and urban settings, as well as subsurface environments such as layered ground, water, and ice with applications in wireless communication. Remote-sensing activities pertain to the understanding of many of the Earth's processes that affect the climate and solid Earth, and the prediction of natural hazards, such as earthquakes, flooding, landslides, etc., as well as studies of man-made activities such as agriculture, deforestation, land use, and urbanization.

Figure 17. The HAARP (High-frequency Active Auroral Research Program) antenna array [14].

2.4 USNC-URSI Commissions G and H

Major milestones in the past thirty years included the development of new and highly innovative tools for providing high-precision measurements of ionospheric properties with unprecedented spatial and temporal resolutions. Chief among these new tools was the Global Positioning System (GPS) satellites, continuously providing global data coverage since the early 1990s. Satellite systems capable of measuring total electron content variation in the ionosphere provide opportunities to characterize spatial and temporal variability of the global ionosphere with unprecedented accuracy, as well as to detect and measure natural hazards such as earthquakes, tsunamis, and volcanic eruptions.

Active experiments in ionospheric modification with high-power radio waves first became prominent in the 1980s, but achieved a new level of capability with the opening of the HAARP (High-frequency Active Auroral Research Program) facility (Figure 17) in Alaska in 1999, and its ultimate completion in 2007 with 3.6 MW of radiated power. The unprecedented power radiated in the 2 MHz to 9 MHz band allowed for new effects to be observed, such as the generation of artificial aurora visible to the naked eye, and the generation of artificial plasma layers in the ionosphere. The facility was also used extensively for the generation of ELF/VLF waves via modulation of natural currents in the overhead ionosphere. These ELF/VLF waves were injected into the Earth-ionosphere waveguide and into the magnetosphere to study cyclotron-resonant wave growth and wave triggering. A new HF heating facility was also constructed at the Arecibo Observatory in Puerto Rico in 2017. Active simulation of the near-Earth plasma was also explored, with multiple particle-release experiments onboard rockets and using the Space Shuttle.

Numerous scientific orbital spacecraft were launched in the last thirty years that provided fresh insight into radio-wave interactions with space plasmas. Worth highlighting is the NASA Van Allen Probes mission (2012-2019), which flew in the Earth's radiation belts and provided observations of energetic particles and low-frequency waves over a wide area of near-Earth space (Figure 9). The two Van Allen Probes spacecraft allowed observation of wave-particle interactions that underlie complex energy dynamics commonly referred to as space weather. The last decade closed with a successful launch of the US Air Force DSX satellite mission in 2019, which has unique hardware for radiation of VLF waves directly in the space environment.

Attempts to reproduce the complex physics of space-based wave-particle interactions were actively pursued at the Naval Research Laboratory and also at the University of California Los Angeles. At both locations, large plasma chambers with multi-meter dimensions and intense magnetic fields were used to recreate the space plasma environment, and to replicate nonlinear interactions and wave-mode conversions.

The complex and three-dimensional nature of wave-plasma interactions make rigorous simulation very computationally expensive. One powerful technique is the so-called particle-in-cell (PIC) algorithm, in which individual charged-particle trajectories are tracked under the influence of all electromagnetic forces. In the last fifteen years, a number of PIC and hybrid-PIC codes have been developed to reproduce key wave-particle interactions. Another area of focus has been leveraging machine-learning neural-network algorithms for space-weather-state prediction.

Figure 18. One of the finished ALMA (Atacama Large Millimeter/sub-millimeter Array) antennas [15].

Figure 19. An artist's rendering of the future ALMA array on Chajnantor [16].

Figure 20. Albert A. Michelson, recipient of the Nobel Prize in Physics in 1907, the first American to receive a Nobel Prize [17].

Figure 21. Robert A. Millikan, recipient of the Nobel Prize in Physics in 1923 [18].

2.5 USNC-URSI Commission J

Radio astronomy (the domain of USNC Commission J) has seen incredible advances in signal detection and high-speed data-processing technologies over the past 30 years, ushering in new instrumentation that pushed the boundaries of signal sensitivity, spatial resolution, and short-wavelength observations. The development of practical, robust InP HFET amplifiers and SIS mixers, operating to 120 GHz and 1 THz, respectively, with sensitivities approaching the quantum limit, introduced high-resolution imaging arrays at millimeter and sub-millimeter wavelengths. Examples include the Smithsonian Astrophysical Observatory's Submillimeter Array in Hawaii, Owens Valley millimeter array, the Berkeley-Illinois-Maryland Association millimeter array, and the NRAO-ESO Atacama Large Millimeter/sub-millimeter Array (ALMA) (Figures 18, 19) in Chile. The single-dish radio telescope saw advances from computer-aided design, enabling the clear-aperture, 100 meter-class Green Bank Telescope to operate with incredible sensitivity at wavelengths as short as 3 mm by moving surface panels to correct for gravity deformations based on finite-element modeling of the structure. Tremendous improvements in signal-processing speeds allowed simultaneous observations of multiple spectral lines, timing pulsars to such high precision that gravity-wave detection is possible, sifting through mounds of data for elusive Fast Radio Bursts, and creating the first image of a black-hole event horizon in the galaxy M87 from coordinated millimeter-wave observations around the world. This advancement, coupled with revolutionary new digital-correlator technologies, such as the "packedized correlator" introduced by UC Berkeley in the 2000s, opened the door to super arrays, harnessing the power of hundreds and even thousands of antennas to form multiple simultaneous beams on the sky. New aperture arrays, such as the Square Kilometre Arrays now under construction and the NRAO ngVLA design concept, incorporate this technology. Focal-plane arrays, based on early pioneering work in Green Bank, make use of this digital technology to transform existing single-dish telescopes into powerful multi-beam instruments that enhance sky survey speeds and make possible the multi-pixel radio camera. Cosmology of the Early Universe also benefited from these technical developments, yielding a pathway for precise measurements of highly-redshifted neutral hydrogen in the 20-200 MHz band, the spectrum of which will probe the epoch of initial star formation, black hole creation, and galaxy formation for the first time. Instruments such as the Precision Array for Probing the Epoch of Reionization (PAPER), the Hydrogen Epoch of Reionization Array (HERA), and the Experiment to Detect the Global EoR Signature (EDGES) are among the pioneers in the this new, challenging field. Spaceborne instrumentation, enabled by improvements to detector technologies, made the first maps of the Cosmic Microwave Background, beginning with COBE in the 1990s and WMAP in the early 2000s, a mission that also gave us the most precise estimate of the age of the universe to be 13.772 billion years. Based on these technological and scientific successes, a new era of radio astronomy from the lunar far side is now within reach.

2.6 USNC-URSI Commission K

In the past thirty years, radio science has found many applications in the biomedical area in the US, ranging from fundamental studies on vision and on the effects of electric and magnetic fields on cancer to diagnostic and therapeutic technologies for medical applications, such as microwave-imaging capabilities and hyperthermia cancer treatment.

Figure 22. Arthur H. Compton, recipient of the Nobel Prize in Physics in 1927 [19].

Figure 23. Clinton J. Davisson, co-recipient of the Nobel Prize in Physics in 1937 [20].

3. Nobel Prizes Impacting Radio Science Awarded to US Scientists

Since radio science is rooted in discoveries made in the physical sciences, it is to be expected that many such discoveries have played a fundamental role in the development of radio science. This is especially true for those URSI Commissions the field of interest of which is closely related to physical sciences.

A measure of the importance of a scientific discovery is the awarding of a Nobel Prize to those making the discovery. For that reason, the Nobel prizes awarded to US scientists whose research impacted radio science directly or indirectly are listed below, with reference to the URSI Commissions presumably most influenced and benefiting from the discoveries. The prizes that affected radio science only tangentially, such as those related to elementary particles, are not mentioned.

It should be noted that the following listing of Nobel Prizes awarded to US scientists is an important but imperfect means of showcasing the contributions to radio science by illustrious US researchers. The work of many US scientists in fields intimately connected to radio science was never recognized by a Nobel prize, despite richly deserving of that honor. Examples of such oversights are the research on LEDs by Nick Holonyak and on graphene by a research team at Georgia Tech.

3.1 Basic Electromagnetic Science Affecting All Ten URSI Commissions

Albert A. Michelson (1852-1931) (Figure 20) was born in Prussia and moved with his family to the USA when he was two years old. He studied at the US Naval Academy, where he conducted fundamental interferometric experiments to measure the speed of light and debunk the aether theory. He was awarded the Nobel Prize in Physics in 1907 “for his optical precision instruments and the spectroscopic and metrological investigations carried out with their aid,” becoming the first American to receive a Nobel prize in science.

Robert A. Millikan (1868-1953) (Figure 21) was born in Morrison, IL, and studied at Oberlin College and Columbia University. He is best known for his determination of the charge of the electron, and received the Nobel Prize in Physics in 1923 “for his work on the elementary charge of electricity and on the photoelectric effect.”

Arthur H. Compton (1892-1962) (Figure 22) was born in Wooster, OH, and studied at Princeton University. He proved the particle nature of electromagnetic radiation (the Compton effect), and received the Nobel Prize in Physics in 1927 “for his discovery of the effect named after him.”

Clinton J. Davisson (1881-1958) (Figure 23) was born in Bloomington, IL, and studied at Princeton University and the University of Chicago. He received a share of the 1937 Nobel Prize in Physics “for experimental discovery of the diffraction of electrons by crystals,” the Davisson-Germer experiment.

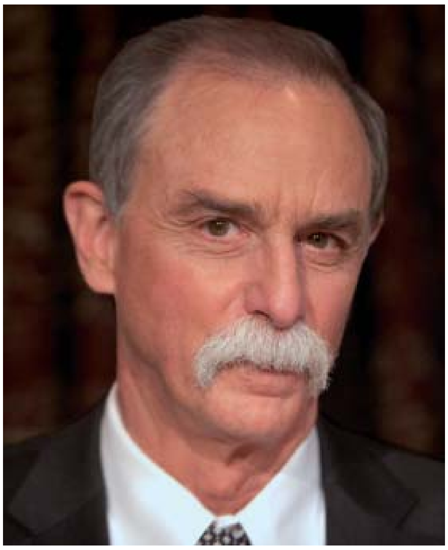

Figure 24. David J. Wineland, co-recipient of the Nobel Prize in Physics in 2012 [21].

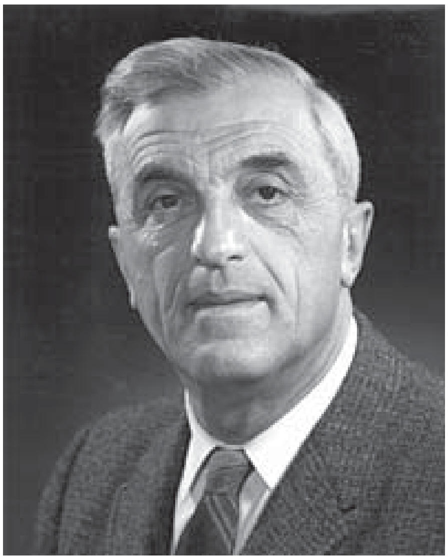

Figure 25. Felix Bloch shared the 1952 Nobel Prize in Physics [22].

3.2 URSI Commission A

Norman F. Ramsey Jr. (1915-2011) was born in Washington, DC, and studied at Cambridge University and Columbia University. He was awarded part of the 1989 Nobel Prize in Physics "for the invention of the separated oscillatory fields method and its use in the hydrogen maser and other atomic clocks."

David J. Wineland (Figure 24) was born in Milwaukee, WI, in 1944. He studied at Harvard University, the University of Washington, and the University of California. He received a share of the 2012 Nobel Prize in Physics "for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems." Dr. Wineland is presently a Research Professor at the University of Oregon, but he conducted his seminal research on atomic clocks while at NIST in Boulder, CO, where he maintains research collaboration with a team of scientists. He delivered an invited plenary lecture on atomic clocks at the URSI Asia-Pacific Radio Science Conference in New Delhi, India, in March 2019.

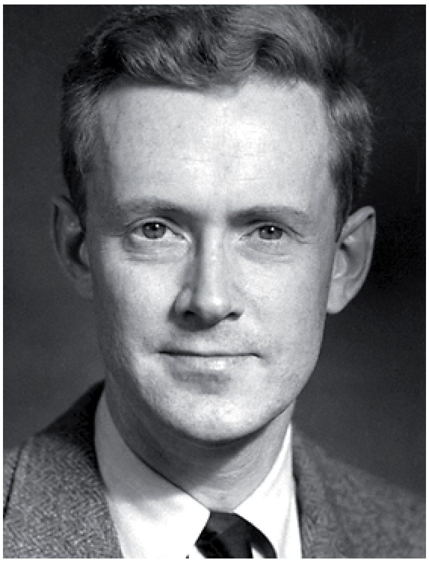

Figure 26. Edward M. Purcell shared the 1952 Nobel Prize in Physics [23].

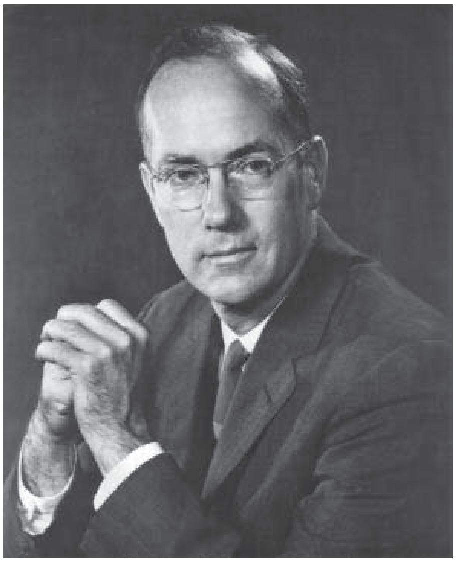

Figure 27. Charles H. Townes, co-recipient of the Nobel Prize in Physics in 1964 [24].

Figure 28. Nicolaas Bloembergen, co-recipient of the Nobel Prize in Physics in 1981 [25].

Figure 29. Arthur L. Schawlow, co-recipient of the Nobel Prize in Physics in 1981 [26].

In July 2019, the scientific team at NIST announced that it had built the most accurate atomic clock ever made, utilizing an aluminum ion. The new clock outperformed the Cesium standard by a factor of one hundred, and may err by one second in thirty-three billion years.

3.3 URSI Commissions A, B, and D

Felix Bloch (1905-1983) (Figure 25) and Edward M. Purcell (1912-1997) (Figure 26) shared the 1952 Nobel Prize in Physics "for their developments of new methods for nuclear magnetic precision measurements and discoveries in connection therewith." Their work became widely used in studying the molecular composition of materials. Bloch was born in Zurich, Switzerland, and moved to the US where he became a naturalized citizen and did his award-winning research at Stanford University. Purcell was born in Taylorville, IL, and studied at Harvard University and Purdue University.

Figure 30. Roy J. Glauber, co-recipient of the Nobel Prize in Physics in 2005 [27].

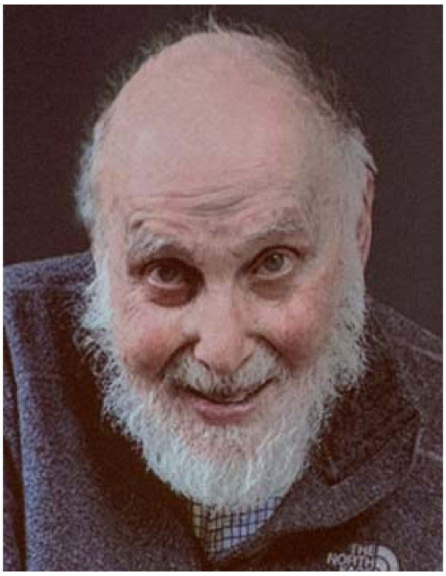

Figure 31. Arthur Ashkin, co-recipient of the Nobel Prize in Physics in 2018 [28].

3.4 URSI Commissions B and D

Charles H. Townes (1915-2015) (Figure 27) was born in Greenville, SC, and studied at the California Institute of Technology. He received a share of the 1964 Nobel Prize in Physics “for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle.”

Nicolaas Bloembergen (1920-2017) (Figure 28) and Arthur L. Schawlow (1921-1999) (Figure 29) shared a portion of the 1981 Nobel Prize in Physics “for their contribution to the development of laser spectroscopy.” Bloembergen was born in Dordrecht, Netherlands, studied at Leiden, Utrecht, and Harvard Universities, and was a professor first at Harvard University, and later at the University of Arizona. He did fundamental research work in nonlinear optics. Schawlow was born in Mount Vernon, NY, studied at the University of Toronto, and worked at Bell Labs before accepting a professorship at Stanford University in 1961. Among other discoveries, he is credited with the introduction of two mirrors to create an open resonator.

Roy J. Glauber (1925-2018) (Figure 30) was born in New York, NY, and studied at Harvard University where he became a professor. He was also an adjunct professor at the University of Arizona. He was awarded a portion of the 2005 Nobel Prize in Physics “for his contributions to the quantum theory of optical coherence.”

Figure 32. Ivar Giaever, co-recipient of the Nobel Prize in Physics in 1973 [29].

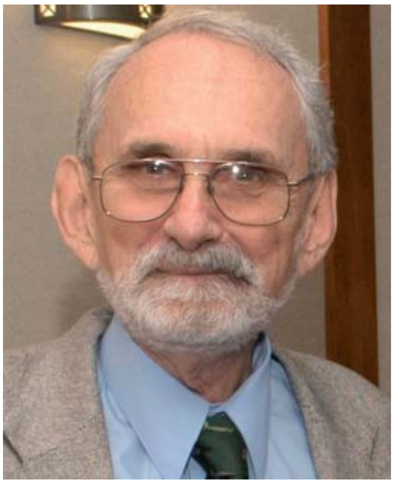

Figure 33. Robert Curl, co-recipient of the Nobel Prize in Physics in 1996 [30].

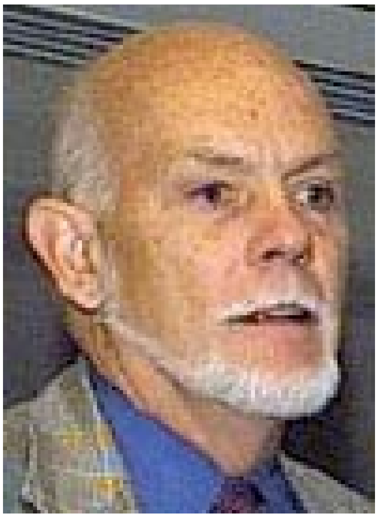

Figure 34. Richard E. Smalley, co-recipient of the Nobel Prize in Physics in 1996 [31].

Figure 35. Steven Chu, co-recipient of the Nobel Prize in Physics in 1997 [32].

Figure 36. William D. Phillips, co-recipient of the Nobel Prize in Physics in 1997 [33].

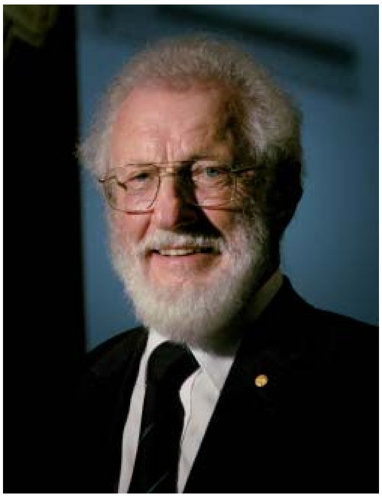

Figure 37. Herbert Kroemer, co-recipient of the Nobel Prize in Physics in 2000 [34].

3.5 URSI Commissions B, D, and K

Arthur Ashkin (Figure 31) was born in 1922 in Brooklyn, NY, studied at Columbia and Cornell Universities, and then joined Bell Labs. He received a share of the 2018 Nobel Prize in Physics “for the optical tweezers and their application to biological systems.”

3.6 URSI Commission D

John Bardeen, Walter H. Brattain, and William B. Shockley (Figure 5) of Bell Labs were awarded the 1956 Nobel Prize in Physics “for their researches on semiconductors and their discovery of the transistor effect.” John Bardeen (1908-1991) was born in Madison, WI, and studied at the University of Wisconsin and at Princeton University. He is the only recipient of two Nobel Prizes in Physics, the second one in 1972 for his work on the theory of superconductivity at the University of Illinois. Walter Brattain (1902-1987) was born in Amoy, China, and studied at Whitman College, the University of Oregon, and the University of Minnesota. William Shockley was born in London, UK, and studied at MIT and CalTech.

Ivar Giaever (Figure 32) was born in 1929 in Bergen, Norway, and studied at the Ransselaer Polytechnic Institute, where he is a Professor Emeritus. He shared the 1973 Nobel Prize in Physics with two other scientists “for their experimental discoveries regarding tunneling phenomena in solids.”

Robert Curl (Figure 33) was born in 1933 in Alice, TX, and studied at the University of California, Berkeley, and at Rice University, where he is a Professor Emeritus. Richard E. Smalley (1943-2005) (Figure 34) was born in Akron, OH, and studied at the University of Michigan and at Princeton University. Curl and Smalley shared a portion of the 1996 Nobel Prize in Chemistry “for their discovery of fullerenes.” Among carbon structures, fullerenes predated the discoveries of carbon nanotubes and of graphene.

Steven Chu (Figure 35) was born in 1948 in St. Louis, MO, and studied at the University of Rochester and at the University of California, Berkeley. He then joined Bell Labs, where he carried out the research that would eventually gain him the Nobel Prize. He went to Stanford University in 1987 and served in many prestigious governmental positions, including as US Secretary of Energy under President Obama. William D. Phillips (Figure 36) was born in Wilkes-Barre, PA, in 1948. After studying at MIT, he joined NIST and is also a professor at the University of Maryland. Chu and Phillips shared a portion of the 1997 Nobel Prize in Physics “for development of methods to cool and trap atoms with laser light.”

Herbert Kroemer (Figure 37) was born in 1928 in Weimar, Germany, and studied at the Universities of Jena and Gőttingen. He is a dual German-American citizen and a professor at the University of California, Santa Barbara. He received a portion of the 2000 Nobel Prize in Physics “for developing semiconductor heterostructures used in high-speed- and opto-electronics.” Another portion of that same Nobel Prize was awarded to Jack S. Kilby “for his part in the invention of the integrated circuit.” Kilby (1923-2005) was born in Jefferson City, MO, and studied at the University of Wisconsin and the University of Illinois before joining Texas Instruments.

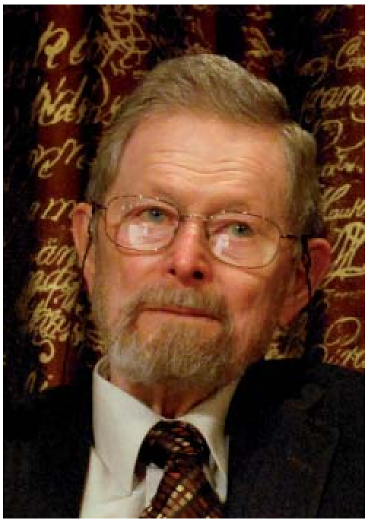

Figure 38. George E. Smith, co-recipient of the Nobel Prize in Physics in 2009 [35].

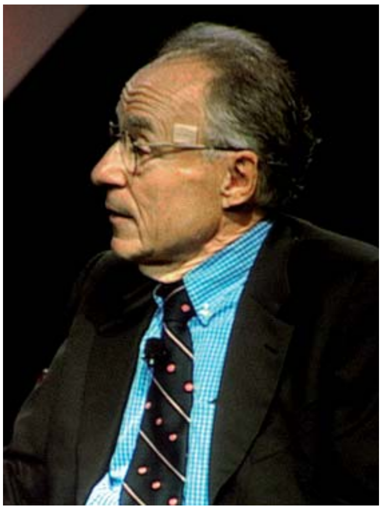

Figure 39. Arno A. Penzias, co-recipient of the Nobel Prize in Physics in 1978 [36].

George E. Smith (Figure 38) was born in 1930 in White Plains, NY, and studied at the University of Pennsylvania and the University of Chicago before joining Bell Labs, where he worked until retirement. He was awarded a share of the 2009 Nobel prize in Physics “for the invention of an imaging semiconductor circuit – the CCD sensor.”

3.7 URSI Commission J

Arno A. Penzias (Figure 39) was born in 1933 in Munich, Germany, moved to the US in 1940, and became a naturalized citizen in 1946. He studied at the City College of New York and at Columbia University before joining Bell Labs. Robert W. Wilson (Figure 40) was born in 1936 in Houston, TX, studied at Rice University and at CalTech before joining Bell Labs and, later, the Harvard-Smithsonian Center for Astrophysics. Penzias and Wilson were awarded a share of the 1978 Nobel Prize in Physics “for their discovery of cosmic microwave background radiation,” which they made in 1964 (Figure 13) and which provided support to the big-bang theory of the origin of the universe.

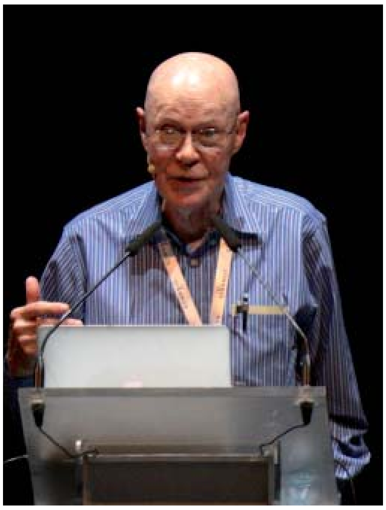

Figure 40. Robert W. Wilson, co-recipient of the Nobel Prize in Physics in 1978 [37].

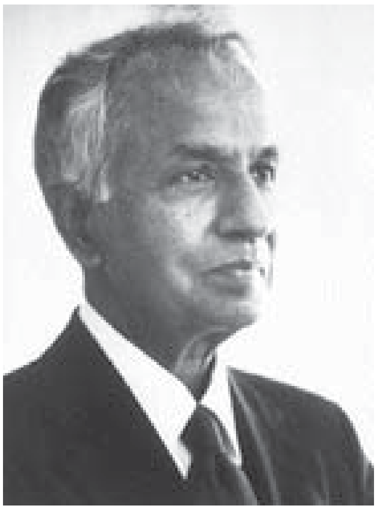

Figure 41. Subrahmanyan Chandrasekhar, co-recipient of the Nobel Prize in Physics in 1983 [38].

Figure 42. Russell A. Hulse, co-recipient of the Nobel Prize in Physics in 1993 [39].

Figure 43. Joseph H. Taylor, Jr., co-recipient of the Nobel Prize in Physics in 1993 [40].

Subrahmanyan Chandrasekhar (1910-1995) (Figure 41) was born in Lahore, Pakistan, and studied in Madras and at Cambridge University before moving to the US, where he spent his entire life as a professor at the University of Chicago. He was awarded a share of the 1983 Nobel Prize in Physics "for his theoretical studies of the physical processes of importance to the structure and evolution of the stars."

Russell A. Hulse (Figure 42) and Joseph H. Taylor, Jr. (Figure 43) shared the 1993 Nobel Prize in Physics "for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation," which they made while working at the Arecibo Observatory in 1974. Hulse was born in New York in 1950, and studied at the Cooper Union and at the University of Massachusetts, where he had Taylor as his PhD advisor. Taylor was born in Philadelphia, PA, in 1941, studied at Haverford College and at Harvard University, and served on the faculties of the University of Massachusetts and of Princeton University, where he retired in 2006.

Raymond Davis, Jr. (1914-2006) (Figure 44) was born in Washington, DC, studied at the University of Maryland and at Yale University, and spent most of his professional life at Brookhaven National Laboratory. He received a share of the 2002 Nobel Prize in Physics "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos."

Figure 44. Raymond Davis, Jr., co-recipient of the Nobel Prize in Physics in 2002 [41].

Figure 45. John C. Mather, co-recipient of the Nobel Prize in Physics in 2006 [42].

Figure 46. George F. Smoot, co-recipient of the Nobel Prize in Physics in 2006 [43].

Figure 47. Saul Perlmutter, co-recipient of the Nobel Prize in Physics in 2011 [44].

Following up on the earlier work by Penzias and Wilson, John C. Mather (Figure 45) and George F. Smoot (Figure 46) shared the 2006 Nobel Prize in Physics "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation," thus establishing a solid scientific basis for the big-bang theory. Mather was born in 1946 in Roanoke, VA, and studied at Swarthmore College and at the University of California, Berkeley. He works at the NASA Goddard Space Flight Center and is an Adjunct Professor at the University of Maryland. Smoot was born in 1945 in Jacksonville, FL, studied at MIT and is a professor at the University of California, Berkeley.

Saul Perlmutter (Figure 47) and Adam G. Riess (Figure 48) were awarded a portion of the 2011 Nobel Prize in Physics "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae." Perlmutter was born in Champaign-Urbana, IL, in 1959, and studied at Harvard University and at the University of California, Berkeley, where he is a professor of physics. Riess was born in Washington, DC, in 1969, studied at MIT and Harvard, and is a Distinguished Professor at the Johns Hopkins University.

Figure 48. Adam G. Riess, co-recipient of the Nobel Prize in Physics in 2011 [45].

Figure 49. Rainer Weiss, co-recipient of the Nobel Prize in Physics in 2017 [46].

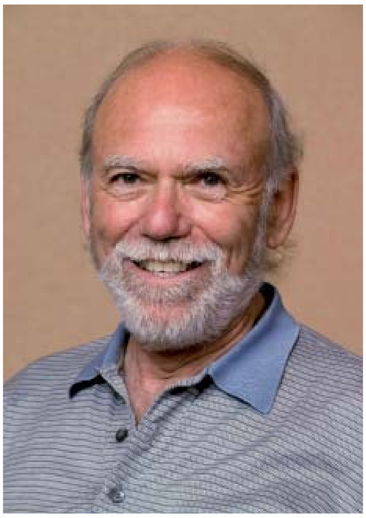

Figure 50. Barry C. Barish, co-recipient of the Nobel Prize in Physics in 2017 [47].

Figure 51. Kip S. Thorne, co-recipient of the Nobel Prize in Physics in 2017 [48].

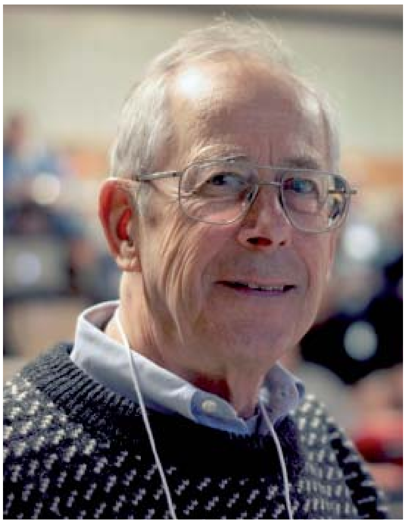

Figure 52. Phillip J. E. Peebles, co-recipient of the Nobel Prize in Physics in 2019 [49].

Rainer Weiss (Figure 49) was born in Berlin, Germany, in 1932, and studied at MIT, where he is a Professor Emeritus. He developed the laser-interferometric technique used in LIGO, and shared the 2017 Nobel Prize in Physics with Barry C. Barish (Figure 50) and Kip S. Thorne (Figure 51) "for decisive contributions to the LIGO detector and the observation of gravitational waves." Barish was born in Omaha, NE, in 1936, and studied at the University of California, Berkeley. He is a Professor Emeritus at CalTech. Thorne was born in Logan, UT, in 1940, studied at Iowa State University, CalTech, and Princeton, and was a professor at CalTech until 2009.

Phillip J. E. Peebles (Figure 52) was born in 1935 in Winnipeg, Canada, and studied at the University of Manitoba, and at Princeton University where he is a Professor Emeritus. He received a share of the 2019 Nobel Prize in Physics "for theoretical discoveries in physical cosmology."

4. URSI Awards to US Scientists

4.1 Balthasar van der Pol Gold Medal

US scientists have received eight of the nineteen van der Pol awards.

1966 – William E. Gordon (1918-2010): "Development of the incoherent scatter technique for ionospheric studies." Gordon studied at Cornell University, and became known as the "father of the Arecibo Observatory."

1975 – Leopold B. Felsen (1924-2005): "Application of ray-optical methods to studies of propagation and diffraction of electromagnetic waves." Felsen studied at the Polytechnic Institute of Brooklyn (later part of New York University), where he became a professor.

1978 – James R. Wait (1924-1998): "Work on propagation of electromagnetic waves in the Earth's crust, and applications of results." Wait studied at the University of Toronto, worked at NIST in Boulder, CO, then at NOAA, and lastly as a professor at the University of Arizona.

1990 – Arthur A. Oliner (1921-2013): "Contribution to theory of guided waves, especially leaky waves, and novel radiating structures." Oliner studied at Cornell University and was a professor at the Polytechnic Institute of Brooklyn.

1993 – Thomas B. A. Senior (1928-2017): "For theoretical contributions to diffraction and scattering of electromagnetic waves, with particular reference to the simulation of material effects in scattering." Senior studied at the University of Manchester and at Cambridge University, and was a professor at the University of Michigan, where he also was Associate Director of the Radiation Laboratory.

1996 – Roger F. Harrington: “For contributions to electromagnetics and the development of the Method of Moments.” Harrington studied at Syracuse University and at The Ohio State University. He worked as a professor at Syracuse University until his retirement.

2008 – William J. Welch: “Pioneer in millimeter wavelength interferometry to investigate astronomical objects ranging from solar system planets to galaxies at the edge of the Universe with spectral and angular resolution.” Welch studied at Stanford University, and at the University of California, Berkeley, where he is a Professor Emeritus.

2014 – Nader Engheta: “For groundbreaking contributions and innovations in electromagnetic theory and applications of composite materials, metamaterials and nanoscale optics, bioinspiring imaging and sensing, and material-based optical nanocircuitry.” Engheta studied at the University of Tehran, Iran, and at CalTech. He is a professor at the University of Pennsylvania.

4.2 John Howard Dellinger Medal

US scientists have received six of the eighteen Dellinger awards.

1975 – Neil M. Brice (1934-1974): “Theory of the Earth’s plasmapause and theoretical investigations of the physics of Jupiter nagnetosphere.” Brice studied at Queensland University, Australia, and at Stanford University. He was a professor at Cornell University when he died in a plane crash before receiving his medal.

1978 – Donald A. Gurnett: “Investigations relating to electromagnetic and electrostatic wave propagation in the Earth’s plasma environment.” Gurnett studied at the University of Iowa, where he is a Professor Emeritus.

1999 – Akira Ishimaru: “For contributions to the theories and applications of wave propagation and scattering in random media and backscattering enhancement.” Ishimaru studied at the University of Tokyo, Japan, and at the University of Washington, where he is a Professor Emeritus.

2002 – Donald L. Carpenter (1928-2019): “For his discovery of the plasmapause, for pioneering studies of the plasmasphere structure and dynamics and for development and use of whistler-mode waves as diagnostic probes of the magnetosphere.” Carpenter studied at Stanford university, where he was a research professor.

2008 – Alan E. E. Rogers: “For his outstanding contributions to instrumentation in radio astronomy and its use to make fundamental discoveries about interstellar masers, superluminal expansion of quasars, deuterium abundance in the galaxy, and plate tectonics.” Rogers studied at MIT and is a researcher at the MIT Haystack Observatory.

2011 – David H. Staelin (1938-2011): “For seminal contributions to the passive microwave remote sensing of planetary atmospheres and the development of remote sensing of the atmosphere and environment of the Earth from space.” Staelin studied at MIT, where he remained as a professor for his entire life.

4.3 Appleton Prize

US scientists were awarded eight of the seventeen Appleton Prizes.

1972 – Robert A. Helliwell (1920-2011): “Radio wave propagation in the magnetosphere.” Helliwell spent his entire professional life at Stanford University, where he studied and was a professor.

1975 – John V. Evans (1933-2013): “Ionospheric physics, including applications of the incoherent scatter technique.” Evans studied at the University of Manchester, UK, and spent his professional life as a researcher at the MIT Lincoln Laboratory.

1978 – P. M. Banks: “Theoretical and observational studies of the plasma flow between the ionosphere and the magnetosphere.” Banks studied at the University of California, San Diego, where he was also a professor, as well as at Utah State, Stanford, and the University of Michigan.

1996 – Donald T. Farley (1933-2013): “For contributions to the development of the incoherent scatter radar technique and to radar studies of ionospheric instabilities.” Farley studied at Cornell University and at Chalmers Technical University, Sweden. He was a professor at Cornell University.

2002 – Raymond A. Greenwald: “For conceiving, designing, developing and deploying two ground-breaking measurement techniques that have provided unparalleled spatial and temporal measurements of the ionosphere, and for inspirational international leadership.” Greenwald is a Research Professor at the Virginia Polytechnic Institute and State University

2008 – Umran S. Inan: “For fundamental contributions to understanding of whistler-mode wave-particle interaction in near-Earth space and the electrodynamic coupling between lightning discharges and the upper atmosphere.” Inan studied at Stanford University where he is a Professor Emeritus; he is also the President of Koç University in Turkey.

2011 – Bodo W. Reinisch: “For revolutionizing radio sounding from ground and space with development of the Digisonde and the IMAGE/RPI satellite instrument, both essential data providers for space weather monitoring and ionospheric modeling.” Reinisch studied at the University of Freiburg, Germany, and at the University of Massachusetts Lowell, where he is a Professor Emeritus.

2014 –Robert F. Benson: “For fundamental contributions to knowledge of the interactions of space borne radio sounders with the Earth’s plasma environment and to the use of sounders as diagnostic probes of that environment.” Benson studied at the University of Minnesota and the University of Alaska. He is an Astrophysicist Emeritus at the NASA Goddard Space Flight Center.

4.4 Booker Gold Medal

US scientists received four of the seven Booker awards.

2005 – Yahya Rahmat-Samii: “For fundamental contributions to reflector antenna design and practice, near-field measurements and diagnostic techniques, handheld antennas and human interactions, genetic algorithms in electromagnetics, and the spectral theory of diffraction.” Rahmat-Samii studied at the University of Tehran, Iran, and at the University of Illinois, and is a professor at the University of California, Los Angeles.

2011 – Ingrid C. Daubechies: “For her outstanding contributions to mathematics, and in particular to wavelet theory, and for the remarkable impact of her work in a wide range of applied science disciplines.” Daubechies studied in Belgium and France, and is a professor at Duke University.

2014 – Harold V. Poor: “For outstanding contributions to the science and technology of communications and signal processing.” Poor studied at the University of Aalborg, Denmark, and at Princeton University, where he is a professor.

2020 – **John Volakis: “**For seminal contributions to electromagnetics, including small, ultra-wideband and textile antennas and arrays, low power transceivers, diffraction and for transitioning hybrid finite element methods into commercial computational toolsets.” Volakis worked at Boeing, was a professor and the Director of the Radiation Laboratory at the University of Michigan, and Director of the ElectroScience Laboratory of The Ohio State University. He is currently Dean at the College of Engineering and Computing at Florida International University.

4.5 Issac Koga Gold Medal

US scientists received seven of the twelve Koga medals.

1987 – David M. Pozar: “Contributions to the analytical, numerical and experimental study of printed antennas and phased arrays, and related problems in applied electromagnetics.” Pozar studied at the Ohio State University, and is a Professor Emeritus at the University of Massachusetts.

1993 – Gabriel M. Rebeiz: “For contributions to the advancement of sub-millimeter wave antenna science and technology.” Rebeiz studied at CalTech and is a professor at the University of California, San Diego.

1996 – Zoya Popovic: “For contributions to the field of active microwave circuits, in particular, the original demonstration of the planar grid oscillator, as well as continuing efforts with quasi optical amplifiers and active antennas.” Popovic studied at the University of Belgrade, Serbia, and at CalTech. She is a Distinguished Professor at the University of Colorado.

1999 – Eric Michielssen: “For contributions to computational electromagnetics, in particular the development of fast frequency and time-domain integral equation analysis techniques and nature-driven synthesis method.” Michielssen studied at the Katholieke Universiteit Leuven, Belgium, and at the University of Illinois. He is a professor at the University of Michigan.

2005 – Susan C. Hagness: “For contributions to the development of enhanced finite-difference time-domain methods in computational electromagnetics, and ultra-wideband microwave imaging techniques for early breast cancer detection.” Hagness studied at Northwestern University and is a professor at the University of Wisconsin.

2008 – Daniel F. Sievenpiper: “For contributions to the development of artificial impedance surfaces and conformal antennas.” Sievenpiper studied at the University of California, Los Angeles, and is a professor at the University of California, San Diego.

2011 – Andrea Alù: “For contributions to the theory and application of electromagnetic metamaterials, in particular the conception of plasmonic-based cloaking, optical nanocircuits, and anomalous propagation and radiation in metamaterials.” Alù studied at Roma Tre University, Italy, and is the Einstein Professor of Physics at the CUNY Graduate Center, City College of New York.

4.6 Santimay Basu Prize

All three Basu prizes were awarded to US scientists.

2014 – Morris B. Cohen: “For contributions to ELF/VLF radio wave instrumentation, propagation, and generation, in the ionosphere and magnetosphere, and for initiating and fostering an international network of young scientists in developing countries.” Cohen studied at Stanford University where he is an associate professor.

2017 – Jamesina J. Simpson: “For advancing three-dimensional finite-difference time-domain (FDTD) solutions of electromagnetic wave propagation within the global Earth-ionosphere waveguide applied to space weather, remote sensing, and very low-frequency propagation.” Simpson studied at Northwestern University and is an associate professor at the University of Utah.

2020 – **Xiaolan Xu, “**For Developments in Wave Propagation and Scattering in Dense Random Media with Applications to Microwave Remote Sensing of Snow.” Xu is a scientist at the NASA Jet Propulsion Laboratory.

4.7 Karl Rawer Gold Medal

Both Rawer medals were awarded to US scientists.

2017 – Dieter Bilitza: “For leading the development of the empirical International Reference Ionosphere (IRI) climatology model and making it the international ISO standard, and for advancing the Real-Time Assimilative IRI model.” Bilitza is a Chief Scientist at the NASA Goddard Space Flight Center.

2020 – Raj Mittra (1932-): “For Contributions to Analytical and Numerical Techniques in Electromagnetics and to Antenna Theory and Design.” Mittra studied at Agra College, Uttar Pradesh; the University of Calcutta; and the University of Toronto. He was a professor and Director of the Communications Laboratory at the University of Illinois in Urbana, IL, followed by being the Director of the Electromagnetic Communications Laboratory at the Pennsylvania State University. He is currently a professor at the University of Central Florida. He is currently President of Stoneware Ltd., a consulting company.

4.8 URSI President’s Award

The first President’s Award was awarded to a US scientist.

2017 – W. Ross Stone: “For his leadership as the Assistant Secretary General for Publications, his editorship of the Reviews of Radio Science and the Radio Science Bulletin, and for his pivotal roles in the organisation of many GASS.” Stone studied at the University of California, San Diego, and held a variety of positions in industry, including corporate Chief Scientist of McDonnell Douglas Technologies. He is President of Stoneware Ltd., providing consulting and expert witness services in telecommunications and radio science.

5. Officers of URSI from the United States

5.1 Presidents and Honorary Presidents

L. W. Austin (1932-1932)
A. E. Kennelly (1932-1934), Honorary President (1934-1939)
J. H. Dellinger, Honorary President (1952-1962)
L. V. Berkner (1957-1960), Honorary President (1963-1967)
S. Silver (1966-1969), Honorary President (1972-1976)
H. G. Booker, Honorary President (1978-1989)
W. E. Gordon (1981-1984), Honorary President (1990-2010)
T. B. A. Senior (1996-1999)

5.2 Vice-Presidents

A. W. Austin (1921-1933)
J. H. Dellinger (1934-1952)
C. R. Burrows (1952-1955)
L. V. Berkner (1954-1957)
H. G. Booker (1969-1975)
W. E. Gordon (1975-1981)
T. B. A. Senior (1993-1996)
C. M. Butler (2002-2008)
U. Inan (2008-2011 and 2014-2017)
P. L. E. Uslenghi (2011-2014 and 2017-2021)

5.3 Chairs of Scientific Commissions

URSI set up Commissions I through IV in 1922, then added Commission V in 1928, Commissions VI and VII in 1948, and Commission VIII in 1969. At the 1975 URSI General Assembly in Lima, the Commissions were restructured and the present nine Commissions A through J were set up. Commission K was added in 1990, at the General Assembly in Prague.

Before 1975:
Commission I – J. H. Dellinger (1946-1952)
Commission II – J. H. Dellinger (1946-1952)
Commission III – C. O. Hines (1966-1968); S. A. Bowhill (1972-1974)
Commission IV – R. A. Helliwell (1957-1962); H. G. Booker (1963-1968); F. L. Scarf (1972-1974)
Commission VI – L. C. Van Atta (1953-1955); K. M. Siegel (1972-1974)
Commission VII – W. G. Sheperd (1957-19620; M. Chodorow (1969-1972)

After 1975:
Commission A – H. M Altshuler (1975-1977); M. Kanda (1996-1999); Q. Balzano (2002-20050; W. A. Davis (2011-2014)
Commission B – L. B. Felsen (1978-1980); T. B. A. Senior (1987-1989); C. M. Butler (1996-1999)
Commission C – J. K. Wolf (1981-1983); A. F. Molisch (2005-2008); A. Zaghloul (2017-2020)
Commission D – T. Itoh (1993-1995); F. X. Kaertner (2008-2011)
Commission E –G. H. Hagn (1978-1980); R. L. Gardner (1999-2002); D. V. Giri (2014-2017)
Commission F – A. T. Waterman (1978-1980); R. K. Crane (1987-1989); R. K. Moore (1993-1995); R. H. Lang (2011-2014); V. Chandrasekar (2017-2020)
Commission G –J. Aarons (1984-1986); B. W. Reinisch (1996-1999); J. D. Mathews (2011-2014); P. Doherty (2017-2020)
Commission H – F. W. Crawford (1978-1980); R. F. Benson (1990-1992); U. Inan (2002-2005)
Commission J – G. Westerhout (1975-1977); R. Ekers (1990-1992); J. N. Hewitt (1999-2002); R. Bradley (2017-2020)
Commission K – J. C. Lin (1996-1999)

6. URSI General Assemblies in the United States

There have been four General Assemblies held in the United States.

IInd General Assembly, Washington, DC (1927)[2] – The second General Assembly was held in 1927 in Washington in conjunction with the International Radio Conference, which may be called the first truly modern conference on telecommunications. There were 11 Member Countries in attendance. Among the participants, the names of Dellinger, Van Der Pol, Mesny, Bureau, Appleton, Smith-Rose, Koga, Yagi, Austin, and Kennelly were of particular note. At the meeting of Commission I, it was generally agreed that the unit of frequency was identical with the unit of time interval, and that no independent definition should be given. It was further agreed that although frequency was measured in terms of the astronomical unit of time, it was nevertheless important to compare the national frequency standards in order to check the measurement techniques. Indeed, URSI has been instrumental in arranging many series of comparisons by both physical transport of standards and by the simultaneous measurement of the frequency of radio transmissions. Much attention was devoted to radio-propagation problems. Between 1922 and 1927, the subject of ionospheric radio had rapidly developed. In 1925, Breit and Tuve in the USA and Appleton and Barnett in the UK had showed for the first time that radio waves could be reflected from the ionized portion of the atmosphere. From then onwards, scientists began to realize that, on the one hand, radio provided them with a powerful tool for exploring the upper atmosphere and, on the other hand, that the study of the upper-atmospheric physics would help them to understand the propagation of radio waves. Edward Appleton had been President of URSI for more than 10 years, and that he was awarded the Nobel Prize for Physics in 1947. Tuve developed the pulse-echo method, which was in fact the first pulsed radar in the world.

XIIth General Assembly, Boulder, CO (1957) – Proceedings of the seven Commissions (I-VII) are available from the historical files at URSI Headquarters. The General Assembly was held August 22-September 5. There were more than 500 attendees from 25 countries. The General Chair was J. Howard Dellinger. A report on the meeting was published as a special issue of the *Proceedings of the IRE*, July 1958.

XXth General Assembly, Washington, DC (1981) – Proceedings of the General Assembly are available from the historical files at URSI Headquarters.

XXIX General Assembly, Chicago, IL (2008) – Held August 7-16, the Assembly had 1,201 registered attendees, including 125 Young Scientists and 262 students. The number of scientific papers presented was 1,456, evenly divided between oral and poster sessions. P. L. E. Uslenghi (USA) was the General Chair and Associate Scientific Program Coordinator, and Goel (India) was the Scientific Program Coordinator. The URSI Council approved a resolution to rename future General Assemblies as "URSI General Assembly and Scientific Symposium (GASS)." For the first time in the history of the URSI General Assemblies, a student paper competition was held, with prizes provided by the US National Committee of URSI; it was decided to conduct the student paper competition again at future GASS.

In addition to four General Assemblies, the United States has hosted several symposia sponsored and organized by URSI Commissions.

7. URSI Publications in the United States

The *Bulletin of the Bureau of Standards* of the United States began publication in 1904, publishing what were known as Scientific Papers. In 1928, the Scientific Papers were combined with the Technologic Papers (reporting results of material investigations and testing methods) to create the *Bureau of Standards Journal of Research*. In 1959, this *Journal* began publication in four sections: A, B, C, and D. *Section D* covered research in radio propagation, communications, and atmospheric physics. From 1961-1963, *Section D* was known as *Radio Propagation*. In 1964, the title of *Section D* changed to *Radio Science*, and it began being sponsored by the US National Committee for URSI. In 1966, publication moved from the National Bureau of Standards to the American Geophysical Union (AGU) and the publication's title became simply *Radio Science*, while the sponsorship shifted from USNC-URSI to URSI. Publication has subsequently been taken over by Wiley for the AGU. *Radio Science* has remained an URSI-sponsored publication.

The URSI *Radio Science Bulletin* began publication in the 1920s shortly after URSI was founded. It went through a period in the 1980s when it was called the URSI *RadioScientist*, although it retained the same issue numbering. It reverted to the *Radio Science Bulletin* in the 1990s. W. Ross Stone (USA) became Editor in 1999, and has remained Editor since.

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[2] Much of this material was taken from [50].

In 2019, the URSI Board authorized the publication of a new online and open-access journal, the *URSI Radio Science Letters*, with P. L. E. Uslenghi (USA) as its first Editor-in-Chief and Allen Press, Lawrence, KS, as the publishing house.

8. A Brief History of the United States National Committee of URSI[3]

The United States National Committee of URSI (USNC-URSI) was originally organized under the Research Council of the US National Academy of Sciences. The Research Council was organized in 1916 at the request of US President Wilson. Subsequent reorganizations have led to USNC currently being a committee of the Board on International Scientific Organizations of the US National Academies of Sciences, Engineering, and Medicine.

What was then called the American Section of URSI began its participation in URSI with the start of URSI, at the first meeting of the International Research Council in 1919. The first Chair of the American Section was W. L. Austin. URSI held its first General Assembly in Brussels, Belgium, in July 1922, and the US National Committee was one of the four National Committees that participated in that General Assembly.

USNC-URSI has held technical meetings, at least annually and usually twice per year, since 1926. At least one of these was always held jointly with the Institute of Radio Engineers or its successor organization, the Institute of Electrical and Electronics Engineers (IEEE), or one of their constituent groups. Since 1963, the pattern has been to meet jointly with the IEEE Antennas and Propagation Society in the summer in an IEEE AP-S International Symposium on Antennas and Propagation/USNC-URSI Radio Science Meeting, and for USNC-URSI to hold a separate National Radio Science Meeting. This latter meeting was originally held in the fall through the 1960s and 1970s, and since then having settled on very early January, almost always being held in Boulder, CO.

USNC-URSI has always been organized into Commissions mirroring the Commission structure of international URSI (and it thus has changed to mirror the changes in the Commission structure of URSI over the years). Individual scientists are elected to membership in individual Commissions. Membership is restricted to active radio scientists who meet significant qualifications; Membership is considered a significant honor for a radio scientist. The Commissions also admit Associate Members who may not be as well qualified, and Early Career Members. The voting members of the US National Committee include the Chair; the immediate Past Chair; the Secretary/Chair-Elect; the Chairs of the USNC-URSI Commissions; six elected Members at Large; representatives from certain associated scientific organizations; Officers and members of the URSI Secretariat resident in the US, including Honorary Presidents; and Chairs and Vice Chairs of URSI Commissions resident in the US.

The following is a list of the Chairs of USNC-URSI since 1965:

1965-1967	**M. G. Morgan,** Dartmouth College
1968-1970	**Edward C. Jordan,** University of Illinois
1971-1973	**Alan T. Waterman,** Stanford University
1974-1976	**Francis S. Johnson,** University of Texas at Dallas
1976-1978	**John V. Evans,** Massachusetts Institute of Technology, Lincoln Laboratory
1979-1981	**C. Gordon Little,** NOAA, Environmental Research Labs
1982-1984	**Thomas B. A. Senior,** University of Michigan
1985-1987	**Robert K. Crane,** Environmental Research & Technology
1988-1990	**Sidney A. Bowhill,** University of Massachusetts at Lowell
1991-1993	**Chalmers M. Butler,** Clemson University
1994-1996	**David C. Chang,** Polytechnic University in Brooklyn, NY
1997-1999	**Susan K. Avery,** University of Colorado at Boulder
2000-2002	**Gary S. Brown,** Virginia Tech**2003-2005** **Umran S. Inan,** Stanford University
2006-2008	**Piergiorgio L. E. Uslenghi,** University of Illinois, Chicago
2009-2011	**Yahya Rahmat-Samii,** University of California, Los Angeles
2012-2014	**Steven C. Reising,** Colorado State University
2015-2017	**David R. Jackson,** University of Houston
2018-2021	Sembiam Rengarajan, California State University, Northridge

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[3] Some of the material in this section was taken from [51].

9. The Next One Hundred Years

During the first one hundred years of existence of URSI, the United States has played a dominate role in the development of radio science. Even though it is not possible to predict future scientific discoveries, it is unlikely that any country will exercise such a leading role in the next one hundred years, for a couple of interrelated reasons. First, the ease and rapidity of communications across the globe makes it likely that many scientific advances will be the product of teams of scientists collaborating across national boundaries. Second, many projects will require complex and expensive instrumentation that a single country might find unproductive to pursue alone, as already documented, for example, by the ALMA radio telescope and by the Square Kilometre Array. Nevertheless, it is to be expected that the USA will continue to play a leading role in radio science for the foreseeable future. We venture to predict those areas of research and development to which radio science in the United States will contribute significantly.

The impact of quantum physics on traditional radio-science disciplines has already begun, and will become more prominent in the future. Examples of such activities in the United States are the work on atomic clocks and on measurements of physical constants at NIST, of interest to Commission A. The development and applications of novel optical devices and of electronic materials such as graphene is driven by the need to miniaturize devices and to synthesize materials of pre-assigned behavior. This is being carried out at several research centers, and is of interest to Commissions B and D. A resurgence of engineering physics as an academic discipline is to be expected.

In communications (Commission C), the implementation of 5G systems is well under way. The next few years will witness the development of 6G systems and beyond.

Miniaturization of devices and advances in signal processing, coupled with an improved understanding of the effects of electromagnetic fields on biological systems, will lead to the widespread use of wearable electronics: Commissions B, C, D, and K will be involved.

The exploration of our solar system and beyond will be vigorously continued with the aid of additional satellites and radio telescopes, as well as human missions. This complex effort will involve all ten Commissions to different degrees, but will rely primarily on Commission J.

Applications of radio science to disaster prevention, such as early warnings of tsunamis and of collisions of asteroids with Earth, and to disaster management, such as communications among intervening agencies, will be the responsibility of Commissions B, C, F, J, and K.

Finally, the next one hundred years will witness an enormous development in the applications of electromagnetism to biomedicine (Commission K), including scientific advances in understanding the interaction of electromagnetic fields with biological systems, noninvasive medical diagnostics, the use of electromagnetic fields in the cure of diseases, and in artificial organs.

10. References

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URSI
SCIENTIFIC
COMMISSIONS

Contribution from Commission A

1. History and Evolution of Commission A

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As one of the ten URSI commissions, Commission A deals with one of the most fundamental fields of radio science, i.e., Electromagnetic Metrology. The origin of the commission is deep in URSI's history; it was one of the first four commissions formed at the time of the first general assembly in 1922 [1] under the name Measurement Methods and Standardizations. Other commissions have been divided and re-configured since then, and also new commissions were generated, but this commission has been remained, since its establishment, through the long history of URSI. According to S. Hah, the chairman of the Commission A at the time of the Corsendonk Meeting in 1984, the terms of the reference of the Commission A were the following [2],

- Time and frequency measurements and standards, including infrared and optical frequencies.
- Time domain measurements.
- Frequency domain measurements.
- Laser measurements.
- Quantum metrology and electrical methods in fundamental constants.
- Microwave to sub-millimeter measurements and standards.
- Bioeffects measurements.

Clearly, the measurements of time and frequency were the most important topics of the commission. It is also interesting to see that the measurements of the bioeffects were included in the scope of the commission. The Working Group on Interaction of Electromagnetic Fields with Biological Systems was formed under Commission A and this Working Group eventually stimulated the establishment of the new Commission K on Electromagnetics in Biology and Medicine at the time of the URSI General Assembly in Prague, in 1990. The terms of reference of the commission is regularly reviewed and updated at each General Assembly (GASS, since 2011). The most drastic changes were made at the time of General Assembly in New Delhi in 2005, resulting in the current terms of reference for Commission A on Electromagnetic Metrology, Electromagnetic measurements and standards, covering new topics:

The Commission promotes research and development of the field of measurement standards and physical constants, calibration and measurement methodologies, improved quantification of accuracy, traceability, and uncertainty, and the inter-comparison of such.

Areas of emphasis are:

1. The development and refinement of new measurement techniques and calibration standards;
2. Primary standards, including those based on quantum phenomena, and the realization and dissemination of time and frequency standards;
3. Characterization of electromagnetic properties of materials, physical constants, and properties of engineered materials, including nanotechnology;
4. Methodology of electromagnetic dosimetry/measurements for health diagnostics, applications, and biotechnology, including bio-sensing;
5. Measurements in advanced communication systems, space metrology, and other applications, including antenna and propagation measurement techniques.

The Commission fosters the best practices and training for accurate and consistent measurements needed to support research, development, and exploitation of electromagnetic technologies across the spectrum and for all Commissions.

As it is more evident in the current version of the terms of reference, Commission A wishes to become a forum for discussion of accurate and consistent measurements necessary for any scientific research including impacting on the activities of other commissions.

A particular characteristic of Commission A is that it has active interactions with other international bodies and scientific unions. This has historically led to discussions with international bodies such as the International Telecommunications Union (ITU), the International Committee for Weights and Measures (CIPM), the International Astronomical Union (IAU), and the International Union of Geodesy and Geophysics (IUGG).

1.1 Proposal to Discontinue Leap Seconds

Most recently, the commission has been interacting with these organizations in discussions on the possible redefinition of Coordinated Universal Time (UTC). The discussions were initiated in URSI Commission A at the time of its open commission meeting during the General Assembly in Toronto, in 1999, when Sigfrido Leschiutta, the President of the Consultative Committee for Time and Frequency (CCTF) of the CIPM, proposed a recommendation to be adopted by URSI. The proposed recommendation concerned the proposal to discontinue the practice of inserting leap seconds in UTC. After some consultation, Commission J, on Radio Astronomy, accepted an offer to undertake a joint study with Commission A on the impact of the proposed redefinition of UTC. Although formally limited to systems related to Commission J, the request for input was forwarded not only throughout URSI, but also to other scientific groups that might have a technical interest in the matter. In addition, recipients of the request were encouraged to forward it to other scientists, as well as the general public. The report was completed on July 6, 2000 and its executive summary was as follows:

> An e-mail survey to find possible adverse effects of a redefinition of UTC has identified some possibly expensive or unsolvable problems involving software rewriting or checking, which are listed below. Although it was not possible to quantify the financial scale of resolving the software problems, the largest expenses appear to be for satellite systems, of which one estimate of several hundred thousand dollars was supplied. The quantity and quality of the responses opposed to a change indicate that those who favor any change must be prepared to make a very convincing argument to people and groups who initially will disagree with them.

At the XXVII GA, in 2002, an URSI-wide committee was set up to study the leap seconds issue, chaired by Demetrios Matsakis. The committee limited its range to the chairs of the URSI Commissions, asking them to poll their membership. No responses indicating a preference for or against the redefinition were received. Therefore, at the XXVIII GA in 2005, the Working Group was dissolved and the URSI Secretariat decided not to respond to the ITU's request for an opinion. It was not until the XXX GA, in 2014, that Commission A reconsidered the issue and voted to request the URSI Secretariat send a letter to the ITU endorsing the abolition of future leap seconds after a suitable warning period. This was accepted, and the letter was sent to the ITU Radiocommunication Sector (ITU-R) for their consideration. ITU, however, decided in its World Radiocommunication Conference (WRC) in 2015 that further studies were required on the impact and application of a future reference time-scale, and to discuss the topic again in 2023. ITU then asked for closer coordination with related international organizations, including URSI. It is therefore very important for URSI and Commission A to consider how to respond to this request.

1.2 The Development of Standards

Our commission was the theater where the progress on atomic standards was reported and discussed between 1950 and 1957 through the works of Lyons, Essen, Parry, Zacharias and others. Also, the first international comparisons of frequency standards were arranged and supported by our commission, at that time under the name Commission I.

At the time of URSI's 50th anniversary, the adoption of an atomic unit of time was under discussion, opening five decades of international cooperation and coordination towards the accuracy improvement of the time unit.

The progress in the development of cesium atomic standards, their operation in some metrology institutes, and the understanding that they could realize the second with unprecedented accuracy moved the Consultative Committee for the Definition of the Second (CCDS, today CCTF) to recommend, in 1967, that the unit of time of the International System of Units (SI) is that realized with the isotope 133 of the cesium atom, and that the second defined by the General Conference on Weights and Measures (CGPM) in 1956 be called "ephemeris second". This recommendation was welcome by the IAU. The CCDS also recommended that the CIPM) should promote a meeting with the relevant organizations, including the Bureau International de l'Heure (BIH), the IAU, the IUGG, the URSI and the International Consultative Committee of Radiocommunications (CCIR) of the ITU (today ITU-R) to study the problems issuing from the adoption of the new unit of time. These organizations gathered all scientific activities related to Earth, space and time references, and represented the most important communities of users.

A consequence of the new definition was the construction of an atomic time scale based on the atomic second. From the interaction of representatives of the organizations convocated by the CIPM, two time scales were created: a uniform time scale based on the atomic second named International Atomic Time (TAI), which should be the basis for the construction of an international time reference, and Coordinated Universal Time UTC. TAI was constructed at BIH with the cooperation of the institutes achieving local atomic time scales. Because ITU established the rules for the emission of standard frequencies and time signals, it was at its CCIR that the mechanism for obtaining UTC through the insertion of a leap second was described. BIH was also responsible for predicting and announcing the dates for inserting leap seconds. The International Earth's Rotation and Reference Systems Service (IERS), which was founded in 1988, took responsibility for maintaining the terrestrial and celestial reference systems, and the parameters for orientation of the Earth, and for deciding and announcing the date for the insertion of leap seconds in UTC. The maintenance of the time scales TAI and UTC was transferred to the International Bureau of Weights and Measures (BIPM), putting all the activities relating to the time references under the umbrella of the Metre Convention.

URSI is at present a liaison of the CCTF, represented by Commission A. The Consultative Committee for Units of the CIPM has invited URSI to make a contribution on the impact of a possible redefinition of the second in radio science.

1.3 Training and Education

URSI's Commission A's Working Group on Training and Education in Electromagnetic Metrology was founded in the Spring of 2017. Chaired by Demetrios Matsakis of the USNO, it rapidly grew to 13 members, roughly equally from Europe, Asia, and North America. The principle effort of the committee was to create web pages that could serve as pointers to resources. Accordingly, experts created pages in the field of Antenna Metrology, Electromagnetic Coupling Metrology, and Time and Frequency Metrology. In addition, a page for job advertisements was established. These were presented later that year, at the XXXII GA. The URSI web designers then incorporated them into the general URSI web page system, at the following tab: http://www.ursi.org/commission.php?id=A#tab-section5. As more experience was gained, it was decided to host the web pages on Google docs, with the original link providing a redirect to https://sites.google.com/view/ursi-comma-training/home. The style was altered so there would be no confusion as to where the browser was pointing.

The Working Group also sponsored sessions on training as the 2017 GA, AT-RASC 2018, and AP-RASC 2019 meetings. At these sessions there were sometimes lively and always interesting discussions on educational techniques. As of this writing, the WG plans to extend its web page system to host some of the papers presented at these meetings.

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2. Time and Frequency Dissemination

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We currently consider time, time interval, and frequency to be related quantities that are all derived from the SI definition of frequency. A method that transmits time, therefore, is also transmitting time interval and is implicitly transmitting frequency. This implicit connection between time and frequency parameters became explicit in the 1950s with the development of the first cesium atomic clock by Essen and Parry [1,2] at National Physics Laboratory (NPL), in the UK, and by the calibration of the frequency of this device by astronomical observations by Markowitz at the US Naval Observatory [3]. The result of this work was the now well-known definition of the duration of the cesium second as 9 192 631 770 cycles of the frequency associated with the hyperfine transition in the ground state of cesium 133. [4,5]

The definition of frequency based on the transition in cesium provided a unified definition of time, time interval, and frequency that was much more stable and much more easily realized than the previous methods for realizing any of these quantities. However, realizing the stability and eventually the accuracy of the cesium frequency at a remote location depended on developing methods of disseminating time and frequency information that would not degrade the characteristics of the reference device and would support the requirements of the three user communities who were primarily interested in time, time interval, and frequency.

Since all of these quantities were derived from the same frequency standard, it was natural to consider a single system that would disseminate them simultaneously, and so Coordinated Universal Time (UTC) was born. The definition and the dissemination of the UTC time scale had to satisfy a number of requirements:

1. The frequency and implicitly the time interval of UTC must be traceable to the hyperfine transition frequency in the ground state of cesium as discussed above;

2. Dissemination of the frequency and time interval required the transmission delay to be stable;

3. Dissemination of time added the requirement that the transmission delay be calculable or measurable;

4. Atomic time must be monotonically and uniformly increasing and single-valued so that the time-ordering of events is unambiguous and causality is well defined;

5. The transmitted time should be linked to UT1 to be consistent with the long-standing historical connection between time and the mean solar day.

In order to realize requirement 1, the length of the UTC second was derived from International Atomic Time (TAI), which is designed to be an implementation of the "cesium second" on the rotating geoid. From the very beginning, the value chosen for the number of cycles in a "cesium second" was too small, so that time intervals based on the cesium frequency were shorter than the corresponding values based on astronomy, UT1 (essentially the discontinued Greenwich Mean Time). In fact, the length of the second derived from astronomy has short-term irregularities and a long-term secular drift, so that no choice for the number of cycles in a cesium second could have matched the length of the second determined from astronomy in the long term. To address the difference between UTC and UT1, starting in 1972 the link was realized by adding extra "leap" seconds to UTC, as needed, to limit the magnitude of the difference between UTC and UT1 to be no greater than 0.9 s [6]. Both positive and negative leap seconds could be used in principle, but only positive leap seconds have ever been required. The operators of broadcast services were encouraged to transmit the difference between UTC and UT1 with a resolution of 0.1 s [7,8]. The official name of the extra positive leap second is 23:59:60 UTC, but clocks cannot represent that time, and the leap second is generally implemented by stopping the clock for an extra second when the time is 23:59:59 UTC on a leap-second day. The name of the next second is 00:00:00 UTC of the next day, so that the interval associated with the positive leap second is effectively lost once it has occurred. Since the leap second is linked to UTC, it occurs late in the afternoon (4 pm or 1600) local time in the Pacific Time Zone of the United States, and in the middle of the morning of the next day in Australia and much of Asia. This method of realizing requirement (5) to maintain a link between UTC and UT1 impacted requirement (4) for time intervals that included the leap second, or for time stamps in the vicinity of a leap second. Navigation, and other applications that depended on requirement (4) could not use UTC, and developed special-purpose time scales as a result. GPS system time is an example of such a time scale, but there are others [9, 10]. Unfortunately, the increasing number of commercial, financial, and computer-based applications that require unique and monotonic time stamps and that depend on strict causality mean that it is almost certain that these non-standard time scales are likely to proliferate and to become de-facto replacements for UTC in many applications. To some extent, this has defeated the initial intent of the design of UTC as a time scale that could be used for multiple purposes and that could satisfy almost all time and frequency requirements.

It has proven difficult to design a time scale or a dissemination system that can simultaneously satisfy requirements (4) and (5). The UT1 time scale is based on astronomical observations and cannot be predicted algorithmically very far in the future. One method that could be used to satisfy both requirements (4) and (5) would be to discontinue leap seconds and require all time dissemination services to transmit explicit meta-data to convert the transmitted signal to whatever time scale was needed by the application – to compute UT1 from a UTC transmission, for example. Applications that currently use the broadcast difference between UTC and UT1 would not be affected because they are already using this meta-data. The main difficulty with this approach is that a number of existing applications use the UTC time scale *without adjustment* as a low-accuracy proxy for UT1. This approximation would not be possible if leap seconds were eliminated to make UTC a smooth and monotonic time scale, and these applications would have to use the meta-data explicitly to compute UT1 from UTC. It would be much more difficult to transmit UT1 with a meta-data offset to UTC, although a broadcast of TAI that included offsets to both UTC and UT1 could be a possibility. This would be similar in concept to using the signals currently transmitted by global navigation satellites, which depends on receiving and parsing the data channel to convert the broadcast satellite system time to UTC. (The proposal to transmit two timescales – one for disseminating the frequency of the SI second and a second method for a time scale that was directly linked to UT1 is too cumbersome and is probably too confusing to be seriously considered.)

If leap seconds were discontinued, the value of the UT1 – UTC or UT1 – TAI time differences would increase slowly; the current rate of increase is about 1 minute per century, a value that is much smaller than the width of time zones or of the offset resulting from Daylight Saving Time ("Summer Time"). Transmission formats that assume that the UT1 - UTC difference would always be not greater than 0.9 s in magnitude would have to be modified.

I will now discuss the 3 methods that are generally used to transmit UTC. These methods are designed to realize requirements (1) and (2) – to support the need to characterize the transmission delay between the source of time and the receiver and are not sensitive to the internal data of the time messages that are transmitted.

In the first method, the transmission consists of a base time signal that supports some of the requirements listed above with ancillary data that must be used to realize the remaining requirements. Signals from global navigation satellites use this method. The transmitted signal is derived from an oscillator on the satellite, and the time and frequency offsets of the oscillator and the parameters that are needed to compute the transmission delay are transmitted as a separate data stream [11]. Time-service radio signals, such as those that are broadcast by the National Institute of Standards and Technology (NIST) radio stations WWV, WWVB, and WWVH, transmit a time that is traceable to UTC and the approximate time offset of UT1, but there is no information that can be used to compute the propagation delay [12]. The accuracy of this type of service depends strongly on the meta-data, so that time-service radio signals are inherently limited by the lack of any data that can be used to determine the path delay. The broadcast data from navigation satellites can be augmented by post-processing, which can improve the accuracy from tens of nanoseconds, when the broadcast ephemeris is used, to sub-nanosecond accuracy with post processing [13, 14].

In the second method, two (or more) stations receive the same signal from any source [15]. The reception times are subtracted to yield the time difference between the two stations. This method can be used to distribute UTC if one of the stations maintains a realization of the UTC time scale or it can be used to compare two realizations of UTC. In the simplest configuration, the path delays between the source and the two receivers are equal, so that the path delays and the characteristics of the source are not important and need not be known. It is difficult to make the two path delays exactly equal in a practical configuration, so that the common-view method attenuates, but does not eliminate, requirements to determine the characteristics of the source and the differential path delay. This method is currently associated with signals from the GPS satellites and other navigation systems, but its use pre-dates these systems. Transmissions by LORAN stations were used to compare the time scales of national laboratories, [16] and signals from television stations [17] and even lightning flashes have also been used for the same purpose.

In the original version of common-view, multiple stations received a signal from a single physical transmitter, which limited the geographical separations of all of the stations to those that could receive that signal. In a more modern version of common-view, the common parameter is the reference time scale of multiple, independent transmitters and not the times of the transmitters themselves. Instead of using the physical signal from a GPS satellite in common-view, the “all in view” or “melting pot” method observes the signals from all of the satellites in the constellation that are in view at any time, and the common-view calculation is with respect to the system time of the constellation [18]. The usefulness of this method depends on the accuracy of the meta-data that relates the signals transmitted by the satellites to the reference system time scale, and this method usually depends on post-processing the received data with meta-data computed after the fact. The “all in view” and “common view” methods are essentially equivalent for very short baselines, since all of the stations see the same physical sources; “all in view” is the only practical solution when the distance between the stations is very large; the comparison is more complicated for intermediate-length baselines, but the “all in view” method will generally be the method of choice if ancillary data of sufficient accuracy are available, which generally limits the method to non-real-time applications.

The third general dissemination method is two-way. The transmission delay between the source and the receiver is estimated as one-half of the measured round-trip value. This method is commonly used to transmit time over digital circuits [19]. In the NIST implementation of two-way transmissions over dial-up telephone lines, [20] the one-way delay estimate is performed by the master station transmitter; in the Internet implementation, the one-way delay is estimated by the slave station receiver; in the two-way satellite method, [21] the time offset and delay are estimated at both stations, but the basic method is the same in all of these configurations. The accuracy of the method depends on the fundamental assumption that the one-way delay is one-half of the measured round-trip value, and the stability of the measurements depends on any rapid fluctuations in the delay or in its symmetry. (Depending on the details of the implementation, the inbound and outbound signals may not be sent at exactly the same time and may not be transmitted over exactly the same physical circuit.) Therefore, the accuracy over a dial-up telephone circuit is generally tens of milliseconds; a channel based on the public Internet can realize an accuracy of better than 1 ms but is often significantly poorer, while a two-way link realized through a communications satellite can realize an accuracy of 0.1 ns or better. The two-way method is generally used with little or no post-processing.

The common-view and two-way methods are generally not sensitive to the details of the format that is used for the exchange of timing information, so that no one format is inherently more accurate or more stable than any other format. The signals transmitted by navigation satellites, and in the two-way satellite method, transmit a time “tick” as a pseudo-random code with cross-correlation detection, whereas telephone and digital-network methods use the time of arrival of a packet or a special “on-time” character as the reference time.

In general, the common-view and two-way methods transmit a time scale derived from the reference time scale of the source. The reference time scale is generally UTC, but the methods could be used to transmit UT1 or TAI without modification [22]. The transmission formats generally do not include any information on the reference time scale or the additional parameters that could support the conversion from one reference time to another one – from UTC to UT1, for example. There is also no provision in most of the transmission protocols for indicating that a time value of 23:59:59 UTC could be a leap second.

A discussion about time dissemination is divided into two practically independent aspects – how the magnitude of the transmission delay will be estimated, and what data will be transmitted. It is likely that the three transmission methods will continue to be incrementally improved, but the definition of UTC and how it will be disseminated may require more fundamental changes to support the increasing number of applications that depend on a continuous, monotonic, single-valued source of legal time.

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3. Primary Frequency Standards

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"Standards of frequency and their comparison have been an important item of discussion at U.R.S.I. throughout its history." We find this and the following phrases by Louis Essen, National Physical Laboratory (NPL), UK, in the U.R.S.I. Golden Jubilee Memorial [1] report on Radio Measurements and Standards (Chapter 1).

The first work on atomic frequency standards by H. Lyons in the U.S.A. was reported to the General Assemblies of 1950, 1952 and 1954, and an account of the first operational atomic standard at NPL was given at the 1957 Assembly.

This device, designed by Essen himself and J. V. L. Parry [2] and shown in Figure 1, was the very first of the generation of primary frequency standards that employed a thermal atomic beam of cesium atoms and the separated oscillatory field method invented by Norman Ramsey [3, 4]. Essen continued,

> An extended comparison between the astronomical and atomic units was made by NPL in co-operation with the United States Naval Observatory (USNO) and gave a value of 9 192 631 770 ± 20 c/s for the frequency of the cesium line in terms of the second of ephemeris time.

In the Proceedings of the 16th U.R.S.I. General Assembly (GASS), Ottawa, 1969, it was reported from Commission I that

> During the present Assembly much attention has been given to the measurement of time. An important event in the history of standards was the adoption of the atomic unit of time at the 1967 General Conference on Weights and Measures (CGPM) based on the numerical value given above. The standard frequency and the unit of time are thus electromagnetic quantities and will continue to be the concern of URSI Commission I.

This section is written in this spirit and shall briefly outline the progress made in the field up to 2019, closing with an outlook to current trends for future development.

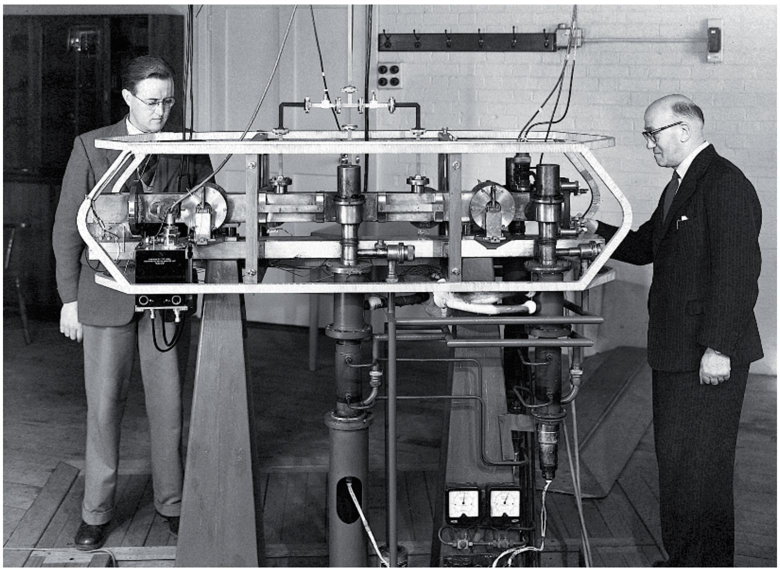


Figure 1. The first cesium atomic frequency standard at NPL, with Louis Essen (right) and Jack Parry (source: NPL).

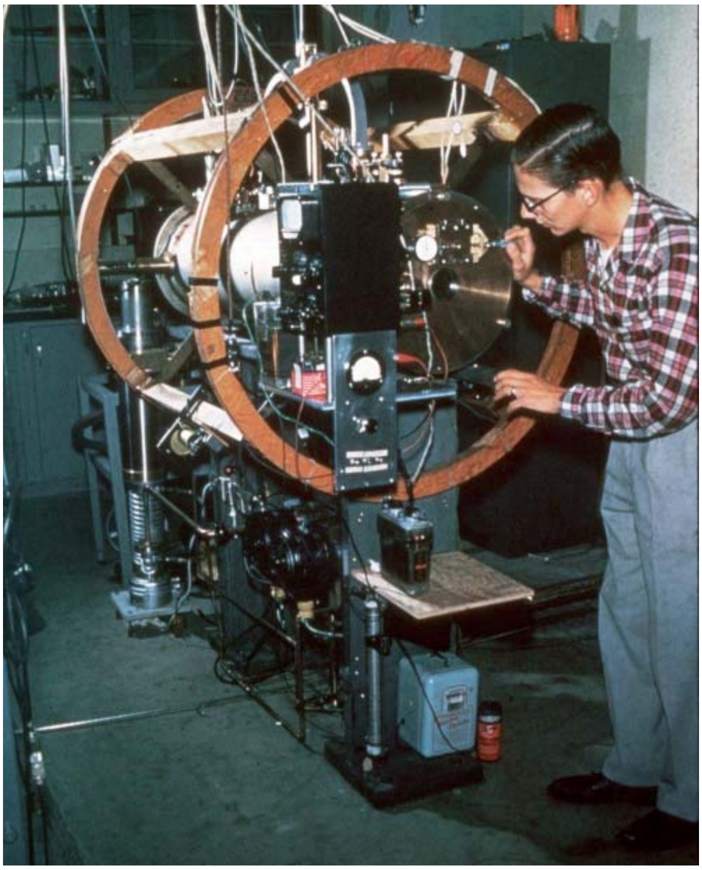


Figure 2. Roger Beehler of NBS with NBS-1 (source: NIST)

The development of the NPL clock happened in an atmosphere of collaboration but also competition with colleagues at the US National Bureau of Standards [5] who had started work earlier but could get their clock NBS-I operational only by 1958 [6]. The apparatus is shown in Figure 2 with Roger Beeler who was part of the team and who some years later provided a concise report on the history of atomic clocks [7]. The year 1958, however, also saw the release of the first commercial cesium clock, the Atomichron® [8], and for the next decades progress in the development of atomic clocks was substantially driven by research carried out in industry, particularly in the US firm Hewlett-Packard [9] in addition to work in National Metrology Institutes (NMIs) and government research centers.

At this stage it seems necessary to explain the term "primary frequency standard". The definition of the second today refers to "the unperturbed ground-state hyperfine transition frequency of the cesium 133 atom" [10]. Such an idealized situation can be reached in practical realization only with some uncertainty. Following the pioneering work at NPL and NBS, a small number of other NMIs designed and built so-called primary frequency standards with the intention to understand, minimize and quantitatively characterize the disturbances to the atoms and the frequency shifts related to their design and operation. Corrections are applied such that the output frequency (1 Hz and standard frequencies) agree with the nominal value with the smallest possible uncertainty. This uncertainty was estimated as about 1 part in 10^{10} for the NPL clock in 1955 and is close to one part in 10^{16} in 2019. The operation of primary frequency standards has been reported from institutes in 11 countries world-wide. For a detailed description of the physics in such devices the reader is referred to [4, 11]. In the mid-1960s, the Physikalisch-Technische Bundesanstalt (PTB) started to make efforts to develop a cesium atomic clock of its own and these efforts were – eventually – successful. The CS1 clock (see Figure 3) implemented new design features, with the potential advantages in terms of:

- reduced frequency instability due to a two-dimensional focusing of the atoms with magnetic lenses (instead of the dipole magnets used until then);
- axial-symmetric geometry of the atomic beam with small radial extension, and
- reduced inhomogeneity of the C field by using a long cylindrical coil and cylindrical shielding – instead of a magnetic field transverse to the beam direction.

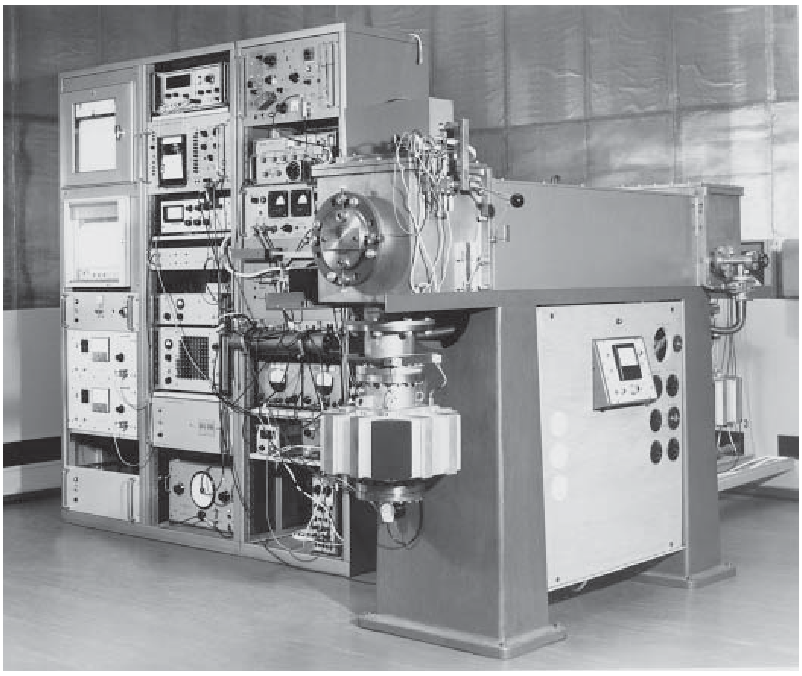


Figure 3. The primary atomic beam frequency standard CS1 in PTB's atomic clock hall (1969).

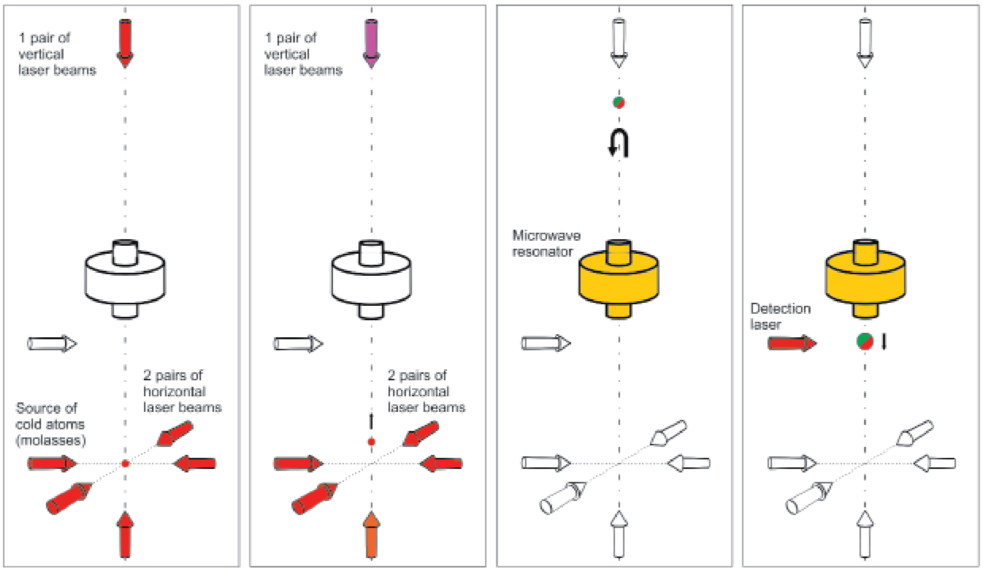
Figure 4. Cesium fountain clock FO-1 of LPTF, Paris (source: BNM-SYRTE, Observatoire de Paris).

CS1 was used for the first time in 1969 [12] and has been ticking ever since – so we can celebrate 50 years operation of the CS1 in this year, 2019. CS1 was featured in a session of Commission A at the URSI GA 1981. A second clock, CS2, was put in operation with similar design in the mid-1980s [13]. Other institutes decided to employ state-selection and detection of atoms using irradiation with lasers, subject of presentations for the first time at the URSI GA 1987 and 1990. Here two are noted: the standard "Jet de Pompage Optique" from the Paris-based Laboratoire primaire du temps et des fréquences (LPTF) [14]; and NIST-7 [15], the last US thermal beam cesium clock in a long series.

The concept of laser cooling of atoms in the 1980s [16-18] opened the way for the development of the second generation of primary frequency standards, the so-called atomic fountains whose principle was explained by André Clairon of LPTF at the 1993 URSI GASS. The name goes back to early experiments by Zacharias, mentioned in [8], in which extremely slow atoms from an upwards directed thermal beam should be detected after a trajectory similar to those of water droplets in a fountain. The first operational fountain standard, FO-1, was presented to the public in 1996 at the Paris Observatory [19, 20] and is seen in Figure 4. It is a fortunate coincidence that the cesium atom, selected as the reference for primary frequency standards with thermal beams, also possesses excellent properties for laser cooling like a strong resonance line at a convenient diode laser wavelength 852 nm and a limiting temperature in the microkelvin range. In the modern atomic fountains, an atomic cloud is cooled to a temperature in the microkelvin range so that the residual thermal expansion of the cloud remains small enough to enable an interaction time with the probing microwave field as long as half a second. This drastically reduces the atomic line width and thus the frequency instability. At the same time several frequency shifting effects are much reduced or almost absent, so that several groups have reported uncertainties of their devices to realize the unperturbed hyperfine transition frequency of almost one part in 10^{16}. The underlying physics and challenges can be found in [21, 22]. Without going into details, the crucial design features are the following: Contrary to a continuous thermal beam, cesium atoms are periodically trapped, cooled and then accelerated upward. To be able to excite the atomic resonance transition with as few disturbances as possible, free atoms must be observed and the trapping and cooling light field must be switched off. The sequence of the individual function steps is illustrated in Figure 5.

It is worth mentioning at this stage that the improved accuracy of primary frequency standards brings an immediate benefit to the time and frequency community and society in general [23]:

> International Atomic Time (TAI) is a continuous time scale produced by the BIPM (Bureau international des poids et mesures) based on the best realizations of the SI second. TAI is a realization of Terrestrial Time (TT) with the same rate as that of TT, as defined by the IAU Resolution B1.9 (2000). Coordinated Universal Time (UTC) is a time scale produced by the BIPM with the same rate as TAI but differing from TAI only by an integral number of seconds.



Loading a cloud of cold cesium atoms; the atoms are prepared in a hyperfine structure (HFS) state (1).

Starting the cloud in state (1) by detuning the frequencies of the vertical laser beams.

Flight of the atoms after their first interaction with the microwave field in the resonator; the population of the second HFS state (2) is shown by the green color.

Detection of the population of the atomic states (1) and (2) in the cloud; exactly in resonance all atoms would be in the state (2) and the cloud would be totally "green".

Figure 5. Temporal cycle of the functional steps of a fountain clock.

This quotation points to two important facts. The frequency of TAI [24] is gently steered towards the SI second as realized by primary frequency standards with their results adjusted so as if each device was operated on a conventional surface of equal gravity potential, earlier known as the rotating geoid. In Figure 6 the remaining differences between the individual fountains and TAI for 12 months are shown. On the other hand, UTC has been recommended for use as a time reference in science and civil applications. The comparison of local time scales with UTC gives access to the extreme accuracy of the UTC scale unit to about 80 NMIs and scientific institutes collaborating with BIPM. In turn an institute "k" realizes a local time scale UTC(k) which then serves as basis for the dissemination of legal time and standard frequency in its respective country. In Figure 7, the deviation between UTC and three UTC(k)-scales is plotted, where the institutes "k" use their locally operated fountain frequency standards as references for steering of the scale.

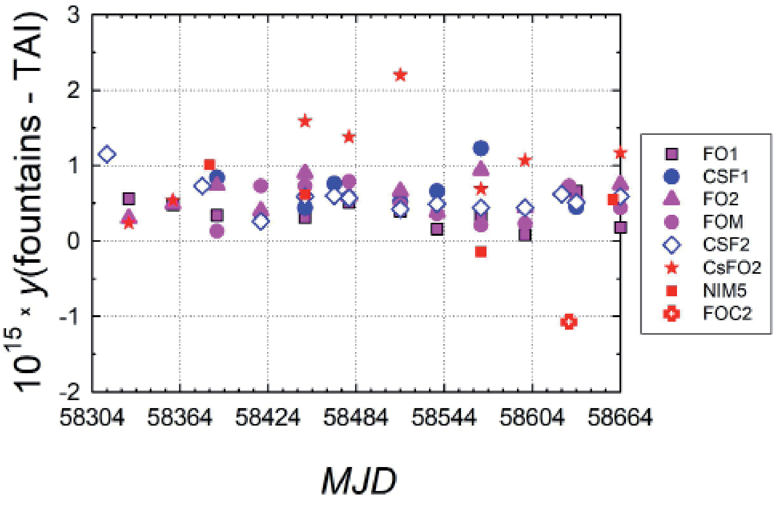


Figure 6. A comparison of fountain frequency standards with TAI for one year, ending with MJD 58664 (June 30, 2019). Each point represents a mean value over the respective operating time of the standards, typically 20 to 30 days. The uncertainty of the single measurement values varies between 0.25 and 1.2 parts in 10^{15}, depending on the standard and on the measurement period. Designations: FO1, FO2, FOM: LNE SYRTE/Observatoire de Paris; CsFO2: VNIIFTRI, Russia; NIM5: NIM, Beijing; FOC2: METAS, Wabern, Switzerland; CSF1, CSF2: PTB (source: BIPM Circular T).

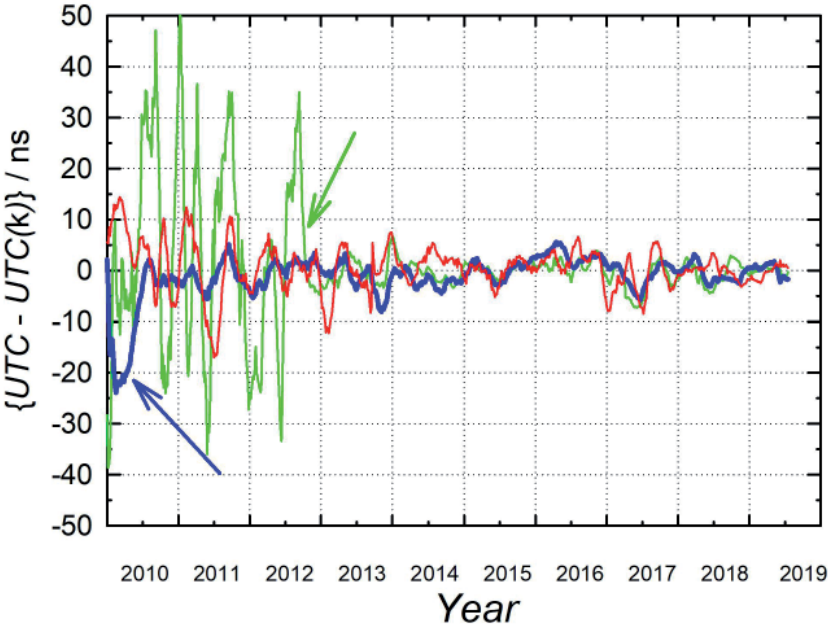


Figure 7. The evolution of three of the most stable time scales realized to date with the help of local fountain frequency standards: UTC(OP) (green) of LNE SYRTE (Observatoire de Paris), UTC(SU) (red) of VNIIFTRI, Russia, and UTC(PTB) (blue) of PTB with reference to UTC over the period from 2010 until mid-2019. Arrows point to the effective date when steering with reference to the respective fountains was declared operational.

A new type of atomic clock, the optical clock [25], has been intensively investigated for more than 30 years. They also rely on an atomic transition as a reference, however, not in the microwave range, but in the optical spectral range. The oscillator used in these clocks is, correspondingly, a frequency-stabilized laser. By increasing the clock frequency by five orders of magnitude (from approx. 10^{10} Hz in a cesium clock to approx. 10^{15} Hz in an optical clock), considerable stability and accuracy gains have been demonstrated. The short-term stability is improved due to the considerably higher number of oscillations per time unit. Enhanced accuracy is obtained because some of the disturbing external influences on the atom cause a characteristic shift of fixed magnitude, which has, however, less influence at the higher frequency of the optical clock than for a clock operating in the microwave range. A combination of laser cooling and trapping in an electric field provides the localization of the atoms in a region that is smaller than the optical wavelength, required for the suppression of Doppler shift. On short time scales, optical clocks are now more stable by a factor of 100 and also more accurate by a factor 100 than cesium fountain clocks. In visionary proposals, H. G. Dehmelt (Nobel Prize 1989) had foreseen the possibility of attaining 10^{-18} relative uncertainty of realizing an unperturbed optical transition as early as 1981 [26]. Already in 1978, David Wineland (Nobel Prize 2012) had introduced the subject at URSI GA. Until mid-2019, four groups of scientists carried out different experiments (two with the ions Al^+ and Yb^+ and two with Sr atoms) that succeeded in reaching this accuracy range [25].

Based on this progress, frequency comparisons and the measurement of frequency ratios of optical clocks are now possible with lower uncertainties than that of the current realization of the SI second. This has triggered considerations towards a redefinition of the second in terms of an optical transition frequency. In preparation thereof, a working group of the Consultative Committee for Time and Frequency has been collecting and evaluating the results of frequency measurements of suitable transitions since 2001 and has derived recommended frequencies for so-called "secondary realizations of the second" [27]. Eight different transitions are currently recommended: the hyperfine structure frequency of ^{87}Rb, which can be realized in a rubidium fountain, the atoms ^{87}Sr and ^{171}Yb investigated in optical lattices, and five transitions of the ions $^{27}Al^+$, $^{88}Sr^+$, $^{171}Yb^+$ (with two transitions) and $^{199}Hg^+$. All these systems have individual advantages and disadvantages in terms of their accuracy, stability and reliability in long-term operation. Research in the field of optical clocks is very dynamic and it is not yet possible to determine a clear favorite as the successor of the cesium hyperfine transition as the reference for a future SI second.

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4. Measurements for Communication Systems

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4.1 Mixed-Signal Characterization

Characterization and measurement procedures and techniques play an important role in the validation of circuits and systems, since they provide information to improve and optimize their operation. One of the challenges of 5G is to increase the signal bandwidth, where the use of higher speed data conversion is required. For instance, the Radio Frequency (RF) Analog-to-digital converters (ADC) and the RF digital-to-analog converters (DAC) operate directly at RF bands. When RF engineers design RF systems, mixed-signal components are considered ideal in their designs. However, this scenario is unrealistic because its frequency response must be considered throughout the design process. Thus, measurement equipment capable of characterizing mixed-signal components emerged as a requirement to evaluate RF components, so that its model can be inserted into the system-level simulator to design and optimize RF systems.

With this in mind, a mixed-signal network analyzer was proposed, to allow the characterization of mixed-signal components (Figure 1), with appropriate calibration process [1], based on National Instruments PXI platform.

new characterization method to extract the mathematic model of mixed-signal components was developed [2], where new parameters were proposed, similar to scattering parameters, called *D* parameters. In this approach, the analog and digital ports are related, where the digital port of the mixed-signal is defined as a single port. The incident and reflected waves for analog and digital ports are considered and the *D*-parameters formulation for linear characteristics is

$$\begin{bmatrix} b_{RF}(\omega) \\ db_{DIG}(\omega) \end{bmatrix} = \begin{bmatrix} D_{11}(\omega) & D_{12}(\omega) \\ D_{21}(\omega) & D_{22}(\omega) \end{bmatrix} * \begin{bmatrix} a_{RF}(\omega) \\ db_{DIG}(\omega) \end{bmatrix} \tag{1}$$

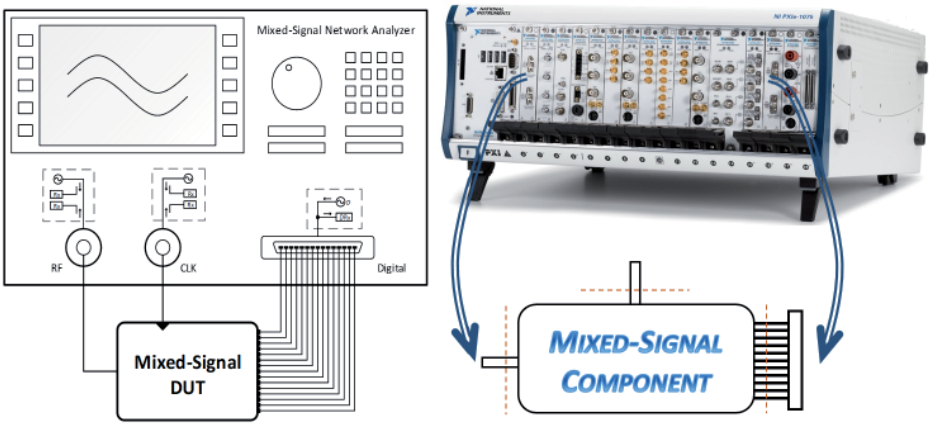


Figure 1. The mixed-signal network analyzer approach.

where ω is the user-defined frequency grid. Consequently, the $D_{21}(\omega)$ parameter is the gain from the analog RF input port to the digital output port in a mixed-signal receiver, dependent on frequency, which is represented by

$$\begin{bmatrix} D_{11}(\omega)=\dfrac{b_1(\omega)}{a_1(\omega)}\left|a_{CLK}=\beta, da_2=0\right| \\ D_{21}(\omega)=\dfrac{db_2(\omega)}{a_1(\omega)}\left|a_{CLK}=\beta, da_2=0\right| \\ D_{12}(\omega)=\dfrac{b_1(\omega)}{da_2(\omega)}\left|a_{CLK}=\beta, a_1=0\right| \\ D_{22}(\omega)=0 \end{bmatrix}. \qquad (2)$$

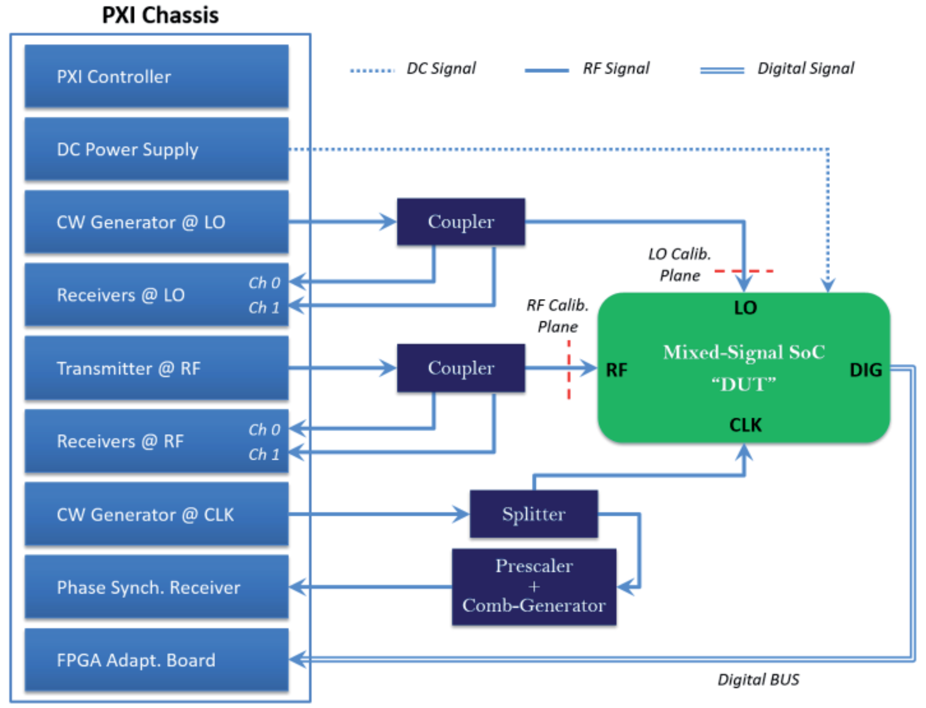
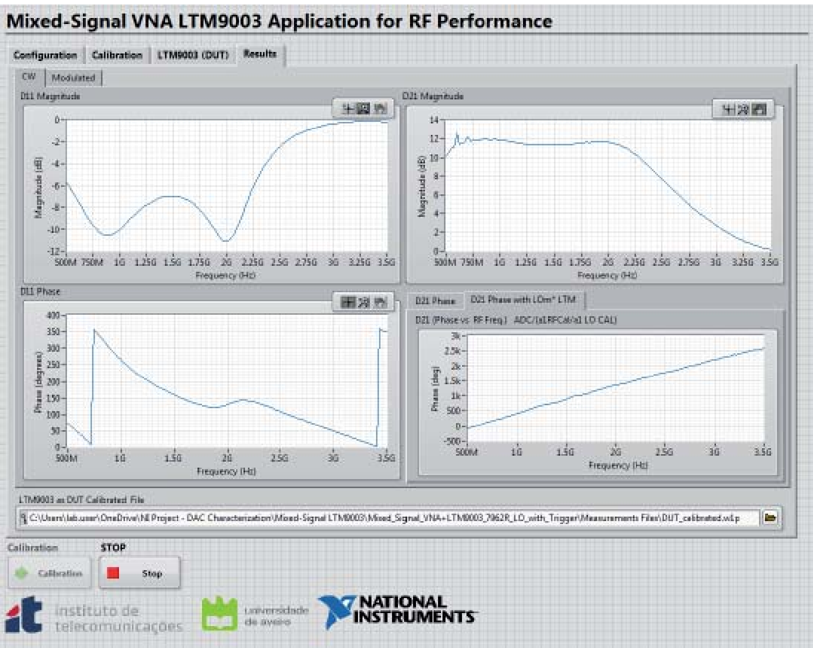


Figure 2. The mixed-signal measurement setup based on National Instruments PXI platform.



Mixed-Signal VNA LTM9003 Application for RF Performance

LTM9003 as DUT Calibrated File: C:\Users\lab.user\OneDrive\NI Project - DAC Characterization\Mixed-Signal LTM9003\Mixed_Signal_VNA+LTM9003_7962R_LO_with_Trigger\Measurements Files\DUT_calibrated.wl.p

Figure 3. A LabVIEW application with *D* parameters results.

The LTM9003 was chosen as the device under test (DUT), to demonstrate the benefits of the mixed-signal characterization measurement setup. The entire description of the measurement setup [3] is shown in Figure 2.

A LabVIEW application was developed, to perform the characterization process, which is divided into 4 stages. In the Configuration stage the frequency, power voltages and other system parameters are defined. Then, the calibration is the next step, where Short, Open, Load (SOL) calibration is applied, using a power meter, to calibrate the magnitude, and a comb generator, to calibrate the phase [1]. The DUT characterization is performed for the frequency grid, chosen in the third stage. Lastly, the D-parameters of the DUT are presented in terms of magnitude and phase, for the selected frequency grid and they are also saved in files. Figure 3 presents the LabVIEW application with the *D* parameters results for the LTM9003, in magnitude and phase.

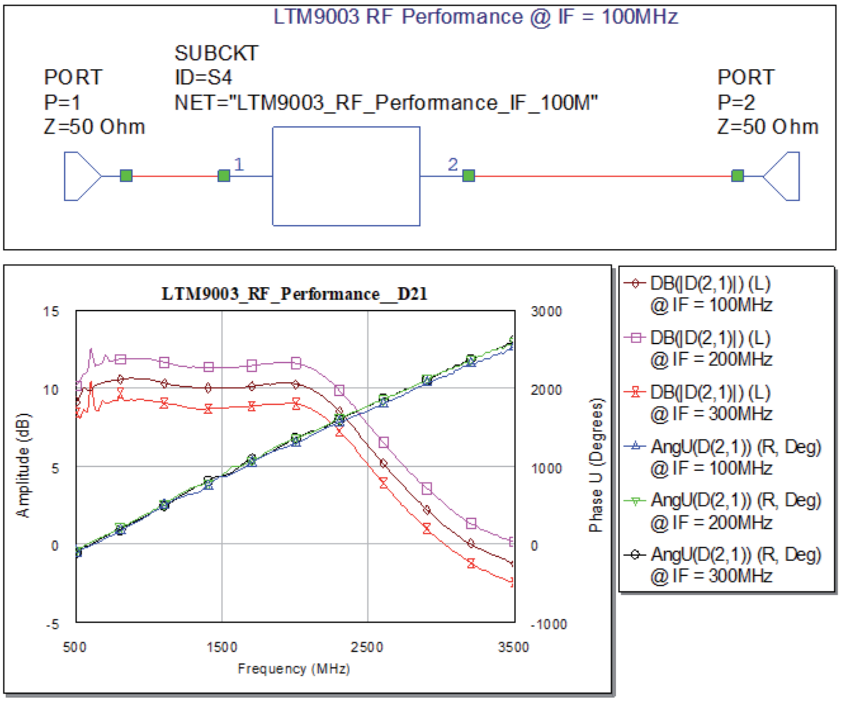


Figure 4. The *D* parameters integration in the NI AWR simulator.

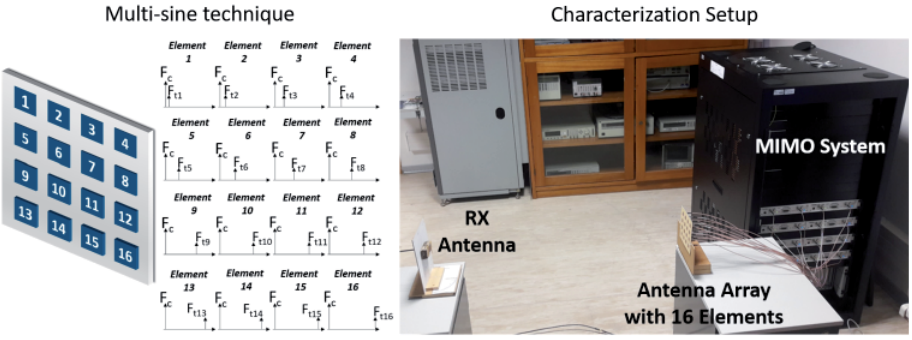


Figure 5. The multi-sine technique and characterization setup using a MIMO system.

Since, the *D* parameter results are saved in *.d2p files, which are compatible with SnP Touchstone format (*.s2p) used for *S* parameters, the files can be loaded in simulators to integrate the DUT characterization with other RF components, in order to optimize RF systems. Figure 4 shows an example of the results integrated into the NI AWR simulator.

In conclusion, this characterization system allows the evaluation of mixed signal components, where its model is extracted and can be used in simulators, to optimize the RF system design.

4.2 MIMO Systems Characterization

In 5G, MIMO antenna arrays will be applied in communications, to increase the number of users, since they enable beamforming so that parallel data streams can be transmitted. However, MIMO systems present several challenges, not only in terms of hardware, but also in terms of software, since MIMO antennas are composed by many elements. More precisely, mutual coupling effects occur in MIMO antenna arrays, since the antenna elements are close to each other, which degrades the antenna beam pattern. When power amplifiers (PA) are used before each MIMO antenna element, they are affected by the coupling effect phenomena, decreasing their performance and the entire MIMO system performance as well. Moreover, calibration is required to perform beamforming and to achieve the highest system efficiency possible. Therefore, it is useful to apply techniques capable of characterizing MIMO antenna arrays.

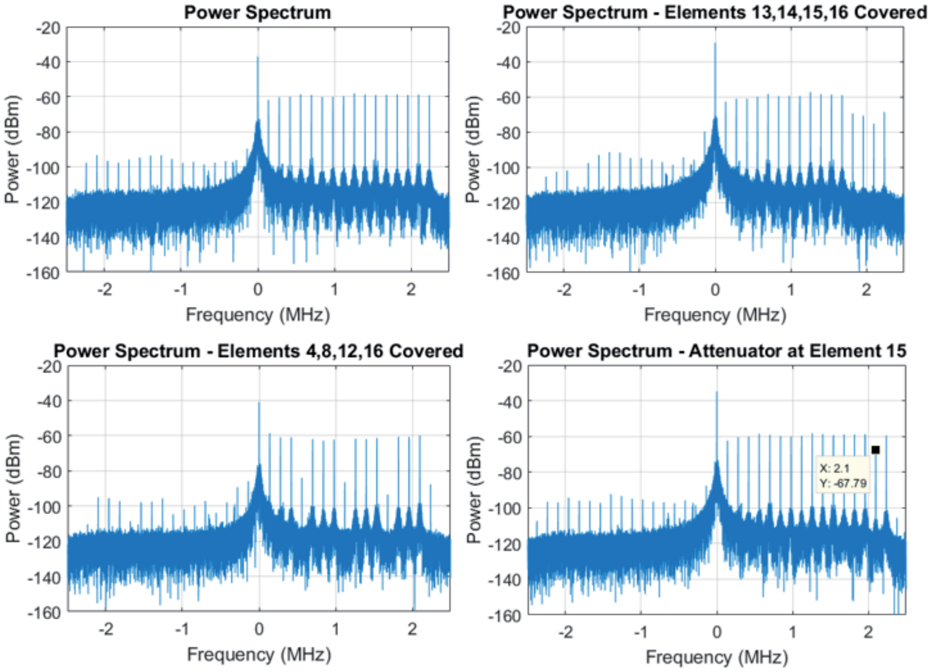


Figure 6. The multi-sine technique results from a receiving antenna.

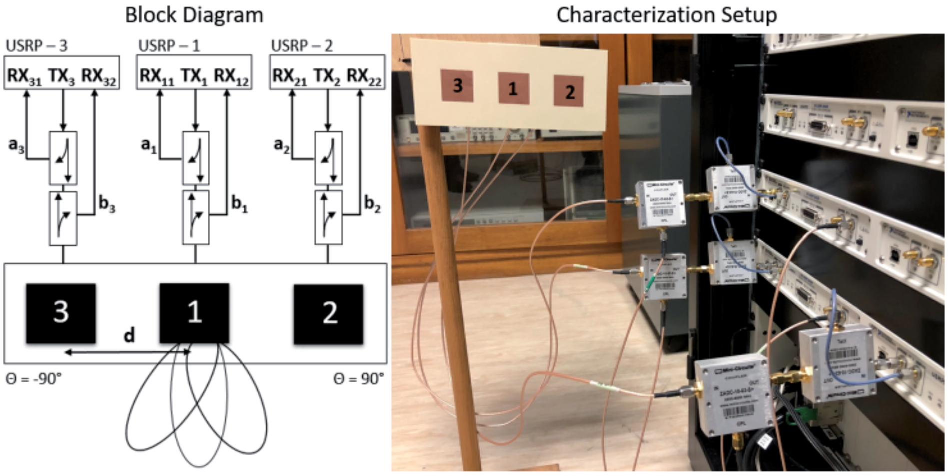


Figure 7. The coupling block diagram and characterization setup.

In this respect a MIMO characterization system was developed to characterize MIMO antennas, using the multi-sine technique, and to evaluate the mutual coupling effects which occur in MIMO antennas when beamforming is performed in real-time. A MIMO system using low-cost software defined radio (SDR) was selected for this work, since it comprises 16 transmitters and receivers [4]. The multi-sine technique was used to identify each antenna element individually, which is composed of the main tone (F_c), equal in all elements, and a tickle tone (t_i), with smaller power than the main tone and at different frequencies in each antenna element. By exciting the transmitting MIMO antenna (working at 5.65 GHz) with this strategy, the receiving antenna gives information about the behavior of each MIMO antenna element, as shown in Figure 5.

An experiment was performed, where several elements of the transmitting MIMO antenna were covered. Then, an attenuator was introduced before one of the MIMO antenna elements to validate the decreasing of tickle tone. The results of these experiments are shown in Figure 6.

To measure the coupling effects when beamforming is applied in a MIMO antenna array, several changes into the setup have been made. Couplers were introduced in order to read the incident and reflected waves. A calibration procedure using

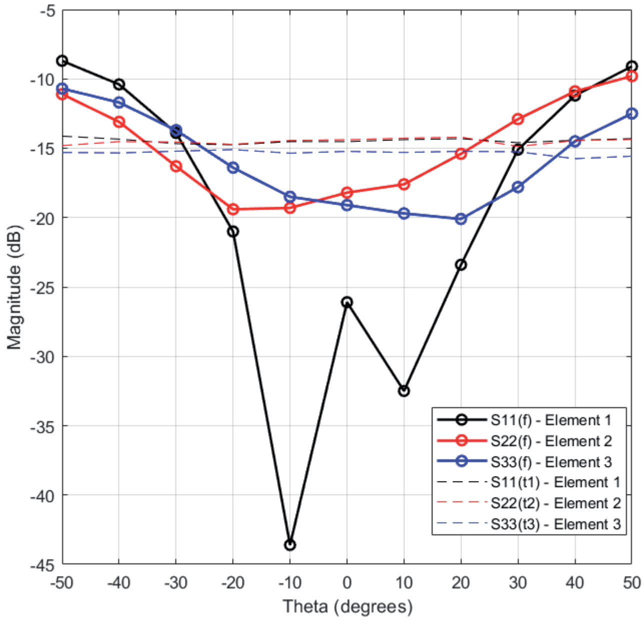


Figure 8. The reflection coefficient of each port with the main tone and tickle tones, when beamforming is performed.

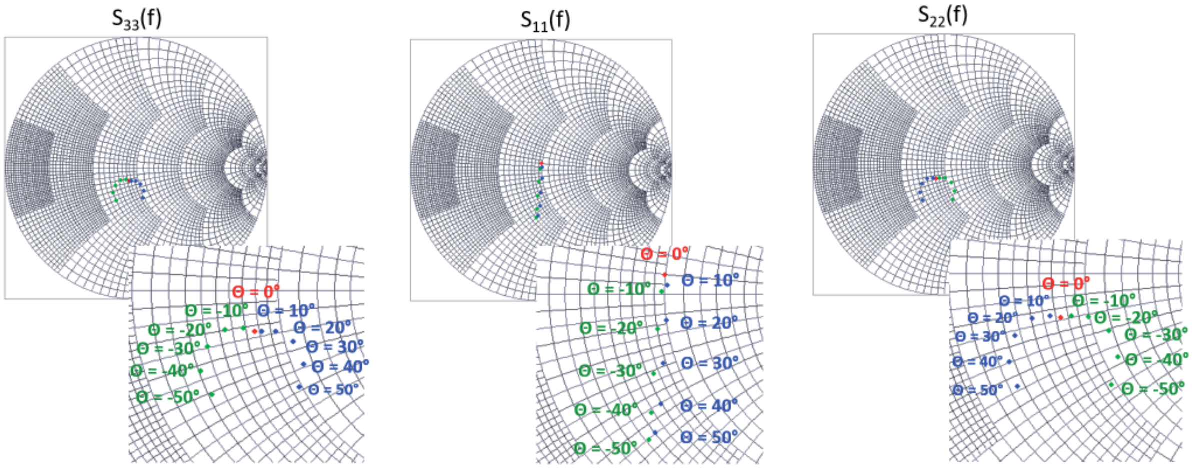


Figure 9. The Smith chart results of the reflection coefficient of each port when beamforming is performed.

SOL, power meter and a USRP (SDR), as a phase reference, was applied to have all the MIMO system ports calibrated in terms of magnitude and phase [5]. In this case, a MIMO antenna with three elements working at 2.6 GHz was selected to apply the beamforming, as can be seen in Figure 7.

Thereafter, the array factor of the MIMO antenna was calculated to perform the beamforming with the MIMO system, using the multi-sine technique as well, and each port of the antenna was evaluated in terms of reflection coefficient, as it can be seen in Figure 8 and Figure 9.

From the obtained results can be concluded that the beam steering increases the magnitude of the reflection coefficient of the elements. When the antenna beam moves away from broadside direction, the magnitude of reflections in each element increases and depending on the steering angle, the elements are affected accordingly. Using these techniques, the MIMO antenna array can be characterized in order to improve the performance of MIMO systems.

4.3 References

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URSI Commission B Centennial History Contribution

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1. Introduction

Quoting from [1], it is widely known that Heinrich R. Hertz was the first to demonstrate the generation of radio waves at Ultra High Frequency (UHF) using a gap dipole in 1885-1886 at Karlsruhe University (Germany), and was able to detect radio waves 20 m away. However, the recorded conversations suggest that Hertz did not seem to understand the impact of his experiments, but instead did it to validate the newly developed Maxwell's equations.

By 1906, Tesla at the Franklin Institute in the US, Marconi in Bolognia, Italy, Popov in Russia, and Bose in India, had demonstrated "wireless telegraphy." Tesla delivered a widely distributed presentation at the IRE of London about "transmitting intelligence without wires," and in 1895, he transmitted signals detected 50 miles (80 km) away. Concurrently, in 1894 Bose used wireless signals to ring a bell in Calcutta, and Popov presented his radio receiver to the Russian Physical & Chemical Society on May 7, 1895.

Marconi (see Figure 1a, [2-5]) is certainly considered the key individual for commercializing radio waves. The culmination of his experiments was the demonstration of a trans-Atlantic link on December 12, 1901, where Morse code for the letter S was successfully transmitted via radio waves. In 1903 Marconi established a transmission station in South Wellfleet, MA, and its dedications included exchanges of greetings between American President Theodore Roosevelt and British King Edward, VII. In 1916, during WWI, the advantages of short wavelengths and long-distance wireless communications became apparent, and the desire for narrow beams prompted the placement of reflectors around the aerial to increase signal distance and avoid interception by the enemy. Notably, in 1919 Sir Robert Alexander Watson-Watt patented a radiolocation device, and this can be considered as the forerunner of the Radar system. Other developments

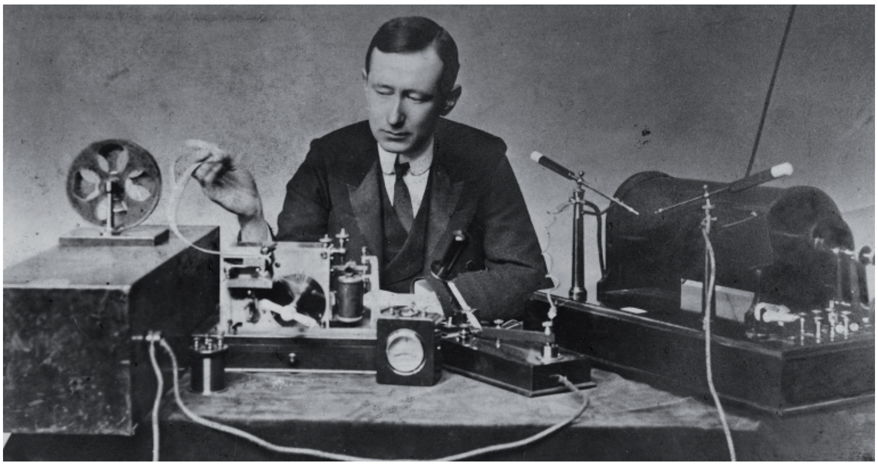


Figure 1a. Published by *LIFE Magazine*, this 1901 photo depicted one of the very first spark-gap transmitters (r) [2] and coherer receivers (l) [3] used for long-distance radiotelegraphy [4] in the 1890s; also available at [5] http://images.google.com/hosted/life/4a204d82f07524bd.html.

related to radio wave generation and propagation relate to several inventions in the early 1920s. Among them are: 1) an all-electric frequency modulator by E. S. Purington, 2) the magnetron oscillator by A.W. Hull that operated at 30 kHz and outputted a power of 8 kW with 69% efficiency, and 3) audio frequency modulation for carrying telephony over wires by E. H. Colpitt and O. B. Blackwell.

Marconi continued to research short-wave radios for day and night long distance communications and asked his assistant, Charles Franklin, to examine radio apparatus. Franklin used a 25 kW transmitter at 3 MHz with a very large antenna in Poldhu, England, and in July 1923 he achieved radio contact with the Marconi's yacht (Elettra) at Cape Verde Island (West Africa). In September 1924, a 11 MHz radio signal reached the yacht of Marconi at Beirut. Franklin understood the importance of antenna gain and developed the high gain directional curtain antenna. These achievements led to negotiations with the British Postmaster General about the contract with Marconi's company to establish a network of short-wave wireless telegraph stations covering England, South Africa, India, Australia, and North America. This network was the skeleton of the "Imperial Wireless Network" that started to operate in 1926. The interest in radio waves can be compared to the internet in the 1990s. Notably, in September 1924 radio amateurs in California contacted the amateurs in New Zealand and in October 1924 English amateurs performed the longest distance communication lasting 90 minutes, with amateurs in New Zealand.

Figure 1b. One of the first-ever radar stations (Chain Home), west of London, at Canewdon, UK used to detect aircraft during World War II. The towers were 240 ft tall and were initially transmitting at four frequencies between 20 MHz and 55 MHz, and later at two frequencies between 20 MHz and 30 MHz. The power being transmitted was 340 kW and was later upgraded to 750 kW. Horizontal polarization was used for detection. The photo shows the transmitter array at the front and the receiving array in the back. A 20 µS pulse was used for transmission with an interval of 40 µS [6] http://www.rochforddistricthistory.org.uk/documents/ChainHomeCanewdon1.pdf.

By the late 1920s, the US had hundreds of radio stations, and in 1922, the BBC began transmitting in England. It is said that by 1928 about half of the international telegrams were delivered by short-wave radio and the other half by submarine cables and long wave radio systems. The submarine cable systems continued to operate till satellite communication systems began, the first being TELSTAR, in the 1960s.

The year the BBC station began its transmissions concurs with the first General Assembly of the International Union of Radio Science (URSI), held in July 1922 in Brussels, viz. ~100 years ago. At that time, only four National Committees were officially formed: Belgium, France, the United Kingdom, and the United States. Propagation studies also began in the 1920s, and the presence of ionized regions in the upper atmosphere was scientifically established. It was further understood that the free electrons at different heights altered the refraction index [7], typically 50 to 400 km above the Earth's surface, which also varied with seasons, i.e. monthly and diurnally. Indeed, URSI's Appleton and Chapman played an important role in studying propagation characteristics and predicting that indeed the refraction index is a function of frequency.

One may say that the 1920s was the beginning of radio, two-way wireless communications, propagation, and ionospheric studies. The radar development just before and during WW II (see Figure 1b, [6]) and associated radio detectors, vacuum tubes, coupled with the transistor in 1947 played a critical role in the practical everyday use of radio waves for communication and wireless transmission of information. In the early 1920s, most of the antennas, especially those installed in ships, were of the wire type and were hung on masts. No major development in antennas occurred till Yagi and Uda introduced their classic high gain dipole array antenna in the 1920s, now referred to as the Yagi-Uda antenna [8]. In fact, Yagi would attend the 1927 2nd General Assembly in Washington, DC along with Appleton, Koga, Van Der Pol and Dellinger [7]. But it was not until 1955 that DuHamel and IsBell [9] would propose the wideband/broadband log-periodic antenna, and in 1958 Victor Rumsey will introduce the concept of frequency independent antennas [9], including spirals. Also, in 1954, John R. Pierce [10] advocated use of satellites for communications between widely separated points on the ground. Also, after the Sputnik I launch [11] in 1957, the U.S launched communication satellites. The early 1950s also saw the introduction of the transistor radio [12]. Initial efforts are credited to Texas Instruments and the Industrial Development Engineering Associates (I.D.E.A.), both in the US This collaboration led to the introduction of the Regency TR-1 [13] radio, the first ever transistor radio. Paul D. Davis, Jr., with radio experience from WW II, was the lead engineer for this TR-1 radio project at Texas Instruments, and the Regency TR-1 was patented by the I.D.E.A. project engineer, Richard C. Koch under US 2892931[14]. A second transistor radio, 8-TP-1 was introduced by Raytheon in February 1955. And in August 1955, the Japanese company Tokyo Telecommunications Engineering Corporation introduced their TR-55 [15] transistor radio under the new brand name Sony [16]. Notably, Sony transistor radios have gotten smaller, but continue to be sold to this date [17].

The increasing popularity of television in the 1950s and 1960s gave rise to a need for high gain reception antennas, making the Yagi-Uda antenna popular for TVs. Antenna technology was primarily dormant until WW II when UHF and microwave sources, such as klystrons, magnetrons, and traveling wave tube amplifiers were developed. Also, until the 1970s, antenna design was primarily based on practical approaches using off-the-shelf antennas, such as various wire geometries (dipoles, Yagi-Uda, log-periodics, spirals), horns, reflectors, and slots/apertures as well as arrays of some of these [18-21,1].

Undoubtedly, the explosive growth of wireless communications and microwave sensors, microwave imaging, and radars was the catalyst for introducing a multitude of new antenna designs over the past 20 to 30 years. These new antenna designs focused on gain, bandwidth and size requirements using the increasingly available computational toolsets offered by large-scale and personal computers. One of the authors noted in his EM Programmer's Notebook column [22] that 16 MB of RAM using available PCs can readily invert a 1500 unknown dense matrix, but iterative methods were becoming more popular for larger size problems. Further requirements for conformal antennas (non-protruding) on airborne systems, increased bandwidth requirements, and multi-functionality led to strong interest in printed (patch) antennas [23, 24] or other slot-type antennas. Notably, parabolic antennas and other forms of reflector antennas were developed during WWII, and increasingly used for all sorts of long-distance, satellite and deep-space communications. Also, waveguide slot antennas, dielectric rod antennas, helical antennas, and the likes, appeared.

This article is structured in historical periods of 1) WWII and Post-WWII during, i.e., the 1940s and 1950s, 2) 1960s and 1970s with a focus on radar scattering and high frequency methods, 3) 1980s and mid-1990s with a focus on computational methods, large computing power, measurement methods and the wireless revolution, making commercial applications more prevalent, 4) the mid-90s to 2010s with the cellular revolution, earth observation arrays and astronomy, 5) 5G, wearable electronics, IoT and sensing, terahertz and secure millimeter wave communications.

Briefly, during the 1940s and 1950s, the basic theory for antennas and scattering, including geometric optics [25] and Keller's Geometrical Theory of Diffraction (GTD) [26, 27] were introduced and established. Impedance diffraction solutions [28-31] were also published. Also, antenna testing techniques were developed along with antenna array theories. Notably, many of the developments in WWII (1940 to 1950) are described in the 28 MIT Radiation Lab reports.

During the 1960s and 70s there was much focus on radar scattering analysis and diffraction methods, starting with canonical structures (spheres, cylinders, ellipsoids and the likes) [32, 33], culminating to full scale analysis of airframes using UTD, UAT and ILDC analysis [30. 34-38]. With the Apollo missions, there was also much focus on satellite communications and exo-atmospheric links.

In the 1980s, scientists had several personal computers, and workstation terminals at hand. Among them, DEC's VAX-11/780 (introduced in 1978) [39] became popular as one of the first terminal-based computers using on-screen editing and even texting among terminal users. Various plotting toolsets were introduced and established for electromagnetics applications. The microprocessor chips of the 1970s also gave rise to hand-helds, popular electronic toys, including the speak and spell toy [40]. The Personal Desktop Computer [41] gained popularity, with the first Macintosh computer (initially with only 128 kB of RAM) introduced in 1984, causing typewriters to disappear by the late 1980s. In 1983, the brick-like mobile phone, DynaTAC 8000X [42] was launched by Ameritech. This was the initiation of the 1G network [43] that required $100M to develop and took a decade to reach the market (since its introduction by Martin Cooper of Motorola [44]). The phone had a talk time of just thirty-five minutes and took ten hours to charge. The popular 2G mobile phone using the GSM standard were introduced in 1991.

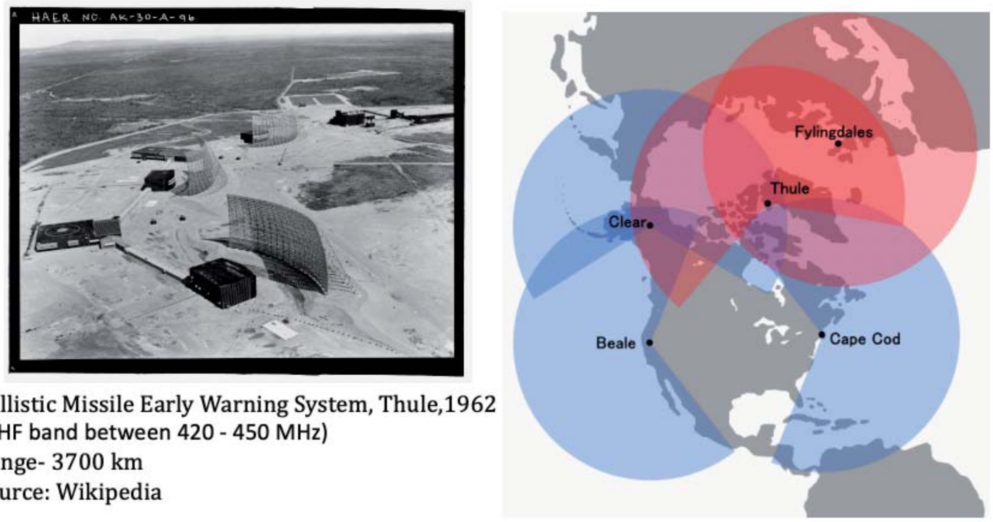
With the accessibility of significant desktop computing power, graphical interfaces and SGI desktops by late 1980s [45], with Z-buffer for real-time shadowing and rotation of complex objects, electromagnetics analysis had a strong resurgence. It was also possible to pursue simplifications of complex diffraction coefficients for impedance and coated edges [31]. Also, full wave analysis and computational tools for radar scattering and antenna design were re-thought and reconsidered. Moment-method techniques [46] and patch antenna arrays' analysis using multilayered substrate Green's functions were established [47]. Also, accessibility and easy to use anechoic chambers allowed the validation of computational tools. In fact, a set of public reference structures were introduced in the late 80s by the US Electromagnetics Code Consortium [48] and French Agencies.

In the mid-1980s, the introduction of absorbing boundary conditions, meshing techniques, edge-elements [49], iterative methods, and the boundary integral mesh truncations, all led to a resurgence of the finite element method (suitable for material modeling). The Finite Element-Boundary Integral (FE-BI) [50] with the conjugate gradient, k-space solver or adaptive integral method (AIM) [51] allowed rigorous, large-scale simulation, with smaller memories requirements. The first FE-BI paper was published in 1989 [52] and array analysis was presented in 1991. FEM was well established in the mid-1990s and the introduction of fast multipole methods (FMM) [53, 54] made finite element integral methods even more popular. The mid-90s was also a period when commercial computational packages began to appear, even though companies were still working with their upgraded computational toolsets for cellular antenna placements, antenna design and radar scattering analysis. Notably, the introduction of the J.P. Berenger's perfectly matched layer (PML) [55] allowed for more popular mesh truncations by the late 1990s. A Google search of the term "finite element method for electromagnetics" brings over 800,000 citations (as of Oct 2019), indicating its strong popularity.

The early 1980s also saw the adaptation of the finite difference-time domain (FDTD) method, originally introduced by Yee in 1966 [56]. The simplicity of FDTD and the increasingly larger computational power at the desktop provided strong impetus to adapt the method for a variety of applications in the 1990s [57], particularly for multi-frequency and wideband computations of anisotropic media. A Google search of term 'finite difference time domain method for electromagnetics' brings over 500,000 citations (Oct 2019 search), indicating its widespread use in the community.

With the development of numerical toolsets in the 1980s to mid-1990s, the subsequent 15 years saw a growth of radio frequency applications in medical technologies, wireless links, radar imaging, automotive guidance, and cellular telephony, among others. Radar scattering of full scale structures, complex antenna geometries with multilayer materials, design with metamaterials [58] negative index media, optimization and design for optimally small antennas [59], optimal mobile cell placement, conformal and multiple antennas for handheld smart phones, medical imaging, medical ablation, among others, came within reach. This was also a period of faculty growth in the universities, educating graduates with expertise in electromagnetics. Many of the new era cell phone companies were also hiring and integrating electromagnetics and antenna designs into their teams. At the same time, the mid-1990s to 2010 saw an emergence of commercial computational toolsets on the desktop of every engineer and student. After 2005, commercial packages, such as XFTD, IE3D, WIPLD, XPATCH, CST, FEKO (now ALTAIR), HFSS, and COMSOL multi-physics, were freely used for design optimization for all sorts of RF front-end applications, from the chip pins to the antennas, and then back to the receivers. On-body and off-body communication was also studied. Incidentally, the typical reliance on well understood wire antennas was no longer required, and many new antenna designs were introduced for MHz to millimeter wave and Terahertz applications. Notably,

Figure 2a. A photo of the BMEWS installation at Thule, Greenland.



Ballistic Missile Early Warning System, Thule,1962
(UHF band between 420 - 450 MHz)
Range- 3700 km
Source: Wikipedia

Figure 2b. The location map for the BMEWS installation.

by the end of the 1990s, the popular whip antenna used in previous cell phones was replaced by patch antennas [23, 24], and by the early 2000s all cell phones were using conformal antennas. The number of antennas on the cell phone was also increased with the 2008 iPhone to incorporate several antennas to cover all cellular bands, as well as the bands to establish Wi-Fi, GPS and Bluetooth links. During the same 15-year period, the growth in satellite and deep-space communications, small satellites, cubesats and big data links, among others, provided further impetus for wireless innovations.

The last several years (2010 to present) have seen a continuous growth of wireless links for automated vehicle guidance, better spectrum exploitation using simultaneous transmit and receive radios, millimeter wave designs for 5G and 6G cell phone networks, wearable sensing and textile electronics, terahertz, all with secure communication links in mind. Indeed, the insatiable consumer demand for wireless links (most laptops are already connected wirelessly to networks, even at the workplace), makes the future of antennas, propagation, and electromagnetics exciting and bright.

2. Radar and Reflector Antenna Developments in 1940-1960s

M. Shields

Early in 1940, there was intense interest in developing a microwave radar to detect a flying aircraft and, after a survey of existing efforts, and a collaboration with British efforts that introduced the magnetron (a higher power microwave generator), a study group was convened. On November 10, 1940 fifteen physicists from around the USA, identified by the National Defense Research Committee (NRDC) Microwave Committee, assembled at MIT, and by January of the

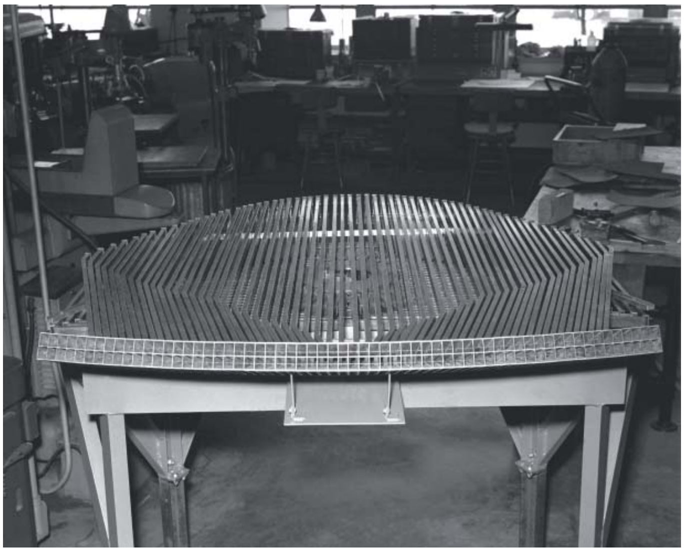


Figure 3. A scale model of an organ-pipe scanner.

following year, an early model of a microwave radar was operating. In the following March, a radar was successfully flown on a B-18 aircraft. The designs were given to Bell Telephone Laboratories and the SCR-520 and the improved SCR-720 radars were produced. The SCR series radars were crucial in WWII, because they gave a 13 min air-raid warning against German bombers. As the legend goes, a mobile SCR unit, stationed at Oahu island in Hawaii, detected the incoming Japanese air-raid of the Pearl Harbor attack.

By December 7, 1941, the Radiation Laboratory of MIT had grown to 400 staff and had produced detailed studies into a fire-control radar and the LORAN system. By the end of the war, the staff at MIT Radiation Lab had grown to nearly 4000 and had fully or partially produced over 100 radar models for land, sea and air. They had done research on microwave equipment, developed components and assisted in both identifying necessary new technology, and in field trials of the systems. As stated in the Radiation Laboratory Index Volume 28; “It must be remembered that parts, tubes and equipment for radar, especially microwave radar, simply did not exist in 1940.” Two of the 27 volumes that are still relevant today are volume 10 – *Waveguide Handbook* by N. Marcuvitz [60] and volume 12 – *Microwave Antenna Theory and Design* by Samuel Silver [60]. The first of these volumes presents the basic theory underlying the operation of waveguides, including rectangular, circular and coaxial guides and other waveguide components. In antennas, Silver’s volume details the EM theory behind radiation and reflection as well as the design of various antennas, including reflectors and arrays. Following these developments, the MIT Lincoln Laboratory was established in the early 1950’s and subsequently moved to Lincoln, Massachusetts, where it continues developing technology for national security needs [61].

USSR’s demonstration of ballistic missile technology prompted the need for radars with a much longer detection range against newly developed ballistic missile threats. This translated to, both, a higher transmit power and a larger antenna due to the longer ranges and smaller radar cross-sections of the physically small warhead carrying vehicles. A result, in the USA, was the development of the Ballistic Missile Early Warning System (BMEWS) [62] in 1954**.** The 1950s was also the decade with research on advanced radar techniques (including phased-array radars), analytic studies on detection and trajectory prediction, digital computer usage for data processing and research in propagation, particularly tracking over the north pole. In 1958, the Western Electric Company and RCA were given contracts for the management and installation of the radars. Antennas were also designed and built by GE, including one that was 400 foot wide and 165 foot tall. The Thule site at Greenland had four of these antennas, Figure 2, and the Clear Air Force Base site in Alaska had three antennas fed by two organ-pipe scanner switches, Figure 3. A UHF radar was also built to perform the tracking function. This was an 84 foot parabolic antenna, producing a 2 degree wide beam that was mechanically steerable over 180 degrees in elevation and 300 degrees in azimuth, and had high slew rates in azimuth (22 deg/sec) and elevation (6 deg/sec). This antenna had a five-horn mono-pulse feed for tracking. Due to the extreme environment, the MIT Lincoln Laboratory also developed a space-frame radome after consultation with Buckminster Fuller on a geodesic dome design connected by dielectric panels.

Integration of several radars, early use of a digital computer, solving the ballistic motion equations for tracking, discriminating between true threats and satellites, or other false targets (actually, including the moon), were problems addressed in these system studies. Construction began at the Thule site in May, 1960, and, in 1964, all sites were complete. The Thule site is shown in Figure 2 [62]. The radar operated from 1960 to 1987, when it was replaced by a phased array radar [62, 63].

Figure 4. Millstone, with the original conical scan feed.

The Millstone Radar is another instance, whose development started in 1954. It was developed in response to the Soviet's work on UHF long-range radars. The goal was to expand the 200 mile range of existing radars to the 3000 mile range, implying an improvement of over 60dB using increased RF power and antenna size. It was determined that the existing 60 ft antennas had to be increased by an additional 24 ft with proper structural design. An external-cavity magnetron with an output power of 1.25 MW peak was also employed along with an increase in pulse length and use of a Doppler filter bank to address the required detection range improvement. A location near MIT's Lincoln Laboratory, Westford, MA was chosen for building the radar because of its low population, view of launches from Cape Canaveral and closeness to Lincoln Laboratory in Lexington, MA. This radar detected the Russian Sputnik launch in 1957, proving the effect of propagation through the ionosphere could be handled. Higher power klystron tubes and the first solid-state computer were used in this system. This radar paved the way for the Ballistic Missile Early Warning Radars in Alaska, Greenland and England. Notably, the original UHF antenna employed a circularly polarized, conical-scanning feed to enable tracking, Figure 4 [63, 64].

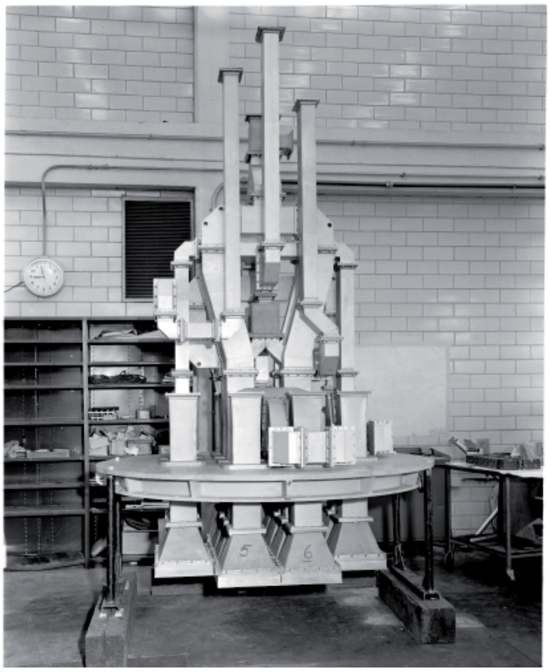


Figure 5. The 12-horn feed for the Millstone L-band radar.

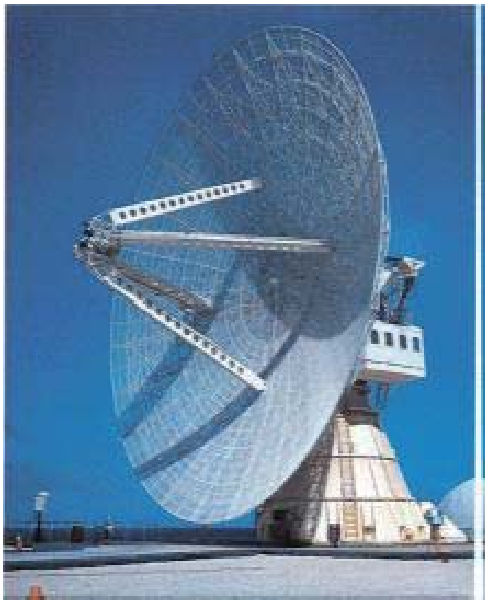


Figure 6. The TRADEX 84-foot antenna.

Around 1969, the radar was upgraded to L-Band (while maintaining a UHF receive capability) and continues operating today, supporting satellite tracking and missile launches. The upgraded L-Band feed uses a 12-horn, mono-pulse feed that is also dual-polarized, Figure 5.

To improve the understanding of tracking ballistic missiles, especially in the reentry phase, ARPA (the Advanced Research Projects Agency) funded the TRADEX radar [63-66] on the Kwajalein atoll, 2100 miles southwest of Hawaii. It was built by RCA in 1962 under contract with ARPA and operated by Lincoln Laboratory as an ICBM missile tracking radar. It has an 84 foot antenna, Figure 6, that operated at VHF, UHF and L-Band with sufficient transmit power to detect warheads as they transitioned over Hawaii, at the radar's horizon. The UHF maximum peak power of this radar was 4 MW and this early system measured both range and Doppler. The L-Band system (1320 MHz) operated with a peak power of 5 MW in chirp mode, as pulsed CW mode or with a burst of pulsed CW pulses and transmitted a circular polarized signal. Its range resolution varied from 960 feet to 48 feet depending on the mode. Both circular polarizations are received. At VHF (60 MHz), the peak power was 500 W and operated with linear polarization. The UHF feed is a square horn, with angle-error horns mounted on the sides. The L-Band, circular-horn feed is in the center of the UHF horn. The VHF feed consisted of four monopoles each with passive directors, Figure 7. In 1970, the radar was upgraded to a dual-frequency, L-Band and S-Band system and a wide range of waveforms was implemented. The new feed consisted of an L-Band, five-horn feed with a center circular horn that provided the S-Band feed [65, 67].

To achieve a higher detection range over the TRADEX radar, a very large 150 ft diameter antenna, powered with a higher power signal, was built as part of the ALTAIR radar system (ARPA Long-Range Tracking and Instrumentation Radar) nearby on Kwajalein. Completed in 1970, the large antenna was mounted on a 110 ft track for rotation in the azimuth plane. The transmit power was 100 kW on-average at VHF and 120 kW on-average at UHF. Also, the radar's range resolution was 32 m (VHF) and 15 m (UHF). The antenna was a Cassegrain configuration that employed a Frequency Selective Surface (FSS) at UHF to replace the sub-reflector. This FSS consisted of two layers of crossed dipoles, each printed on a substrate separated by a dielectric. The FSS was transparent at VHF and reflective at UHF. The antenna is shown in Figure

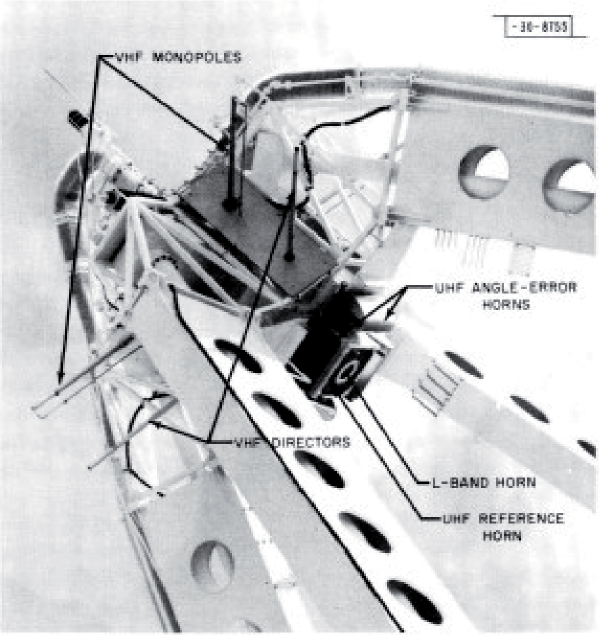


Figure 7. The original TRADEX feed: VHF, UHF, and L-Band [4].

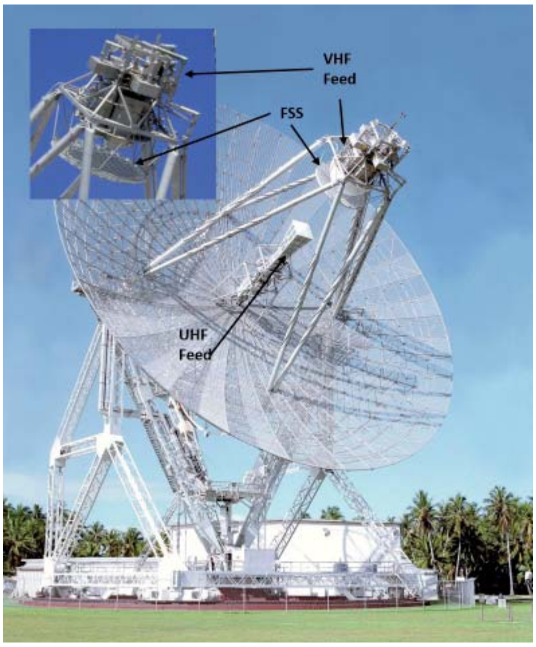


Figure 8. The ALTAIR antenna: UHF Cassegrain feed, VHF feed at the prime focus, and FSS subreflector.

Figure 9a. The millimeter-wave radar antenna, operating at 35 GHz and 95 GHz, constructed in 1977 for the Army BMD Advanced Technology Center. This shows the millimeter wave antenna under construction (note large backup structure).

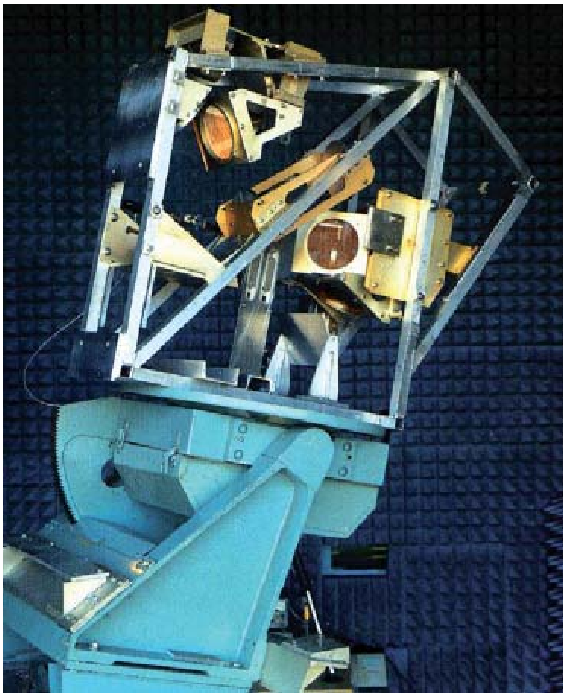


Figure 9c The millimeter-wave antenna under test in range.

8. Later in 1977, a Millimeter Wave Radar, operating at 35 GHz and 95 GHz was added to the site under the direction of the Army BMD Advanced Technology Center. As before, major challenges for this radar were RF power generation and the antenna design. Figure 9a shows the antenna while under construction with the large backup structure that minimizes the dish distortion with changing elevation angle and temperature. The antenna employed a quasi-optical feed with an FSS to achieve monopulse-tracking at both frequencies as depicted in Figure 9b. This radar became operational in 1983, and has continued to produce excellent images of reentry vehicles as well as satellites [67, 68].

The desire to track satellites and employ satellites in communication promoted a desire for use of higher frequencies.

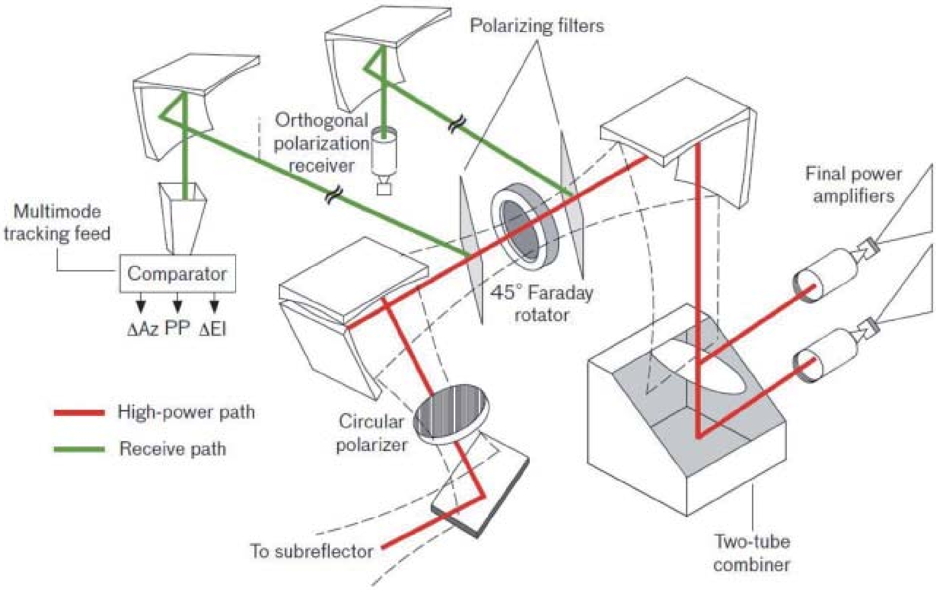


Figure 9b. The quasi-optical feed schematic for the millimeter-wave antenna.

Figure 10. The original Haystack design.

Operation at 8 GHz would afford both: a higher radar range resolution, and multi-channel communication possibilities. In 1964, a 150 ft diameter radome from the Air Force allowed the design of a 120 ft diameter reflector to be placed beneath it. This construction was a major challenge, even under the protection of a radome, as it required 0.05” surface tolerance for the higher frequencies and this needed to be maintained over elevation angles and all temperatures. The design featured a removable, RF box which housed both, the feed and the amplifiers. This permitted the antenna to be used for both radio astronomy and as a radar. The antenna and radar were completed in 1964 (Haystack Observatory). Radio astronomers used this antenna to form images of the moon and were able to confirm Einstein’s theory of relativity with planetary observations. In 1978, the Long Range Imaging Radar (LRIR) was added to Haystack to enable images of low and geosynchronous Earth-orbiting satellites using this system. This antenna is shown in Figure 10, with the main ring back support and, on the right, the RF box is shown being raised to the feed location. It contains the radar’s transmit amplifiers, low noise receivers, and feeds. A similar box for radio astronomy contained the feeds, and cryo-cooled receivers

Figure 11. The upgraded antenna for HUSIR showing the new backup structure.

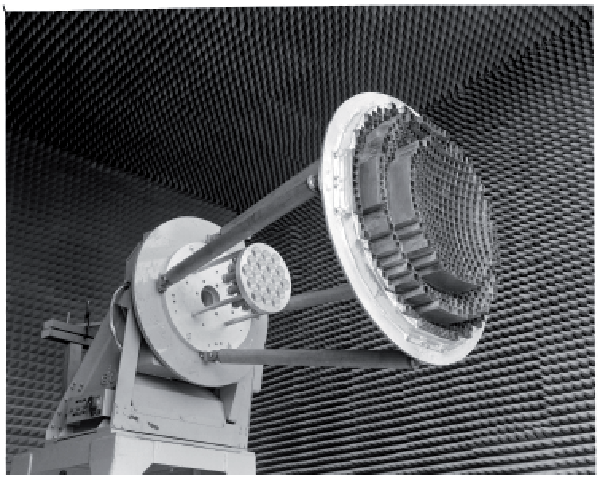


Figure 12. A multi-beam antenna under test in an antenna range.

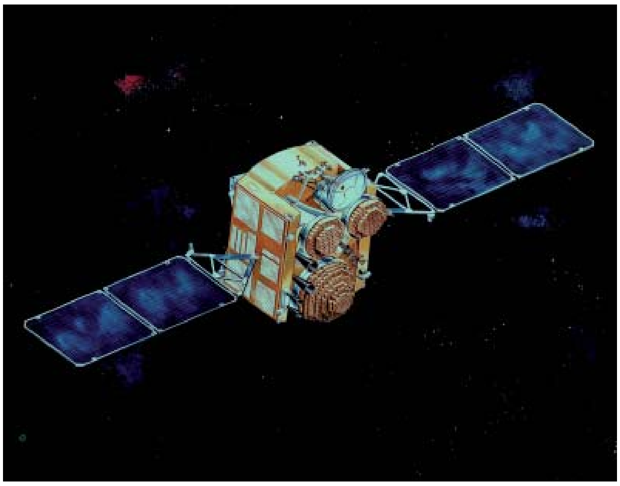


Figure 13. An artist's drawing of the DSCS-III using the Lincoln multi-beam antenna design.

for various RF bands of interest [63, 64, 68].

In 2004, the Haystack Ultrawideband Satellite Imaging Radar (HUSIR) was brought online after a lengthy development. It incorporated a new antenna (141 ft diameter), designed and integrated to operate at X-Band (9.5-10.5 GHz) and W-Band (92-100 GHz), simultaneously, Figure 11. Achieving a surface tolerance of 100 microns with a fixed structure (no movable panels) was the key to its operation. The individual surface panels were painstakingly aligned using holography, using a satellite radiating at 20 GHz. To mitigate waveguide losses at 95 GHz, a circular, corrugated waveguide (manufactured by General Atomics) was used at the expense of a much larger diameter (2.5"), with losses of 0.0008dB/meter. The new reflector also allowed operation at millimeter wavelengths for radio astronomers after the radar feed box was exchanged for one used by the radio astronomers. This W-Band feed employed beam waveguide techniques similar to that used for the millimeter-wave radar. Because the radar concurrently operated at X-Band, a Frequency Selective Surface, consisting of tri-poles on a dielectric surface, was employed to re-focus the offset W-Band feed. Air cooling of that surface was also employed due to its high transmit power at W-Band [64, 69].

In the 1960s, there was strong focus on space-borne communications satellites along with accompanying ground terminals. Small satellites, LES-1 and 2, operating in the 7-8 GHz band were launched in 1965. A follow-on satellite, LES 4, was also built to demonstrate communication from a geosynchronous altitude. The LES-3 satellite, launched with LES-4, contained a UHF beacon to characterize propagation paths through the ionosphere. MIT Lincoln Labs (MITLL) also designed the LES-5 and LES-6 satellites to demonstrate UHF communication using circular polarization to avoid the issues with Faraday rotation through the ionosphere. A follow-on generation of satellites used X-Band with the goal of employing a higher gain, less than full earth-coverage, antenna. A multi-beam antenna using a cluster of 19 feed horns and a waveguide lens was built and tested on an antenna range, Figure 12. This multi-beam antenna allowed for 3 degree beams to be commanded from the ground by controlling the feed excitations. This multi-beam design using a lens was later incorporated into the DSCS-III satellite, Figure 13. Two final satellites in the LES program, LES-8 and LES-9, were built and successfully demonstrated communication to the ground at UHF and cross-link communication between the satellites at Ka-band. These were launched in March 1976 and one of them, LES-9, is still in operation. These satellites are in a slightly inclined, geosynchronous orbit, allowing view of earth's poles [66, 70, 71].

3. Other Antenna Developments Since the 1960s

S. Rengarajan

Until the 1960s, antenna development was mostly focused on dipoles, wire antennas and reflectors. The helix, a wire antenna version, was introduced by Kraus in 1947 [21] to produce circularly polarized radiation over an octave of bandwidth. The concept of frequency independent antennas, defined by angles without any characteristic lengths, was first proposed by Rumsey [9]. Subsequent developments of conformal spiral antennas, and log periodic dipoles led to good directivity over broad bandwidths. In the late 1960s, research on horn antennas was also pursued, with a focus on corrugated inner walls and flared lip versions, for radiation pattern control to be used for reflector feeds and other applications. In the 1980s, concepts of hard and soft horns were developed to suppress edge diffraction from the horn's rim. Inexpensive alternatives to the corrugated horns were also introduced using dielectric loaded horns and metamaterial-lined walls to

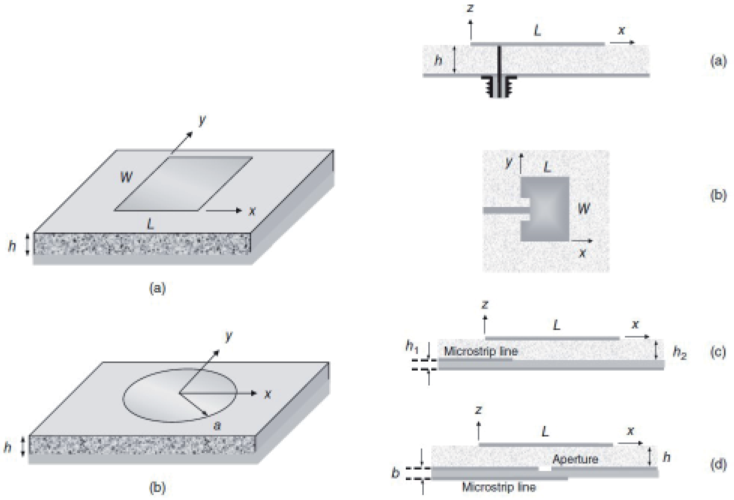


Fig. 14. The geometry and feed layout of the popular microstrip antenna (see Chapter 7 by D. R. Jackson in the J. L. Volakis (ed.), *Antenna Engineering Handbook, Fifth Edition*, 2019).

achieve octaves of bandwidth for satellite applications [72].

Much of the antenna development since the 1980s has been on printed elements and arrays. Microstrip patch antennas [24] are nowadays popular in military, wireless communications, and airborne systems due to their conformal nature. A patch antenna is characterized by a planar metal patch on top of a grounded dielectric substrate (see Figure 14). In 1952, Deschamps and Sichak's [73] provided inspiration for later developments such as Gutton and Baissinot's patent [74] on a flat aerial in 1955, and Munson's conformal realizations [23] of microstrip patch antennas in the 1970s. Rapid advances in microstrip antennas followed the advent of CEM codes and the availability of powerful computational platforms that led to accurate analysis and design tools (see Figure 15 and Figure 16). Many variations of microstrip patch antennas have been developed for different polarizations, wideband, and multiband operation. For example, planar inverted F antennas has been used in laptop and tablet computers. Miniaturized versions of microstrip antennas were also used in smart phones for applications such as GPS, LTE, and WLAN.

Exponentially tapered slot antennas, referred to as Vivaldi antennas [75], and their variations can radiate across large bandwidths once equipped with wideband matching. They are widely used in phased array applications. Figure 17 shows a 3D printed Vivaldi array antenna for UHF to S band operation. Pairs of Vivaldi antennas have been used for orthogonal polarizations or for circular polarized radiation in array structures.

For conformal wideband applications, tightly coupled and overlapping patches or printed dipoles were first proposed in 2007 [76] to achieve a decade of bandwidth or more. Arrays of these overlapping dipoles, referred to as Tightly Coupled Dipole Arrays (TCDAs), see Figure 18, have been shown to deliver scan volumes with scalability from a few MHz up to millimeter wave frequencies. This TCDA concept has also been adapted to a body-worn antenna printed on a conductive

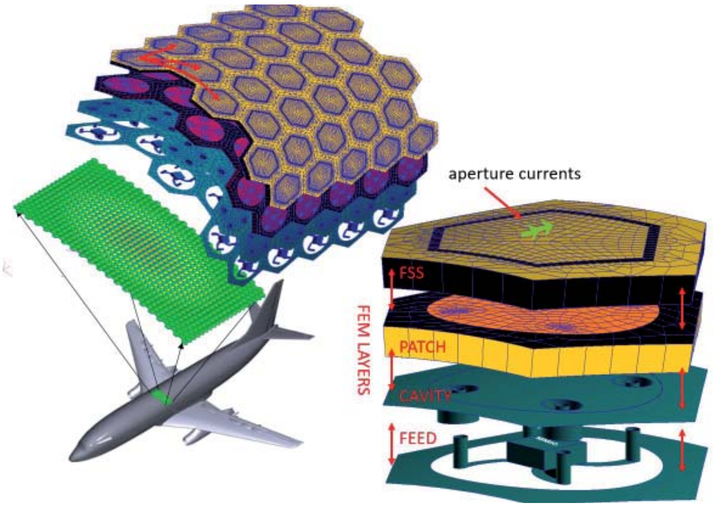


Figure 15. Multi-layered conformal antenna modeling on airframes using finite element-boundary integral methods (from a 2005 AP-S paper by R. Kindt, P. Janpugdee, P. H. Pathak, and J. L. Volakis). The figure shows the remarkable modeling and material detail used in rendering radomes and printed or patch antennas on complex structures.

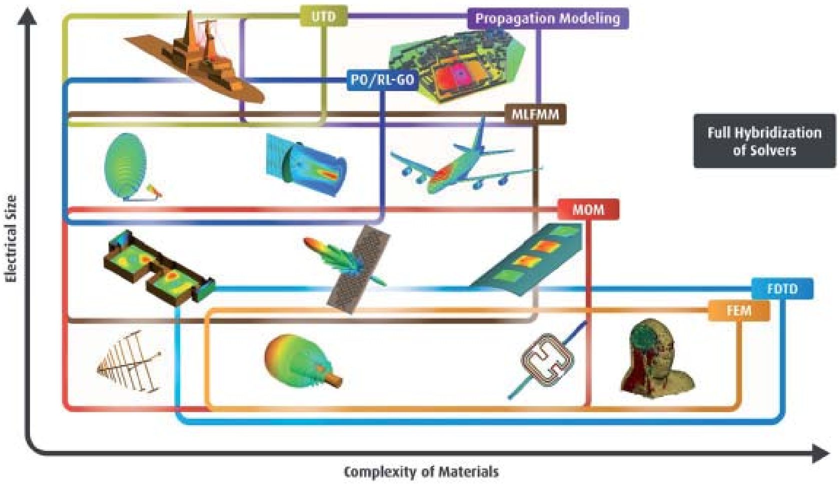


Figure 16. An illustration of numerical techniques found in Altair's *FEKO* (from Altair *FEKO User Guide* 2019.1.1, Altair HyperWorks, 2019, https://altairhyperworks.com/product/FEKO).

textile operating over a frequency range of 60 MHz to 2 GHz [77].

Smart and/or adaptive antennas have also been introduced recently for wireless communication systems. In this context, adaptive or multiple input multiple output (MIMO) [78] antennas and wideband arrays have been used in cellular base stations. Wideband antenna arrays with low cost digital beam formers will likely be of growing interest, and antennas that mitigate signal-to-interference and noise ratios in congested environment are likely to remain a challenge, particularly for millimeter wave links.

4. High Frequency Studies in the 1960s and 1970s

G. Manara and J. L. Volakis

In the 1960s and 1970s, research focused on high-frequency solution approaches to electromagnetic radiation and scattering problems. In the beginning, studies were based on analytical methods and oriented towards the analysis of canonical structures, such as spheres, cylinders, cones, wedges, rectangular plates, ellipsoids and other simple shapes [32]. This was a consequence of the growing interest in the radar systems. Indeed, the objective was mostly focused on evaluating Radar Cross Section (RCS) of different structures. However, realistic structures, such as aircrafts and ships, could hardly be described by a canonical object. Rather, a simple approach was to use a combination of simple shapes, and the introduction of the Geometrical Theory of Diffraction (GTD) by J. B. Keller [27] opened a new important direction in radar scattering analysis.

Indeed, GTD opened the way to a systematic use of rays for an efficient description of electromagnetic radiation and scattering from complex structures. In this context, suitable diffraction coefficients (see Figure 19) were derived by an

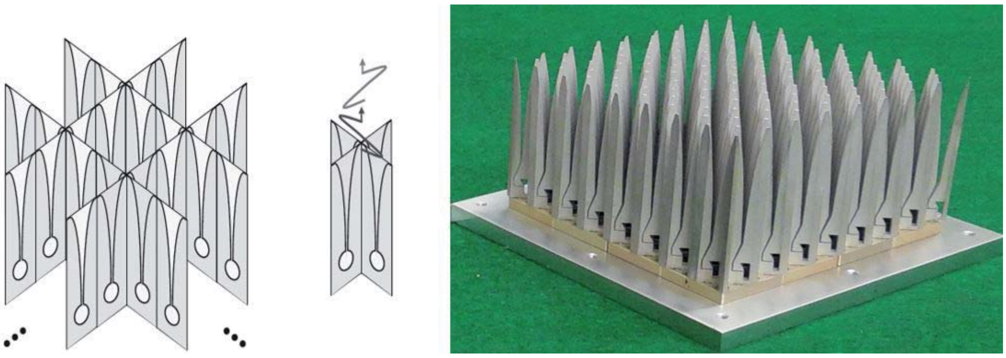


Figure 17. An illustration of a Vivaldi array provided by R. Kindt of NRL (R. W. Kindt and J. T. Logan, "Benchmarking Ultra-Wideband Phased Antenna Arrays," *IEEE Antennas and Propagation Magazine*, 60, 3, June 2018, pp. 34-47).

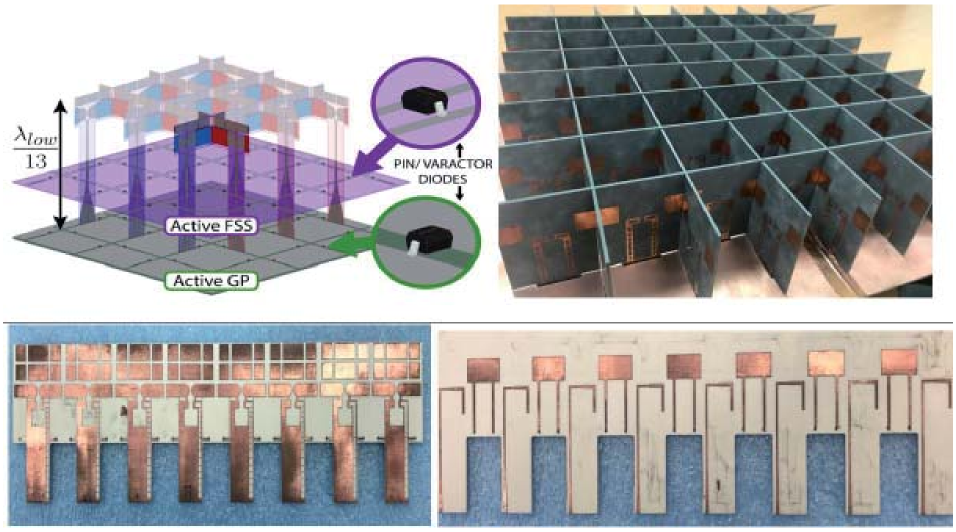


Figure 18. An illustration of the Tightly Coupled Dipole Array (TCDA). (upper left) A general illustration with reconfiguration options; (upper right) The assembled egg-crate array using rows of printed board; (lower right) A close-up view of a single PCB board, including wideband feed, dipole, and FSS at the top; (bottom right) The other side of the same PCB board showing microstrip feed and the pad used to emulate the overlapping dipoles for increased inter-element capacitance.

asymptotic approximation of the previously mentioned solutions for electromagnetic scattering from canonical objects. According to the localization principle, the canonical shape should approximate the geometry of the real structure only in the close neighborhood of the diffraction point or edge. As such, radiation and scattering problems from realistic structures could be predicted by a suitable ray description of the general radiation or scattering phenomenon. GTD provided the required systematic set of rays to describe high-frequency radiation and scattering, complementing the classical Geometrical Optics (GO). However, GTD had to overcome a number of drawbacks due to field singularities at shadow and reflection boundaries. To address these issues, at the shadow and reflection boundaries, two uniform versions of GTD were introduced: the Uniform Geometrical Theory of Diffraction (UTD) [34] and the Uniform Asymptotic Theory of Diffraction (UAT) [35]. Although very effective in solving radiation and scattering problems, both UTD and UAT had difficulties in evaluating the RCS of complex targets or to calculate the electromagnetic field at caustics. In these and other cases, equivalent currents provided an alternative. The Physical Theory of Diffraction (PTD) was proposed by P. Ya. Ufimtsev [36], and independently by K. M. Mitzner at Northrop-Grumman Corp. PTD, and complemented the classical Physical Optics (PO) by introducing suitable "fringe currents" at the geometrical discontinuities (edges) of the scattering body. It can be said that Mitzner's Incremental Length Diffraction Coefficients [37] is a version of PTD. Independently, Tiberio et al. proposed an extension of UTD, the Incremental Theory of Diffraction (ITD), by resorting to equivalent edge currents to represent the scattered field at caustics [34].

To account for material properties and coatings on the scattering objects, it is important to note the pioneering paper by G. D. Maliuzhinets [29]. In this paper, a procedure is proposed to characterize the diffraction by a wedge having two different impedance faces (see Figure 19). Higher order or Generalized Impedance Boundary Conditions (GIBCs) were later used by Senior and Volakis [79] to account for dielectrically coated objects. Another strategy for solving the impedance wedge problems followed the Wiener-Hopf technique [80], and the Spectral Theory of Diffraction [81].

Notably, several papers have been published on the scattering by canonical impenetrable bodies, characterized by different boundary conditions at their exterior surface. A summary of the different boundary conditions and associated canonical solutions can be found in [31].

5. Computational Tools and Commercial Wireless Applications in the 1980s and 1990s

S. Rengarajan and J. L. Volakis

Numerical solutions of electromagnetic problems have been studied since the late 1950's, with the method of moments for wire antennas and wire grid structures emerging in the 1960's [82, 83]. The Numerical Electromagnetics

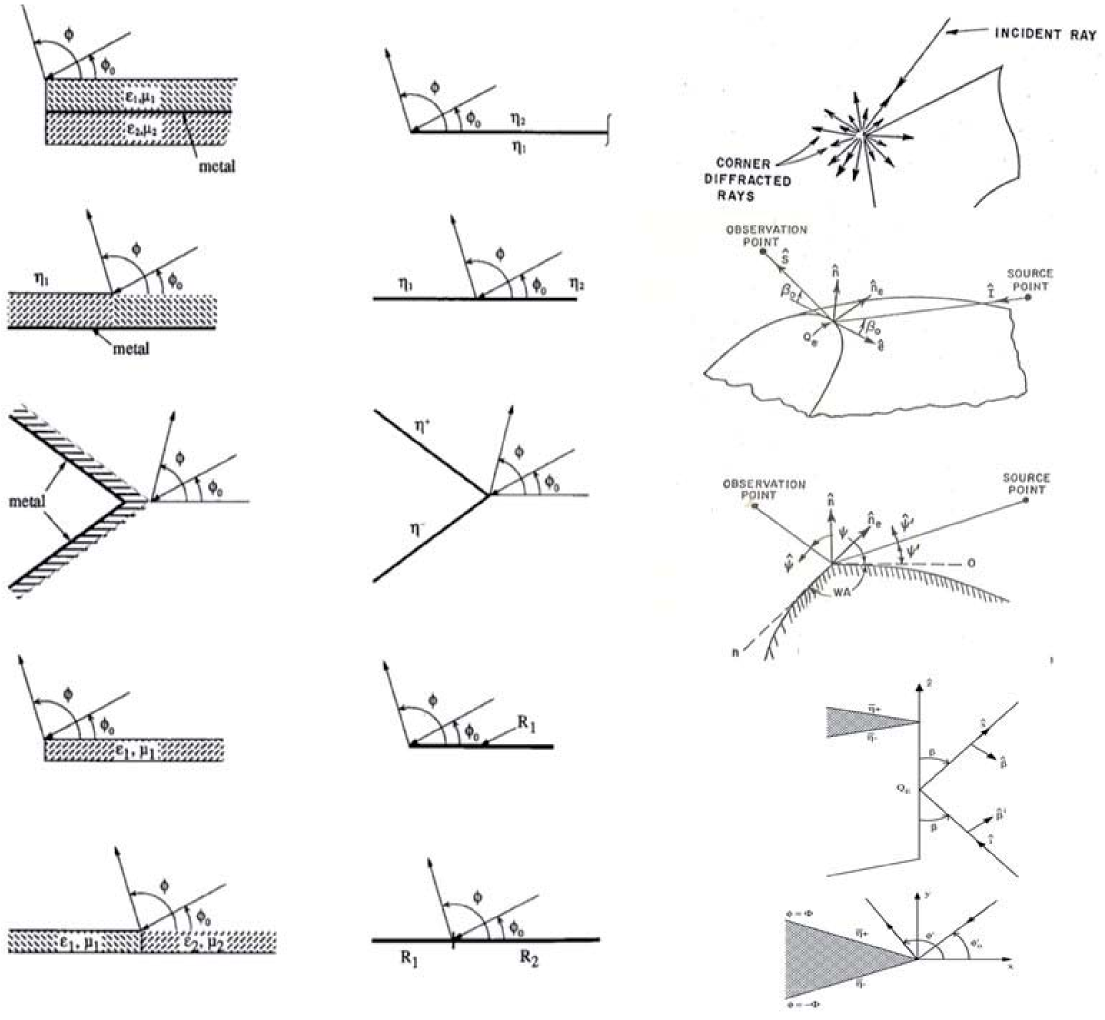


Figure 19. Some diffraction geometries the coefficients of which were computed during the 1960s to 1980s (some of the above figures are from [31]).

Code (NEC), developed at Lawrence Livermore Labs, is an example of the early moment method codes. Harrington's ground-breaking publication [84] on the method of moments generalized Galerkin's technique, originally presented in 1920 (in Russia), generated strong interest. With the advent of the triangular surface basis functions, popularly called Rao-Wilton-Glisson basis functions [46], the method of moments solution to the integral equations became efficient and accurate. Green's functions for many standard structures were also employed in conjunction with moment method solutions. Iterative techniques such as the conjugate gradient method [85] and the Adaptive Integral Method (AIM) helped in the solution of large-scale antenna and scattering problems [51, 86]. Also, the fast multipole method helped in accelerating the integral equation solutions, thereby reducing order of solution from N^3 to $N^{1.3}$ [53, 54, 87-89]. Usner et. al.'s [90] work on conformal Galerkin's testing for volume integral equations using parametric geometry for surface tessellation (see Figure 20) provided for even more efficient moment method solutions of volumetric structures bounded by curved surfaces.

In terms of direct differential equation solutions of Maxwell's equations, in a seminal 1966 paper, Kane Yee proposed an algorithm to solve the two first-order partial differential equations [56], referred to as FDTD. However, because of the slow speed and limited storage computers, back then, it took nearly two decades for this method to become popular. The FDTD was later popularized by A. Taflove and co-authors [57, 91-93] by solving a variety of antenna and scattering problems using the Yee algorithm [56]. FDTD was later used for breast cancer detection systems [92], and for studying electromagnetic interactions of handset antennas with the human body in personal communications [93], among other applications. FDTD has since been used in terahertz and optical device design and for multi-physics modeling.

The finite element method, is another method for solving Maxwell's equations. It was already popular in structural mechanics and was first considered in electromagnetics in the late sixties [94]. Unlike the method of moments, the finite element technique is better suited to the analysis of penetrable structures, possibly comprised of inhomogeneous media.

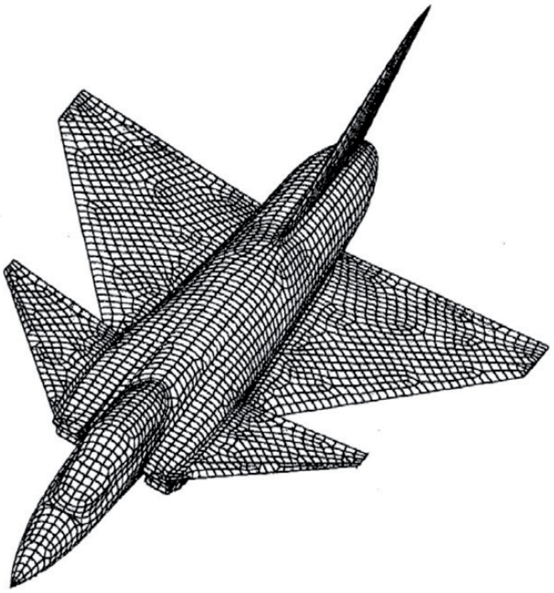
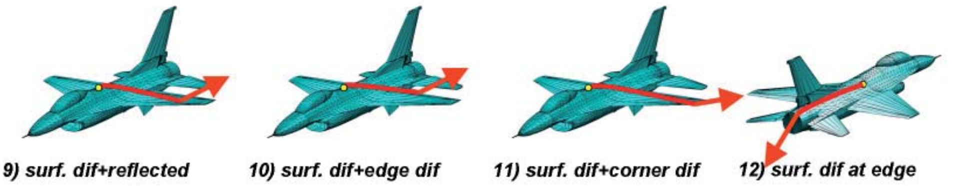


Figure 20. CAD meshes of curvilinear patches for accurate rending of complex surfaces with thin edges and rapidly bending surfaces. This is the fictitious VFY 218 that was used for code validation in the 1990s. The mesh was courtesy of Kubilay Sertel.

During the 70s, through 90s the finite element method matured with numerous applications [52, 95-100]. Combining the finite element method and the boundary integral method led to a powerful and accurate method of solving antenna and scattering problems [52, 95-100]. This boundary integral mesh truncation became essential for establishing the accuracy of the FEM, and also provided a reference for using the less accurate absorbing boundary conditions as described in [101, 102]. The FEM is now a standard algorithm in general-purpose commercial codes, routinely used for electromagnetic

1) direct (line of sight) 2) reflected 3) edge diffracted 4) corner diffracted

5) surface diffracted 6) reflected+edge dif 7) edge dif+reflected 8) doubly edge dif



9) surf. dif+reflected 10) surf. dif+edge dif 11) surf. dif+corner dif 12) surf. dif at edge

Figure 21. The depiction of multiple diffraction mechanisms for improved scattering analysis and antenna pattern prediction on an airframe structures (from C. Tokgoz, C. J. Reddy, R. J. Burkholder, and P. H. Pathak, "Application of UTD for Prediction of Radiation Pattern and Mutual Coupling Associated with Antennas on Faceted Airborne Platforms," IEEE Antennas and Propagation Society International Symposium Digest, Charleston, SC, USA, June 2009; see also C. L. Yu, W. D. Burnside, and M. C. Gilreath, "Volumetric Pattern Analysis of Airborne Antennas," ***IEEE Trans. Antennas and Propagat.*****, 9, 1978).**

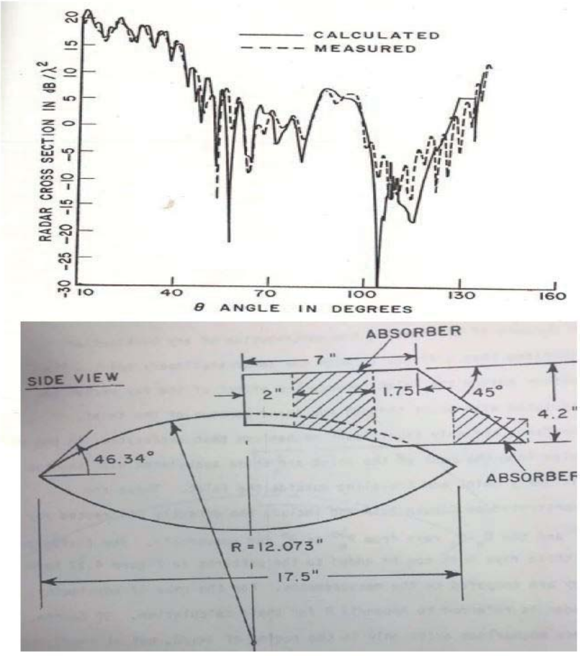


Figure 22. Inlet scattering simulations and measurements (1982). The figures are the first ever measurements and simulations of a structure with inlet appendages, published in the Ohio State dissertation by J. L. Volakis

analysis and design problems.

Indeed, with the development of more powerful computing platforms, from the early 1980s to the early 1990s, numerical methods became increasingly more popular for scattering and antenna solutions of more realistic objects. But initially, computer codes focused on using high-frequency methods for scattering by complex structures (see Figures 21 to 23). More specifically, complex structures were constructed from a combination of canonical bodies and their scattering was computed using ray methods (PO, GO, UTD, PTD) in conjunction with multiple scattering effects. An example of high frequency code is the Numerical Electromagnetic Code (NEC) – Basic Scattering Code (BSC), developed at The Ohio State University's ElectroScience Laboratory [103]. This computer code was applied to radiation from the antennas that are installed on complex platforms, including aircraft geometries associated with multiple scattering phenomena as shown in Figure 21. By the early 1980s, high frequency codes were available for accurate prediction of scattering by jet engines on fuselages (Figure 22) and by antenna arrays through radomes (see Figure 23). By the late 1980s, Computer

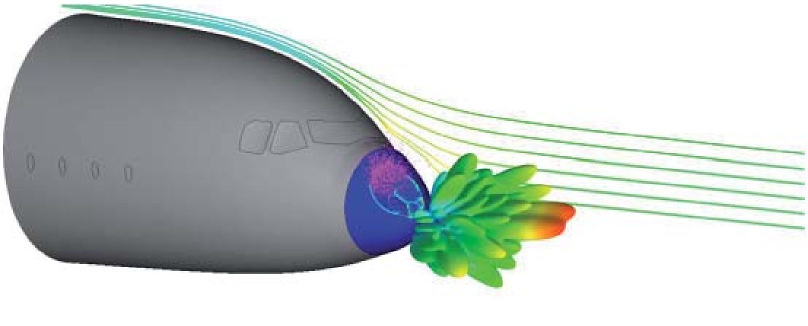


Figure 23. The antenna pattern prediction for an antenna behind a nose radome using hybrid methods. Specifically, the Multi-Level Fast Multipole Method (MLFMM) was used to characterize the radiation pattern of the waveguide antenna arrays, high-frequency/ray methods were used to characterize the transmission through the radome, and the Method of Moments (MoM) was used to predict the radome transmission losses (E. Whalen, G. Gampala, K. Hunter, S. Mishra and C. J. Reddy, "Aircraft Radome Characterization via Multiphysics Simulation," 40th Annual Meeting and Symposium of the Antenna Measurement Techniques Association, AMTA 2018, 2018, Williamsburg, Virginia; https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8604253).

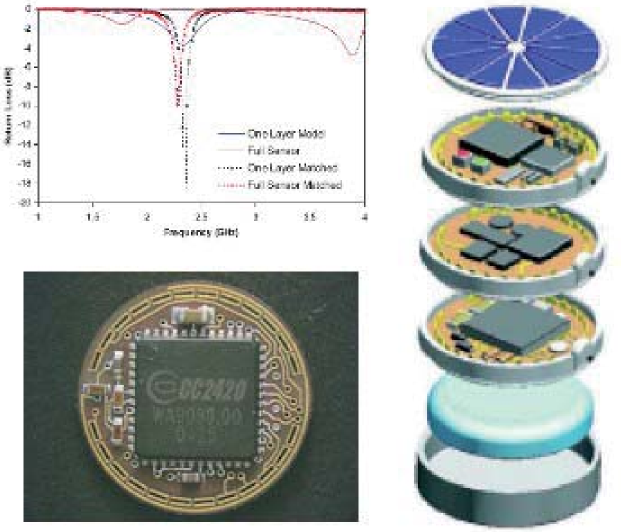


Figure 24. A typical antenna design in modern packaging scenarios (A. Alomainy, Y. Hao, F. Pasveer, and Z. Chen, "Antennas for Wearable Devices," in *Antennas for Portable Devices*, New York, John Wiley & Sons, 2007, pp. 197-226.

Aided Design (CAD) meshes began to appear on fast workstations, such as the SGI, for simulations with real-time spinning and visualization of large airframe structures. This capability led to the widely used GPUs for real-time graphical rendering in video games. A successful package that used CPU capabilities with high-frequency methods was the development of *Xpatch* [104], originally developed at the University of Illinois at Urbana-Champaign.

By 1990, the accuracy of high-frequency methods for realistic structures had become impressive. However, the need to model materials, coupled with the rapidly growing capabilities of CPUs led to a new era in electromagnetics (see Figure 15). Methods based on integral equation techniques, such as the moment of method (MoM), became increasingly popular. But even more importantly, fledgling methods such as the finite element (FEM) and finite difference time domain (FDTD) methods, including hybrid versions, took center stage. These developments, started in the late 1980s, became the main focus in the 1990s, leading to commercial packages, widely used today. One could say that if the cell phone became an

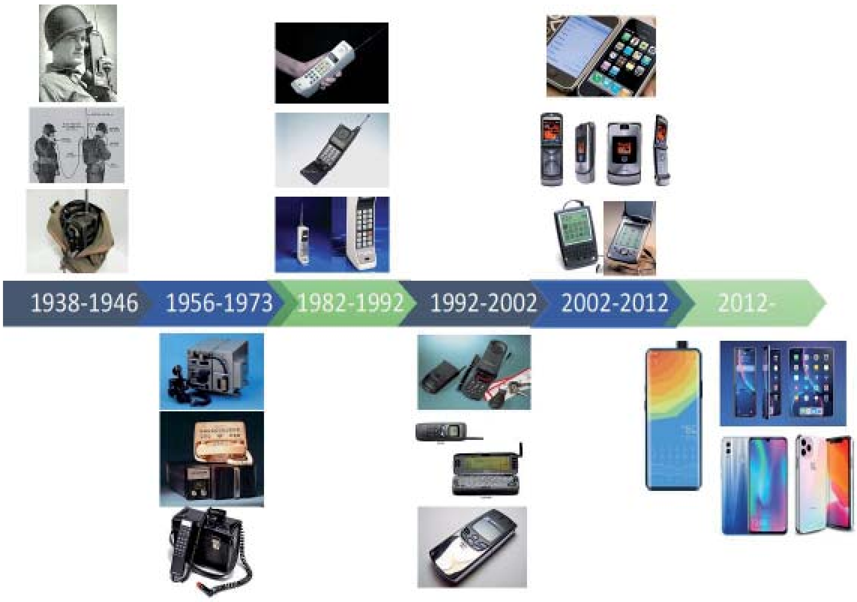


Figure 25. The historical timeline of handheld and cell phone evolution and related antennas, from protruding to conformal and embedded designs (collected and compiled by Y. Hao from various Internet searches).

Figure 26. The antenna array with matching and harvesting circuits for woven electronic textile surface used for Wi-Fi energy harvesting (D. Vital, S. Bhardwaj, J. L. Volakis, "Textile Based Large Area RF-Power Harvesting System for Wearable Applications," *IEEE Trans. on Antennas and Propagation*, 2020, https://ieeexplore.ieee.org/document/8883249).

inseparable daily device, the same can be said about simulations packages when it comes to antenna design, propagation studies, imaging and scattering analysis, or cell tower placement. As numerical solutions became more popular, code parallelization on high-performance computing for antenna and scattering applications was also pursued [100]. Notably, to validate the emerging computational tools, an Electromagnetics Code Consortium was established in the 1990s to propose standard computer code validation geometries, such as almond, ogive, double-ogive, and cone spheres [48, 105].

For antennas and scatterers in layered media, the spectral domain solution technique was found quite effective [106]. This technique was introduced in the 1970s and matured in the 1980s, finding numerous applications in planar transmission lines and antennas, such as microstrip patches and reflectarrays. Mode matching techniques were also used during the 80s and 90s for waveguide discontinuities and horns [107, 108].

6. Antennas for the Cellular Revolution and Astronomy

Y. Hao

Motivated by the cellular revolution and better aesthetics for mobile wireless devices, base stations, and wearable electronics, a significant effort was dedicated in the last 15 years to smaller antennas and well-matched microwave circuits. Using computation tools, designs of conformal and device integrated antennas were carried out in the presence of neighboring devices/components, matching RF circuits, and device chassis. Figure 24 is a typical antenna design in the presence of a modern packaging environment.

The evolution of antenna design for portable devices is depicted in Figure 25. It can be seen that wireless telephony and links underwent step changes every ten years. Initially, fixed length antennas, mounted externally, were the standard for early wireless devices. Subsequently, retractable antennas were used until 2002. These extendable antennas gave improved performance and better styling when retracted. The latter also delivered improved signal integrity at a reduced Specific Absorption Rate (SAR). During the late 1990s and early 2000s antennas encased within the handheld device were introduced. Currently, all handhelds employ several antennas, all embedded within the device cases in a highly aesthetic manner. Notably, among the earliest cell phone integrated antennas was the dual-band inverted-F antenna [109] placed in the Nokia 8810 handheld. Today multiple antennas are integrated within handheld devices serving several bands, including D-AMPS at 800 MHz, CDMA at 800/1900 MHz, PCS at 1900/1900 MHz, GSM at 900/1800 MHz, JDC at PDC800/1500 MHz, DCS at 1800/1900 MHz, Wi-Fi and UMTS at 2.4 GHz. Also, there are antennas and arrays available

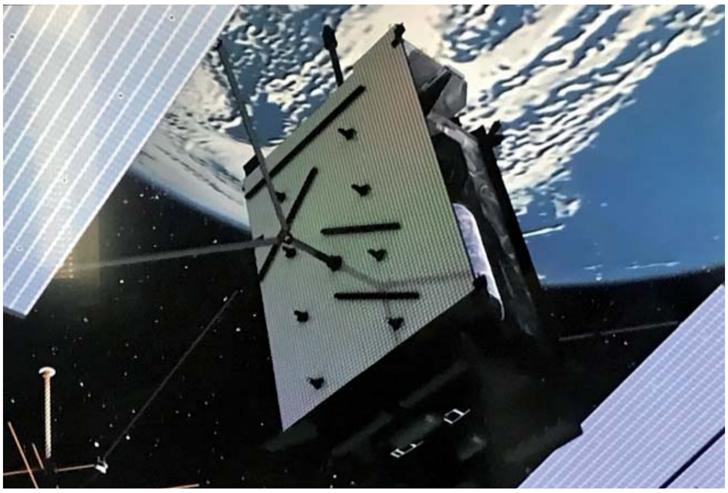


Figure 27. An artist's view of the GPS III satellite that will soon be fully operational. These satellites will enable three frequency band transmissions instead of the traditional L1 and L2. The associated frequencies will be L1 (1575.41 MHz), L2 (1227.6 MHz) and L5 (1176.45 MHz).

for 4G mobile communications at 6 GHz and for 5G and 6G links, including millimeter wave frequencies. Notably, some of the earliest millimeter wave antennas appeared in [110, 111]. And future mobile antennas are required to cover even broader frequency ranges ranging from 0.9 GHz to 6 GHz, and millimeter wave frequencies.

Indeed, significant development of other types of small antennas for wireless communications has also been carried. These include Meander Line Antennas (MLA) for suitable multi-mode operations within a single antenna structure, dielectric chip antennas for surface mounting, dielectric resonant antennas (DRA) [112] and other types for broadband operations [113]. An interesting antenna design exploits the Sierpinski triangle, which was a mathematically generated pattern reproducible at any magnification or reduction. In [114], the multiband fractal Sierpinski antenna was studied. Understandably, there has been a focus as well on antennas overcoming the Chu-Harrington limit. This was discussed in a paper given by McLean [115], within an overview provided on small-antenna limits provided in [116]. While electrically small antennas (ESAs) have been a subject of academic research for many years, renewed interest arose by integrating non-Foster circuits [116, 117] or by employing automated tuning circuits for frequency reconfiguration. Many of these approaches have been lab demonstrations, but a quiet revolution has been taking place in industry to replace the popular PIFA designs. Nowadays, most smartphone designs rely on a stainless-steel band that runs around the edge of the phone. For example, the iPhone antenna for Wi-Fi, Bluetooth, and GPS is a smaller strip beginning at the bottom left and running to the top. The corresponding cellular radio antenna for voice and data is a much larger strip tracing almost three quarters of the phone periphery. These alternative designs coupled with other internal antennas have enabled advances to increase wireless channel capacities, such as antenna diversity and multiple-input multiple-output (MIMO) [118]. Other smart antennas provide low correlation (diversity gain), as well as spatial, polarization and angle diversity for the many antennas within portable or handheld wireless devices [119]. Using nanomaterials such as graphene, replacing traditional indium tin oxide (ITO) materials, it is anticipated that future phones will likely employ optically transparent antennas [120] that are frequency agile with beam-steering capabilities [121], all integrated in a single wideband antenna with multiple functionalities. In addition, future radios are likely to employ simultaneous transmission and reception across the entire allocation band using back-end and cancellation techniques to suppress self-interference. Meanwhile, metamaterials, including photonic bandgap (PBGs) [122] and electromagnetic bandgap structures (EBGs) [123], left-handed materials [124] and metasurfaces [125], among others, have played and will continue to be considered in future designs of RF components and antennas.

7. Concluding Remarks

Our reliance on the wireless links and communications has become an integral part of our everyday life. Therefore, we can expect strong and continuing interest in RF/microwave components for a variety of day-to-day applications. These include, sensors and sensing for IoT applications across industrial building and homes, entertainment everywhere using 5G/6G connectivity, wearable electronics for medical and other monitoring applications (see Figure 26), geolocation (see Figure 27), earth resource monitoring, smart cities, automation and smart vehicles, robotics, augmented reality, artificial intelligence, and remote control, to mention a few. Indeed, all these applications and directions are part of the 4th industrial generation of AI-driven automation and remote expert assistance. They are bound to change spectrum utility, communication links, as well as information gathering, and usage.

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Commission C Contribution Orthogonal Frequency Division Multiplexing: From Spectral to Energy Efficiency

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Abstract

This article highlights the very popular transmission scheme known as OFDM for Orthogonal Frequency Division Multiplexing. OFDM dates back several decades and has known tremendous success in the telecommunications area: audio and video digital broadcasting, mobile communications, local wireless networks, power line communications, and so on. The OFDM principle is to transform a frequency selective channel into many flat fading channels over which the channel response can be approximated by a single attenuation value. This gives OFDM its multi-frequency nature and has a twofold consequence: (i) it is possible to transmit high data rates over multi-path channels with reasonable complexity at the receiver (ii) the multi-carrier scheme generates a signal with high Peak to Average Power Ratios (PAPRs) that greatly decrease the energy efficiency of the transmitters.

After a historical outline of OFDM, this article gives three examples of applications of OFDM (adaptive modulation and coding, resource allocation, and ultra low power devices). Then, the remainder of the paper focuses on the balance between spectral efficiency, for high data rate transmission, and energy efficiency, to lower energy waste on the transmitter side while using OFDM. The article ends with a focus on how energy efficiency can be increased by using a PAPR reduction method.

1. Introduction and Some Historical Elements of OFDM

Current communication systems require high connectivity, reliable transmissions in mobility and increasing spectral efficiency. LTE, the Worldwide Interoperability for Microwave Access (WiMAx), WiFi, DVB and other communication systems today use multicarrier modulation, which is considered one of the key technologies able to fulfill all these demands. The basic principle of multicarrier systems relies on a parallel data transmission scheme where multiple data symbols are transmitted simultaneously. Therefore, each symbol occupies a part of the available bandwidth. Multicarrier systems have many advantages in comparison to the conventional single carrier systems, and they have found a wide range of applications in both wired as well as wireless communications systems. First, these systems exhibit the attractive feature of high spectral efficiency. Second, the InterCarrier Interference (ICI) and Inter-Symbol Interference (ISI) are mitigated by the insertion of guard intervals (i.e. Cyclic prefix). Besides, by dividing the channel into narrowband, flat-fading subchannels, multicarrier systems are more resistant to frequency selective fading than single carrier systems. In this paper, we first establish the history and the basic principles of Orthogonal Frequency Division Multiplexing (OFDM), which is one of the most popular types of multicarrier systems. Then, we highlight some applications of OFDM before focusing on the Peak to Average Power Ratio (PAPR), which is investigated through the trade-off between energy and linearity efficiencies. Thereafter, we present some PAPR reduction techniques and one example for PAPR reduction techniques to illustrate the energy and linearity efficiencies trade-off.

OFDM is a special form of multicarrier modulation, which transmits a single data stream over a number of lower rate subcarriers. It has long been studied and implemented to combat transmission channel impairments. Due to the advantages of OFDM, especially in the multipath propagation, interference, and fading environments, its applications have been extended from High Frequency (HF) radio communication to digital audio broadcasting, digital television terrestrial broadcasting, and telephone networks [1]. In fact, OFDM has already been adopted by many communication standards, i.e., Asymmetric Digital Subscriber Line (ADSL), European Digital Video Broadcasting Terrestrial Digital Video Broadcasting Second Generation Terrestrial (DVB-T2), and Japanese Integrated Services Digital Broadcasting Terrestrial (ISDB-T), LTE, as well as the network standards such as IEEE 802.11a/g/n, and WiMAx.

Although OFDM systems were standardized for the first time in 1993, OFDM-based systems already existed during the Second World War. OFDM was used by the US military in several high-frequency military systems such as KINEPLEX, ANDEFT, and KATHRYN [2]. In fact, the first fundamental contribution to OFDM was introduced by Robert W. Chang when, in December 1966, he published a synthesis of band-limited orthogonal signals for multi-channel data transmission without ISI and ICI [3]. Then, in 1971, Weinstein and Ebert proposed an easier and efficient implementation by using a technique based on the Discrete Fourier Transform, which eliminates the need for a bank of subcarrier oscillators [4]. Afterwards, another breakthrough in the history of OFDM came in 1980, when Peled and Ruiz introduced Cyclic Prefix (CP) [5]. Thus, the cyclic extension replaced the empty guard spaces in the frequency domain. Hereafter, due to substantial advances in digital signal processing, the implementation of the modulation and demodulation in OFDM systems became simple and practical using the Fast Fourier Transform (FFT), and the Inverse Fast Fourier Transform (IFFT) pair, respectivelly, which made OFDM an important part of the telecommunications landscape. In 1993, the European Digital Audio Broadcasting (DAB) project adopted OFDM on its physical layer. The DAB standard was the first commercial use of OFDM technology. At the dawn of the 21st century, several communication standards such as Wireless Local Area Network (WLAN) standard, DVB (T and T2) standard, 4G, and 5G, also adopted transmission techniques based on OFDM.

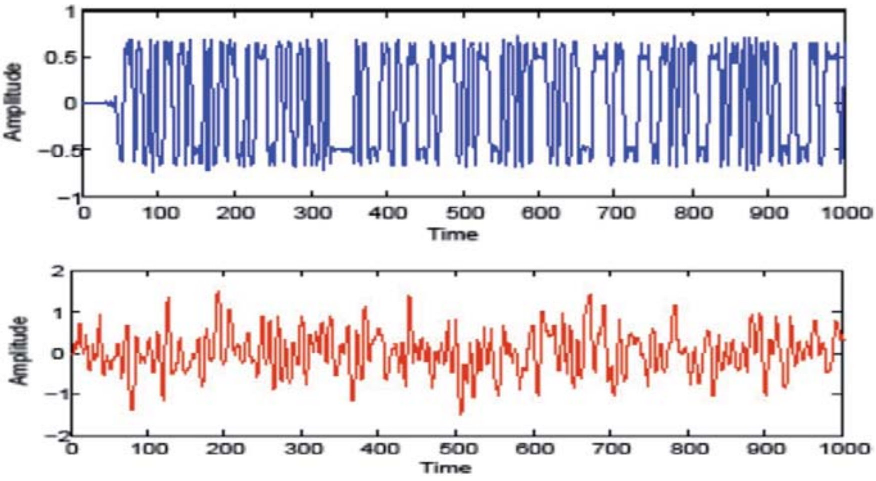

Figure 1. The time domain representation of the filtered single carrier (upper panel) and multicarrier (lower panel) signals.

2. OFDM: A Non-Constant-Envelope Signal

There are two types of signal with respect to signal carrier frequency. The first type is that of single carrier signals, where the data is transferred on a single carrier frequency, like in a Global System for Mobile communications (GSM) where each user's data is transmitted on a particular frequency. The second type is that of multi-carrier signals where the data is transmitted over many carrier frequencies, like in Orthogonal Frequency Division Multiplexing (OFDM), where the information is modulated on several carriers. The envelope characteristics of single carrier and multi-carrier signals are different from each other and in this section we will highlight these differences.

In single carrier communication like the transmission of a Quadrature Phase Shift Keying (QPSK) or Gaussian Minimum Shift Keying (GMSK) modulated data, the information is transmitted over a single carrier frequency. Thus, the power fluctuations of this signal depend upon the constellation scheme and shaping filter characteristics. For example, in the case of amplitude modulations, such as Quadrature Amplitude Modulation (QAM), more power fluctuations should be observed compared to those of phase modulations, like QPSK, as the maximum and mean power of the symbols is the same in the case of phase modulation. Also, the characteristics of the shaping filter affect the signal envelope, as in case of the Root Raised Cosine (RRC) filter, the envelope varies with the change in the filter's roll-off factor. Figure 1 shows the power fluctuations of a QPSK modulated single carrier signal with roll-off factor of 0.22. As can be seen, the signal envelope is quite constant without much fluctuation ie., maximum and mean values are almost the same.

In the case of a multi-carrier communication like OFDM, a large number of sub carriers are added simultaneously to make a multi-carrier signal. For example, an OFDM symbol containing N sub carriers would be formed as,

$$S(t)=\sum_{j=-\infty}^{+\infty}\sum_{k=0}^{N-1}C_{j,k}\,g(t-jT_S)\,e^{2i\pi f_k t} \qquad (1)$$

where $g(\bullet)$ is the rectangular pulse of duration T_S, $C_{j,k}$ represents the complex information symbol of carrier k with $f_k=\frac{k}{T_S}$ of *j*th OFDM symbol.

According to the central limit theorem, when a large number of independent and identically distributed (i.i.d) random variables are added simultaneously, their distribution becomes Gaussian, which means that there is a big gap between mean and maximum values. As OFDM signals can be treated like a summation of many i.i.d random variables, its distribution tends to be Gaussian and results in high power fluctuations following the central limit theorem as shown in Figure 1.

3. Some Applications of OFDM

3.1 Application 1: Adaptive Modulation and Coding

Whatever the actual application of an OFDM scheme, one powerful characteristic of this multicarrier system is that each subcarrier could be independently modulated with its own modulation and coding. This means that we can optimize the order of the modulation and the coding rate for each narrowband propagation channel between the emitter and the receiver. As indicated, this was already used in xDSL or DVB standards, but also in IEEE 802.11 for WiFi networks or in LTE for 4G [6].

In most of the recent wireless network standards, the demand for higher throughputs and better mobility has increased. Therefore, higher channel bandwidths are allowed, leading to large fluctuations of the propagation charactestics in time and in frequency. It is then straitforward that with a large bandwidth, we can use OFDM with a large number of subcarriers (from tens to thousands), each subcarrier optimized in modulation and code in order to ensure a better rate and reliability of the wireless link [7]. Of course, this optimization supposes that the emitter is able to evaluate the time-frequency channel conditions, thus the whole system has to be designed depending on the degrees of freedom of the communication medium and the operational environment characteristics [8].

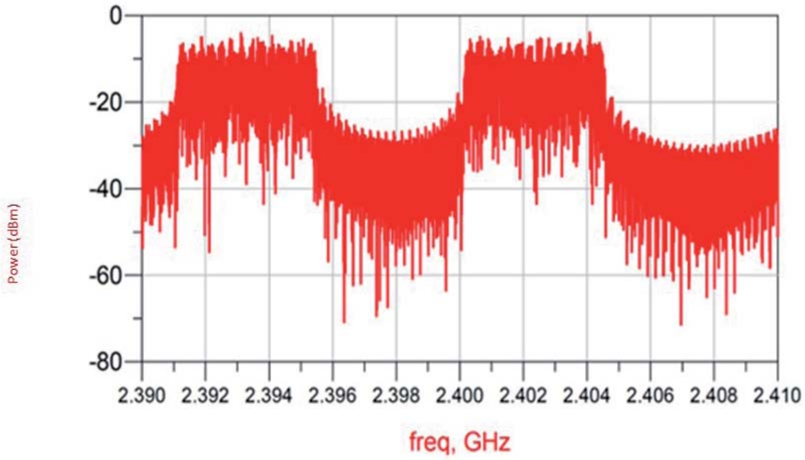

Figure 2. The frequency signature of a Wake-Up Radio.

3.2 Application 2: Resource Allocation

Orthogonal frequency division multiple Access (OFDMA) is about a multiple access technique based on OFDM. Thus, in the multi-user communication system, different sub-carriers can be allocated to different users to exploit multi-user diversity. Moreover, the association of Multi Input Multi Output (MIMO) and OFDMA techniques in multi-user configuration, called multi-user MIMO–OFDMA (MU MIMO–OFDMA) system [9, 10] is an efficient way for providing a high data rate, taking into account multi-user, frequency and spatial diversities. This association is already included in several standard applications.

In the MU MIMO–OFDMA system, multi-user interference occurs, when several users communicate simultaneously. This phenomenon considerably degrades the system performance. For this reason, the authors in [11] and [12] have proposed a novel heuristic strategy, which shares the users in different groups, on the basis of their average channel gain. Afterwards, channel allocations are sequentially addressed, starting from the group with the most adverse channel conditions. The spatial dimension is employed to present multiple access interferences, hindering the performance of the sequential allocation. Otherwise, the adaptive strategies with respect to power allocation [13, 14], subcarriers distribution [15, 16], modulation, and coding [17, 18] can be used in order to improve the performance. Hence, adaptive radio resource allocation schemes in MU MIMO – OFDMA systems have become an important research topic. These approaches achieve a significant improvement in overall system performance either by minimizing the total transmited power, subject to bit error rate (BER) constraint [19, 20, 21], or by maximizing the sum-rate capacity [22], under a total power budget constraint.

3.3 Application 3: Ultra-Low-Power Devices

OFDM was originally created mainly for high performance devices, but surprinsingly it has progressivly gained some interest from the low power devices designers. Even if multiccarier signals are not the most energy efficient, the flexibility of using multiple tones could offer some interesting applications to reduce the overall energy consumption of a network.

First, we can cite the case of Wake-Up Radio receivers (WURx). A WURx is a secondary radio interface with very low power consumption, complementary to the main (energy greedy) radio interface. This WURx allows completely switching off the main radio when no traffic is required, avoiding the important consumption of the idle mode in lots of networks with sporadic communications. One keypoint of an efficient WURx is the ability to identify the device to wake-up, then a way to ensure this identification builds a frequency footprint based on an OFDM signal with some subcarrirs on or off (see for instance Figure 2). This structure, proposed in [23], enables identification of the correct device with a quasi passive WURx.

Another usage of OFDM for low-power systems is in the field of Wireless Power Transfer (WPT). It was shown [24] that the rectifiers used to collect energy in WPT are more efficient when the input signals are presenting a high PAPR. Thus, OFDM signals are good candidates for WPT, particularly if we can optimize the multi-carrier waveforms in order to

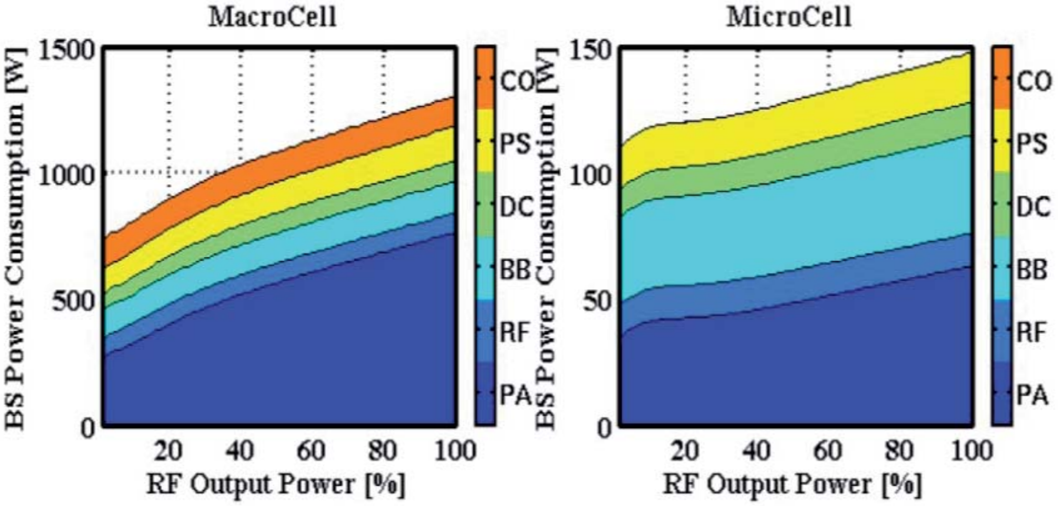

Figure 3. Power consumption in all LTE base station types for a 10MHz bandwidth, based on the 2010 State-of-the-Art estimation. Legend: PA=Power Amplifier, RF=small signal RF transceiver, BB=Baseband processor, DC: DC-DC converters, CO: Cooling, PS: AC/DC Power Supply (source: M. A. Imran and Project Partners. "Energy Efficiency Analysis of the Reference Systems, Areas of Improvements and Target Breakdown," Technical Report, EARTH Project Report, Deliverable D2.3, 2012).

maximize the overall efficiency of the wireless link, taking into account all electronic parts, and the propagation channel [25, 26].

Finally, using OFDM also has the great advantage that we can simultaneously transmit energy and information with high efficiency, optimizing each subcarrier either for data rate or for energy collection [27].

4. The Price to Pay for OFDM: Its Low-Power Amplification Efficiency

4.1 The Need to Save Energy

After its invention, the telegram took 90 years to spread to four-fifths of developing countries. However, for the cell phone, the comparable diffusion was achieved in 16 years. In fact, the first mobile phone call using the Global System for Mobile Communications (GSM) took place in 1991, in Finland. Then, just 15 years later, there were over two billion mobile subscriptions. Today, more than half of the population of the planet has a mobile subscription. Thanks to the high-speed mobile data networks, such as 4G, the users are intensive consumers of internet, including video streaming, i.e., Video on Demand (VoD), uploading and downloading files to/from cloud storage, and also surfing on social networks (Facebook, Twitter, etc.,) and playing online games, etc. This continuous demand for high data rate wireless communication and ubiquitous access, comes at the cost of a sizable carbon footprint, and huge energy consumption. For example, it has been estimated that the whole Information and Communication Technology (ICT) produced 2% of the global CO_2 emission in 2012, which is equivalent to the aviation industry emission, or one quarter of the emissions by all vehicles around the world [28]. Moreover, if nothing is done, the overall ICT footprint might almost triple between 2007 and 2020 [29]. For example, regarding Vodafone's business footprint, Vodafone had a total worldwide annual emission of 1.45 million tonnes of CO_2 in 2007/2008 [31], the total energy consumption of Vodafone is estimated to 3,000 GWh. In addition, the energy demand is always increasing. Therefore, ICT energy consumption became a crucial concern, where industries and universities are trying to reduce it. Thence, "Green Communication" has become one of the top areas in the field of ICT. Currently, one of the biggest challenges is to reduce the energy consumption of base stations (BSs), which make up to about 80% in the total energy consumption of cellular infrastructure. In fact, in today's macro base stations, the high Power Amplifier (PA) efficiency plays a key role in the energy efficiency of the whole transmitter chain, as the PA is one of the most power-consuming components. Based on different studies, the PA dominates the power consumption in base stations and requests focusing its energy efficiency improvements. For example, EARTH project reports an estimation of the power consumption of diffierent LTE base station types for 2010 and 2012. Figure 3, [30], shows the power consumption of different sections in macro and micro LTE base stations. The PA power consumption account for 55- 60% of the overall power consumption at full load. Under those circumstances, the power amplifier, in macro base stations, consumes at full load between 743 W and 810 W, which is significant.

For digital terrestrial TV networks, the percentage of PA power consumption is even higher, where transmission power can reach 100 dBm (compared to 43 dBm for a 4G LTE macro base station). As an example, for France, with 12 000 transmitters in operation (with radiated power ranging from a few watts to 5 kW), the French Digital terrestrial TV transmission network has a total radiated power of about 1 200 kW and consumes about 46 GWh electrical energy per year for the RF amplification part alone. The resulting yearly energy cost for the network operator is about 4 000 k€. Thus, improving the PA efficiency by 10 to 15% means saving 360 to 540 k€ a year. This highlights the vast potential for energy savings by improving the PA energy efficiency.

4.2 The Power Amplifier Issue

For all sorts of telecommunication systems, in order to properly transmit the information, the signal has to be amplified to cope with the channel impairments and attenuations. Hence, the Power Amplifier (PA) is a vital element in a telecommunication system transmission chain. The principle of the mobile phone PA is much the same as that of a television with the difference of transmitting powers varying from few hundreds of milli-watts in mobile phones to hundreds of watts in television transmitters.

However, the PA is still hard to design because of the key factors related to its performance, which include: the emitted mask power; battery consumption (linked to power amplifier efficiency); the channel propagation attenuation (linked to power amplifier gain); and the carrier-to-intermodulation ratio requirement (linked to power amplifier linearity). The PA design problem is exacerbated due to the conflicting parameters of linearity and efficiency: the efficiency has a maximum near the saturation point of the amplifier, the point where non-linear effects are most severe. These non-linear effects are the major power amplification drawback.

On the other hand, in addition to the compromises that have to be made among all these factors, the ever-increasing improvements in digital communication techniques for high data rate transmissions, bandwidth improvement, and ever-rising spectral efficiencies have led to high signal envelope fluctuations. This is clearly illustrated by the evolution in-modulation techniques that evolved from analog single-carrier modulations for low data bit rates to digital multi-carrier and coded systems for very high data bit rates. This trend has largely modified the signal waveforms, especially their Peak-to-Average Power Ratio (PAPR), which is defined as the ratio of maximum instantaneous power to mean power.

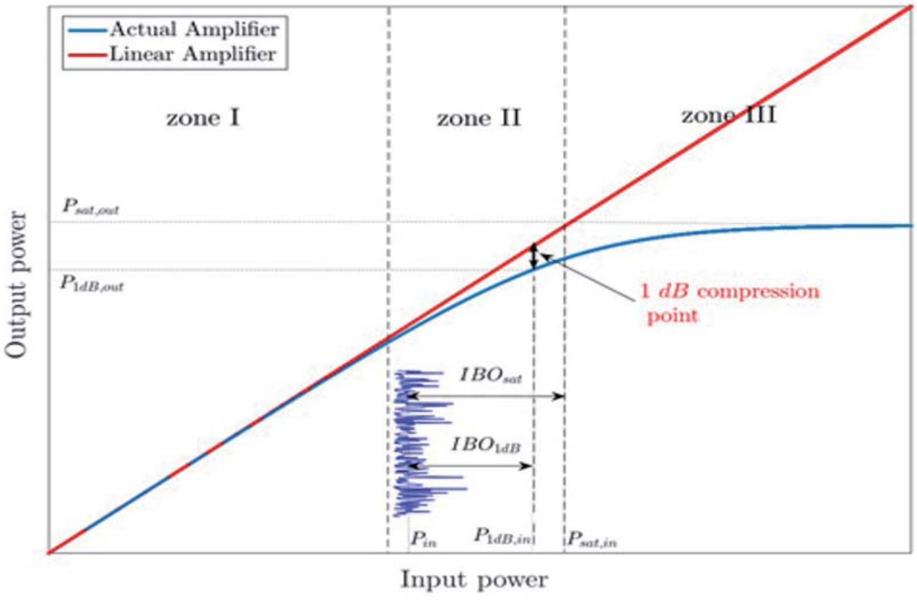

Figure 4. Power amplifier characteristics: linear, compression and saturation areas.

Consequently, the efficient power amplification of such signals (ie., PA operation near the saturation point), in the absence of any special processing, induces severe impairments: the well-known non-linear distortions. Hence, this returns to the problem of efficient power amplification of large envelope signals with non-linear distortionThe high Power Amplifier (PA) dominates base station power consumption and implies focusing energy efficiency improvements on this device. Considering the PA characteristics and the PA power efficiency, we can see that while the PA linearity increases, the PA efficiency decreases and vice versa. Therefore, a trade-off between the power amplifier efficiency and linearity must be carefully considered, especially when multicarrier modulations are used, because they exhibit a high Peak-to-Average-Power Ratio (PAPR). Consequently, the PA efficiency and linearity are of primary concern due to the aforementioned reasons.

In this section, we will start with an overview of power amplifiers, including their power consumption and efficiency, their nonlinear characteristics, as well as memory effects. Next, we will present some PA behavior models existing in the literature. Afterwards, to quantify the nonlinearity effects, we will define some figures of merit like the Error Vector Modulation (EVM) and the Adjacent Channel Power Ratio (ACPR). Later, the state of the art of the PA linearization techniques is presented. Then, we discuss the trade-off between the PA linearity and the PA efficiency, as well as the exciting different approaches in the literature to combine the PAPR reduction and linearization to improve this compromise. Finally, a global approach that controls the PAPR reduction and linearization in a flexible way and based on the transmission conditions is proposed.

4.3 Efficiency and Linearity Trade-Off

Traditionally, an input power back-off (IBO) is applied to the signal in order to minimize saturation effects. As we can see in Figure 4, the larger the back-off, the lower the PA distortions. However, this solution is not practical since the PA efficiency dramatically decreases as the back-off increases. In Figure 4, we present an actual PA characteristic. It is designed for Digital Video Brodcasting-Terrestrial in the 174 MHz to 230 MHz VHF broadcast band, where it can deliver 50 W [32]. We can clearly see that as the PA operates at power levels below saturation, the PA efficiency degrades. Therefore, while the PA linearity increases, the PA efficiency decreases and vice versa. So, a trade-off between the PA linearity and the efficiency should be carefully considered. Furthermore, this problem is more complicated when we use signals with nonconstant envelopes such as multicarrier signals that are characterized by high PAPR values. In fact, if we have to avoid the saturation of high signal peaks, then the average power level will be removed significantly from the saturation zone. Consequently, this will result in very low PA efficiency. On the other hand, if we drive the PA with the average power near saturation, to maintain maximum power efficiency, then peak power levels will drive the amplifier into the saturation zone, creating larger nonlinearities. In the next subsection, we will present the PAPR reduction and how to establish the best compromise between linearity and efficiency.

5. PAPR Reduction for OFDM: One Way to Save Energy

5.1 PAPR Definition

The signal fluctuations referred to above are mostly described using a value called the PAPR for Peak to Average Power Ratio.This parameter is a good estimate of the range over which the signal power fluctuates, and is related to its mean value. For a continuous signal $x(t)$ defined over $[0,T]$, $\mathrm{PAPR}\{S(t)\}$, is defined by

$$\mathrm{PAPR}\{S(t)\} = \frac{\max\limits_{t\in[0,T]} \left\lfloor \left|S^2(t)\right| \right\rfloor}{\frac{1}{T}\int_0^T \left|S^2(t)\right| dt} . \qquad (2)$$

This definition can be derived for any kind of signal and the definition provides the PAPR upper bound, but without taking into account the probability of the occurrence of peaks. This is derived by the Complementary Cumulative Distribution Function (CCDF) $F(l)$ defined by

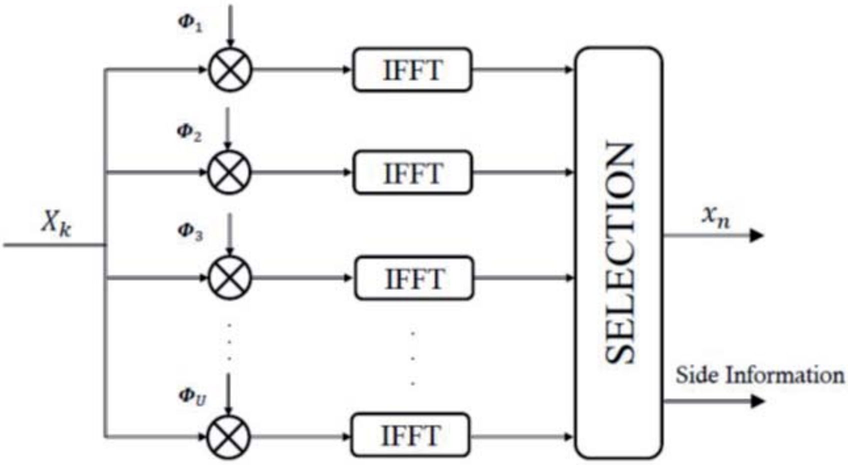

Figure 5. Selected Mapping (SLM) method for PAPR reduction.

$$F(\lambda) = \Pr\left[\text{PAPR}\left\{S(t)\right\} > \lambda\right]. \tag{3}$$

Finding F yields a more accurate description of the signal power fluctuations. This has been done mostly in the OFDM context. It is shown that the mean value of the PAPR increases logarithmically with the number of subcarriers. Nevertheless, filtered single carriers are subject to amplitude fluctuations and can be described this way.

5.2 PAPR Reduction Techniques

As far as the PAPR problem is concerned, numerous PAPR reduction techniques have been proposed in the literature. In fact, PAPR reduction techniques can be classified in three major categories: coding methods, probabilistic methods and adding signal methods. This section briefly introduces each of these categories and the criteria for PAPR reduction techniques selection.

5.2.1 Coding Methods

When N signals are added with the same phase, they produce a peak power, which is N times the average power. Coding methods consist of reducing the occurrence probability of the same phase value of these signals. A simple block coding scheme was introduced in [33], and it consists of finding all possible codewords, and then selecting those codewords of lowest PAPR. It maps 3 bits data into 4 bits codeword by adding a Simple Odd Parity Code (SOBC) at the last bit across the channels. It has been shown that using this scheme the PAPR of the signal can be reduced from 6.02 dB to 2.48 dB. This technique has two limitations. First, an exhaustive search is required to find the most suitable codeword. Second, it also suffers from complexity to store large lookup tables for encoding and decoding in the transmitter and receiver respectively. In [34, 35], authors used the Golay complementary sequences, where more than 3 dB PAPR reduction has been obtained. In [36], Davis et al. proposed codes with error correcting capabilities to achieve a lower PAPR for OFDM signals by determining the relationship of the cosets of Reed-Muller codes to Golay complementary sequences. However, for OFDM systems with a large number of subcarriers, these block codes significantly reduce the transmission rate. In summary, the actual benefits of coding for PAPR reduction for practical multicarrier systems are limited by the low coding rate, the intractable requirement for the search for a good code, as well as the prohibitive complexity of a large number of subcarriers.

5.2.2 Probabilistic Methods

The idea behind the probabilistic methods is to perform several copies of the initial signal by modifying the phase, amplitude and/or position of subcarriers and then select the copy with the minimum PAPR. These methods cannot guarantee the PAPR below a specified level. Moreover, it decreases the spectral efficiency, and the computational complexity increases as the number of subcarriers increases. The probabilistic methods include Selective Mapping (SLM), ands Partial Transmit Sequence (PTS) [37]. A block diagram of SLM technique is shown in Figure 5.

In SLM, the input data sequences are multiplied by U different phase sequences to generate alternative input symbol sequences. Each of these alternative input data sequences are then applied to IFFT operation, and then the one with the lowest PAPR is selected for transmission [38]. Therefore, its performance, in reducing the PAPR directly, depends on the number and the design of the phase factors. The corresponding selected phase factor also needs to be transmitted to the receiver as side information to properly extract the original information.

5.2.3 Clipping

Clipping is one of the most common techniques for PAPR reduction due to its simplicity and its straightforward gain reduction. Its main objective is to constrain high amplitude peaks of a signal to a given threshold, $A_{\max}$, without affecting the phase, $\Phi(x)$. Thus, the clipped signal, $x_2(t)$, is represented as

$$x_2(t) = \begin{cases} x(t) \text{ if } |x(t)| < A_{\max} \\ A_{\max} e^{j\phi(t)} \text{ if } |x(t)| > A_{\max} \end{cases} .$$

This technique results in both in-band and out-of-band distortions because of its nonlinear operation, which degrades the system performance, including the Bit Error Rate (BER), and spectral efficiency. Filtering can reduce out of band radiation after clipping at the cost of peak re-growth so that, at some point, the signal after clipping and fitering will exceed the clipping threshold [39]. Additionally, it changes the amplitude probability distribution function of the signal and decreases the signal average power, which will be discussed in the next section. To reduce the distortion effects of the clipping technique, many other contributions were proposed in the literature to modify the clipping function, such as deep clipping [40], and invertible clipping [41].

5.2.4 Tone Reservation (TR)

The TR concept was introduced by Tellado in 1997 [42]. This method is based on reserving subcarriers that do not carry any useful information and are called peak reduction tones. These tones are used for generating a PAPR reduction signal, which when added to the original multicarrier signal decreases its peaks. The peak reduction tones and data tones are orthogonal to each other, which makes recovering the data trivial.

Let $R = \{i_1, \ldots, i_w\}$ be the ordered set of the positions of the reserved tones, and R^C denote the complement set of R in $\mathbf{N} = \{0, 1, \ldots, N-1\}$, where N and W are the numbers of subcarriers and reserved tones, respectively. Thus, the transmitted signal is given by

$$X_k + C_k = \begin{cases} C_k \text{ if } k \in \mathrm{R} \\ X_k \text{ if } k \in R^C \end{cases} ,$$

where C_k is the PAPR reduction symbol with 0 in the set R^C and X_k is the data symbol with 0 in the set R, as shown in Figure 6.

The performance of this technique depends on the number and the location of these reserved tones. While increasing the number of reserved tones improves the capability of PAPR reduction, the throughput proportionally reduces because of reduction in data bearing subcarriers. Consequently, since these dedicated tones are not used for data transmission, spectral efficiency will naturally decrease. Therefore, there is a trade-off between finding the PAPR reduction and the spectral efficiency.

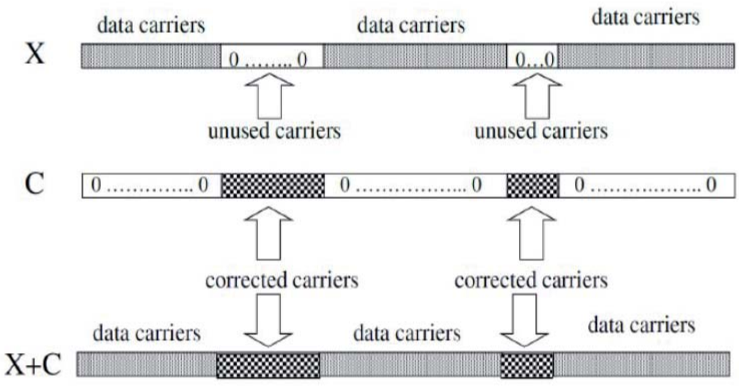

Figure 6. The Tone Reservation (TR) method for PAPR reduction.

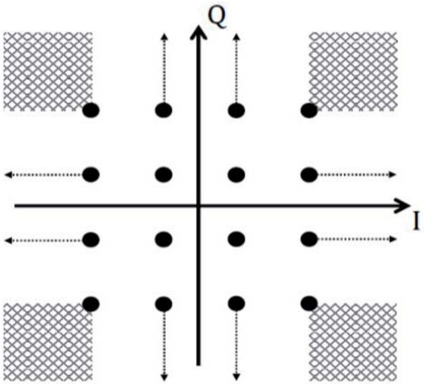

Figure 7. The Active Constellation Extension (ACE) method for PAPR reduction.

To enhance the spectral efficiency, the non-utilized tones of a standard are used as peak reduction carriers [43]. For example, there are 12 tones out of 64 that are unused in the WLAN standard and can be employed to reduce the PAPR of the OFDM modulated standard. Besides, several broadcasting standards such as: DVB for Nex Generation Handheld (DVB-NGH); the DVB-T2; and the recent version of Advanced Television Systems Committee (ATSC) 3.0 that adopted the tone reservation as a PAPR reduction technique. Generally, in these broadcasting standards, only 1% of the subcarrier is dedicated to the PAPR reduction. For example, in the 32K mode of DVB-T2, which is today the most deployed terrestrial broadcasting mode, 288 tones out of 27265 active tones are used for the PAPR reduction. The advantages of tone reservation means there is no need for either side information, or special receiver-oriented operation. While promising, to the best of our knowledge tone reservation is not implemented in most of DVB-T2 transmitters because the performance observed with TR algorithms proposed in the DVB-T2 standard do not offer a good performance-complexity trade-off.

5.2.5 Active Constellation Extension (ACE)

ACE was introduced by Krongold and Jones in 1999 [44] based on a Projection-Onto-Convex-Sets (POCS) approach to extend the outer points of a given constellation and then minimize the PAPR. In 2003, Krongold and Jones proposed a simple implementation of ACE for faster PAPR reduction, which paved the way for ACE in modern telecommunication standards. ACE is now adapted to the European Computer Manufacturers Association (ECMA) standard that specifies an Ultra-Wideband (UWB) physical layer (PHY-UWB) for Wireless Personal Area Network (WPANs) [45]. In addition, like TR, ACE is proposed as an optional PAPR reduction technique for DVB-T2, DVB-N5H, and ATSC 3.0.

The basic principle is easily explained by the following example of a 16-QAM constellation, shown in Figure 7. The constellation point at the boundaries can be freely moved in the shaded region. Likewise, the other outer points can be dynamically extended away from the original constellation point (see Figure 7). Consequently, additional co-sinusoidal and/or sinusoidal signals are added to the transmitted signal. These signals are then used to reduce the time-domain peaks in the transmitted signal by intelligently adjusting the new constellation points. The advantage of ACE is that no side information is needed and the BER performance and data rate are not affected. However, this comes at the cost of a moderate increase in the power of the transmitted signal. In addition, ACE has poor performance when the number of constellation points increases as the percentage of points that can be manipulated decreases.

5.3 PAPR Reduction Example and Efficiency Gain Illustration

This example shows that the HPA efficiency exhibits a maximum, highlighting the trade-off between the PAPR reduction gain and the complexity of the SLM method (Figures 8 and 9, [46]): before this maximum, the PAPR gain provides a large HPA efficiency versus the SLM complexity and consumption. But after this maximum, even though the PAPR gain is larger, the associated SLM complexity is too large, which penalizes the HPA efficiency [46].

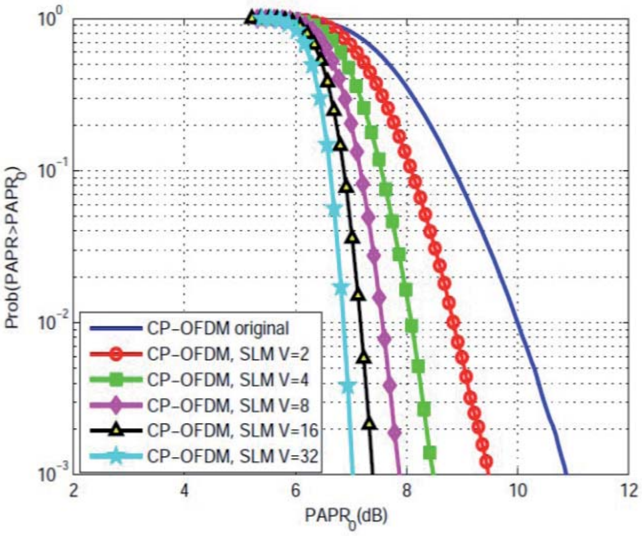

Figure 8. SLM performance for CO-OFDM (N=256 and CP=18) (source: "Global Power Amplifier Efficiency Evaluation with PAPR Reduction Method for Post-OFDM Waveforms," Y. Louet, D. Roviras, A. Nafkha, H. Shaiek, R. Zayani, IEEE ICWCS 2018, Lisboa, Portugal).

6. Conclusion

This article gave a picture of OFDM and why so many telecommunication systems are based on it. Due to the frequency-wise characteristic, OFDM can handle very selective channels to convey high date rates with reasonable complexity both at the transmitter and the receiver. Nevertheless, the price to pay for this frequency vision is the PAPR of the signal to be transmitted, which is very high, and which decreases the energy efficiency of the amplifier. Several efficient methods have been proposed to mitigate this PAPR and make the amplification more power efficient. This article highlights the use of one PAPR reduction method (Selected Mapping) to increase the energy efficiency of an amplifier: it appears that the overall energy budget is driven by a trade-off between the gain obtained with the method and its complexity.

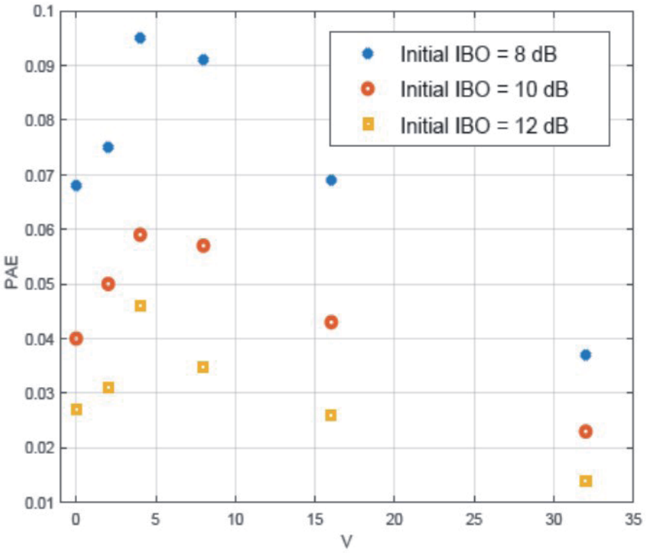

Figure 9. HPA efficiency for OFDM and WOLA-OFDM with the SLM method (source: "Global Power Amplifier Efficiency Evaluation with PAPR Reduction Method for Post-OFDM Waveforms," Y. Louet, D. Roviras, A. Nafkha, H. Shaiek, R. Zayani, IEEE ICWCS 2018, Lisboa, Portugal)

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Commission D Contribution From Transistor and Laser to Wireless Communication and Sensing: Seventy Years of Service to Radio Science

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Abstract

This paper is the Commission D contribution to celebrate the URSI centenary. The paper is primarily a set of contributions from previous Chairs of the Commission. Each contribution focuses on one of the hot topics and the evolutionary vision discussed in URSI meetings, in particular, the GASS. It also includes a contribution from the IEEE Microwave Theory and Techniques Society (MTT-S), a sister society.

1. Introduction

While the URSI Commission C structure was formed after 1975, the origin of Commission D certainly goes back to the invention of the transistor, in 1948. Indeed, thanks to this remarkable and decisive invention, the concepts of component, circuit and system became a clear reality in the scientific community. Naturally, the notion of integration appears to be fundamental because it encourages the coherent association of several components to achieve a predefined target function. This notion of integration appeared in the early 1960s, in the field of electronics, with the birth of printed circuits and silicon Integrated Circuits (ICs). A decade later, the invention of the laser, and laser diode, followed by integrated optical circuits shaped the foundation of photonics. From the beginning, Electronics and Photonics were the key terms of reference for Commission D. It is relevant to note that due to the very rapid progress of hybrid and monolithic integration technologies, the topics for the sessions organized by Commission D, during the GASS, overlap diverse themes and applications based on the exploitation of features offered by Electronics and Photonics. Commission D was considered a service Commission for URSI and the subjects discussed, during URSI meetings, overlap topics for some IEEE societies in particular: Microwave Theory and Techniques Society (MTT-S), Photonics Society, Antennas and Propagation Society (APS), Electronic Devices Society (EDS), Electromagnetic Compatibility Society (EMC-S), and Communications Society (COM-S).

While sharing the same integration technologies and exploiting the same Maxwell's equations, the electronics and photonics topics were not collaborating well. Commission D contributed to the birth of optical microwave applications. Electronics and photonics will benefit greatly if both sides opening their technical windows and shared common technical solutions, while promoting the specific features of each domain. The other challenge, Terahertz domain received, and continues to receive remarkable attention as an emerging domain. More recently, wireless solutions have become popular as they are implemented everywhere and are impacting everyday life and human societies. Since GASS 2008, topics like Terahertz, Wireless Sensing, RFID and Energy Harvesting have been covered at specific sessions, Tutorials, and General Lectures, during GASS, and the two URSI Radio Science Conferences (AP-RASC and AT-RASC).

This commemorative paper reports on the evolution and some of the hot topics and the vision of commission D. After this introduction, the rest of the paper is organized in seven sections provided by previous Chairs and a final conclusion. Each section is dedicated to a hot topic and evolutionary vision. Contributing Chairs are Prof. T. Itoh, Prof. A. Seeds, Prof. P. Russer, Prof. F. Kaertner, Prof. S.Tedjini, and Prof. A. Georgiadis. Moreover, due to the strong natural link between commission D and IEEE societies, in particular MTT-S, Prof K. Wu, former president of MTT-S, has provided a contribution.

2. Optical Techniques to Assist Microwave Components Contribution from Prof. Tatsuo Itoh, Commission D Chair 1993-1996

2.1 Introduction

Currently, a number of different approaches are employed for microwave and optical interactions. In some approaches, an attempt is made to replace the traditional microwave functions with optical functions. In these methods, understanding the merits and demerits of the optics is important so that the functions that can be enhanced, or only become possible by the use of optics, are realized. In the present paper, a method will be addressed in which the microwave functions are preserved, as much as possible, and the well-established microwave techniques are used to the fullest. The optical technique is only used to assist the realization of the microwave functions.

2.2 Optical Control of Microwave Oscillator

It is well known that the nature of the Schottky contact in the Field Effect Transistor (FET) can be controlled by optical illumination. Therefore, the illumination can be thought of as a hidden (fourth) terminal for the FET and this is useful as an unwired interconnection to control complicated microwave circuits made of FETs. For instance, the oscillation condition, for an integrated antenna with an FET oscillator, can be controlled if the Gate area of the FET is illuminated [1]. Since the DC bias and the optical bias can be used, the degree of freedom in controlling the oscillation is enhanced. The technique is even more important in the complicated coupled oscillator-antenna. It was demonstrated that the coupled oscillator can keep only one mode, due to the nonlinear dynamics, depending on the initial and boundary conditions in the circuit. The FET was used as a passive device, illuminated to change the boundary condition, and the resultant switching of the oscillation mode was observed [2]

2.3 Antenna Remoting

It is often necessary to control an antenna at a remote site. Since optical fiber has extremely low loss, it is advantageous to deliver the microwave signal over an optical fiber. To this end, the optical carrier has to be modulated at the control site, and demodulated at the antenna site. One realization is to use a coupled active antenna for both beam steering and beam switching. The reference signal injection, locking all oscillators, is delivered by an optical carrier. It is also possible to deliver the control signal by an optical carrier [3, 4]

2.4 Conclusions

Several examples have been presented in which the optics assisted the microwave functions of microwave circuits, such as active antennas.

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2.6 Comment

With leadership by Professor Okoshi of Japan and Madam Henaff of France, I was asked to chair Commission D with a tenure for 1993 – 1996. As usual, I was elected as Vice Chair of the Commission for 1990- 1993. Prior to involvement in the international activities of URSI, I held the position of Commission Chair of United States National Committee (USNC) from 1988 through 1990. I have learned that Commissions C and D were considered as service commission to URSI in earlier times. Some of the unique features, and problems, of URSI and its Commissions were discussed repeatedly among the leadership of the URSI. Of course, my involvement with URSI started with technical activities such as the presentation of papers at URSI related conferences. However, URSI activities are unique in that the Union comprises countries called Members, while technical activities are organized by the Commissions. URSI technical activities are wide-spread. Several Commissions have technical overlap with several IEEE Societies: some overlap with as many as 10 (Record from XXVI GA in Toronto 1999). Commission D is no exception and encompasses the territory of IEEE Societies like MTT-S, EDS, Photonics, APS, EMC, COM, and more. Furthermore, Commission D activities overlap with many Physics organizations. Such a unique feature is both an advantage and a disadvantage for a scholastic organization. Externally, most Commission D Radio Scientists (individual membership as Members are countries) have a home base elsewhere. Internally, coordination between Electronics and Photonics has always been a challenge. To attack this problem, various efforts were implemented. One example was ISSSE (International Symposium on Signals, Systems and Electronics), a coordinated effort between Commissions C and D. I was involved in the organizing committee for Paris, in 1994, and in San Francisco, in 1995, as Vice Chair. Although the program was successful, the impact on URSI left much to be desired. However, it is unfortunate that the ISSSE was terminated.

3. Commission D's Scope: 1

Contribution from Prof. Alwyn Seeds, Commission D Chair 1999-2002

Electronics and Photonics encompasses all technologies required for modern communication systems. This scope is of particular value in addressing the challenges of converged systems, such as the internet, which includes wireless access, line transmission over copper or optical fibre, routing, switching and information storage in electronics, and long-distance connections through fibre and (to meet aeronautical, maritime, rural, temporary and resilience requirements) satellite.

The next two decades are likely to see a further steep growth in the data volume transmitted, together with an even more rapid growth in the number of devices connected as a result of the Internet of Things products, see Figure 1. The theme of integration of electronics and photonics on silicon, already recorded by Commission D, is likely to come to full fruition, enabled by the first demonstration of long lifetime (> 100,000 hours) monolithically integrated telecom wavelength lasers on silicon [1].

Major challenges to be addressed will include reducing the energy consumption of information systems, managing the co-existence of the huge numbers of wireless devices and overcoming inherent inefficiencies of the Internet Protocol. System complexity will make hardware supported information security features of special value. Radio frequency spectrum scarcity to support the expected growth in device numbers, and increases in data rates for applications such as immersive video, will lead to requirements for high performance terahertz devices and systems [2].

Quantum communication systems have made rapid advances in the last decade [3] and lower cost technologies for their widespread deployment are also likely to be of interest to Commission D in the future.

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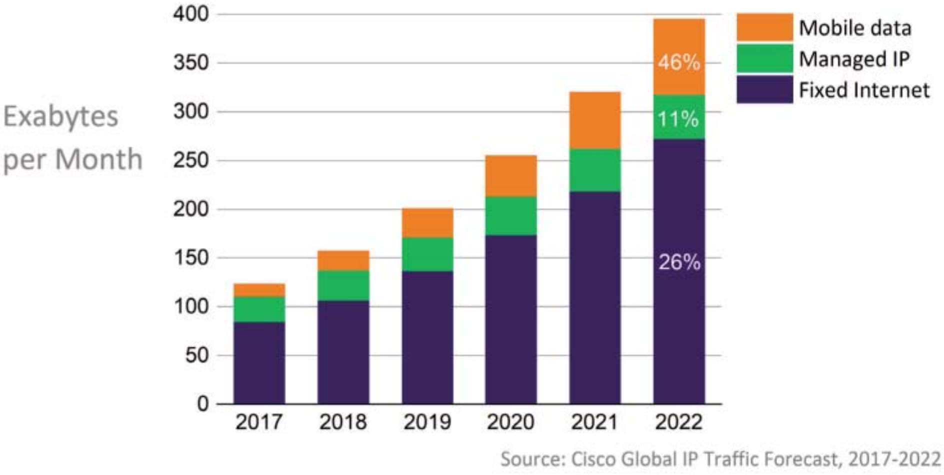

Source: Cisco Global IP Traffic Forecast, 2017-2022

Figure 1. The growth in data traffic by year.

3.2 Comment

Commission D's scope – Electronics and Photonics – encompasses all technologies required for modern communication systems. The combination of electronics with photonics is not commonly found in other technical societies.

Important external links for the Commission will continue to be with the IEEE Microwave Theory and Techniques, Electron Devices and Photonics Societies.

A major developing issue is the pollution of the electromagnetic spectrum from electronic systems ranging from computing devices, and their power supplies, to solar photo-voltaic inverters and digital subscriber line access networks. This is leading to a major rise in the radio-frequency noise floor, with levels already 30 dB above the natural background in urban areas, requiring corresponding increases in power output from transmitters to obtain reliable system operation. This is undesirable on both energy efficiency and electromagnetic exposure grounds. There is scope for joint work with Commissions B and E to address this challenge.

4. Commission D's Scope: 2

Contribution from Prof. Peter Russer, Commission D Chair 2002-2005

Over the past fifty years, microelectronic development has followed Moore's Law, an empirical law that predicts that the device density and performance of monolithically integrated silicon circuits will double every 18-months [1]. During these fifty years, the feature sizes of transistors decreased from 10 000 nanometers (10 microns) to about 15 nanometers. Over the last 40 years, silicon-based Complementary Metal Oxide Semiconductor (CMOS) technology has become mainstream technology for digital, analog, and mixed-signal applications. The downscaling of CMOS transistors follows Moore's Law and primarily improves signal processing and data storage in the so-called system-on-chip. Today the main trends are categorized as follows [2, 3]:

- More Moore: These developments are aimed at further miniaturizing switching elements with feature sizes below 100 nm down to the physical limits of CMOS technology, as well as complete system integration on-chip.

- More than Moore: This branch extends beyond the boundaries of conventional semiconductor and semiconductor applications and integrates various non-digital functionalities by combining different types of chips into miniaturized systems in packages.

- Beyond CMOS: This area focuses on innovative components based on novel principles, novel materials, and novel technologies.

For high-frequency analog applications SiGe Heterojunction Bipolar Transistors (HBTs), with transit frequencies and maximum oscillation frequencies above 300 GHz and monolithic integrated millimeter-wave circuits based on these HBTs, were developed [4]. The on-chip integration of antennas opened new vistas for novel devices and integrated systems for sensing, detection, and wireless communications [5]. Terahertz technology [6] based on Quantum Cascade Lasers [7] as transmitter elements, and high-speed antenna-coupled thermocouples as detectors and Mixers [8] will facilitate extreme high-bandwidth wireless communications.

The long-term goals of a technology are determined by reasoning about the evolution of technology requirements and the desire to open new horizons. During this evolution, ideas always existed that point the way to reach the goals [3]. A good example of this is the invention of transistors, and integrated circuits, that have led to today's chip technology. The basic idea was to replace vacuum tubes with solid state devices. The higher charge carrier density in the solid-state devices, compared to vacuum electronic devices, enabled miniaturization. Although this long-term goal of the last century was achieved, today's microelectronic devices are unable to fully exploit the electron density of solids. The reason for this is that all state-of-the-art solid-state devices are based on the doping of semiconductors. The doping, and resultant charge carrier density available, are approximately, by a factor of 10^4, below the total electron density in the material. Most concepts for realizing the long-term goals of nanoelectronics are based on the idea of gaining this factor of 10^4, and finding ways to circumvent the limits imposed by the low densities of the dopants. This trend towards higher density follows the famous statement "there's plenty of room at the bottom" by Richard Feynman [9], and the associated invitation to explore the nanoworld and to realize high-performance three-dimensional systems based on the smallest structures.

The trend towards ever larger systems with ever smaller components leads to requirements that can only be met with new types of components combined with new system architectures. Examples include quantum computers [10, 11] and cellular automata [12, 13], as well as molecular [14, 15] and biologic [16] devices and system architectures. These architectures promise to either allow higher electron densities or cope with smaller densities.

The influence of nanostructured electronics extends to many disciplines, ranging from optoelectronics and nanomechanics to biology and environmental technology. Future nanoelectronic technologies will be highly important for technology development in a broader context, such as information and communication technology, biology, and "green" power generation, and storage [13]. The enormous mobility of electrons in carbon-based materials, such as carbon nanotubes [17], and monolayer and multilayer graphene [18], as well as the interesting property of a completely vanishing effective mass of the electrons in graphene have raised hopes to apply this material on a large scale in an advantageous manner.

Superconducting RF nanoelectronic devices exhibit considerable potential for application in future electronics [19, 20]. Josephson effect-based devices allow generation, detection, mixing, and parametric amplification of high-frequency signals up into the terahertz region and exhibit high sensitivity, low energy consumption, and small size. Nonlinear lumped-element circuits can be realized that are small enough so that quantum mechanics governs the circuit dynamics. This permits the generation of two-photon coherent states and entangled states [21, 22] and opens the door for quantum information processing. Nanotechnological fabrication techniques have a strong impact on the development of novel Josephson-effect-based devices and systems for quantum information processing [23, 24] and the efficient simulation of physical systems [25, 26].

4.1 References

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5. Silicon Photonics

Contribution from Prof. Franz Kaertner, Commission D Chair 2008-2011

A recurring strong theme in the past URSI GASS Meetings was the area of silicon photonics, which is rapidly growing and has many commercial applications already in the field. The vision that silicon, the major materials platform for electronics, CMOS-Technology, is also a superb material for optics and opto-electronic applications was pioneered in early research papers in the late 1980s and early 1990s [1-3]. Many challenges were addressed since then with innovative ideas and progress in semiconductor fabrication, such as the demonstration of low loss silicon waveguides, with losses well below 1 dB/cm [4, 5]. Silicon photonics, was originally driven by applications in telecommunication networks and intra-chip communications, and the increasing demand for low-cost, short-range optical interconnects in data centers and the computing industry. Many products are already available in the market and have been widely deployed in the field [6]. The expansion of silicon photonics platforms with other silicon compatible materials, such as silicon nitride, III/V-semiconductors [7], graphene [8], and Electro-Optic (EO) polymers [9] greatly expands the versatility of silicon-photonics. Especially, silicon nitride micro-rings facilitated the transfer of micro-resonator frequency combs in the silicon photonics platform, leading to the implementation of complex optical systems. These are still in the research arena, and fill whole optical tables on a chip, such as optical frequency combs and complete digital optical frequency synthesizers [10, 11], and in the future will overcome electronic limitations in current analog-to-digital converter technologies [12].

Other areas that continue to thrive in Commission D is the growing area of THz Technology, ranging from efficient THz generation by optical and electronic methods to THz systems [13]. Optical sources, which rapidly expand in wavelength, to the mid- and far-infrared range, in power, to the multi-kW range [14], and in pulse duration, to single-cycle duration facilitating atto-second pulse generation, and atto-second science [15] via strong field physics in gases and solids. In quantum optics, quantum information [16], quantum sensors [17], and quantum measurements are opening up new areas of quantum technology. In electronics, new frontiers in nanoelectronics, wireless systems [18], and RFID [19] are rapidly expanding.

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5.2 Comment

Commission D, representing both Photonics and Electronics within URSI, is strongest in those areas where a convergence in underlying technology platforms, or a convergence in frequency ranges is happening, or is imminent. This is the case for silicon photonics, which merges integrated optics with integrated electronics, facilitating completely new systems such as intra and inter chip optical communications, solving some of the bottlenecks of purely electronic systems, or enable the miniaturization to the chip-scale of complex optical systems by co-integration with electronic control loops. Despite silicon photonics technology already being in the commercial arena, there is still great potential for researchers to invent completely new devices of an intrinsic opto-electronic nature, which are only possible due to the convergence of optics and electronics on a joint technology platform, the CMOS-platform, and enabling functionality not know in optics or electronics alone. This has yet to occur. Similarly, with wireless communication progressing into the THz wavelength range, to cope with the enormous amount of data necessary for 5G-applications and generation of systems beyond, we will, even more, enter what we call today microwave photonics: A seamless merging together of optics and electronics. It is in these areas that URSI and Commission D can fill a unique space, by bringing these communities together.

6. Radio Frequency Identification, An Old Technology With a Brilliant Future

Contribution from Prof. Smail Tedjini, Commission D Chair 2011-2014

The physics behind Radio Frequency Identification (RFID) technology is primarily the well-known backscatter phenomena, which can occur in quite different physical situations, where radio-waves are present. Backscatter exploitation became trendy in electromagnetism as it allowed the attainment of very low power wireless applications that are very, or even totally passive. One of the early backscattering applications was reported in the patent of E. Brard, published in 1930 [1]. Later works of H. Stockman [2], who explained the physical operating principle of RFID, and L. Theremin [3], who developed a passive wireless spying microphone device were considered the cornerstones of the RFID. This device called the "thing" is certainly the very first passive wireless sensor and the ancestor of the RFID technology. Nowadays Radar technology and RFID systems are probably the most relevant and popular techniques exploiting backscatter signals.

To model the backscatter signal, the Radar Cross Section (RCS) is often considered. The RCS measures the ability of a given target to reflect the incident signal either in the same direction, as the incident signal (monostatic RCS), or in another direction (bistatic RCS). The RCS is usually noted as σ and expressed in m^2 or dBsm (decibel to square meter). It can be seen as the combination of three factors of the target: projected cross-section, reflectivity, and directivity. So, depending on the shape and material composition of the target, the RCS can be frequency dependent. For example, the monostatic RCS for the structural mode of a rectangular conductor plate of size W and H, at the frequency f (c is the velocity of light), and under normal illumination, is given by

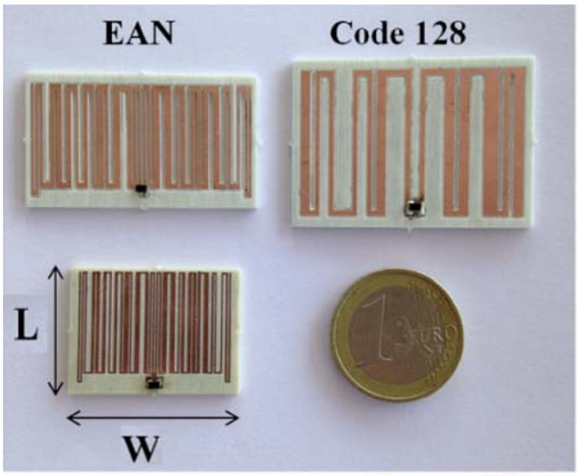
$$\sigma = 4\pi\left(WHf/c\right)^2 \qquad (1)$$

Another RCS contribution known as the antenna RCS mode is due to antenna re-radiation. In most cases, only one of the two modes is considered depending on their amplitude. The total RCS for the monostatic case is [4]

$$\sigma = \left(\frac{{\lambda_0}^2}{4\pi}\right) G_0^2 \left|A - \Gamma^*\right|^2 \qquad (2)$$

where λ_0 is the operating wavelength, σ is the total RCS, G_0 is the antenna gain, A is a complex parameter independent of the antenna load, Z_L, and

$$\Gamma^* = \left(Z_L - Z_A^*\right) \Big/ \left(Z_L + Z_A\right) \qquad (3)$$



Dimension (mm)	Code128	EAN (Large)	EAN (Small)
W	41	40	29
L	29	23	22

Figure 2. Examples of advanced UHF RFID tags: in this advanced design, the barcode is transformed into a UHF antenna connected and matched to the RFID chip (visible in the center of the figure). These tags are compliant to Code 128 (right) and two different sizes of EAN (left) and can be read by both RFID and barcode readers.

where Z_A is the antenna impedance.

Conventional RFID: The expression (2) introduces the idea of controlling the antenna RCS using varied load impedance resulting in different reflection coefficients and therefore different RCS. This is the case of conventional RFID, where the tag is composed of an appropriate antenna connected to an RFID chip. The RCS variation is achieved through the RFID chip by switching its impedance between at least two states, thus making it compliant with a digital signal. The UHF RFID tag is shown in Figure 2. To make the tag fully passive the RFID chip is composed, among others, of a harvesting section, and a digital unit. The former allows the tag to be fully passive, while the later perform digital communication.

One of the most important properties of RFID tags is their read-range, which depends on the chip sensitivity and antenna tag design. Modern RFID chips require less than -22 dBm to be activated, which results in read-range of more than 25 m (under strict conformance to power and frequency regulation). Conventional RFID is thoroughly standardized and complies with several regulations and norms that support its implementation in real applications worldwide. While the RFID tags are nowadays extensively exploited for identification purposes, as each RFID chip receives a 32 bits ID code, the transformation of RFID tags into RFID sensors is intensively investigated, allowing RFID technology to perform the last few meters of the Internet of Things and to enable Artificial Intelligence.

Chipless RFID: For a general passive target, with no variation in impedance or geometry, as illustrated in equation (1), the RCS is frequency dependent even for a simple shape. Moreover, any target composed of some metallic part can be seen as a short-circuited antenna, where the RCS is governed by equation (2), in which the parameters $\Gamma\Gamma$ and A must be specified. It is worth noting that depending on the operating frequency, the target can have a response of a resonant and/or anti-resonant circuit. Under these circumstances, the RCS could reach optimum values that define a specific electromagnetic signature of the target. If each target is well designed, it will exhibit a specific electromagnetic signature that can serve as the ID. A chipless tag is primarily a target designed to have a predefined electromagnetic signature in the backscatter signal.

In the literature there are two visions for the predefined signature: time domain coded, or frequency domain coded. Time domain coded chipless tags based on a Surface Acoustic Wave (SAW) were demonstrated with coding capacity of more than a hundred bits operating in the 2.45 GHz ISM bands. However, SAW devices are quite expensive and their technology is much more complex than the usual printed PCB tags and therefore they are less competitive in the context of low-cost RFID. Frequency domain coded chipless tags are more popular and easier to design, however their capacity is limited to some tens of bits, which is far from the coding capacity of conventional RFID (32 bits). Another shortcoming of chipless RFID is the absence of solid regulation and a lack of a commercial reader.

It is amusing to note that the very first tag developed, which is certainly the ancestor of modern tags, is a chipless tag-sensor, but nowadays it is the conventional tags that are implemented in the real world and everyday life. The two families of RFID continue to progress and are expected to respond to specific and sometimes complementary applications. However, conventional RFID has reached a very high level of maturity and its applications are counted by thousands, whereas the chipless RFID is still in its infancy and many developments are essential before considering its implementation in real applications. Both RFID families are extensively investigated in industrial and academic laboratories worldwide.

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7. Energy Harvesting

Contribution from Prof. Apostolos Georgiadis, Commission D Chair 2017-2020

In the recent decade, energy harvesting has enjoyed significant attention both from industry and academia as it represents an enabling technology towards the realization of "zero power" wireless sensors. Especially in the last few years, the introduction of concepts such as the Internet of Things (IoT) and Machine-to-Machine (M2M) communications, as part of the umbrella of the fifth generation (5G) communication systems, has led to an increasing interest in energy harvesting technologies due to the multitude of new applications of wireless sensors in smart environments (smart cities, smart skins etc.) monitoring security, and others functions [1].

Under these concepts, millions of networked miniature sensing devices are employed and communicate useful information about their environment to the users of the network. Wireless sensors require an energy storage device, typically batteries, to provide them with the necessary electrical power to operate. Naturally the sensing devices' batteries could not be changed or charged regularly, as that would pose an environmental concern both in terms of the resources required to make large numbers of batteries, and the disposal of the batteries when they are spent. In addition, in certain applications such as environmental disasters or, for example, when the sensors are installed inside the human body, it may not be possible to access the sensors in order to change their spent batteries. As a result, numerous research efforts have recently been directed towards low profile, low power, energy efficient, and self-sustainable sensor networks that harvest, or scavenge available ambient energy in order to significantly extend the time interval between battery charge cycles, or even eliminate the use of batteries.

Four main categories of commonly used energy harvesting technologies can be identified, namely: solar, kinetic, thermal, and electromagnetic. In all technologies a transducer device is necessary in order to convert the form of energy that is harvested into useful electrical energy. Electric energy generation using different transducer types is a vast field with many different applications, and large variation among the size of the transducers, and the amount of energy that is being generated. As a result, the final selection of the type of transducer employed depends greatly on the application requirements and set-up.

Most energy harvesting technologies are based on phenomena that were already known, even for centuries, and recent advances in materials, fabrication, and computational capabilities have led to their performance optimization and practical application. Photovoltaic technology explores the photovoltaic effect in order to convert solar energy to electrical energy. The discovery of the photovoltaic effect is attributed to A. E. Becquerel [2], who, in 1839, discovered that certain materials generate an electrical current when exposed to light. Thin film technology both reduced the material cost, and allowed a much larger size unit to be manufactured compared to the first-generation solar cell size, which was limited to a wafer size [3]. By applying thermodynamic principles [4], the theoretical efficiency limit for first-generation silicon solar cells was estimated to be around 30%. Third-generation photovoltaic technology combines the low-cost fabrication of thin film technology with novel design concepts, leading to higher efficiency values [3].

Kinetic energy harvesters convert mechanical movements to electrical energy. A large number of applications can be classified under this category as there are many different types of mechanical movements, such as vibrations, displacements, and forces, or pressure. Consequently, there are different types of transducing mechanisms [5]. One may identify applications related to buildings, and other construction projects, such as bridges, exploring vibrations originating from a plurality of sources, such as near-by or on-going car or train traffic, human movement, wind, heating ventilating and air-conditioning (HVAC) air currents, water, and other fluid movements [5]. Vibrational energy can be harvested in moving vehicles, such as cars, trains, ships, and airplanes by properly installing transducers in sensitive places on the vehicle, such as the wheels of the car for example. There are three transducing mechanisms that are used to convert kinetic energy to electrical energy: a) electrostatic (capacitive), b) electromagnetic (inductive), and c) piezoelectric. Maximizing harvested energy by controlling the natural frequency of the transducers is a great challenge in the vibration to electrical transducer design. There are several different possibilities proposed in the literature, which include transducers with mechanically, or electrically tunable resonant frequencies, and self-tuning or adaptive tuning capability on one hand, and wideband and multiband arrays of generators on the other hand [5, 6].

Thermoelectric transducers convert thermal energy into electrical energy. Thermal energy is generated as a result of a multitude of phenomena and applications, in some cases intentionally, but most of the time as waste heat: from a process or reaction, from industrial plants to buildings, heating systems, automobiles, to the human body, which, in turn, provides numerous applications for thermal energy harvesters. There are three thermoelectric phenomena that govern the conversion of thermal energy to electrical energy and vice-versa: a) the Seebeck effect, b) the Peltier effect, and c) the Thomson effect [5, 7]. Thermoelectric generation is based on the Seebeck effect where a temperature gradient between two different metals, or semiconductors, which are in contact, creates a voltage difference between the two components [5, 7]. Because semiconductors offer much higher Seebeck coefficients than metals and metal alloys, Thermo-Electric Generators (TEGs) are built using semiconducting materials. They are usually constructed by forming arrays of pairs of p-type and n-type semiconductor pellets. The pellets are electrically connected in series using conducting (for example copper or aluminum) strips, and are sandwiched between thermally conductive ceramic plates. One important challenge of TEGs is that the efficient conversion of heat to electrical energy is inherently small when operating at room temperature, and at temperature differences of a few degrees to ten degrees [5, 7].

The concept of power transmission by electromagnetic waves initially appeared in the works of Hertz and Tesla [8]. Subsequently, in the second half of the twentieth century, beginning in the late 1950s, microwave signals were used to transfer power that was subsequently converted back to a direct current (DC). This was considered in applications such as the microwave-powered helicopter and the concept of the solar-power satellite, with microwave transmission to Earth [8]. The circuit that is used to convert electromagnetic power to DC power is the rectenna, which was patented by W. C. Brown, in 1969, and consists of an active antenna combining a radiating element (antenna) with a rectifier circuit [9]. The initial microwave power transmission applications focused on situations where directive, high-power transmission was required. The recent interest in autonomous sensors has led to the concept of ambient electromagnetic energy harvesting, or scavenging, where rectennas are used to provide DC power by converting to DC available power from existing ambient low power electromagnetic sources not specifically transmitting to power a sensor [10]. The amount of DC power that can be harvested from the existing available power is proportional to the rectenna RF-to-DC efficiency. The rectenna efficiency varies with the different rectifying circuit topologies and devices used and is dependent on the available average input power and envelope characteristics of the signal received by the rectenna, as well as the load resistance at the rectifier output [10, 11]. Rectifier circuits typically use Schottky diodes to convert microwave power to DC power. Low, and zero barrier diodes are required in order to rectify low power input signals similar to the ones used in detector applications. Typically, envelope detectors and charge pump circuits are implemented. Reported rectenna efficiencies at UHF frequencies for available input power levels of the order of 10 uW (-20 dBm) are between 15% - 25%, and increase to 40%-60% for available power levels of 100 uW (-10 dBm) [1, 10, 11].

Each type of transducer has distinct advantages and disadvantages, and is thus suitable in different application circumstances. Solar energy, provided there is sufficient light, generally represents the largest energy source, although it is challenging indoors and during the night or in cloudy conditions. Thermal energy harvesters are typically limited by low transducer efficiency, while kinetic energy harvesters are sensitive to the natural vibration frequencies of the harvester and application settings. Finally, the available electromagnetic (EM) energy density is usually orders of magnitude below the corresponding values for other energy sources. However, recent publications [12, 13] have shown that in crowded urban settings harvesting a useful amount of EM energy from the ambient background, especially using wideband or multi-band harvesters, is possible. Despite the low ambient EM energy densities, electromagnetic harvesters are intimately related to systems exploring intentional EM radiation to power up electronic devices, which leads to numerous applications of wireless power transfer, with RFID technology being a notable application example. The concept of a first generation 1G Mobile Power Network was recently proposed, integrating wireless communication and wireless power [14]. The large variation in available ambient energy of various types, and the implementation of energy autonomous circuits for communication and sensing suggests the need to integrate multiple energy harvesters of different technologies [15]. In this case, the efficient combination of DC electrical energy from different sources becomes an additional challenge for the designer.

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8. Substrate Integrated Waveguide (SIW)

Contribution from Prof. Ke Wu, President IEEE MTT-S 2016

Guided-wave structures are no doubt the most fundamental building elements of high-frequency antennas, circuits, and systems. They are usually composed of metallic and dielectric topologies, or mixed forms of both, which are made in the form of planar, and non-planar geometries, depending on design approaches, processing technologies, and application requirements. Before the year 2000, the development of high-performance RF wireless, microwave, and millimeter-wave (mmW) techniques over MHz-through-THz frequencies had often experienced difficult and expensive integration issues between planar integrated circuits, and non-planar waveguide components. Usually, the non-planar structures were bulky, and costly, and not mechanically, thermally, or electrically compatible with low-cost planar counterparts. This unfortunate mismatch, or incompatibility, created a huge challenge for transceiver front-end integration and packaging at that time.

Since 2000, the Substrate Integrated Waveguide (SIW) [1 - 4] has emerged as a powerful set of guided-wave techniques providing alternate solutions to the existing planar and non-planar structures, such as microstrip lines and metallic waveguides. Now, SIW technology has become an indispensable research and development scheme in the fields of microwave and mmW engineering. This technology has provided an attractive choice to support cost-effective, integrated transceiver front-end design and development thanks to intensive worldwide research and development activities over the last 20 years, which is demonstrated by the roughly 15,000 paper publications and countless patents, to date, on this topic.

The invention of SIW sets the stage for exploiting the inherent integration nature and common design space of planar and non-planar structures through single or multilayer substrate, in which the non-planar part is structurally synthesized in planar form. In other words, the SIW solution is nothing but a non-planar-to-planar transformation, which can theoretically be applied to any non-planar structure, including coaxial lines and dielectric waveguides, among many others, even though the earliest versions of SIW were merely related to the presentation of the metallic rectangular waveguide and non-radiative dielectric waveguide cases. As such, nearly any specific processing (fabrication) technique can be used for developing such dissimilar geometries within the same platform. This planarization of non-planar structures was realized by the use of arrays, or fences of metallized via, or air hole, or other features created on substrate for mimicking metallic walls, or creating dielectric contrasts. This approach fundamentally preserves the essential features of the original non-planar structures in terms of their electromagnetic properties and modal integrity. Thanks to the rapid evolution of processing

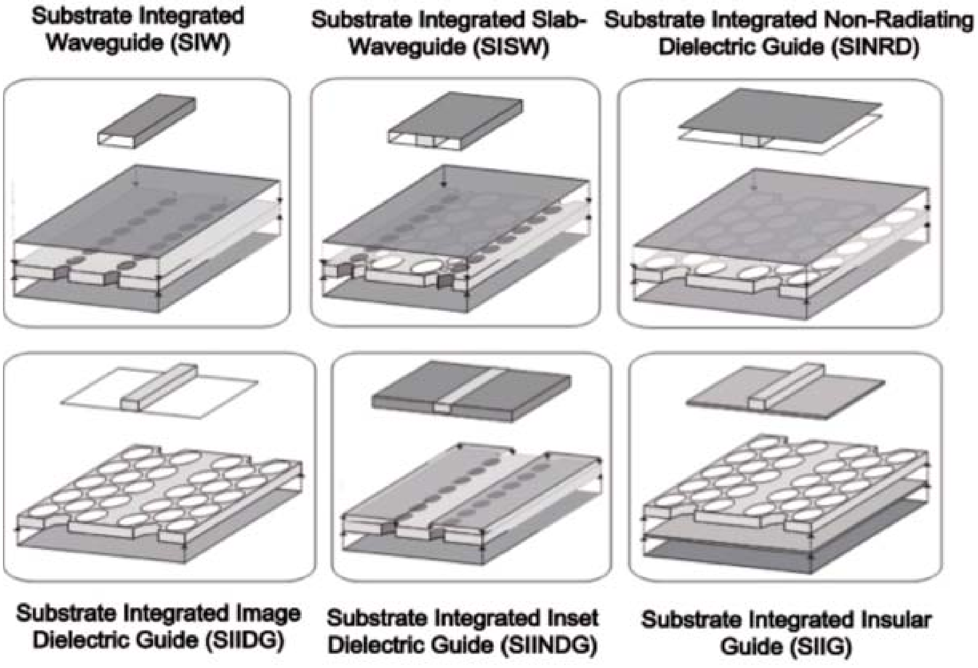
Substrate Integrated Waveguide (SIW)
Substrate Integrated Slab-Waveguide (SISW)
Substrate Integrated Non-Radiating Dielectric Guide (SINRD)
Substrate Integrated Image Dielectric Guide (SIIDG)
Substrate Integrated Inset Dielectric Guide (SIINDG)
Substrate Integrated Insular Guide (SIIG)

Figure 3. Typical topologies of non-TEM mode-based substrate integration structures.

facilities and enabling techniques, currently deployed processing techniques allow for a very efficient, high-precision fabrication of those metallized via holes, or air holes, within any substrate of interest. Such precision synthesis techniques were not readily available before the year 2000.

Figure 3 describes typical, non-TEM mode-based SIW structures [5], which are synthetized within substrate for creating similar electromagnetic wave-guiding conditions for the original waveguide counterparts. Of course, there are also TEM mode-based non-planar structures (not shown in Figure 3) such as coaxial lines, which can be directly synthesized in a similar way. Interestingly, the rapid emergence and mega-popularity of substrate integration technology for the development of antennas, circuits, and systems can be readily understood from both the historical advancement and the future prospect of a transmission line or waveguide technology development roadmap, where future trends are extrapolated with reference to the evolution of guided-wave structures, as briefly explained in [6].

The current and future expansion of SIW activities is motivated by the following interests and aspects: (1) substrate integrated metallic and dielectric waveguides for CMOS and 3D ICs development, allowing for an unprecedented exploration of high-performance microsystems; (2) the use of advanced smart materials in creating reconfigurable and innovative SIW techniques; (3) 3D multi-layered SIW solutions through emerging processing techniques such as 3D printing; (4) large-scale integration and exploitation of dissimilar SIW structures for front-end system developments; (5) design convergence and structure integration of SIW-based antenna-circuit; and (6) search for nonlinear SIW structures for exploring non-TEM mode active circuits and systems. Some of those activities were predicted and discussed in [4, 7-8].

Although there are already so many papers published and patents released in the literature on these topics, it seems that research interest and development enthusiasm, in this connection, is not expected to cease any time soon. In fact, there is an unbelievably upbeat mood for continuous expansion and evolution with reference to both fundamental research and practical development. This is essentially driven by the unprecedented growing requirements for low-cost and highly reliable microwave, mmW and THz products, and deployments for emerging 5G wireless communications and applications, Internet of Space (IoS), autonomous driving, and flying, next generation IoT, intelligent manufacturing (Industry 4.0), virtual (augmented) reality, and hardware intelligence converged by electromagnetic identification, sensing, positioning, and image recognition among many others.

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9. Conclusion

In recent decades, there has been remarkable growth in the fields of electronics and photonics. Electronics and photonics have an inherently multidisciplinary nature and their technological breakthroughs are strongly linked with advances in materials science, materials fabrication, as well as scientific computing. Nanomaterials, such as grapheme and nanotubes, progress in semiconductor fabrication expressed by CMOS transistor devices reaching nanometer gate sizes on one hand, and the explosive growth of additive manufacturing with 3D printing of metal, semiconductor, and insulator materials with resolution in the order of a few micrometers on the other hand, combined with low-cost computational resources have enabled a multitude of applications in both electronics and photonics.

The fifth generation (5G) communication networks with the commercialization of millimeter wave electronics, the Internet-of-Things and the integration of sensing and communication from RF to THz and optical regimes, with THz communications expected to lead to the sixth generation (6G) communication networks, quantum optics, and attosecond optical sources are some notable examples of recent electronics and photonics application domains.

Based on the above examples, one can therefore both identify and expect a strong interaction between Commission D and other URSI Commissions embracing interacting fields such as Metrology (Commission A), Fields and Waves (Commission B), Radio-communication Systems (Commission C), Electromagnetic Environment and Interference (Commission E), and Electromagnetics in Biology and Medicine (Commission K).

Furthermore, the Institute of Electrical and Electronics Engineers (IEEE) has a long history in the fields of Electronics and Photonics through the IEEE Microwave Theory and Techniques Society and the IEEE Photonics Society primarily, as their names suggest, a direct link to the electronics and photonics fields. Other IEEE Societies with links to URSI Commission D topics include the IEEE Electron Devices Society, and IEEE Antennas and Propagation Society. URSI Commission D has a long-standing link with IEEE Societies through the participation of its members in both IEEE and URSI activities. Last but not least, the activities of Commission D in the photonics area presents a direct link with activities of the Optical Society (OSA).

The evolution of materials with ever smaller feature sizes, and material fabrication with higher resolution and lower cost permit remarkable advances in electronics and photonics with topics such as i) THz electronics for communication and sensing, presenting the next frontier of 6G communication networks, ii) true “zero-power” electronics combining ultra-low power electronics architectures and energy harvesting technologies with concepts such as ambient backscattering and iii) electronics and photonics applied in quantum computing, representing some notable technological challenges for URSI Commission D.

100 Years of URSI: The Past, Present, and Future of Commission E

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1. Introduction (Frank Gronwald)

Commission E officially entered the stage of URSI during the General Assembly in 1975 when, after several years of discussion, URSI was reorganized and a total of 9 Commissions were defined. At that time, Commission E was named "Electromagnetic Interference Environment", a description that already was close to its current title "Electromagnetic Environment and Interference". An earlier predecessor of Commission E was Commission VIII "Radio Noise of Terrestrial Origin", established during the General Assembly in 1966, and, possibly the Commission "Atmospheric Perturbations", one of the four foundation Commissions formed at the first URSI General Assembly. In fact, the subject of Electromagnetic Environment and Interference already appeared in daily life, during the 1920s, when early music radio transmissions were disturbed by ignition sparks from passing cars, leading, in turn, to the first standards and regulations to limit unwanted electromagnetic interference fields. Along with further technological progress the subject of Electromagnetic Compatibility emerged as a discipline during the 1950s and 60s, when the protection of aircraft and other complex technical equipment against a possible Nuclear Electromagnetic Pulse (NEMP), the Lightning Electromagnetic Pulse, and other electromagnetic disturbances were intensively investigated and tested, mostly in a military environment [1, 2]. Nowadays, with the spread of electrical and electronic systems into most corners of daily life, the need to control Electromagnetic Interference (EMI) has entered into practically all areas of Electrical Engineering and Information Technology. As a consequence, the Commission E topics are interdisciplinary within Electrical Engineering and Radio Science. Many related methods are borrowed from electromagnetic field theory, microwave engineering, communication theory, the design of electronic systems, and other related fields such as the interaction between electromagnetic fields and biological systems. To cover all aspects of Commission E would necessitate covering all possible interference sources and interference victims, leading to a treatment of Electrical Engineering and Information Technology as a whole.

This Chapter intends to convey an impression of the variety of topics and methods that are considered by the scientists that have URSI and Commission E as an important part of their scientific home. To begin with, Pierre Degauque explains important measurement techniques that are used to quantify the emission of and susceptibility against interfering electromagnetic fields. This is followed by an overview of statistical electromagnetism by Luk Arnaut and Gabriele Gradoni. Statistical electromagnetism is of great importance for understanding mode stirred chambers as a special and effective test environment. As an additional aspect, testing against electromagnetic fields in the lower resonance region led to the observation that many complex electronic systems are characterized by a late-time response, which is composed of various damped sinusoids. This was the motivation for the formulation of the Singularity Expansion Method (SEM), explained by Dave Giri, which characterizes the electromagnetic response of complex electronic systems with a relatively small number of poles and zeros. Turning to natural electromagnetic noise, Yasuhide Hobara and Masashi Hayakawa summarize the most important classes of natural sources of electromagnetic interference fields. This is followed by an introduction to an exceptional lightning experimental research facility in the Swiss Alps, provided by Farhad Rachidi and Marcos Rubinstein. Turning to communication systems, Virginie Deniasu summarizes the history and issues of Electromagnetic Compatibility in Wireless Systems. The fact that Electromagnetic Interference can also intentionally be created and used is explored by William Radasky in his contribution on Intentional Electromagnetic Interference (IEMI). Finally, Chaouki Kasmi and Jose Lopes Esteves provide an up-to-date information security perspective for the URSI Century of Commission E.

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2. Measurement Techniques (Pierre Degauque)

Measurement techniques cover both radiation and conduction aspects as well as emission or susceptibility tests of equipment. In the following, radiated disturbances, or immunity tests, are emphasized. Progress in measurements of conducted disturbances were mainly related, on one hand, to the development of fast analog and then digital oscilloscopes to capture transients generated by the Equipment Under Test (EUT), and on the other hand, to the design of wideband injection or measurement probes.

Nevertheless, a special mention must be made of the characterization of shielding material and the shielding effectiveness of cables and connectors. In the 1950s and 60s, a non-negligible part of the research on measurement systems was driven

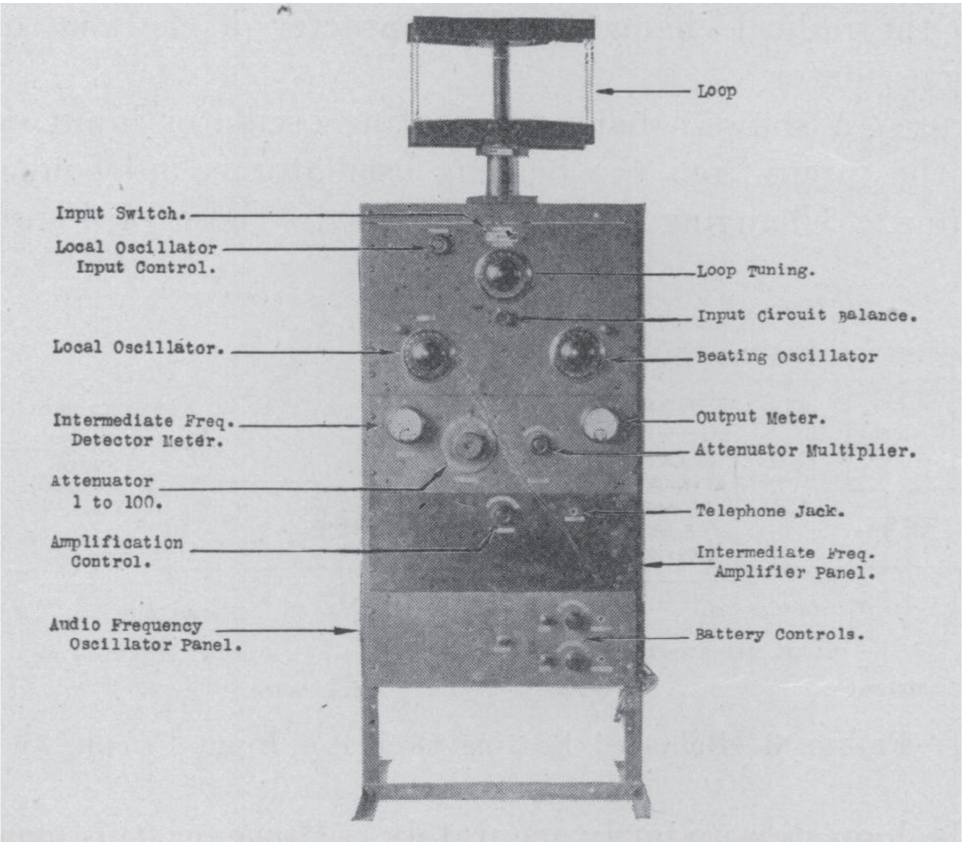

Figure 1. Field strength measurement apparatus employing grid modulation. (Source: from [3]).

by military applications and particularly applied to a frequency band extending up from 30 to 100 MHz, associated with the high altitude nuclear electromagnetic pulse [1]. However, due to the emergence of new sources of electromagnetic disturbances, modifications of measurement set-ups were proposed to make possible the measurement of cable transfer impedance at higher frequencies, typically up to 1 GHz [2].

Focusing now on radiation aspects, we outline the changes in the measurement benches to achieve increasingly reproducible results for a continuously increasing frequency band.

2.1 From Laboratory Measurement to Standardized Open Area Test Site (OATS)

At the beginning of the 20th century, it was quickly evident that there was a need to measure radio field strength not only to characterize the transmitting power of a system, but also to quantify the level of interference in the vicinity of the receiver. Indeed, the correct long-wave radio reception of a music program was a fundamental criterion for the development of radio broadcasting. Yet sometimes, so-called "static" due to disturbing sources, and corresponding to crackling or hissing, was often superimposed on the desired signal. Field strength measures were developed to cover a frequency band around 150 kHz and then extended up to 40 MHz [3]. Such a measuring device is shown in Figure 1.

The proposed method for measuring interfering noise consists of:

> "introducing into the antenna of a field strength measuring set a local signal of adjustable amplitude whose frequency traverses a narrow range of a few hundred cycles, back and forth, at the rate of several times per second. This frequency, together with the static, is heterodyned down to voice frequency in the measuring set so that the two are heard together. Measurement consists of reducing the amplitude of the tone until it can scarcely be recognized in the presence of the static" [4].

Under this condition the equivalent field strength of the tone, as determined from the calibration of the measuring set, is a measure of the amplitude of the static, expressed in µV/m.

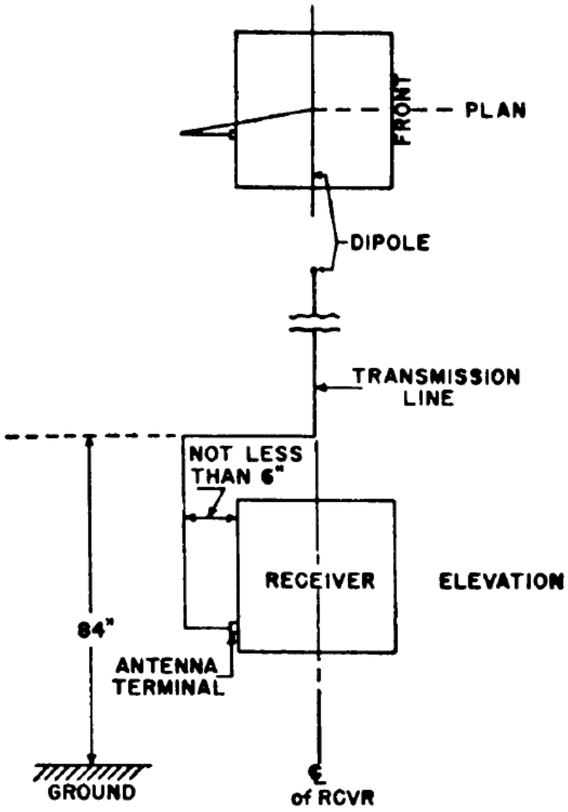

Figure 2. Schematic view of the open space measuring system. (Source: from [6]).

To make more reliable measurements of the field strength emitted by a device, intentionally or not, the idea of using an Open Area Test Site (OATS) gradually gained ground. The first attempt to introduce specifications and standards started in the early 1940s and resulted in a joint US Army-Navy specification [5].

An IEEE standard for radio receivers then appeared in 1951, and described set up methods for open field measurements of spurious radiation from frequency modulation and television broadcast receivers [6]. The standards, among other recommendations, give details for the platform upon which the receiver under test is mounted, and the non-conducting, a rotatable mast carrying a dipole antenna. The schematic view of the measurement system is shown in Figure 2.

As OATS became a popular method for measuring interference levels, it was necessary to define the geometrical configuration and the measurement conditions precisely. The CISPR (Comité International Spécial des Perturbations Electriques) standardized this in 1977 [7]. The FCC (Federal Communications Commission US), and the VDE (Verein Deutscher Elektrotechniker, Germany), made similar recommendations. The area, cleared of reflecting objects, is defined by an ellipse whose foci are the measuring antenna and the EUT, the distance between foci depending on the frequency band. Furthermore, a procedure for calibration, or for measuring a Normalized Site Attenuation (NSA), is needed account for the role of the ground, which reflects part of the emission of the EUT to the receiving antenna. Since a perfect ground plane is expensive, use of a mesh ground plane was widely studied. To take this ground reflection into account, a position for the receiving antenna, which gives the maximum signal, is sought, its height usually varying between 1 to 6 m, the EUT being at a height of 1 to 2 m.

2.2 From OATS to Anechoic Chambers

From the electromagnetic point of view, one of the main drawbacks of OATS is the need for a “quiet” site and its practical implementation is sometimes difficult. To overcome this problem, the basic idea is to put both the EUT and the measuring antenna into a screened room, and by placing absorbing material on the walls, the ceiling and the floor to get a full anechoic chamber. However, depending on the application, it can be useful to leave the ground as a reflecting plane leading to a so called “semi-anechoic” chamber. Even if the basic idea is simple, the construction of an anechoic chamber was held up for quite a while, due to the lack of suitable absorbing materials. This material must reflect only a small percentage of the incident power over a wide frequency range and angle of incidence to be able to simulate OATS conditions.

In April 1953, a new broadband absorbing material was tested and implemented in a chamber, the frequency band extending from 3 to 10 GHz [8]. In 1956, the Naval Research Laboratory, in Washington, constructed a chamber working in the 2.5 -25 GHz band. The non-reflecting material was made by impregnating commercially available curled animal hair with a mixture of conducting carbon black in neoprene [9]. A comprehensive historical presentation of the development of absorbing materials, and anechoic chambers, can be found in [10].

Nowadays, there is a wide range of anechoic chambers, from the size of household microwave ovens to ones as large as aircraft hangars. A picture of a typical chamber with a volume of 70 m^3 is shown in Figure 3, its working frequency range being 30 MHz to 18 GHz. In very large chambers, the lowest frequency can be as low as 30 MHz, although this requires pyramidal absorbers whose thickness is as great as 4.6 m [10].

Note that in some cases, it can be more judicious to give the enclosure a tapered shape, i.e., that of a pyramid followed by a cube, to limit the use of high-performance absorbers and provide more room for the test zone.

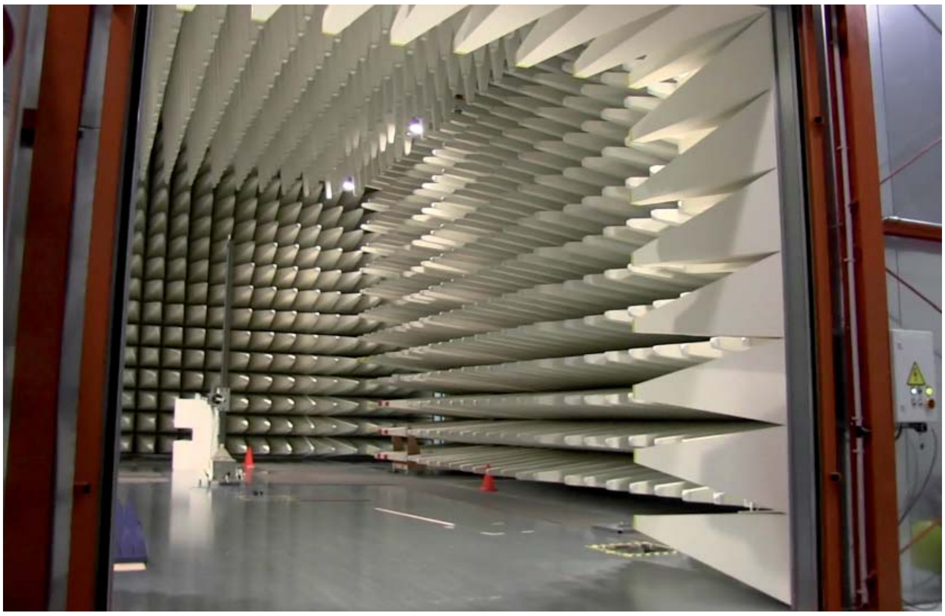

Figure 3. A log periodic antenna illuminating the EUT in an Anechoic chamber. (Source: Wikimedia Commons).

2.3 TEM Cell

OATS and anechoic chamber are well suited for measuring noise generated by equipment, but another complementary aspect in the Electromagnetic Compatibility (EMC) domain is its susceptibility to radiated fields. Difficulties appear when making low frequency, range tests, for example, below 30 MHz. Indeed, to obtain reproducible and interpretable results, a plane wave must illuminate the EUT, often of high energy. Distances between the illuminating antenna and the EUT can become prohibitive, without mentioning the EM disturbances in the environment. In the 1970s, a new technique was developed at the National Bureau of Standards (NBS) for establishing standard, uniform, electromagnetic (EM) fields in a shielded environment. It employs a three-plate type TEM line, open at the sides and whose characteristic impedance is 50 Ohms, providing easy matching of the transmission line at both ends. It is often known as "Crawford cell" [11]. For susceptibility testing, one port of the line is used to feed the power to the cell.

Field strength up to 500 V/m can be easily established, with an uncertainty of less than 1 or 2 dB. However, since only the TEM mode must be excited, the half wave length must remain greater than the transverse dimensions of the line. For dimensions of the cell, about a meter, the useful range extends up to 100 MHz. To get a completely screened structure, the sides of the line are often closed (Figure 4), the price to be paid being a deformation of the field distribution.

Figure 4. A TEM or Crawford cell. (Source: Wikimedia Commons).

Figure 5. A GTEM cell (Source: Wikipedia, Teseq Co.). (Source: Wikimedia Commons).

Using such a cell for emission testing is not straightforward because it is necessary to extract from measurements the radiation characteristics of the EUT in free space. Many theoretical works were carried out, as described in [12], published in 1981.

A first attempt to extend the applicability of a TEM-supporting structure to the high frequency range proposed placing RF-absorbing material on part of the walls of the cell, in order to damp high order modes [13]. To reach the GHz band, a new test facility combining an anechoic chamber and a conventional TEM cell were studied in the 1990s. This led to the GTEM (Gigahertz TEM) concept [14], based on a coaxial line expanding pyramidally (Figure 5). The distributed load section used absorbing material for EM wave termination (as in anechoic chambers) and a distributed load for current termination.

2.4 From Plane Wave-Based Measurement to the Mode-Stirred Reverberation Chamber (MSRC)

As already outlined, the susceptibility test generally required a high-power, incident field on the EUT. In the low frequency range, the TEM cell is an interesting solution, but for frequencies of the order of 1 GHz, measurement in an anechoic chamber may require HF power that is too high for feeding the antenna illuminating the EUT. Furthermore, due to the plane wave excitation, the EUT must be put in different orientations to find the worst case, which is time consuming. Lastly, a question often arose concerning plane wave excitation since, in real life, the equipment is usually situated in a greater or smaller enclosure, but not in free space.

At the end of the 1960s, Mendes proposed making tests in a resonant chamber. However, no significant work was carried out during the next few years because many EMC engineers were skeptical about using a resonant room, with no analytical background, and with the inherent difficulty of comparing results with those obtained from other traditional techniques, such as OATS, or the anechoic chamber.

In 1975, a "Translational" EM Environment Chamber (TEMC), which was later called a Stirred Reverberation Chamber (MSRC), was produced [15]. This was the starting point for a large amount of theoretical and experimental work, as outlined in [16] and [17], to mention just two sources. MSRC is an enclosure of large dimensions, in terms of wavelength, with a high-quality factor, and whose boundary conditions are randomly distributed owing to a rotating conductive stirrer (Figure 6). If the number of modes excited by the cavity is sufficiently large, the field incident on the EUT can be considered as a summation of uniformly distributed plane waves coming from all directions. Consequently, polarization of the field also becomes a random variable. For this test equipment, the deterministic approach must be abandoned in favor of a statistical approach. Calibration procedures, homogeneity of the field, interaction between the chamber and the EUT, and correlation with results obtained in an anechoic chamber were, among many other points, research topics for the EMC community.

To conclude this brief overview, evaluating measurement uncertainties both for conducted and radiated emissions, comparing the performance of various set-ups, and extending their applicability to the 10 GHz band are now widely studied.

Figure 6. A mode stirred chamber, excited by a log-periodic antenna. (Source: Wikimedia Commons).

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3. History of Statistical Electromagnetism: Overmoded Enclosures and Mode-Stirred Reverberation Chambers (Gabriele Gradoni and Luk R. Arnaut)

For over half a century, the characterization of electromagnetic (EM) wave propagation in media and environments with a high number of geometrical and configurational degrees of freedom have benefitted from statistical approaches. Such characterizations thrive on complexity, i.e., they become increasingly efficient and accurate, the larger the number of degrees of freedom becomes, in contrast to deterministic methods. In the early days, innovative statistical methods to describe and understand the structure of EM fields in random media were developed in the context of optics, mainly based on geometrical optics, and advanced analytical methods to describe the structure of laser speckles [1], and remote sensing, mainly adopted to compensate aberration of EM waves propagating through the atmosphere [2], and to develop geo-imaging from scattering off vegetation and the Earth's surface [3, 4]. Eminent scientists and members of Commission J have contributed, developing the early work of Joseph Keller, to establish a solid background in statistical electromagnetics for scattering problems.

Much earlier connections, with the fundamental work of Heaviside was pointed out [5], where over-moded cavities were hypothesized, and average quantities were cited for the energy flux inside such complex structures. Unlike the typical approaches in e.g., statistical physics, however, the interest was not only in obtaining averages, but full first-order probability densities and second-order joint densities and correlations, in order to obtain information on uncertainties and fluctuation levels.

In Commission E, the intellectual thrust to further develop statistical methods came in the 1970s from the mode-stirred reverberation chamber (MSRC), a resonant cavity operated at high frequencies, and supporting a high density of eigenmodes. Early laboratory implementations of the MSRC, in the form of an electrically large-screened room, with aluminum walls and irregular metallic surfaces rotating inside, were pioneered first as large, perturbed, static rooms [6], then as fundamental statistical properties in the shielding of large structures, and applied to the study of radiated emissions [7, 8], and immunity studies [9].

Interesting connections with the operation of acoustic reverberation chambers, as historic predecessors, were explored by various authors. Basic inferential models for the MSRC field were developed, observing the scatter plot of the signals received by antennas operating inside an MSRC. A statistical model that characterizes the field fluctuations of the vectorial electromagnetic field, and its Cartesian components, under movement of irregular surfaces was developed [10]. Ideally, the complex electric/magnetic field in the reverberation chamber can be approximately modeled as having a limiting zero mean Gaussian distribution, with equal variance for real and imaginary parts, for all Cartesian in-phase and quadrature components.

In the early days, more advanced theoretical models were developed by a constant effort of Commission E members worldwide. This included the development of an original theory for a random, plane-wave spectrum – capable of explaining the distributional model of Kostas and Boverie [10] – and developed from past work that provided a deterministic plane-wave expansion as a solution of Maxwell's equations [11, 12], including the interaction of random fields with dielectric and metallic interfaces. Starting from a statistically uniform, isotropic, and uncorrelated field hypothesis, this theory gave an explanation for the limiting Gaussian distributions in terms of entropy maximization. Interestingly, the approach also gave a connection between the standard deviation of the complex random field and the quality factor of the environment, which becomes – along with the magnification factor introduced by Corona [13] – a central quantity in the characterization of well operated reverberation chambers. As alternatives to plane-wave based statistical theories, radio scientists have developed mode-based statistical theories, inspired by quantum chaos theories. Those theories had already interested radio scientists studying scattering of multi-cylinder media [14, 15]; a wave version of the three-body problem, which demonstrated unstable linear wave orbits experimentally. Imperfect reverberation was a central theme that inspired the development of those theories: power statistics based on the effective average number of overlapping eigenmodes [16]; and the extension to the concept of radiation impedance of an antenna radiating inside a reverberation chamber with a variable number of overlapping modes, the so-called random coupling model [17]; development of an effective Hamiltonian model to describe the fluctuation of the field power and its dependence on phase rigidity [18], i.e., the correlation between real and imaginary parts of the statistical field. Inherently, it was found that rigidity drives elliptical random fields [19], which becomes a valuable modelling tool for imperfect reverberation.

The strength of coupling also contributes to more complex statistical characterizations, which become relevant in multi-channel excitation, including aperture [20, 21] as well as multiple-input multiple-output (MIMO) coupling [22, 23].

Imperfect reverberation was found to be characterized by a low modal overlap, which drives the deviation of field distribution from idealized statistics. Drawing on the modal perspective, it was demonstrated that the fluctuation of the cavity quality factor, driven by the stirring process, is characterized by a Fisher-Snedecor distribution [24], where the number of overlapping eigenmodes enters in the distributional parameters. This theory was validated experimentally [25].

Furthermore, imperfect reverberation was better characterized in terms of anisotropy [26] and a low number of stirrer configurations [27], in addition to low number of overlapping modes, where mere sampling effects were found to distort limiting statistical distributions.

Further advancement of the RC theory led to characterizing random transients, and the Doppler shift [28] created by the stirring process. This predicted a Doppler shift larger than the one produced by sources moving in free space [29]. Deeper work is necessary to characterize the source-boundary coupling in the presence of mechanical stirring, which will lead to an extension of the Purcell factor theory [30].

Applications – while studies of MSRCs within Commission E focused on fundamental aspects of EMC and EME (EM environment) viz., coexistence, mutual coupling, and interaction phenomena through radiated emissions, immunity, shielding, and absorption, the emulation of wireless fading is an extended application of the reverberant fields, which was growing steadily since the seminal work in [31] and [32]. Recent efforts developed statistical methods to characterize the stochastic space-time fields radiated by multi-functional digital electronics adopted in the development of printed circuit boards (PCBs) for everyday consumer electronics. The methods are based on correlation [33, 34] and Wigner [35] functions, adopted in the past by Marcuvitz, Ishimaru, and more recently for propagation in random media through the phase-space representation [36, 37].

More recently, Commission E has adopted a physics-based concept related to wave-front shaping in resonant enclosures and rooms, where subsets of cavity eigenmodes are selectively activated by engineered boundary conditions that are implemented in the form of a pixelated, wall-mounted, meta-surface. This was used to improve the working volume and the number of independent realizations, as well as the low frequency operation, of reverberation chambers. It is a development of the last decade's attempt to increase the level of field mixing and chaoticity in a reverberation chamber by rough diffuser [38, 39], wall deformations [40-43], and more efficient mechanical [44] as well as electronics [45] stirring surfaces.

One of the main drivers for using MSRCs is High Intensity Radio Frequency (HIRF) exposure [46], involving testing against maximum field values [47-49], and, by extension, the minimum field in fading applications [50]. The accurate characterization of these paradigms remains a challenging problem.

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4. The Singularity Expansion Method in Electromagnetics (Dave Giri)

The Singularity Expansion Method (SEM) for electromagnetic interaction and scattering has come a long way since its introduction in 1971, by Carl Baum [1, 2] and was applied to antennas and scatterers in free space where the pole contributions dominate. The basic motivation was the observation of ubiquitous damped sinusoids in the transient response of complex electronic systems (e.g., aircraft, missiles) in Nuclear Electromagnetic Pulse (NEMP) simulators.

SEM is an extension of the integral equation solutions to complex frequencies and permits the representation of antenna/scatterer behavior by a few numbers. It also makes it possible to represent the transient behavior analytically and provide insight into the radiation process fundamentals.

The application of SEM to the analysis of antennas and electromagnetic scatterers was applied to simple, isolated bodies in free space. Theoretical studies of SEM were applied to several geometries to yield significant insight into the radiation and scattering process.

The SEM expression for the current distribution on an antenna is written as a continuous function

$$I(s,z) = \sum_{\alpha} \frac{\eta_{\alpha}\, M_{\alpha}(z)}{(s-s_{\alpha})} + F_e(s,z) + F_w(s,z) \qquad (1),$$

where $F_e(s, z)$ is an entire function with no poles, and $F_w(s, z)$ is a term containing poles from the excitation waveform. While the natural frequencies are independent of the excitation parameters, the coupling coefficient is a strong function of incident parameters.

For the various examples of natural-frequency calculations in the literature, some way was required to go from the integral equation to calculation of the pole locations. A common technique formed a moment-method matrix and then take the determinant, forming an analytic function of s as

$$\tilde{F}(s) = \det\left(\left(\tilde{Z}_{n,m}(s)\right)\right) \qquad (2),$$

the problem then becomes one of finding the zeros of this function.

A powerful technique for finding roots of $\tilde{F}(s)$ is based on its properties as an analytic function of s, and the contour integral theorems that then apply. Following [3] we can generalize the principle of the argument which begins with

$$\frac{1}{2\pi j}\oint_C \frac{1}{\tilde{F}(s)}\frac{d\tilde{F}(s)}{ds}ds = \frac{1}{2\pi j}\oint_C d\,\ell n\left(\tilde{F}(s)\right) = N_0 - N_p \qquad (3),$$

where

N_0 = number of poles inside C (4).
N_p = number of zeros inside C.

This can also be expressed as

$$\frac{1}{2\pi}\oint_C \arg\left(\tilde{F}(s)\right) = N_0 - N_p \qquad (5)$$

≡ change in argument going around closed contour C divided by 2π.

This requires that $\tilde{F}(s)$ be analytic and nonzero on C, and analytic inside C except at poles. Now assume that there are no poles within C. Generally, this is a good assumption for the moment-method determinant of equation (2), since the matrix elements are analytic except possibly at $s = 0$. We generalize equation (5) by defining

$$I_n = \frac{1}{2\pi j}\oint_C s^n d\,\ell n\left(\tilde{F}(s)\right)$$

$$= \sum_{n=1}^{N_0} s_\alpha^n \;,\; n = 1, 2, \ldots, N_0 \qquad (6)$$

for the case of only zeros (including a multiplicity of zeros). Consequently, our algorithm is to first determine N_0 in some region of the complex plane bounded by C.

Instead of going to larger numbers of roots inside C, one can break the area within C into smaller regions of the s-plane, each region being enclosed by its own contour. Repeating the procedure for a smaller area will typically include a smaller number of roots. When the area is small enough to enclose one or two roots, the above formulae can then be applied. To evaluate the contour integrals numerically, one can select some number of points on the contour and use various integration rules.

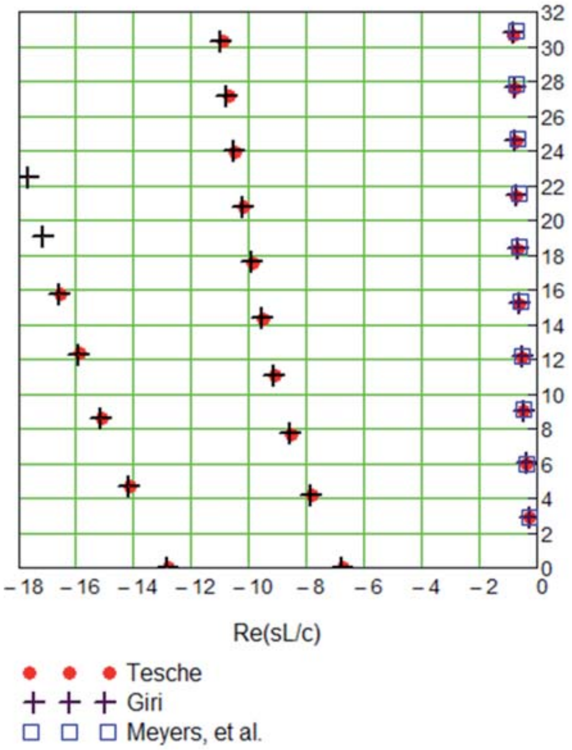

Figure 7 Overlay plots of the normalized resonant frequencies reported in [4, 5 and 6], (Source: D Giri).

As observed [3], by trial examples with a large number of specified poles, a few points around C are required to obtain accurate numerical values of the roots. For this purpose, the s-plane was divided into subdomains containing from zero to two roots. Perhaps further research can pin down why this is so accurate. While the motivation here is for electromagnetic-interaction/scattering problems, this complex-variable procedure should prove useful in other problems requiring computation of poles/zeros.

A simple example is a wire scatterer of length *L*. The complex natural frequencies of the wire scatterer were investigated in detail by many researchers [4-7]. The complex natural frequencies occur in layers in the upper left half of the complex s-plane., as shown in Figure 7. It is interesting to note that the Meyers, et al. solution [7] provides only the resonances for the first layer ($l = 1$). This is likely due to the use of only the first layer current distributions in their variational calculations. It is speculated that if the higher layer modal current distributions were to be used in the calculation, this method might provide the $l = 2$ and 3 resonances as well.

Early in the development of SEM, it was noted that the natural frequencies are complex frequencies (s_α) at which an integral-equation representation of the scattering problem has solutions with no incident electromagnetic field. These could also be found from the zeros of the determinant of the corresponding moment-method matrix. The natural current modes could then be found from the solution for the numerical vector representing the corresponding current on the body. Except for cases of modal degeneracy (e.g., two independent modes for bodies of revolution) the modes are unique up to an overall arbitrary scaling constant.

Furthermore, in analytically investigating the behavior of antennas in a lossy medium, it is known that in addition to simple pole singularities, there is a branch cut linking two branch points in the complex frequency representation of the antenna response. While significant information regarding the nature of the branch cut and its effect on the antenna response can be obtained by purely analytical methods, a numerical study of this can also provide useful results.

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5. Natural Electromagnetic Noise (Yasuhide Hobara And Masashi Hayakawa)

As one might be aware, URSI Commission E topics can be composed of two parts: natural electromagnetic noise, and man-made noise. Since the establishment of URSI in 1919, the frequencies used for radio communications and telecommunications have changed drastically with the developments of radio technologies during the last century, from long waves to short waves (i.e., from low frequency to higher frequency). In accordance with this change, the main frequencies studied in Commission E has also changed from lower to higher frequencies.

URSI Commission E was initially the Commission on Atmospherics, a foundation Commission of URSI. The earlier main topic was the interference in the long-wave communications: that is, VLF (Very Low Frequency)/ELF (Extremely Low Frequency) noises (or atmospherics, simply sferics): lightning discharges are the major source of this interference. Studies in 1950s, found a new type of VLF/ELF atmospherics (named whistlers - whistling atmospherics), which provided upper atmosphere (ionosphere/magnetosphere) information and is still being used to probe the upper ionosphere. In 1970-80s, the geophysical aspects of whistlers became interesting, even though their source is lightning. A global network observing whistlers was established, from high- to low-latitudes. Global observations permitted additional VLF/ELF emissions (unstructured hiss and structured chorus), to be studied as one of the more important aspects of wave-particle interactions in the magnetosphere (now a Commission H topic). Commission E played an important role in initiating these VLF/ELF studies.

Schumann resonance (SR) in the ELF band, a global resonance triggered by global lightning in the Earth-ionosphere cavity, is a Commission E topic, and in the 1990s some important advances were made. There was one suggestion, in 1992, that the intensity of stationary SR can be utilized to monitor global lightning activity as a measure of global warming. Another is a non-stationary SR phenomenon, or ELF transient, which was already found, in 1960s, as Q-bursts, the origin of which was totally unexplained. In 2000s, mesospheric optical emissions were discovered (generally referred to as Transient Luminous Emissions, TLEs, with sprites as a typical type) together with ELF transients. Further studies have shown that TLEs, and the associated ELF transients, are due to powerful positive lightning discharges unlike the conventional negative lightning discharges. These ELF studies are now one of the main branches of Atmospheric Electricity.

Finally, Commission E has taken the initiative in the new science field of electromagnetic phenomena in possible association with earthquakes (EQs), and the possibility for short-term EQ prediction using these electromagnetic precursors. Initially, a Commission E session, and later a joint session with Commissions G and H, advanced the finding of seismogenic ionospheric perturbations. Recently, this topic has become a new science field attracting the attention of scientists and is now recognized as a new geophysical field by the American Geophysical Union. However, in the early days of 1990-2000, when there were very few scientists paying attention to this topic, Commission E continued to maintain the sessions on this topic at URSI, and also made an URSI Resolution on the importance of this kind of study.

The latest activity and future prospects of the general stream of natural electromagnetic studies in Commission E, are outlined below.

5.1 Lightning and Related Phenomena

The study of lightning and lightning discharges was carried out in two directions. One direction is the investigation of global lightning activity (for global warming) with ground-based observations at VLF/ELF and also with satellite observations of optical emissions, VLF/ELF radio noise, HF/VHF radio noise, etc. The real-time monitoring of the global lightning distribution with the inversion of SR data observed simultaneously at several stations around the Earth is in progress as a promising possibility. Another direction is the elucidation of mechanism (or micro-processes) of lightning physics with sophisticated coordinated observations composed of HF/VHF array observations, digital interferometer, VLF/LF measurements, and ELF observation networks.

Many advances were achieved in the study of TLEs (sprites, elves, blue jets etc.), especially the generation mechanism of these TLEs in terms of a quasi-electrostatic field and/or electromagnetic radiation from lightning. Recently, attempts were made to improve coordination of the sub-ionospheric VLF signal observations in order to better understand the atmosphere-ionosphere coupling. Among these sprite problems, it was found that Japanese winter lightning, occurring over the sea of Japan, could play a significant role in the study of the sprite generation mechanism.

5.2 Electromagnetic Phenomena Associated With EQs

Many achievements accumulated during the last three decades, and it was found that electromagnetic phenomena do occur prior to an EQ, with a lead time of a month to one week. The generation of electric currents in the lithosphere is thought to be due to micro-fracturing, generating electromagnetic radiation (or noise). These were observed in a wide frequency range from DC/ULF (Ultra Low Frequency) to VHF or even higher. The most promising candidate for EQ prediction is ULF (0.01 Hz) noise (e.g., the 1998 Spitak, the 1989 Loma Prieta, and the 2003 Guam EQs). A statistical study of ULF noise was performed, indicating the probable gain of ~ 1.5. Since the evidence for a lower ionospheric perturbation precursor for the 1995 Kobe EQ, the Japanese group established the first VLF/LF observation network as the most promising candidate for EQ prediction (with a higher probability gain), followed by similar VLF observation networks in Europe, Russia, India, and South America. The upper ionospheric anomaly was also found using ionosondes, and GPS TEC. Lastly, the French satellite, launched in 2004, confirmed different seismogenic effects. Possible EQ predictions, using various phenomenon, were carried out in Greece, Japan, and Russia and attention was directed to pre-EQ atmospheric perturbations, like outgoing long-wave radiation, although this remains controversial. In future, the following three points should be emphasized in seismogenic studies: (1) multi-parameter, coordinated observations are needed for the study of lithosphere-atmosphere-ionosphere coupling, (2) critical analyses are needed (fractal, natural time method) to study the nonlinear, critical processes in the lithosphere as the possible agents for lithosphere-atmosphere-ionosphere coupling, and (3) increased detection accuracy is needed for precursory signals of EQs by using advanced signal processing techniques based on big data (e.g., machine learning in artificial intelligence (AI)).

5.3 Mitigation of Natural Disasters with Radio Techniques

Probably due to global climate change, we are faced with extreme meteorological phenomena such as very powerful typhoons, tornadoes, and heavy precipitation in many different parts of the globe, causing tremendous loss both of life, and damage to the economy. Total lightning (sum of cloud-to-ground and in-cloud discharges) detection networks with information from advanced phased-array VHF radars is expected to be of extreme importance in mitigating meteorological natural disasters, by detecting precursory phenomena of such extreme weather.

Although damage to the power grid and re-usable energy systems, such as wind turbines, due to energetic lightning (i.e., large amount of charge) is serious in many locations of the globe, detection and characterization of these spatial types of lightning properties are not yet well established. Lightning charge moment changes (as a proxy for the amount of lightning charge) will be deduced from transient radiation in the ELF range, which will be useful for real-time monitoring, and may mitigate future lightning damage.

Electromagnetic effects could be the only possible means for short-term EQ prediction because seismological measurements have not yet helped sufficiently in short-term EQ predictions, and it is certain that successful EQ predictions will save the human lives.

6. An Exceptional Lightning Experimental Research Facility in the Swiss Alps (Farhad Rachidi and Marcos Rubinstein)

6.1 Introduction

Lightning is one of the primary causes of damage and malfunction of telecommunication and power networks. It is also one of the leading causes of weather-related deaths and injuries. Although the risk of personal death from lightning decreased in many countries due, to a large extent, to the dissemination of knowledge on the proper measures and behavior to adopt in dangerous situations, the risk of other adverse effects is increasing as a consequence of climate change, with weather phenomena becoming more severe and lightning itself becoming more energetic.

The widespread use of sensitive electronic devices makes today's networks even more vulnerable to this natural phenomenon than in the past, as well as to all other possible types of electromagnetic disturbance. Future distribution systems, in particular, will have to cope with the increasing inclusion in the power network of power generation from renewable energy sources, such as taller wind turbines and high-altitude solar panel parks, which are known to be especially susceptible to lightning, and the resultant network complexity will make reliability and immunity to external/internal disturbances a key issue.

Figure 8 View of San Salvatore Mountain and the tower on its summit. (Source: Rachidi and Rubinstein).

In addition to the electromagnetic effects of lightning, the relationship between climate and lightning activity has recently attracted the attention of researchers. Positive correlations between global lightning activity and global temperature variations were already confirmed in several global studies. In addition to the direct effect of climate change on the characteristics of lightning, lightning incidence (the number of lightning flashes per year in a given region) was shown to increase when tall structures are erected, which is the case for wind turbines and telecommunication towers, especially, but by no means only, on mountainous regions and coastal areas.

Knowledge of the lightning channel-base current is of primary importance because virtually all of the studies dealing with electromagnetic effects of lightning are based on it.

6.2 Pioneering Work of Karl Berger and His Team

Our current knowledge of lightning current parameters comes essentially from direct measurements obtained using instrumented towers, and from artificially initiated lightning. Extensive experimental data recorded by Prof. Karl Berger, and his team, on top of two instrumented towers in Monte San Salvatore, in Southern Switzerland, from the 1950s through the 1970s [1] resulted in a comprehensive statistical characterization of lightning current parameters. Mount San Salvatore has a height of 640 m above the level of the adjacent Lake Lugano and it is 914 m above sea level. The first lightning measurement tower was constructed on the summit of San Salvatore Mountain in 1943. It was replaced by a radio and television tower in 1958, on which the measurement of lightning discharges continued. In 1950, a second lightning research tower was constructed 400 m to the North of the first one. Both towers were 70 m tall. Later, the second tower was demolished and nowadays only the radio and television tower is present on the summit of the mountain, as shown in Figure 8. Lightning currents were measured by means of a two-stage shunt, just below the needle of each tower, and recorded using electromagnetic and cathode ray oscillographs. On each tower, two different shunts were used in series, one with a resistance of 0.05 Ohms for currents in the 1 kA to 200 kA range, and the other with a 0.8 Ohm resistance for currents from 50 A to 24 kA [1]. The work of Prof. Berger, and the data obtained, were instrumental in our understanding of many of the processes in the lightning discharge and in the classification of lightning into its various types.

6.3 Säntis Tower Experimental Research Facility

The results obtained by Prof. Berger and his team suffered from the technological limitations of the instruments at the time, in particular: (i) a frequency bandwidth limited to a few hundred kHz, despite the fact that the spectrum of the lightning current exhibits significant frequency content up to a few MHz and (ii) a limited time observation window that prevented the observation of inter-stroke phenomena and of positive lightning waveforms characterized by long duration.

Starting from 2009, a new research project, financed by the Swiss National Science Foundation and the European COST Action P18, supported the Säntis tower instrumentation in Switzerland for lightning current measurements. This

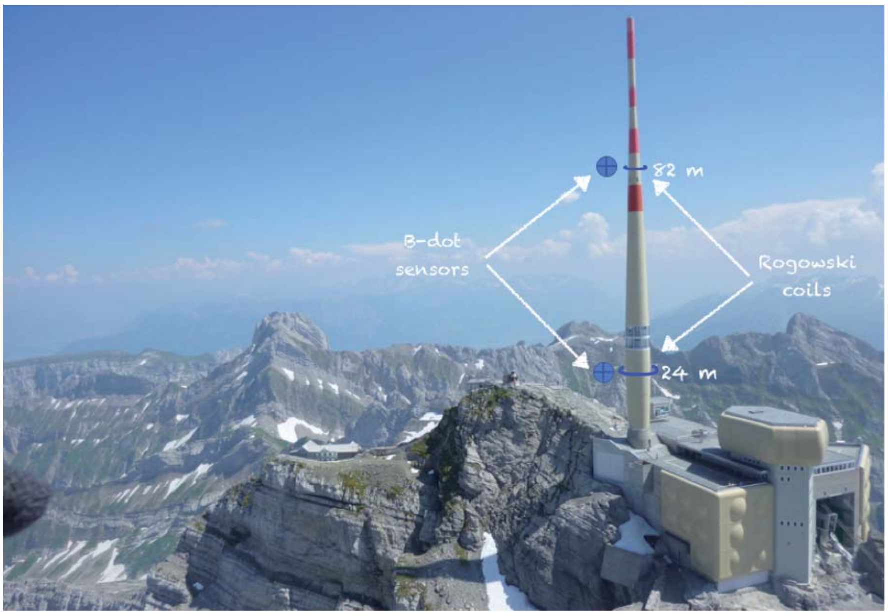

Figure 9 The 124-m tall Säntis telecommunications tower sitting on the top of the Mount Säntis (2502 m) and a schematic diagram showing the current measurement system on Säntis (Source: Rachidi and Rubinstein).

tower is struck by lightning more than 100 times a year so it represents a unique structure for collecting experimental information related to lightning discharges. The Säntis station's instrumentation includes state-of-the art sensors, remote monitoring, and control capabilities for the measurement of lightning current parameters [2, 3].

The Säntis Tower is 124 meters tall and it sits on the top of the Alpstein mountain complex siliceous, limestone sedimentary rock (Figure 9). This structure serves mainly as a telecommunications tower and weather station. The diameter of the tower base is 8 meters, and it is supported by a set of metal supports allowing the structure to sway slightly, thus avoiding damage under heavy winds. The selection of the Säntis Tower site followed an analysis of several candidate sites located in various Switzerland regions, which revealed that the Säntis Tower is by far the most frequently struck structure in the country, and one of the hotspots in Europe. The design constraints of the measurement system were determined on the basis of the statistical lightning parameters already available in the literature.

In the first nine years of operation, nearly 1000 flashes were recorded and analyzed. The data obtained constitutes the largest dataset available to date for upward negative flashes [4].

The Säntis Tower was first instrumented in 2010 to record current waveforms and their time-derivatives. The currents are measured at two different heights: 24-m and 82-m AGL, using, at each height, a Rogowski coil and a multigap B-dot sensor. The measured signals are transmitted over a fiber-optic link to a National Instruments PXI-5122 high-speed digitizer set to record each detected lightning flash with a measurement window of 2.4 s and a sampling rate of 50 MS/s [4, 5]. A schematic view of the current measurement system is also shown in Figure 9.

The measurement system at the Säntis facility was extended since 2010 by the addition a number of sensors. To measure the electric and magnetic fields, a low-frequency field mill, and wideband electric and magnetic field sensors were installed a short distance away, inside a dome near the tower. In addition, wideband field sensors were also installed 14.7 km away from the tower, on the roof of a 20-m tall building belonging to the Huber & Suhner company. The electric fields associated with strikes to the tower are also measured in northwestern Austria, 380 km away, with a wideband, flat plate antenna belonging to ALDIS (Austrian Lightning Detection and Information System), in Vienna.

In 2018, a Phantom high-speed video camera was also installed on the Krönberg mountain, about 4 km north of the tower.

Some measurement equipment was installed on a temporary basis. A Lightning Mapping Array (LMA), belonging to the Polytechnic University of Catalunya, was used in 2017 to detect and locate VHF sources from different processes during lightning flashes to the tower. An interferometer, manufactured by New Mexico Tech, was installed recently and it will be operational during the summers of 2019 and 2020. Finally, X-ray and Gamma-ray detectors will be used from August 2019.

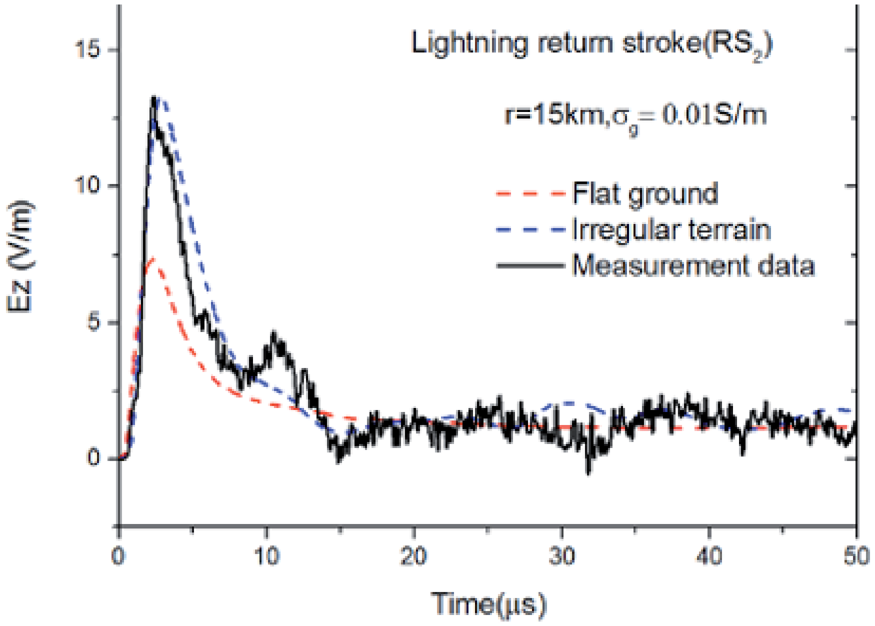

Figure 10 The vertical electric field at 15 km associated with a return stroke in a flash to the Säntis. The solid line is the measured waveform. The red dashed line is the simulated waveform assuming a flat ground. The blue dashed line is a simulated waveform taking into account the terrain profile, the ground parameters: σ_g = 0.01 S/m and ε_{rg} =10. (Source: Rachidi and Rubinstein, adapted from [7]).

6.4 Selected Salient Results

To date, almost a thousand flashes were successfully recorded at the Säntis Tower Facility. Negative flashes (those that effectively lower negative charge between the cloud to the ground) make up 85% of the data. The remaining 15% are divided into 12% positive and 3% bipolar. The great majority of the flashes (about 97%) are of the upward type, meaning that the discharge starts from the tower.

A selection of the results obtained at the measurement facility is given below.

6.4.1 Negative Flashes

The current data obtained since the facility became operational constitutes the largest dataset available to date for upward negative flashes. The analysis has contributed to the characterization of the different types of current and electric field pulses that are associated with this type of flash. This has led to new models for the physical processes involved in their generation, and it has corroborated the statistical similarities between pulses in upward and downward lightning (e.g., [6-7]).

6.4.2 Characterization of Positive Flashes

Although positive lightning flashes are considerably less frequent than negative flashes, they are of great practical importance since they are associated with especially high currents and charge transfer values and therefore represent a higher risk regarding lightning-originated fires and the protection of power and electronic equipment.

Measurements made at the Säntis tower resulted in the characterization of two distinct types of upward positive flashes, based on the current measured at the base of the channel [8]. These two types are similar to those observed by Berger [9]. Type-I upward lighting flashes are characterized by the presence of a large unipolar current pulse, typically preceded by bursts of fast pulses superimposed on a continuous current. Type-II flashes, on the other hand, differ from Type-I flashes in the absence of the large unipolar pulse, but they exhibit longer durations and higher amounts of charge transfer.

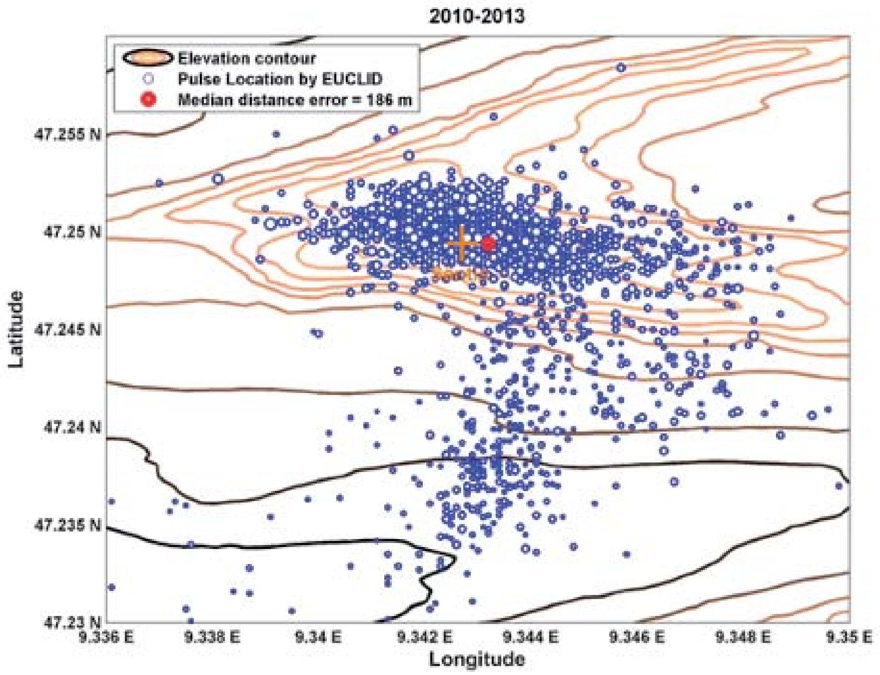

Figure 11 A plot of EUCLID pulse locations for upward negative flashes recorded in the region of the Säntis tower from 2010 to 2013. The size of the circles is proportional to the current peak measured at the Säntis. The length and width of the shown area are respectively 3.34 and 1.06 km. (Source: Rachidi and Rubinstein, adapted from [11]).

6.4.3 Propagation over Irregular Terrain

Simultaneous field and current measurements, together with FDTD simulations, enabled the study of radiation propagation from lightning over mountainous terrain, taking advantage of the Alpine region where the Säntis tower is located. The effect of the rough terrain on the fields can be observed in Figure 10, from which it can be concluded that the assumption of a flat terrain can lead to errors in the peak values of the fields of the order of 40%, and that it is possible to obtain excellent agreement between measured and simulated fields by using a 2D-FDTD approach [10]. This result has important implications for the remote estimation of the lightning currents in lightning location systems.

6.4.4 Performance of the European Lightning Detection Network for Upward Flashes

The availability of the channel-base current and the exact lightning strike location make instrumented towers an ideal ground-truth for evaluating the performance of lightning location systems. A performance analysis of the European Lightning Detection network (EUCLID) was performed using data obtained on lightning currents measured at the Säntis Tower in 2016. The performance of the EUCLID lightning detection network was evaluated in terms of detection efficiency, location accuracy, and peak current estimates for upward flashes [11]. Figure 11 shows a map of the locations of pulses detected by the EUCLID system corresponding to strikes to the Säntis tower. The comparison of the locations given by the system, and the actual location of the tower, as well as the amplitudes measured directly at the tower, and those reported by the lightning location systems, were analyzed to assess the performance of the lightning location system.

6.4.5 Lightning-Ionosphere interactions

Simultaneous measurements of currents from upward lightning strikes to the Säntis tower, and of wideband electric field waveforms at 380 km, constitute the first ever measurements of that type that feature ionospheric reflections for natural upward flashes of the field waveforms. The 380 km field measurements represent, in addition, the longest distance at which natural upward lightning fields were measured simultaneously with their causative currents [12]. Intervals between

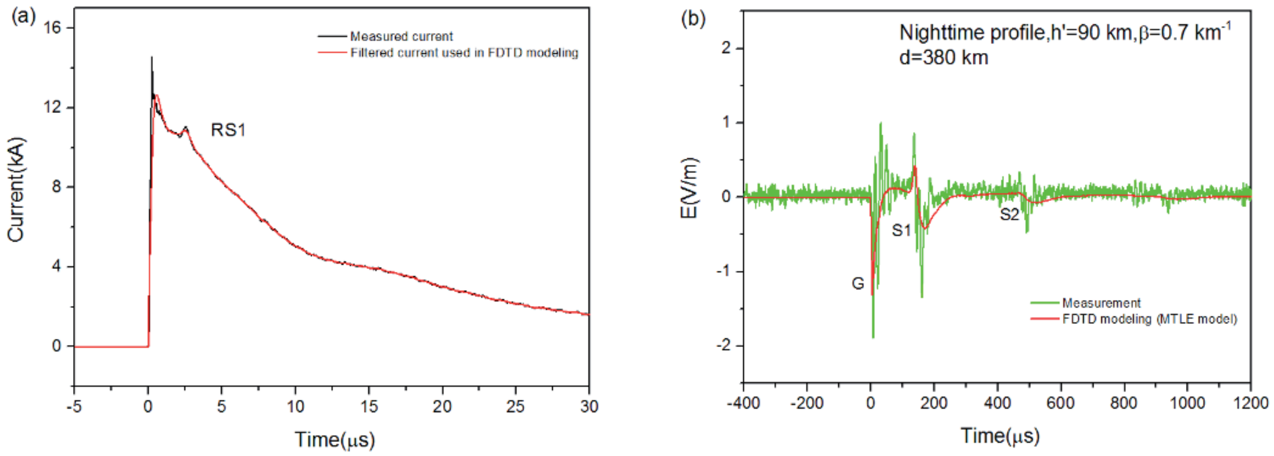

Figure 12 The current and electric field waveforms produced by the first return stroke of the nighttime upward flash that occurred on 21 October 2014 at 20:23:22. (a) Measured current (black) and 2-MHz low-pass filtered (red) current used in FDTD simulations. (b) Measured (green) and simulated (red) E-field waveforms at 380 km. (Source: Rachidi and Rubinstein, adapted from [12]).

the ground-wave field signatures, and those of the skywaves, were used to evaluate ionospheric reflection characteristics during daytime and nighttime based on the so-called zero-to-zero and peak-to-peak methods. Figure 12 shows a plot of the current and electric field waveforms produced by the first return stroke of the nighttime upward flash that occurred on 21 October 2014. Figure 12b shows the comparison between measured and simulated fields at 380 km.

6.5 Outlook

The Säntis Tower was consistently struck by lightning 100 times or more every year over the past ten years. This one-of-a-kind, life-size laboratory for experimental lightning research is currently being exploited by the EMC laboratory of the Swiss Federal Institute of Technology, Lausanne, and the Advanced Communication Systems Group of the University of Applied Sciences Western Switzerland, Yverdon-les-Bains. The two research groups are working to make this remarkable facility into an international center for lightning research, so that it can be made available to other research teams worldwide.

The measurement system was extended to include different types of sensors, some of which were installed on a temporary basis. The system will continue to be extended and enhanced in the future to include permanent energetic radiation sensors, lightning mapping sensors, dedicated atmospheric data sensors, and by increasing the bandwidth, dynamic range, and measurement time window of the existing instrumentation.

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7. EMC in Wireless Systems (Virginie Deniau)

The problem of man-made interference began at the end of the 19th century, with electricity applications and the issues of communication and transmission of information [1]. Indeed, the sensitivity of the receivers, and communication signals, highlighted the disturbances produced by electrical infrastructures and motors. In particular, the sensitivity of telephone equipment to interference, compared to telegraph equipment, highlighted the need for anti-interference solutions. The use of a return cable, instead of the ground, became widespread due to the sensitivity of telephone equipment to interference [2, 3]. Discussions about alternating and continuous current electricity focused on the relative advantages of the interference they produced on telephony, and the first railway signaling systems [4].

The Hertz experiments in 1888, which demonstrated the existence of the EM waves, were the precursor to the early work on wireless communications. At the end of the 19th century, a number of scientists (J. C. Bose, E. Branly, O. Lodge, A. S. Popov, G. Marconi, A. Righi, N. Tesla…) worked on EM wave emission and reception, exploring different frequencies and different transmitter and reception solutions to improve the sensitivity and increase the communication distances [5, 6]. Wireless telegraphy soon gained maritime interest [7], which continued during the World War 1. More generally, both world wars contributed to the automotive and telecommunication sectors progress, one creating interference for the other. In this way, interference management evolved simultaneously towards the requirements of source suppression and receiver protection.

Between the two world wars, interference produced by domestic equipment (vacuum cleaners, fans, electric refrigerators, oil burners, cash registers) began to be taken into account [8], especially for their effect on home radio reception, which was being democratized. The work of evaluating and accurately locating interference increased. The interference caused by the power line proximity, produced by the radiated emission at the receiver input, or driven by the electricity networks supplying the receivers [9], was recognized.

Engineers from different fields were organized into associations, or societies (International Electrotechnical Commission, Society of Automotive Engineers, American Standards Association, Radio Manufacturers Association, the British Post Office…), that established design rules limiting both interference and the sensitivity of receivers, and suggested the most appropriate frequency choices [10, 11]. Standardization committees, born in European and the Americas, now protected broadcasting and communications [12, 13].

With the introduction of regulation, measurement techniques were developed and became more accurate. Measurements that reproduced the behavior of receiver inputs [14] had to be implemented. Even today, in MEMC, applied resolution bandwidths reproduce the input filters of the communication receivers (9 kHz and 120 kHz).

After the Second World War, the increase in the wireless communication systems' frequency, and measurement equipment, continued [16]. Standardized methods, to limit EM interference were again required by the development of communications for radio and television broadcasting services, and new applications in the fields of aviation and navigation [15].

Remotely communications, notably with territories that were not equipped during wars (including colonial ones), also encouraged wireless communications [17]. The development of wireless communications (in the military and civilian sectors) became sources of disruption for themselves, especially for television that spread in homes [18]. Mutual interference between different communication systems [20] lead to the term Electromagnetic Compatibility (EMC), which appeared in the 1950s. Subsequently, wireless systems continued to evolve: on the one hand, to be more efficient in terms of throughput, and on the other hand, to better withstand interference [21].

The miniaturization of electronics progressed in parallel with the rise in wireless system operational frequencies [22]. Miniaturization has led to digital technologies that require lower power, and can be easily disrupted by communication signals, especially those deliberately transmitted for military purposes. Thus, today, the signals produced by the main broadcasting and wireless communication systems are applied during the immunity tests of equipment, in all fields, in order to check their protection against these signals [23].

Wireless communication systems have become so important to states that their deliberate disruption with intentional EM Interference (EMI) becqme a separate discipline [24]. Depending on the era, we talk about electronic warfare, EM pulse, High Power Electromagnetic (HPEM), EM attacks, and Intentional EM Interference. In the 1970s and 1980s, the objective was to create high-power interferences to produce permanent defects in electronic equipment [25]. Today, there is a greater focus on exploiting the weaknesses of wireless communication protocols and intentionally disrupting them with weaker powered interference signals [26] and the challenge is to find ways to neutralize threats to equipment, often generated by wireless systems, without disrupting public communication systems.

With the continuous increase in wireless system operational frequencies, up to 28 GHz for the future 5G [27], these communication signals will constitute new sources of interference at the microelectronics level. The high variability of waves in space and time will present a challenge to the relevance and repeatability of the EMC tests [28, 29]. Given the complexity of the test conditions, EMC test processes will need to include more statistical and stochastic approaches. More generally, wireless communication standards are multiplying, producing a wide variety of waveforms, including rapid changes in time, which will have to be taken into account [30, 31]. Knowing that wireless communication systems are increasingly involved in security applications, EMC tests and standards will therefore have to evolve to cover the risks related to the variety and variability of wireless signals. Wireless systems have always stimulated the evolution of electromagnetic compatibility and will continue to do so.

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8. Intentional Electromagnetic Interference (IEMI) (William Radasky)

8.1 Introduction

In the late 1990s, concerns were raised concerning the improvements of solid state, fast switching components in High Power Electromagnetic (HPEM) sources, and that more advanced antennas systems could allow terrorists, criminals, and hackers to interfere with the operation of modern electronic systems. In particular, there was great concern that the critical infrastructures (e.g., power, telecommunications, transportation, etc.) could be disrupted using new types of “weapons”. Scientists and engineers throughout the world began to evaluate the potential threats, and their ability to create upset, and damage: this field of study was initially known as “EM Terrorism”, but was quickly changed to the more encompassing term of Intentional Electromagnetic Interference (IEMI), which covers both criminals and terrorists. In addition, it was important to consider this field in the context of Electromagnetic Compatibility (EMC), which can provide hardening solutions for different threat levels. This paper reviews the history of this field and provides a bibliography of important papers covering the overall threat, the development of potential weapons, the susceptibility of equipment, and systems, protection methods, and standardization [1].

There were a few early papers dealing with the subject of intentional interference to electronics [2], and there were three separate, significant events in 1999 that were responsible for informing the technical community of the topic’s importance. These included a workshop on EM Terrorism at the EMC Zurich Symposium in February 1999 [3], the decision by the International Electrotechnical Commission (IEC SC 77C) to add IEMI to its standardization program in June 1999, and the decision by URSI to publish a “Resolution of Criminal Activities using Electromagnetic Tools” in August 1999 [4]. The term IEMI was coined at EMC Zurich in 2001 [5] to replace the term, EM Terrorism”. An agreed definition was published in 2005 [6] and is stated as:

> “Intentional malicious generation of electromagnetic energy introducing noise or signals into electric and electronic systems, thus disrupting, confusing or damaging these systems for terrorist or criminal purposes.”

Standards written by IEC SC 77C in later years continued to use the term IEMI. In 2004 the IEEE EMC Society published a Special Transactions Issue on HPEM and IEMI that is a good reference for those who wish to understand the technical aspects of the field [7].

With regard to the URSI resolution on Criminal Activities using Electromagnetic Tools (IEMI) in 1999 [4], there were two aspects to the resolution: 1) to inform the international scientific community of the threat, and 2) to recommend activities to protect against the threat. The resolution is summarized here.

Awareness of:

- the existence of criminal activities using electromagnetic tools and associated phenomena,
- the fact that criminal activities using electromagnetic tools can be undertaken covertly and anonymously and that physical boundaries such as fences and walls can be penetrated by electromagnetic fields,

- the potential serious nature of the effects of criminal activities using electromagnetic tools on the infrastructure and important functions in society such as transportation, communication, security, and medicine, and

- that in consequence, the possible disruption of the life, health, and economic activities of nations could have a major consequence.

Recommendations:

1) Perform additional research pertaining to criminal activities using electromagnetic tools in order to establish appropriate levels of vulnerability.

2) Investigate techniques for appropriate protection against criminal activities using electromagnetic tools and to provide methods that should be used to protect the public from the damage that can be done to the infrastructure by terrorists.

3) Develop high-quality testing and assessment methods to evaluate system performance in these special electromagnetic environments.

4) Provide reasonable data regarding the formulation of standards of protection and support the standardization work which is in progress.

8.2 The Threat of IEMI

One of the earliest aspects of IEMI was to determine realistic threat situations that might occur in the future, and also an effort was made to determine whether attacks using electromagnetic weapons had already occurred. Loborev identified several attacks that had previously occurred in Russia during the AMEREM Conference in 1996 [8], and the media also provided articles of interest on this subject [9-10]. Gardner wrote one of the earliest technical articles dealing with this subject in 1996 [2], followed by Wik and Radasky in 2000 [5]. In the following years several papers examined the threats to different portions of the critical infrastructure including railways, air traffic and power grids [11-16].

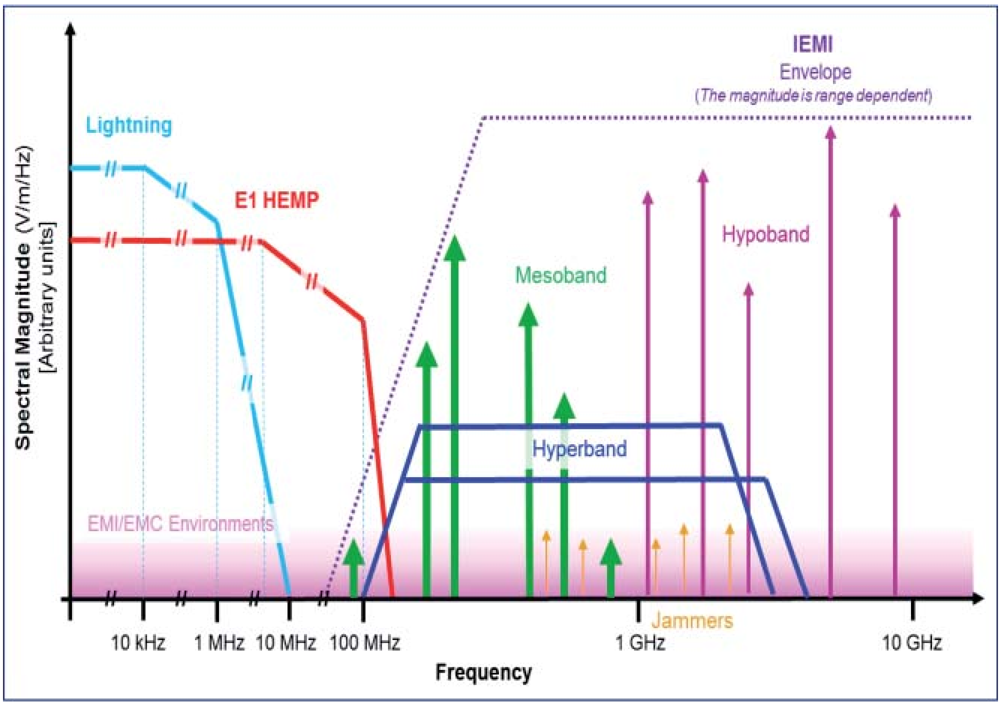

Figure 13. Frequency domain examples of different types of radiated IEMI transients compared to lightning and HEMP fields, and also normal EMC environments. (Source, R Hoad, W A Radasky).

8.3 Development of Potential Weapons

As mentioned in the introduction, one of the significant aspects of IEMI is the ability to use small compact weapons (sources) that, when matched to an antenna, can provide very high peak field levels with rapid rise times. The peak levels can be orders of magnitude above "normal" EMC test levels, which modern electronic equipment is built to withstand. In addition, the rise times of the IEMI waveforms are typically much faster than EMC tests provide, allowing fields to penetrate through small apertures in an equipment case, thereby reaching the internal circuits. There are two categories of narrowband and wideband waveforms that are typical for EM weapons. The rapid improvement in high voltage sources expending little energy at the source and the ability to match the sources to antennas, such as the Impulse Radiating Antenna (IRA), created many small size, wideband EM weapon threats. On the other hand, narrowband threats existed for many years (e.g., radar), and if enough energy was provided, these types of weapons were formidable.

Figure 13 presents the different types of IEMI radiated waveforms in the frequency domain, and these are compared to typical lightning and HEMP sample waveforms [6]. While the time domain waveforms are important, this figure shows much higher frequencies are important for IEMI, and this indicates that protection aspects, such as apertures in shields, and faster rise times in conducted transients, will create problems for surge arrester design.

Several important references are included for both wideband and narrowband sources throughout the world [17-20]. The IEC has provided definitions for wideband waveforms to discriminate between the "wideness" of wideband waveforms, including such terms as mesoband and hyperband [6, 21].

8.4 Susceptibility of Equipment and Systems

During the workshop at the EMC Zurich Conference in February 1999, the paper by Bäckström [22] dealing with the testing of a 1996 Saab automobile against different levels and frequencies of narrowband fields ignited great interest in the field. As we know, there are several aspects to the problem of IEMI, including the strength of the sources, the approach distances of the sources (thus providing the highest fields on "target"), any natural protection that might be provided between the weapon and the equipment, and lastly the strength of the electronic equipment to different types of EM waveform, including both radiated and conducted waveforms over different frequency ranges. While some analyses were performed, the vast majority of the evaluations of electronics susceptibility were done by testing.

Testing was carried out with radiated and conducted test equipment, which required the use of some of the new, recently developed EM sources. Depending on whether the testing was done with radiated fields, or conducted voltages, there was a requirement to start at low-test levels and increase the levels slowly until an equipment response was found. As in the case of EMC testing, upsets can occur and it is necessary to check the stored memory of equipment to ensure that it was not affected. When many cables are attached to equipment, it is also necessary to test each cable separately. In some cases, different cables are attached to the same electronics inside the equipment case, so it is important to test all of the cables at a given low level before raising the test level. If one cable is tested, and causes damage to the equipment, it may not be possible to determine if a lower level of conducted transient on a different cable created the effect.

For radiated field testing, with incident EM fields that have significant content above 1 GHz, it is also important to rotate any equipment through different orientations; small apertures can be found on different sides of the equipment case, and the surface currents induced can change rapidly with orientation (and angle of incidence), which is expected when the wavelengths of the fields are smaller than the lengths of the sides of an enclosure.

The types of equipment tested and published from 1999 to recent years include: automobiles, personal computers, computer boards, GPS and LAN systems, railroad equipment, power networks, network protectors, telephone base stations, and jamming threats on computer systems [22-39].

8.5 Protection Methods

As described earlier, protection from IEMI should be able to use protection methods used in the EMC field. These include EM shielding for buildings, rooms, racks and cables, and surge arresters, although there are special issues concerning these protection methods. It is not easy to determine the "correct" field levels or induced voltage levels that might expose a particular piece of equipment because, for EM weapons, the distance of the attacker from the equipment is unknown. It is clear there is some relationship between the size of the source, and the distance of approach, as a large tank-sized weapon

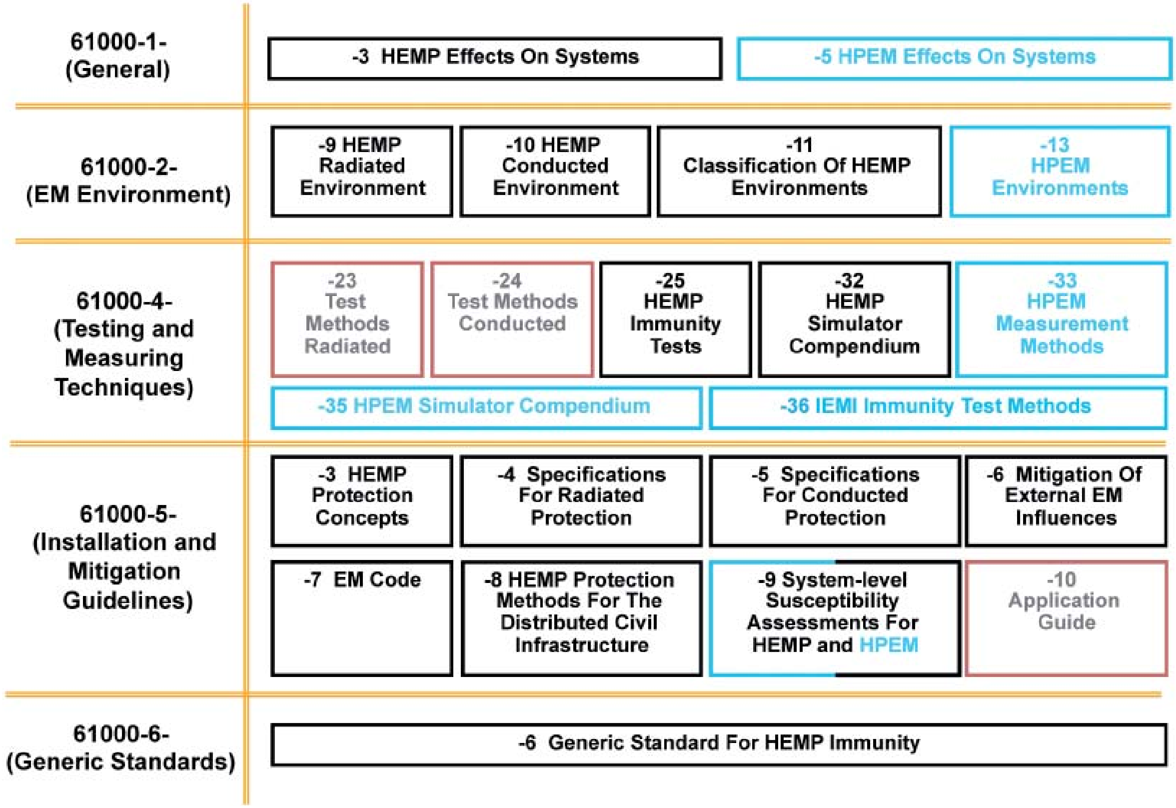

Figure 14. IEC SC 77C publications covering HEMP and IEMI. The red boxes indicate recent standard updates, while the blue color indicates work in IEMI (including 61000-5-10 which was recently updated) (Source, R Hoad, W A Radasky).

is unlikely to be hidden from a commercial facility. Standardization bodies have examined methods to apply reasonable field levels to equipment, and these will be discussed in the next section.

Another important aspect of protection is that, unlike the classical EMC approach, it appears unlikely that equipment alone can be protected to withstand a nearby attack. This is based on equipment test data that showed high levels of protection would be needed (see Section 4 references). Many papers were written to examine the strategy of providing building shielding (if the natural shielding level is not enough), or room shielding, or rack shielding of EM fields, to reduce the interfering field levels to those that the equipment can withstand. Of course, a very small pocket-sized weapon could get very close to electronics, so this mode of attack should also be considered. Another factor, with large-sized weapons, is to use normal physical security methods to keep the attacker weapons away from the building. Distance provides a reduction in the field levels from a weapon. Finally, there are electronic detectors that could be useful to inform a facility manager that the facility is under attack. Work in this area, over the years, is considered part of the protection approach against repetitive attacks over hours or days. These different protection methods are presented in [40-48].

8.6 Standardization

As mentioned earlier, IEC Subcommittee 77C began work in the field of IEMI in 1999 and has produced many reports and standards over the years. These were mainly basic standards dealing with general test and protection methods. Figure 14 presents the full set of publications produced by SC 77C covering both the high-altitude electromagnetic pulse (HEMP) and IEMI.

In later years other organizations, such as the IEEE, CIGRE, and ITU-T, became involved applying the basic IEC standards to particular systems such as publicly accessible computers, power substation equipment, and telecommunications equipment. IEC SC 77C also produced an overview of how to protect a fixed ground-based facility from both (or either) IEMI and HEMP in IEC 61000-5-10 [49-60].

8.7 Conclusions

Over the years, significant progress was made in the field of IEMI to understand the threat, the susceptibility of equipment and systems, and to develop protection methods that can be standardized. The problem is a large one and will require future work to fully understand the most cost-effective ways to protect against this threat. It is expected that new standards will be written, and updated, to ensure critical equipment is protected in a cost-effective fashion.

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9. Information Security Perspective of the URSI Century of Commission E (Chaouki Kasmi and Jose Lopes Esteves)

Electromagnetic security refers to electromagnetic activities impacting information security. It takes into account the susceptibility of electronic devices to electromagnetic interference along with the possible loss of information integrity, or availability, and spurious compromising emanations when a correlation exists between the processed information by electronic devices and the generated electromagnetic noise. Over the last century, the URSI community worked, from different perspectives, on electromagnetic threats to electronic devices by tackling the issues of confidentiality, availability, and integrity of the processed information. These represent the paradigm of information security.

From the first attempt to estimate the NEMP, by Fermat in 1945, to today's EMP research activities, multiple successes in modeling and characterizing effects were realized. During the period of 1980-1989, major publication milestones were with the release of Special Issues in IEEE Journals on Lightning, HPM, EMP 201 (short course), and HPEM technical sessions in various meetings. During this intensive period of research regarding EMP, the URSI Statement recognized scientists rising awareness of electromagnetic weapons and the need for resilience in critical infrastructures. The URSI Commission E supported the creation of different working groups, which are highly active in the domain of HPEM. The first was set up in 1990, and is still active. In 1999, a statement was published by URSI on Intentional Electromagnetic Interference. Since then, many studies were presented during URSI conferences showing high interest in this area., These publications, mostly analyzed from an electromagnetic perspective, demonstrated the URSI community was a leader on this topic. Information security has recently started considering Electromagnetic Attacks as a serious cyber-threat. In 2011, at the URSI General Assembly, Dr. Frank Sabath presented evidence of the real uses of RF weapons.

Electromagnetic noise generated by electronic systems was studied, since near the inception of URSI, by Commission E. A 1985 public release, by Van Ecke, related to the correlation between electromagnetic noise and information processed by a computer display, changed the perspective of how noise could become an information leakage vector. Being a real threat for the confidentiality of the information, the topic of compromising electromagnetic emanations was studied for years by the members of Commission E. A working group, supported by Commission E, studied the physical phenomena inducing the leakage from critical assets. In the triennial review report, published by the Commission E, the chair and co-chair of the working group, Dr. M. Backstrom and Dr. W. Radasky, shared the list of events where URSI Commission E members had organized and presented their research in this field over the 2011-2014 period. Two main communities, namely from South Korea and Japan, are actively working on the topic of electromagnetic information leakage, leading to the organization of a Special Session at every URSI conference in order to raise awareness and motivate people to work on this topic.

Commission F Contribution: Radio Wave Remote Sensing of the Earth

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Abstract

In the last half century, remote sensing methods have been increasingly adopted to provide measurements for many applications that range from the local scale, such as supporting the mitigation of weather emergencies: severe storms and floods; to global-scale help in improving our knowledge of the earth systems geophysical and biological processes. Earth remote sensing uses wavelengths ranging from the acoustic to the optical spectrum. For many applications related to the atmosphere, land, and ocean, methods based on the use of radio frequencies have carried decisive advantages with respect to methods using different frequencies. This chapter provides a survey of how active and passive radio frequency radar remote sensing has evolved up to the present, starting with pioneering research to the development of operational ground-based and satellite-borne systems for Earth monitoring.

1. Introduction

In the last half century, remote sensing methods, especially those based on radio frequencies, have been increasingly used to provide valuable measurements for many applications that range from the local scale, such as the mitigating the impact of environmental emergencies, and the planning and management of natural resources, to the global scale, such as improving our knowledge of the Earth's status to shedding light on the Earth's processes, and to improve our capability to predict changing climate scenarios. In the context of climate change, the World Climate Research Programme (WCRP, https://www.wcrp-climate.org/), has posed seven "Grand Challenges" for the analysis and prediction of Earth system variability. They are i) melting ice and global consequences; ii) clouds, circulation and climate sensitivity; iii) carbon feedbacks in the climate system; iv) weather and climate extremes; v) water for the food baskets of the world; vi) regional sea-level change and coastal impacts; vii) near-term climate prediction. None of these challenges could be addressed effectively without the use of remote sensing. Remote sensing is defined as "a method of obtaining information about properties of an object without coming into physical contact with that object" [1]. Passive remote sensing is carried out with instruments that detect the energy emitted by the object itself or the energy reflected by the targeted object when illuminated by an external source, such as the sun. In an active remote sensing system, a transmitter purposely sends the energy to the object and a receiver measures the radiation that is scattered by the targeted object: the receiver, whose position can be different from that of the transmitter, measures the characteristics of the signal scattered in the direction of the receiver, which conveys information about the object. Such a definition encompasses systems that are either ground-based or onboard a satellite, aircraft, or an Unmanned Aerial Vehicle (UAV). Remote sensing uses a wide range of frequencies from acoustic to optical. Radio-frequency remote sensing is a more recent development compared to the use of optical sensors. Early methods for the interpretation of photographic images date back to the second half of twentieth century. Initially, radio frequencies were attractive because of practical advantages they have with respect to optical frequencies. While passive optical remote sensing is mostly dependent on the availability of the sun, most of the methods based on radio frequencies can provide day and night information. Depending on the frequency used and the environmental conditions, radio waves can penetrate through clouds, precipitation, and even vegetation, providing information in all these cases. Later, it emerged that the radio-wave remote-sensing advantage arose because of the specific radio-wave portions of the spectrum, and the different signal characteristics received, which convey information on many properties of the scene observed. These facts, along with progress in signal processing theory, and technology, have contributed to establishing radio frequencies as a fundamental source of information (eventually in synergy with other frequencies or telemetered measurements) for a number of key applications. At radio frequencies, active remote sensing is primarily identified with radar (RAdio Detection And Ranging) in its different forms. Radar was developed during the Second World War as a device that uses radio waves to detect and locate objects, usually by echoes received from a sequence of short duration pulses, or more complicate waveforms. The idea of radar is attributed to a 1904 patent [2]. A description of early radar developments can be found in many radar textbooks. An article published in the Radio Science Bulletin comprehensively reports early efforts undertaken worldwide to achieve a working system based on radio waves to detect objects [3]. In radar, detection is related to the received power exceeding the noise level, whereas the location is determined by the steering of the antenna, or the position of the sensor if in orbit, and the delay between a transmitted pulse and the corresponding received echo. As illustrated in the relevant section of this chapter, in remote sensing, radar is used not only to detect distributed targets, such as surfaces, or volume distributed meteorological scatter, but also to measure characteristics of echoes from which geophysical properties can be inferred. On the passive side of remote sensing, the instruments that are able to observe electromagnetic signals are known as radiometers. They can detect weak signals emitted by the observed scene and surroundings. Processing must take into account the receiver band, polarization, and observation geometry to retrieve geophysical properties. In recent years, active remote sensing has increasingly used “opportunistic” but systematic signals emitted by systems not designed for earth observation. This is especially the case for signals emitted by telecommunication systems and Global Navigation Satellite Systems (GNSS). These have a high potential for continuous and global Earth observations if properly processed through the GNSS radio occultation (GNSS-RO) and GNSS reflectometry (GNSS-R) techniques. The first makes use of measurements of GNSS signals refracted by the atmosphere, the latter of GNSS signals reflected from the terrestrial surface [4]. The GNSS-RO technique is usually classified as an active technique, while GNSS-R is considered to be passive remote sensing because the source is an artifact that is emitted for purposes other than reflectometry.

The objective of this chapter is to provide an overview on how active and passive radio-frequency sensors, and relative retrieval techniques, have been progressively introduced in remote sensing, providing new measurement and observational capabilities. Although the chapter scope is neither meant to be complete, nor exhaustive, any omission of specific techniques or technologies is unintended. The survey starts with pioneering research in the first half of the twentieth century and progresses to the development of operational ground-based and satellite-borne radio systems for Earth remote sensing, for atmospheric, hydrologic applications, as well as Earth surface feature classification, and ocean observations. A vast literature can be found on the general theory, principles and the peculiar aspects of microwave remote sensing (e.g. [5] or the relevant chapters in [1] and [6]) that will not be covered here. Rather, this chapter aims to provide a necessarily non-exhaustive review of remote-sensing systems and methods that take advantage of the use of radio waves for the benefit of a multitude of applications that are classified according to three main sectors, namely: atmosphere, Earth surface, and ocean observations.

2. Atmospheric Observations

2.1 Active Remote Sensing of the Atmosphere

Active radio frequency remote sensing of clouds and precipitation is mostly associated with radar and radio occultation systems. Radar uses radio waves to detect and locate objects, usually by echoes received from a sequence of short duration pulses. The remote-sensing radars for atmospheric and hydrologic applications are typically referred to as weather radars, or meteorological radars, and are perhaps the most successful active remote-sensing systems. When remote sensing clouds and precipitation, instead of single particles, atmospheric particles filling volumes defined by the characteristics of antenna and transmitted pulses are detected. In addition to the “detection”, these radars retrieve cloud and precipitation properties by observing the different properties of signals scattered back to the receiver. Early systems measured only the amplitude of the received signal, linking the received power to precipitation intensity. Examples of standalone and networked meteorological radars deployed mainly to support weather monitoring at airports date back to 1940s, while efforts to build radar networks used for weather surveillance dated to 1944. Starting from mid 1950s, networks of weather radars were deployed in several countries [7]. Over the years, efforts have been made to utilize more signal property measurements. The term multi-parameter radar [8] was later adopted to identify systems capable of measuring the phase and polarization of the scattered electromagnetic waves from which more geophysical information can be retrieved. Radar can measure the speed of atmospheric particles using the Doppler effect, which is the change in frequency or wavelength

Figure 1. A weather radar: The CSU CHILL dual-frequency, dual-polarization radar.

of a wave for an observer moving relative to the source of the wave. For the weather radar case, a bunch of hydrometeors in the atmosphere, moving with respect to the emission source of the wave (i.e. the radar), will produce continuous time variations of the target-source distance making the time of arrival of the backscatter wave fronts progressively longer or shorter, depending on the direction of movement of the targets [0]. Once proven to be useful in identifying and tracking hazardous storm cells, the Doppler capability was added to most operational systems. Following this trend, in 1998 the US deployed the NEXRAD (Next Generation Weather Radars) and later, the C-band Terminal Doppler Weather Radar (TDWR) at major airports. Experiments carried out in the 1970s suggested that the polarization state of the scattered wave could provide significantly richer information about the nature of the hydrometeors, which would improve quantitative precipitation estimation. While early studies focused on circular polarization [10], operating at the eigen-polarization states of the rain medium (namely the horizontal and vertical states), which do not change in propagation, was found to be a better choice [11]. This was the foundation of the dual-polarization technique that was attractive for large-scale deployment at the beginning of 2000s. In fact, at the time of writing, most of the meteorological radars deployed are dual-polarization Doppler systems. Dual-polarization technology has led to the definition of new radar measurements, which are used both to improve the accuracy of the quantitative estimation of precipitation, and to reveal properties of precipitating clouds for meteorological applications [12].

Weather radars developed so far use frequencies in specific frequency windows ranging from S to W band, and even outside of these bands for some specific applications. Those employed by weather services for monitoring weather in country-wide territories use S-band frequencies (2.700-2.900 GHz), C-band (usually 5.600-5.650 GHz) or X-band (9.300 GHz to 9.600 GHz), with pencil beam parabolic antennas having a beamwidth of the order of 1° [13]. These systems have not only been used to observe clouds and precipitation, but also other volume distributed targets, such as volcanic ash [14]. The frequency determines important weather radar characteristics, such as the size of antenna and the sensitivity of the system. Given the beamwidth is proportional to the ratio between the wavelength and the diameter of antenna, S-band systems need larger antennas than C-band systems to achieve the narrow beams required for most applications (Figure 1). The US WSR88D radars (also commonly known as NEXRAD) use an 8.54 m antenna to achieve a 1° beamwidth. For the same beamwidth, a C-band system needs an antenna half that size, and even smaller for X-band. Since, under certain conditions, the power backscattered by a volume filled by hydrometeors is inversely proportional to the fourth power of the wavelength, at higher frequencies it is easier to achieve a more sensitive system. The drawback is the attenuation experienced by the wave propagating through the precipitation-filled medium. Techniques to mitigate effects of attenuation are necessary for higher C-band and X-band frequencies. The radar database managed by the World Meteorological Organization (WMO) lists more than one thousand operational weather radars worldwide (http://wrd.mgm.gov.tr/) of which 57% are C-band and 37% are S-band. The percentage of X-band installations is likely underestimated, because these systems are often managed by organizations that are not related to WMO. In fact, small-size dual-polarization systems have made meteorological radars affordable for users such as municipalities, and transport infrastructure management that need high-resolution precipitation measurements for specific local applications. Often, they encompass dense networks according to a paradigm demonstrated in the US CASA (Collaborative Adaptive Sensing of the Atmosphere) Engineering Research Center [15].

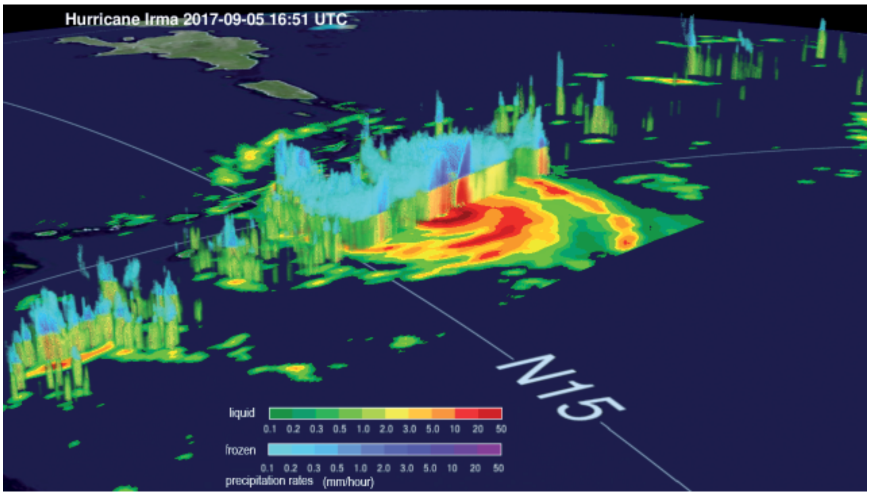

Figure 2. Different views of Hurricane Irma seen by the DPR of the GPM mission Core observatory (source: NASA).

Weather radar systems need to improve the reliability of mechanical scanning and rapid observation updating, especially in the presence of rapidly evolving phenomena, such as thunderstorms. There is renewed interest, both for fixed and mobile installations, in electronic scanning for hybrid systems that use mechanical steering for azimuth, and electronic steering in elevation. Since, nowadays, most radars rely on dual-polarization measurements, the challenge is to make electronic-scanning antennas that preserve, as much as possible, the horizontal/vertical orthogonality when the beam is steered at an angle to its principal plane. Important initiatives are ongoing, and it is expected that phased-array technology will become more available for atmospheric research and operations, especially for the prediction of fast evolving phenomena [16-18].

Clear air echo radars use frequencies lower than S-band. In the VHF - UHF bands (30 MHz - 3 GHz) Doppler radars determine the wind by measuring the line-of-sight Doppler shift of scattered signals (Bragg scattering) from refractive index fluctuations caused by turbulence. Examples are the high-power MST (Mesosphere-Stratosphere-Troposphere) radars, working at ~50 MHz, for investigating various dynamical aspects of the lower and middle atmosphere (up to altitudes of 100 km or more), and ionospheric plasma irregularities [19, 20].

At frequencies higher than X-band, the impact of attenuation resulting from precipitation, especially in the liquid phase, limits their application for observations at horizontal elevation angles. Actually, many radars built at Ku (12-18 GHz), Ka (27-40 GHz), and W (75-110 GHz) band frequencies are employed for profiling clouds and light precipitation. At these wavelengths, radars have excellent sensitivity to small cloud droplets and ice crystals that, in addition, have a lower impact on attenuation than larger liquid particles. These “cloud radars” [21, 22] are usually Doppler systems that measure the Doppler spectrum of falling particle properties at vertical incidence, when dual-polarization, based on the anisotropy of particles seen at quasi-horizontal elevation angles, is almost lost. Examples of dual-frequency, dual-polarization radar are found in [23]. Recent studies investigated diversity measurements related to the use of multiple frequency radars for snow, and small ice particle retrieval [24].

At these high frequencies small-size systems can be built, and used for atmospheric research in radars deployed on aircraft and satellites. In fact, the first precipitation radar in space (in orbit from 1997 until April 8, 2015) used a Ku frequency radar, and was part of the Japan Aerospace Exploration Agency (JAXA) and the National Aeronautics and Space Administration (NASA) Tropical Rainfall Measurement Mission (TRMM) sensor package [25]. Following the success of TRMM, a Dual Frequency Radar (DPR) (Ku- and Ka- band) was deployed on the Core Observatory (CO) of the NASA/JAXA Global Precipitation Measurement (GPM) mission (launched on February 27, 2014) for more accurate precipitation estimation and classification [26] (Figure 2). Higher frequencies (94 GHz) have been used by the nadir-looking Cloud Profiling Radar (CPR) [27] of the NASA CloudSat mission, in orbit since 2006, while a similar but more sensitive system with Doppler capability will be part of the payload of the joint mission of European Space Agency (ESA) and JAXA, called EarthCARE, and expected to launch in 2022 [28].

The recent trend in atmospheric active remote sensing from satellites is to migrate from high-cost platforms to a network of smaller satellites, such as CubeSat (http://www.cubesat.org/), that are capable of assuring higher revisit times, are relatively easy to launch and maintain, and are built on standard platforms. This concept was proved in missions for

Figure 3. Prof. Steven C. Reising, of Colorado State University (CSU), Principal Investigator, shows the 6U Cubesat TEMPEST-D (source: The Denver Channel).

atmospheric observations like Temporal Experiment for Storms and Tropical Systems-Demonstrator (TEMPEST-D) [29] (Figure 3), and Radar in a CubeSat (RainCube), launched on 21 May 2018, featuring a small size (10 cm×20 cm×20 cm, 21 kg) low power (10 W) Ka band radar [30].

Radio occultation is an active remote-sensing technique that has gained ground in atmospheric remote sensing. This form of active remote sensing was first introduced for astronomical studies [31] and later found wide applications in atmospheric remote sensing thanks to the availability of many signal sources, such as: the global GNSS networks, made of satellite systems like the Global Positioning System (GPS, United States), in operation since 1978, and available for global use since 1994; the GLObal NAvigation Satellite System (GLONASS, Russia); Galileo (European Union); BeiDou 2 (China); the Quasi-Zenith Satellite System (QZSS) the regional satellite navigation system from Japan; and the Indian Regional Navigation Satellite System (IRNSS). The GNSS-RO technique relies on measuring changes (bending and delay) in a GNSS satellite L-band radio signal propagating through the Earth's atmosphere (the ionosphere and the neutral atmosphere, below the ionosphere), and a receiver placed on a LEO (Low Earth Orbiting) satellite (Figure 4). The magnitude of the bending in the direction of propagation is due to refractive index gradients normal to the path, which in turn depend on the density and water vapor content gradients. Estimates for water vapor profiles, and other atmospheric parameters, such as pressure and temperature, are obtained with high vertical resolution but coarse horizontal resolution (450 km). Following the successful GPS/MET experiment, managed by the University Corporation for Atmospheric Research (UCAR), which installed a GPS receiver on the Microlab-1 minisatellite [32-34], sensitive GNSS receivers were added to the payload of several LEO satellites launched later. These missions demonstrated the accuracy of profiles obtained compared with conventional radio sounding systems [35, 36]. A 6-satellite constellation was launched in 2006 for operational purposes, namely the joint Taiwan-US Constellation Observing System for Meteorology, Ionosphere, and Climate /Formosa Satellite Mission 3 (COSMIC - FORMOSAT 3) aimed at demonstrating the advantages of a constellation with respect to a single LEO satellite [37]. The follow up COSMIC 2 - FORMOSAT 7 has been in orbit since 2019, again with 6 satellites [38]. Over the years, GNSS-RO has provided data to derive atmospheric parameters profiles that are operationally assimilated by meteorological services for weather modelling and forecasting purposes [39, 40]. The importance of the GNSS-RO technique is expected to increase in the future thanks to continuing research in sensors and retrieval techniques, the increase in the number of GNSS satellite, and the interest shown by weather services in GNSS-RO operational products.

2.2 Radio Waves for Passive Atmospheric Remote Sensing

As described in the previous section, the first space weather radar was launched at the end of the 1990s, when radiometers were already established as a fundamental instrument belonging to the payload of satellite missions to estimate the atmospheric radiative energy budget, hydrological cycle, and provide input to weather modeling. Also, for meteorological satellites, observations started with optical sensors. In fact, although previous satellite missions carried meteorological instrumentation, the history of meteorological satellites is considered to begin with TIROS-1, the first of the 10 TIROSs (Television Infrared Observation Satellites) launched in 1959. It operated for just 78 days, but it demonstrated the feasibility of weather monitoring from satellites with its payload of two cameras for the visible spectrum

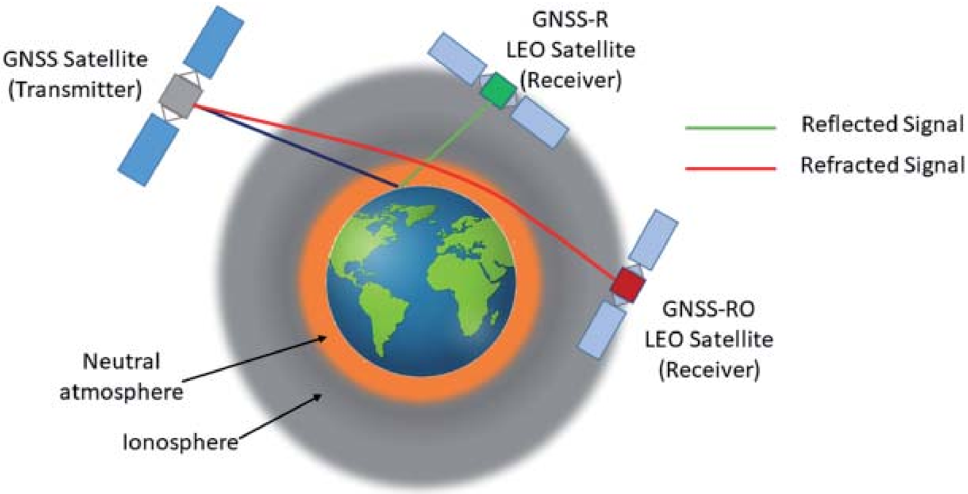

Figure 4. A sketch of the GNSS-RO and GNSS-R approaches.

reconstruction of the global weather from a satellite [41]. Although these satellites were in a polar orbit, in 1964, Verner E. Suomi envisaged the concept for a "cloud camera" on a geostationary satellite. Imaging the weather from a geostationary platform began on 6 December 1966, with the launch of the experimental sensor Spin-Scan Cloud cover Camera (SSCC) onboard the Applications Technology Satellite-1 (ATS-1) [42]. For the first time, a satellite provided, hemispheric images of the Earth's surface and cloud cover. A time resolution of 30 minutes, provided continuous monitoring of the development and movement of weather systems. Nowadays, several operational, geostationary satellites provide seamless monitoring of weather conditions around the globe, with visible and infrared sensors. Again, images in the visible electromagnetic spectrum are only available during the day. This shortcoming was partially addressed by adding IR sensors to the payload, starting with the Synchronous Meteorological Satellite (SMS) launched in 1974. Now these sensors are part of all the global geostationary meteorological satellite observations (http://www.wmo.int/pages/prog/sat/globalplanning_en.php). Visible and infrared observations from geostationary satellites have high time, frequency (from 15 to 5 min default acquisition modes), and spatial resolution. Attempts to use microwave radiometers on these satellites, for atmospheric sounding, have continued over four decades [43-46]. The main limitation is the antenna size, although China has a plan to launch a new GEO meteorological satellite for atmospheric sounding, FY-4M, in 2021, with a passive microwave radiometer [47]. Passive microwave radiometers have frequently been hosted in LEO platforms by a number of space agencies. Their use is not restricted to atmospheric applications (see next sections). There are several reasons for favoring radiometers in GEO satellites. For clouds, and precipitation measurements, geostationary platforms offer temporal measurements for determining the storm life-cycle. However, the solar and infrared measurements do not directly observe precipitation, whereas microwave radiometers respond more directly to internal cloud processes, because they receive contributions from the full atmospheric column. Historical techniques (such as those adopted in the Global Precipitation Climatology Project established in 1986 to provide global datasets for precipitation) are, in fact, based on combining IR and MW techniques [48]. The earliest radiometer demonstrators were on the Nimbus 5 satellites, which carried the Nimbus-E Microwave Spectrometer (NEMS) [49], and the electrically-scanned microwave radiometer (ESMR) [50] used to retrieve the temperature profiles, atmospheric water vapor, liquid water, and wind speed [51]. NEMS could continuously monitor microwave radiation emitted at frequencies of 22.235, 31.4, 53.65, 54.9 and 58.8 GHz, while the ESMR operated at the single frequency of 19.35 GHz. In some respects, this was the forerunner for the Microwave Sounding Unit, first launched aboard the TIROS-N satellite, in late 1978, carrying a 4-channel microwave radiometer with frequencies between 50 and 60 GHz, in the Oxygen region to provide, thanks to the use of radio-frequency instead of IR, estimates less influenced by the weather. This sensor, on successive satellites, provided a 25-year dataset of global temperature for climate study [52]. The sensor was later replaced by the family of cross-track, scanning, Advanced Microwave Sounding Unit (AMSU), which added more channels to the MSU, and was installed on several satellites, namely NASA Aqua, METOP satellites of the EUMETSAT polar system, and the more recent satellites of the NOAA Polar Operational Environmental Satellites, that, in turn, generated the Advanced Technology Microwave Sounder (ATMS), currently onboard the Suomi National Polar-orbiting Partnership (Suomi-NPP) satellite, and the Joint Polar Satellite System (JPSS) series, starting in 2017. ATMS has a swath of 2600 km and an angular span up to 52.77° relative to nadir, and 22 channels, ranging from 23 to 183 GHz.

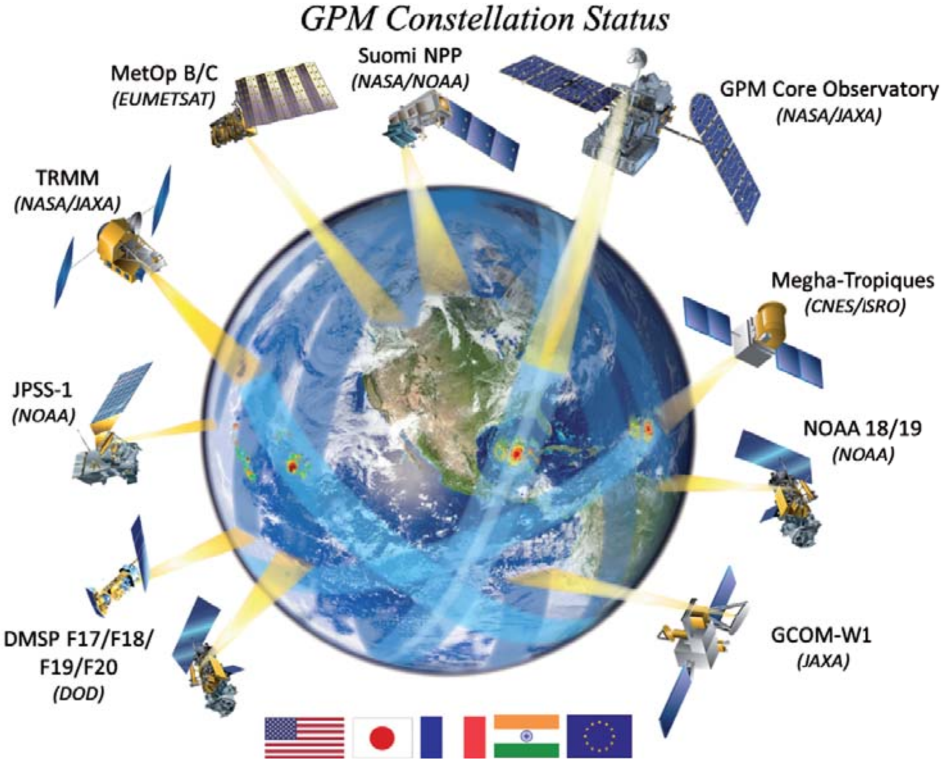

Figure 5. The Global Precipitation Measurement (GPM) mission constellation (source: NASA).

Cloud properties and precipitation estimates have also been carried out with microwave measurements from conical scanning sensors. The Special Sensor Microwave/Imager (*SSM/I*), a seven-channel, four-frequency, linearly polarized passive microwave radiometer system was part of the payload of the US Air Force Defense Meteorological Satellite Program (DMSP), which started in 1978. The instrument, integrated in the Special Sensor Microwave Imager/Sounder (SSMIS) from 2003, measures brightness temperature (TB) from the atmosphere and surface microwave emissions at 19.35, 22.235, 37.0, and 85.5 GHz, sampled at both horizontal and vertical polarization with the exception of the 22 GHz, which was only sampled at the single vertical polarization. A detailed description of the SSM/I instrument can be found in [53]. SSM/I measurements retrieve important meteorological variables such as total columnar water vapor [54], cloud liquid water [55], and precipitation [56-57]. These satellites were in near sun-synchronous orbit at a nominal altitude of 833 km, with 14.1 revolutions per day. The SSM/I antenna bore-sight is designed for an angle of 45° off nadir so that the SSM/I conically scans the Earth surface at an incidence angle of 53° with a swath width of 1400 km. Sample resolution varies from 12.5 to 25 km, depending on the frequency. While the polar regions are sampled quite well, there are large spatial gaps in coverage, especially at low latitudes and the tropics. Following the SSM/I design, a new radiometer, the TRMM Microwave Imager (TMI) was designed, for the aforementioned TRMM mission, to measure the intensity of radiation at five frequencies, namely 10.7, 19.4, 21.3, 37, and 85.5 GHz. The 10.7 GHz channel was added for better high rainfall-rate estimates common in tropical rainfall. TRMM has a low inclination orbit, close to 35°, to allow more frequent observation of tropical regions. TMI orbits at 402 km altitude, which is lower than the 860 km of satellites with SSM/I or SSMIS sensors, and consequently has a narrower 878 km-wide swath at the surface. At low frequencies (<20 GHz), ice particle scattering can be neglected and the variations in the observed brightness temperature result from changes in the optical depth of raindrops, which is approximately proportional to the integrated total rainwater amount, and is related to the surface rain. Over the ocean, raindrops increase the amount of emitted radiation, making rain areas somewhat "warmer" with respect to the ocean background. Over land, rainfall reduces upwelling radiation due to scattering that is mainly related to ice particles above. The relatively low and almost constant emissivity of water makes passive microwave retrieval more effective over the ocean, whereas over land, the emissivity is both much higher and variable in space, implying less accurate retrievals. Frequencies greater than 89 GHz are effective in mitigating the poor knowledge of emissivity and scattering properties of land surfaces. This is because, at these frequencies, retrievals rely on scattering from ice hydrometeors and therefore they can also be more accurate for applications like solid precipitation retrieval. In particular, the 150 GHz channel, exhibiting the strongest scattering signature associated with precipitation-sized ice particles, is scarcely affected by variations in surface emissivity. Among the previously mentioned sounders, the GPM Microwave Imager (GMI) is considered to have some of the most appropriate frequency sets for precipitation retrieval, namely 10 frequencies from 10 GHz to 166 GHz, in dual-polarization, and an additional three channels using single vertical polarization at 23.8 GHz, and two in the water vapor absorption band close to 183.31 GHz [58, 59]. It provides measurements on a 904 km-wide swath at a resolution varying from 4.4 km ~7.2 km for the high-frequency channels (>89 GHz), to 19 km ~32 km at 10 GHz. Such frequencies are also used in the previously mentioned ATMS cross-track scanning radiometer. Future missions, such as the EUMETSAT/ESA Polar System-Second Generation (EPS-SG) will host the Ice Cloud Imager that uses frequencies from 183 to 664 GHz to measure cirrus and, in general, properties of ice clouds [60].

The description above shows that a number of different radiometers, operated by different agencies, are available. Although they fly on polar orbits that allow them to observe small portion of the Earth, it is possible to virtually operate them in a constellation so that they can provide a quasi-continuous coverage of the Earth. This is the concept underlying the design of the GPM mission constellation, in which a CO satellite equipped with both a radiometer and an accurate active sensor (i.e., the DPR) act as a reference for radiometer inter-calibration [61]. Such a constellation (Figure 5), can not only provide global products, such as precipitation [62], but can also provide products to follow the evolution of storms for flash flood prediction [63]. The concept of using a constellation, rather than single satellite mission, is supported by the Aerosol and Cloud, Convection and Precipitation (ACCP), which is going to be explored in the next decades [64].

3. Radio-Wave Remote Sensing of the Earth's Surface

3.1 Active Remote Sensing of the Earth's Surface

Important applications that need to describe the status of Earth surface accurately, and at high resolution, have taken advantage of radar remote sensing. Radar methods use either real aperture, or synthetic aperture radars (SAR). Until the 1970s, the development of SAR was driven by military applications, thanks to its potential for high-resolution, day-and-night, and nearly weather-independent images for a multitude of purposes. SAR was attractive to complement, or in some situations to even replace optical sensors. In addition, the real aperture side-looking radars available had a low azimuth (for such systems azimuth denotes the flight direction) resolution that degraded with range. The brilliant invention of the SAR consists of using the motion of the antenna along the azimuth direction (the "synthetic aperture antenna") to simulate a wider antenna, leading, in principle, to an azimuth resolution of half the length of the physical antenna, independent of the height and range of the sensors [65]. This represented a real step forward, allowing microwave devices to reach ground resolutions of the order of a tenth of a meter, comparable with that obtained with optical sensors. Later, airborne systems also demonstrated the effectiveness of the SAR technique to retrieve geophysical and biological characteristics of land and oceans with adequate accuracy and at high spatial resolution [66]. The natural consequence was a development process that culminated with the launch of the first civilian spaceborne SAR, part of the NASA SEASAT mission. The mission, which lasted just three months due to the loss of the spacecraft, used an L-band SAR along with additional instrumentation, such as radiometers at different frequencies. Although designed for oceanic applications, it paved the way for later missions launched starting from 1990s [67]. Further SAR mission milestones with commercial applications, after the 1990s launch, were the C-band ESA's two European Remote Sensing satellites ERS 1 (1991-2000), and ERS 2 (1995-2011), the L-band Canadian Space Agency (CSA) Radarsat-1 (1995 to 2013), and JAXA JERS-1. These missions proved the reliability of the technology, as testified by the long-lasting operations of onboard SARs.

SAR systems used the same polarization in transmission and in reception. Later, exploiting polarimetry on SAR missions has provided more information about land, snow and ice coverage, and classification of surface features. The SIR-C/X-SAR (where SIR stands for Shuttle Imaging Radar) mission provided a valuable demonstration of these methods. A further mission (April and October 1994) featured multifrequency SAR payloads, at X-, L-, and C-band; the last two with polarimetric capabilities [68]. The mission was a joint venture between the German Space Agency (Deutsche Agentur für Raumfahrtangelegenheiten, DARA, today DLR), NASA, and the Italian Space Agency (Agenzia Spaziale Italiana, ASI). The multi-frequency SAR performed measurements during two 10-day spaceflights.

The SAR principle stimulated the development of new signal processing techniques that required specific flight configurations. The Interferometric SAR (InSAR) exploited two or more SAR images to generate maps of surface deformation or digital elevation, using differences in the phase of the waves returning to the SAR platform [69-72]. An orbiting SAR revisited the same area at regular intervals. InSAR compared two images collected from slightly different positions (spatial baseline) to produce three-dimensional images of the Earth's surface, measuring the topography. After proper processing of two images, which includes co-registration, an "interferogram", whose phase is highly correlated with the terrain topography, is obtained. These capabilities were also demonstrated with the Shuttle Radar Topography Mission (SRTM), which, in 2000, used X-band and C-band [73-75]. In this case, the payload featured two radar antennas:

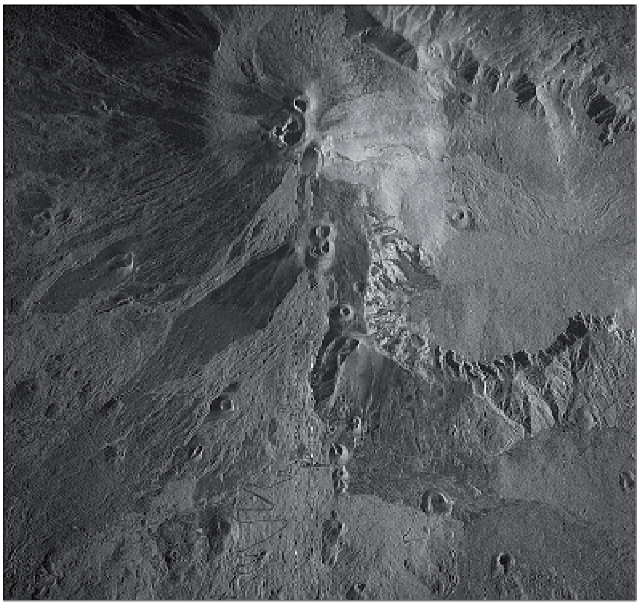

Figure 6. Etna volcano seen by Cosmo Skymed X-band SAR, at 1-m resolution (source: Italian Space Agency – ASI).

one antenna was located in the Shuttle payload bay, the other one on the end of a 60-meter mast that extended from the payload bay. Once the Shuttle was in space, single-pass interferometry was implemented. The SRTM database represented a major global topography from space effort. Successive releases of data are still ongoing at the time of writing (see https://earthdata.nasa.gov/learn/articles/nasa-shuttle-radar-topography-mission-srtm-version-3-0-global-1-arc-second-data-released-over-asia-and-australia), based on data from other sources for filling gaps from the original mission. In general, the InSAR technique can highlight deformations of the Earth surface related to natural phenomena such as earthquakes, landslides, and volcanic eruptions [74].

Differential SAR Interferometry (DInSAR) was a further advance in interferometric techniques. It involved taking at least two images (with the addition of DEM), and normally three images, of the same ground area. Passes 1 and 2 were used to form an interferogram of the terrain topography using the basic interferometric technique. Similarly, passes 2 and 3 produce a further interferogram of the same area. The two interferograms were, in turn, differenced to reveal changes that occurred at the surface. A DinSAR milestone was the use of Permanent Scatterers (PS) developed using data from ESA SARs missions ERS-1 and ERS 2 and later by the ESA ENVISAT satellite [75]. Both the ERS satellites shared the same orbital plane allowing a tandem mission in 1995 and 1996, where interferometric data were collected one day apart. Interferometric measurements were presented as a series of colored bands, called “fringes” or “interferogram”, that detected and measured displacements with high accuracy, of the order of centimeters. Taking advantage of a series of images, acquired over time, it was possible to point out temporal evolution of a deformation. The ground deformation measurement in volcanic areas, for instance, is extremely important because these are often eruption precursors, and may indicate an increase in volcanic activity [76], as well as subsidence, or simply provide precise absolute measurements of heights in urban areas. In this case, a clear advantage, compared to the conventional techniques, especially in case of an eruption, is that the measurements are obtained without needing to visit the volcano. The technique can potentially measure changes in deformation of the order of the SAR wavelength over spans of days to years, and has found monitoring applications even in ground-based systems [77].

The SAR missions, launched in the last decades, have introduced several improvements to the SAR technique. The C-band Advanced Synthetic Aperture Radar, on the ENVISAT mission, was the first SAR satellite exploiting radar antenna beam steering to improve the flexibility in the selection of different imaging modes. For example, the ScanSAR mode adopted in many state-of-art SAR, increases the swath at the expense of degraded spatial resolution. Conversely, the Spotlight mode gives better resolution for a smaller ground patch by steering the radar beam, as the satellite moves, to illuminate an area for a longer period of time. The new millennium has seen the launch of several new X-band systems, typically in a constellation configuration, like the DLR, bi-static SAR satellites TerraSAR-X, and TanDEM-X [78], and the ASI COSMO-SkyMed satellite constellation, made of 4 satellites, to be enriched with the launch of two second generation satellites. COSMO SkyMed is also a dual-use (military and civilian) mission with a schedule determined on the basis of user requests (Figure 6). The constellation approach drives major SAR missions to increase seamless services for critical applications such as flood monitoring [79]. C-band constellations are also pursued. The SENTINEL-1 mission consists of the European Radar Observatory, for the Copernicus joint initiative of the European Commission, and ESA, for the implementation of information services dealing with the environment and security based on observation data received from Earth observation satellites and ground-based information. The mission is composed of a constellation of two satellites, SENTINEL-1A and SENTINEL-1B, sharing the same orbital plane. The mission includes C-band SAR, with dual polarization capability operating with four imaging modes with different resolution (down to 5 m), and coverage (up to 400 km). Differently from COSMO SkyMed, a pre-planning approach has been followed to accomplish observational tasks. Two recent C-band constellations are the Canadian RADARSAT Constellation Mission (RCM), launched on June 12, 2019, with three identical satellites working together, and that composed of the two satellites SAOCOM 1A (launched 8 October 2018) and SAOCOM 1B (expected to be launched in 2020), equipped with a fully polarimetric SAR with the specific aim of mitigating the effects of natural disasters, managed by Comisión Nacional de Actividades Espaciales (CONAE, namely the National Space Activities Commission of Argentina). With the new millennium, SAR satellite technology has reached maturity. New mission designs are driven by user needs and applications. In order to exploit both polarimetric and interferometric capabilities, and shorten revisit times, SARs are increasingly adopting polarization capability and the possibility to fly in constellations.

A further active remote sensing system worth mentioning is Ground Penetrating Radar (GPR). Historically, it was one of the first applications of the radar concept, as testified by a patent dated 1910 [80]. Modern GPR uses frequencies between 10 MHz to 2.6 GHz to reveal discontinuities in permittivities below the surface [81]. The characteristics of certain frequencies of radio waves to penetrate the terrain has been used also for detecting archaeological sites [82], while UAV-born GPR may support search and rescue operations after earthquakes [83

3.2 Passive Remote Sensing of the Earth's Surface

Passive microwave remote sensing is used to estimate important water cycle components, such as the soil moisture, biomasses and vegetation status, and snow coverage properties. Most of the radiometric measurement missions at multiple frequencies, mentioned in Section 2.2, were used to monitor Earth surface properties. Operational algorithms for monitoring land surface properties were first devised for optical and infrared observations. Based on measurements in different bands, several indices were created, such as the popular Normalized Difference Vegetation Index (NDVI) that combined the radiance measurement in the "red" and near infrared (NIR) to provide information on vegetation status. If the reflected radiation is more in the near-infrared than in the "red" wavelength window, the vegetation is "greener" [84]. Again, this, and many other indices based on observation in the visible and infrared bands, can only be used in daytime, are significantly influenced by clouds, and only provide information for the surface layer. Radio frequencies, instead, are only slightly affected by these problems and therefore studies were conducted to explore the possibility of defining new, more robust and accurate indices, based on combining measurements of microwave emissions and polarization in different frequency bands. Several microwave indices related to the important geophysical parameters have been found and used in operational retrieval algorithms based on data collected from satellite borne radiometric sensors. In particular, the definition of several indices relies on the different sensitivity of microwaves to the water content of the observed bodies, and on the polarization behavior [85, 86]. The degree of polarization of the radiation emitted from a specular surface at an angle different from the vertical depends on the soil dielectric constant, and decreases as the roughness of the surface increases. In addition, radiation from canopies appears as less polarized than that from bare soil. Such facts have suggested using polarimetric information to define indices for vegetation studies that are related to physical properties like the plant water content, or for soil classification. Several studies concerning indices applied to SSM/I and AMSR-E channels for vegetation studies have been published [87, 88].

A field of application, whose importance is also related to characterizing climate changes, is the estimation of snow cover parameters. The potential for satellite microwave sensors to accomplish this task were investigated in 1980s using the Nimbus-7 SMMR [89]. Later techniques, based on multifrequency and multi-polarization measurements, were implemented for different satellites. Typically, the difference in brightness temperature between Ku and Ka frequency channels at horizontal or vertical polarization is used: the latter is sensitive to scattering from the snow surface, while the former is sensitive to emission from the layers underneath [90, 91].

Remote sensing of soil moisture was an important measurement that took advantage of radio frequencies. Soil moisture plays an important role as the regulator of near-surface temperature, evapotranspiration, surface runoff, and indicates wetness conditions, or drought. There are many in-situ ground-instrument techniques for measuring soil moisture, including gravimetric methods, reflectometry, capacitance sensors, electrical resistivity measurements, and some of them are implemented in off-the-shelf devices [92]. In remote sensing, soil moisture estimation is obtained, mainly, but not only, through L-band radiometry since the maximum sensitivity to soil moisture is achieved in the range from 1 to 5 GHz. Since land surfaces can be modelled as a mixture of soil, water, and air, soil moisture can be estimated because, at such frequencies,

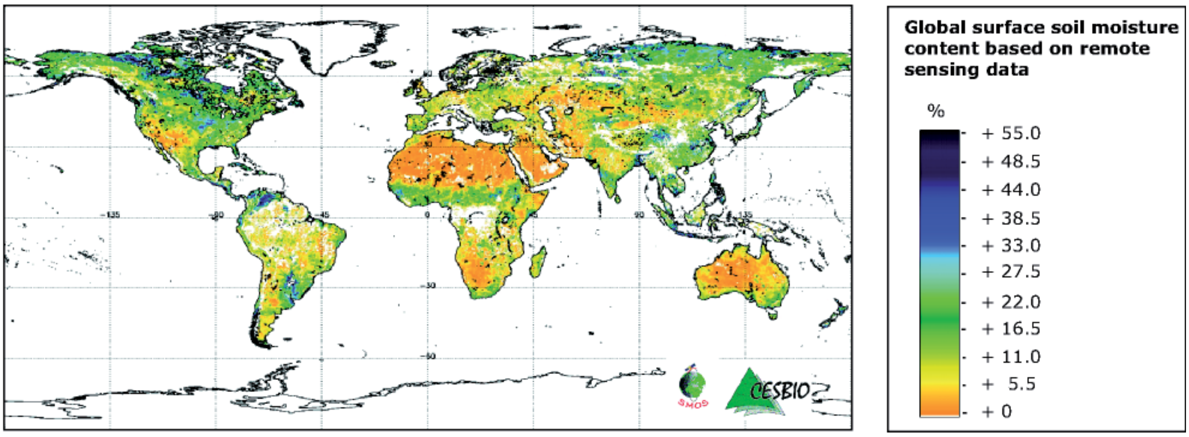

Figure 7. An example of a soil moisture global product with a resolution of 50 km, from the European Environment Agency (EEA) based on SMOS data. The image refers to 8-15 June, 2010. Yellow indicates drier soil surfaces; blue denotes wetter conditions (© EEA).

the real part of dielectric constant of water is 20 times greater than that of soil, providing the necessary contrast between water and soil components [0]. In addition, at L-band (1.4-1.427 GHz), clouds and precipitation appear transparent as well as, to some extent, the vegetation, allowing observation of the underlying layers. It is also a radio astronomy quiet band. For satellite implementation, the main drawback is, for these frequencies, the antenna dimension required to achieve adequate ground resolution. The ESA Soil Moisture Ocean Salinity (SMOS), launched on 2 November 2009, has solved this problem through the MIRAS (Microwave Radiometer by Aperture Synthesis), the first two-dimensional interferometric radiometer in space. It consists of a Y-shaped antenna array with three arms, folded during the launch, each arm having an approximate length of 4.5 m and 21 dual-polarization L-band antennas spaced 0.875 times the wavelength [94]. The spatial resolution varies from 35 km at the FOV (field of view) center to 50 km at the border (Figure 7).

The NASA Soil Moisture Active/Passive, launched on 31 January 2015, adopted a combination of passive L-band, fully polarimetric radiometer, sharing the same deployable 6 m antenna, with Synthetic Aperture Radar (SAR), to achieve both accurate measurements, and high resolution at the ground [95, 96].

As mentioned in the introduction, techniques based on opportunistic reception of GNSS satellites are used for surface observations, particularly those based on GNSS Reflectometry. Theory is often explained with reference to a “passive bistatic radar”, where passive indicates that techniques do not use purposely built sources, and bistatic indicates that the transmitter (on a GNSS satellite) and the receiver, capable of processing (on a different satellite, or in general on an aircraft, or even on a mountain), are separated and far apart. The configuration of the receiver depends both on the applications and the nature of the platform [97]. The use of scattered GPS was anticipated in 1988 [98]. The basic concepts underlying the GNSS-R technique were verified later in 1997 through measurements collected by a specific receiver on a NASA aircraft [99]. The first use of a space-borne GPS was the UK-DMC (Disaster Monitor Constellation) satellite (2003-2011). The UK TechDemoSat-1 mission (TDS-1) was successfully launched in 2014 with an improved GNSS-R payload. Although the first applications of the technique were focused on the ocean, like in active radar remote sensing soil moisture, or vegetation, or status of ice (even in sub-layers), can be inferred through the changes in the soil dielectric constant. Experiments were carried first with aircraft [100], and then with satellite demonstrators [101, 102].

4. Radio Wave Remote Sensing for Oceanic Applications

Oceans are critical, integral parts of the global water cycle, regulating the hydrological cycles on the Earth. Global observations of oceans with in-situ measurements are challenging, due to difficulties in sampling its ever-changing properties on all spatial and temporal scales, and in such an extensive domain, so that a transition to remote sensing has been necessary. The transition took place after the 1950s and affected first ground-based sensors and later satellite-borne sensors [103].

A noticeable ground-based system example was High Frequency (HF) radars used to measure surface currents. This technique, proposed in 1950s [104], and later demonstrated [105], relies on electromagnetic radiation in the 3 to 30 MHz range scattering strongly (Bragg scattering) from ocean surface gravity waves imposing a Doppler frequency shift on the return radio signal due to ocean currents and ocean wave propagation. The movement of ocean surface gravity waves, in radial directions, can be inferred from the Doppler shift, and radial current velocities are then obtained by subtracting the

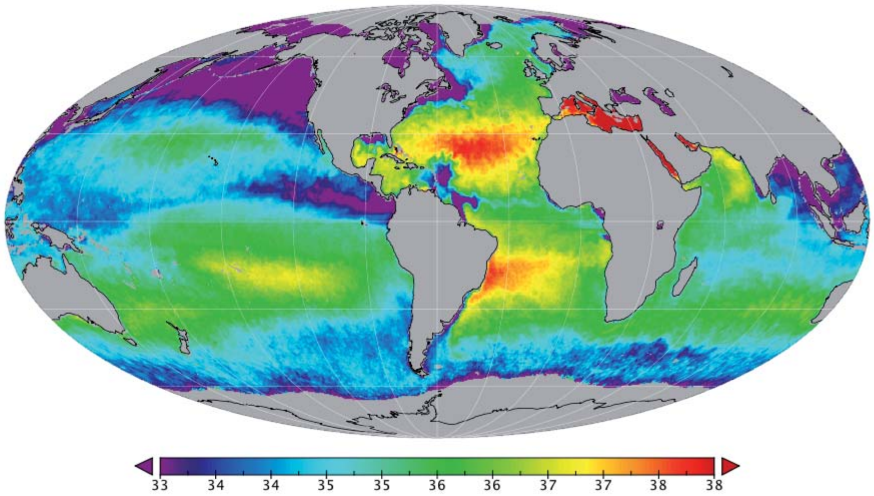

Figure 8. An example of the monthly map of SMAP level 3 sea surface salinity, gridded at 25 × 25 km resolution. The Scale for the Practical Salinity Scale (PSS) is roughly equivalent to parts per thousand (source: NASA Salinity).

theoretical ocean wave phase velocity. Multiple radars, properly deployed, can be used to obtain both the north-south and east-west velocity components. Depending on the frequency, ranges vary from a few kilometers using 40 MHz, to over 200 km at 5 MHz, to provide hourly surface velocity maps with horizontal resolution of 0.3 km (at 40 MHz) to 6 km (at 5 MHz), with accuracies of 0.05-0.1 m s^{-1}. So far, around 400 HF radars have been installed worldwide, and are being used in a diverse range of applications [106-108], such as monitoring and predicting currents, data assimilation inputs, and the validation and calibration of numerical ocean forecasting models, especially near the coast [109]. The growing number of HF radars, optimization operations, and the need for common interpretation of measurements, demands close coordination among these measurement infrastructures.

Technological advances in satellite remote sensing of the ocean using radio frequencies began in the 1970s. The first measurement of sea-surface temperature from space was achieved in the late 1960s using infrared measurements collected by the TIROS weather satellite program [110]. Again, the limitations due to cloud cover was found to be a major issue for continuous monitoring of oceanic processes. As in other application fields, the use of radio frequencies, in synergy with infrared observations has brought significant contributions to ocean research. The radio technologies for specific ocean observations were first demonstrated by the Skylab missions. The Skylab Radiometer/Scatterometer/Altimeter experiment was the first attempt to gather data using earth-oriented, spaceborne, active microwave-systems. For the first time, near-simultaneous radiometric brightness temperature radar backscatter data were acquired over land and ocean scenes [111]. The altimeter demonstration paved the way for the measurement of the sea surface with radar altimetry. The Geodetic Earth Orbiting Satellite-3 (GEOS-3) satellite provided the first survey of the ocean surface relief reflecting Earth's gravity anomalies and surface geostrophic currents [112]. The Seasat mission, mentioned previously as the first example of a satellite borne SAR radar, was actually a mission dedicated to observing the ocean using a comprehensive microwave remote sensing suite of sensors that included real-aperture radars, like altimeter and scatterometer, as well as the novel satellite borne SAR. In addition to demonstrating the feasibility of satellite SAR observations, it showed the effectiveness of these microwave instruments in mapping the ocean surface geostrophic circulation, vector wind field, surface and internal gravity waves, sea ice, and a host of air-sea interaction processes. In addition to active sensors, the Seasat payload also included a passive microwave radiometer (along with visible and infrared sensors), namely the SMMR, adopted also in Nimbus-7 (1978-1994), which provided the basis for the development of all-weather passive remote sensing of the ocean. The new capabilities of Seasat definitely changed the study of global oceans: the use of radar altimeter determined a change in how to map the variability of the sea surface height; the scatterometer measured the surface vector wind, and finally, the microwave radiometer provided a new means to measure Sea Surface Temperature (SST), and other geophysical parameters. Among the satellite missions aimed at ocean observations from space, it is worth remembering a series of satellite radar altimeters launched by various international agencies. These satellites include Geosat (US Navy), ERS-1 (ESA), and TOPEX/Poseidon (NASA and the French Centre National d'Etudes Spatiales, CNES) [113]. This series of measurements was continued by the Franco-American Jason-1, Jason-2, and Jason-3, as well as by ESA ENVISAT, US. Navy Geosat follow-on, the France-India collaborative mission of AltiKa [114], and the ESA CryoSat [115], leading to a continuous record of ocean surface topography available for climate studies. This new capability of satellite oceanography,

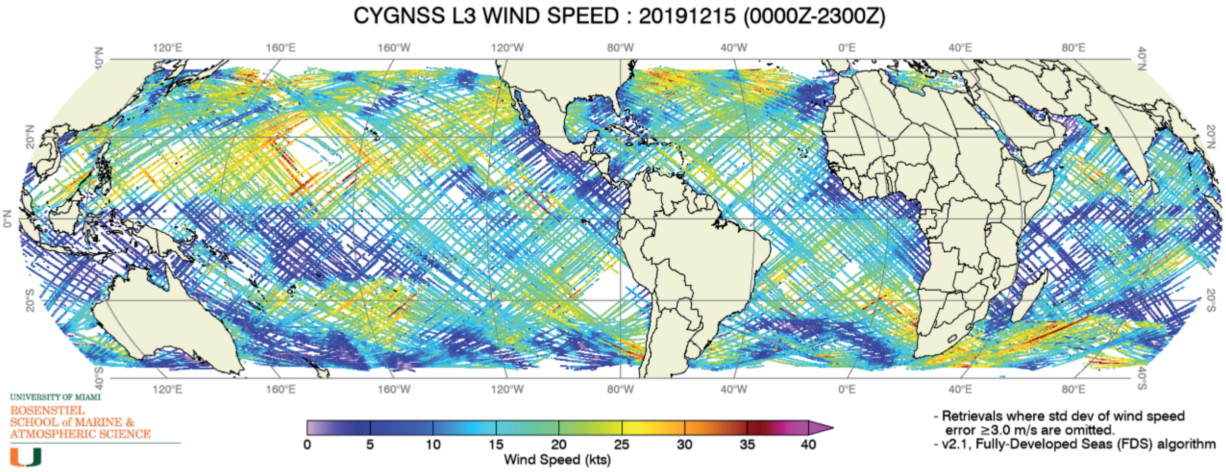

Figure 9. A daily map (December 15, 2019) of wind speed, obtained from CYGNSS level 3 data (source: Brian McNoldy, http://bmcnoldy.rsmas.miami.edu).

and the quality of retrievals, stimulated the development of international programs of global observation of the ocean and atmosphere, such as, in the 1990s, the World Ocean Circulation Experiment (WOCE) [116], as well as the Tropical Ocean and Global Atmosphere (TOGA) [0], leading to today's Climate and Ocean-Variability, Predictability and Change (CLIVAR; http://www.clivar.org/) Program. The NASA QuikSCAT satellite (1999-2009) was a Seasat follow-on mission to measure the vector wind field. It was conceived as a "quick recovery" mission to fill the gap created by the loss of data from the NASA Scatterometer (NSCAT) in 1997, but, in fact, it was able to provide the first decade-long high-resolution wind field [118]. Moreover, although the scatterometer was originally designed to be a wind sensor, the backscatter it measured was found to be more closely related to surface stress than the estimates obtained from the wind [119]. In recent years, a new frontier of satellite oceanography has been established to measure the global ocean Sea Surface Salinity (SSS) using the L-band radiometer of the Soil Moisture Ocean Salinity (SMOS) [120], NASA Aquarius [121], and Soil Moisture Active Passive (SMAP) [95] missions. The synergy of different satellite estimates of geophysical parameters such as wind, SST, SSS, *sea* surface height, and ocean color observations has led to advances in understanding the ocean-atmosphere interaction in relation to climate, ocean dynamics, and marine biogeochemistry (Figure 8). The advent of remote sensing has stimulated the launch of several missions, the most recent using microwave payloads that are providing quantitative characterization of the four-dimensional ocean circulation, its role in climate and weather processes, its linkages with the global water cycle, and its impacts on ocean biogeochemistry.

The GNSS-R method is a further contribution to radio observation of the ocean, both for altimetry (an example of ground based GNSS-R altimetry application is in [122]), and wind estimation. Wind measurements are obtained using the same principles and theory as active radar scatterometers, based on surface roughness. Using GNSS reflected signals for wind scatterometers was first suggested in [123]. Following several campaigns carried out to demonstrate the feasibility of GNSS-R for oceanic applications, the principle was adopted by a constellation implementing the GNSS-R approach, namely the NASA Cyclone Global Navigation Satellite System (CYGNSS). The constellation of eight satellites was successfully launched into low Earth orbit on 15 December 2016. Each satellite has a receiver that measures GPS signals scattered from the surface. Thanks to the L-band frequency, CYGNSS is barely affected by propagation attenuation in heavy rain [124, 125]. A noticeable advantage of this technique, with respect of spaceborne active scatterometers, characterized by a given revisit time, is the ability to provide frequent updates of the wind maps (Figure 9).

5. Summary

Radio remote sensing techniques have provided viable solutions for monitoring essential geophysical parameters on a global scale, and to support practical applications such as severe weather warning, and the forecasting and mitigation of flooding. This chapter has shown how radio frequencies are used for monitoring and probing the atmosphere, ocean, and land. Radio-wave investigations have often been motivated by the typical shortcomings of optical observations, such as difficulties in night operations, and sensitivity to weather effects. However, the relatively recent history of microwave remote sensing (less than 50 years for satellite borne sensors) has shown that its true advantage is related to the usefulness of the different signatures characterizing emissions, or scattering, for different portions of the radio spectrum from an observed scene. This has led to the development of new remote sensing methods, by sensors operating at different frequencies that are capable of estimating geophysical parameters, significantly improving their accuracy and robustness.

Specific advantages of radio waves in remote sensing application were demonstrated throughout this chapter. In recent years, microwave remote sensing has transitioned from a research activity to a full-fledged operational phase, supporting a large number of industries with extensive economic value. Increasingly, operational services are employing microwave remote sensing, such as ground-based weather radar networks, satellites and climate services, just to mention a few. Recent missions, mentioned in this chapter, have demonstrated the feasibility of remote sensing (both active and passive) based on radio frequencies, and emerging architectures, for small satellites. The design of new satellite missions is becoming increasingly driven by application needs, rather than to solve technological challenges. In this context, missions are planned within of a constellation framework, like the US ACCP plan [64], or the EU Copernicus program Sentinel satellites (https://sentinel.esa.int/web/sentinel/home). In fact, the need to understand natural processes, the impact of human activities on environment, and the ambition to predict the future of Earth, necessitate better observations of our planet's status. A multitude of observations involving remote sensing systems adopting different frequencies and modes, eventually combined with in situ measurements, or opportunistic signals, are irreplaceable tools to support the global effort to characterize the processes that model the environment in which we live.

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Commission G Ionospheric Radio and Propagation

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1. Introduction

The ionosphere is a region of the upper atmosphere where large concentrations of free electrons affect the propagation of radio waves. It is primarily produced by ultra-violet radiation. The region begins at approximately 50 km above the surface of the Earth and extends into space. It is a highly variable medium with dependences on geographic location, time of day, season, solar and geomagnetic activity. The ionosphere is important because it reflects and modifies radio waves used for communication, navigation and surveillance systems. Space Weather influences the ionosphere in many ways, which, in turn, have adverse and beneficial effects.

Commission G carries out pure and applied research, the latter to provide the understanding necessary to support space and ground-based trans-ionospheric radio system operation. From the earliest studies of ionospheric morphology, transforming advances in diagnostic techniques, ionospheric modeling, theory and radio system applications, Commission G scientists have been at the forefront of discovery of the complex ionospheric environment and its effects on radio waves.

Specific areas of interest include: observation of ionospheric structure, variability, coupling and trends at all relevant scales, modeling of the ionosphere to enable understanding and prediction of its properties, development of tools, measurement techniques and instruments, theory and practice of ionospheric radio propagation, and applications to radio systems. To further these objectives, the Commission collaborates with other URSI Commissions, corresponding bodies of the International Science Council including IUGG, IAU, COSPAR and SCOSTEP and other organizations such as ITU and IEEE.

Commission G scientists are active participants in the URSI triennium meetings and within the following working groups:

- G.1 Ionosonde Network Advisory Group (INAG)
- G.2 Studies of the Ionospheric Using Beacon Satellites
- G.3 Incoherent Scatter
- GEH Seismo Electromagnetic (Lithosphere-Atmosphere-Ionosphere Coupling)
- GF Middle Atmosphere
- GJFEH Interdisciplinary Space Weather
- EHG Solar Power Satellite
- FGHJ RFI Mitigation and Characterization

With the extensive breadth of studies and activities of Commission G, this chapter presents contributions from just a few long-term studies that reveal historical perspective and future insight. These contributions include:

- Ionospheric Imaging with Ionosondes: contributed by I. Galkin.
- Science and Discovery through Incoherent Scatter Radar, contributed by A. Coster and P. Erickson.
- Active Experiments in Plasmas using RF Waves, contributed by M. Reitveld.
  Ionospheric Modeling, contributed by D. Bilitza.
- History of Radio Scintillation, contributed by C. Rino and V. Zavorotny.
- Long Term Studies on Ionospheric Scintillation and Plasma Bubbles, contributed by E.R. de Paula, A.O. Moraes, M.A. Abdu, J.H.A. Sobral, I.S. Batista, E.A. Kherani, H. Takahashi, E. Costa.

These contributions are presented with their own references.

2. Ionospheric Imaging with Ionosondes: Historical Perspective and Prospective Insight

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In 1926, after two decades of extraordinary advances in the fields of radio science and wireless technology, Scottish physicist Robert Watson-Watt proposed the new term *ionosphere* to denote the radio-reflecting layers of plasma in the upper atmosphere. It was one of these conducting layers called E for "electric" that made the transatlantic propagation of the Morse-coded signal between Marconi's stations possible in 1901. The quest for measuring the altitude of the magic mirror in the atmosphere included remarkable experiments on both sides of the Atlantic. The Cavendish Laboratory, in Cambridge, [1] reported evidence that the skywave "bounced" from the ionosphere by observing the interference pattern between the ground and sky waves using a continuous signal of slowly changing frequency. Two scientists with major interests in high-voltage pulsing particle accelerators, [2] of the Carnegie Institution of Washington (CIW), built two radio devices that transmitted 1 ms pulse trains at 4045 and 8650 kHz to record the ionospherically propagating signals by a string galvanometer. The UK and US teams are both universally credited with establishing the remote sensing of the ionosphere, making it one of the most exciting objects to study in geophysics at the time. By the early 1930s, the research community was eager to probe higher altitudes in the atmosphere with the high-frequency (HF) wireless instruments.

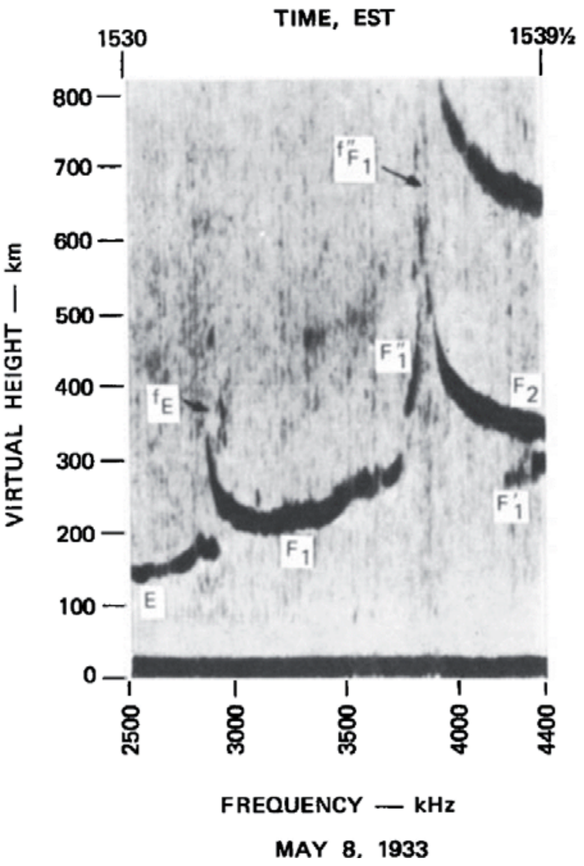

Figure 1. The first NBS sweep-frequency ionogram at in May 1933. (Source: [12]).

It took another two decades to put together the *ionosphere* and *sounder* to form the *ionosonde.* It is less clear when the graphic record taken by the early radio sounders was given the name *ionogram*. In the 1930s, operating an ionosonde involved six workers [3]. Perhaps in recognition that data collection over the whole 24 hours was not a small feat during those days, the first diurnal timeline of the E-layer O-wave critical frequency foE, as recorded on January 11-12, 1931 at Slough observatory in the UK, is now recognized as the first ionogram measurement [4]. This major anniversary is now celebrated by the URSI Commission G Ionosonde Network Advisory Group (INAG) with compilations of the worldwide January 11 ionograms.

The remarkable rise of short-wave radio broadcasting in the 1930s meant the ionosonde community needed to provide continuous data service to society, similar to the demands placed on the terrestrial weather community. Ionosonde operations had to be streamlined and automated to meet the challenge. It was Theodore Gilliland's group NBS in the US that built a brilliant automatic ionogram recording device mated to the first collocated pulse-echo

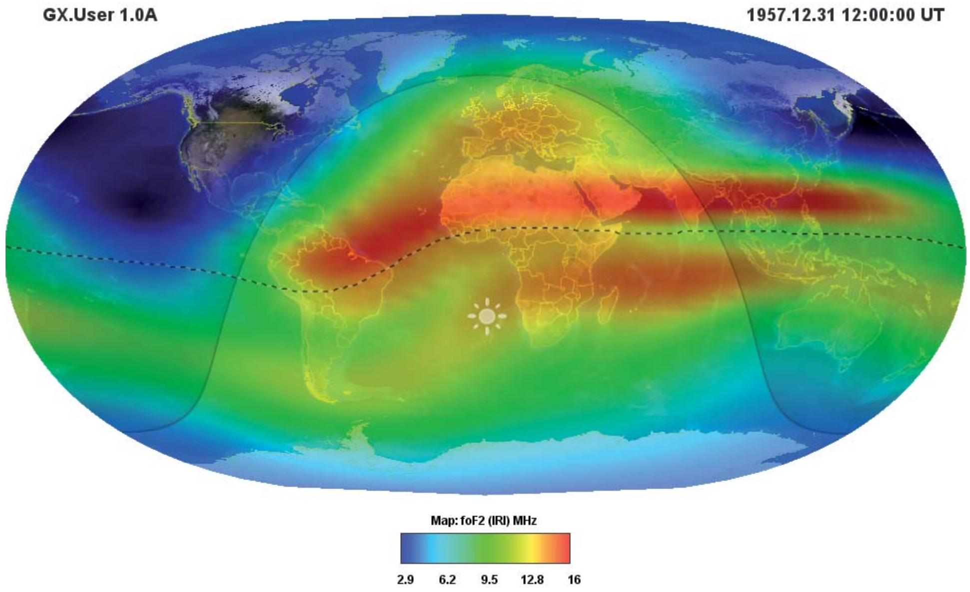

Figure 2. Ionosonde imaging of the ionosphere by fusing averaged ionogram-derived foF2 measurements with the empirical Jones-Gallet spatial/temporal expansion model. (Source: Adapted with data from [13]).

sweep-frequency transmitter-receiver with a shared master oscillator and antenna system [5]. New ionosondes produced images (Figure 1) that would look familiar to modern readers of the URSI Ionogram Interpretation Handbook [6]. NBS soon became the focal point for collecting and distributing “URSI-grams” based on the data acquired by the first-ever ionosonde network. By the end of World War II, about 50 ionosondes were in operation, despite the fact that wartime strategic interests had diverted resources and talent towards the goal of quickly developing more highly sophisticated radars. It was not until the International Geophysical Year (IGY) 1957-1958 that research interests in the ionosphere had a major revival.

An unprecedented and still unmatched total of 160 ionosondes of 14 different models across 67 countries participated in IGY [7]. NBS built twenty-six third-generation C-4 ionosondes [8] for IGY, and the Soviet Union contributed 21 AIS-3 ionosondes designed by the Head Office of Hydro-Meteorological Service (now Roshydromet) in Moscow. In 1957, the World Data Center (WDC) system was established to store acquired data, a remarkable international cooperative project for science without borders that has since extended its operations into the 21st century.

One of the significant outcomes of coordinated worldwide ionosonde measurements in the 1950s was the new capability for global mapping of the F2 layer O-wave critical frequency, foF2. It took several years to develop the optimal empirical modeling formalism [9, 10]. The early global climatological maps of foF2 formed the basis for the data-based International Reference Ionosphere (IRI) model [11]. To this day, the Jones-Gallet’s expansion for ionosonde data remains the gold standard for global mapping of the ionospheric climate, proven to yield exceptional accuracy for describing the average quite-time conditions.

The foF2 maps (Figure 2) have transformed ionosondes into plasma imaging instruments. It is still rare that ionosondes are regarded as “imagers” even though there are arguments to support such classification [12]. In particular, historians point out that use of the probing electromagnetic (EM) radiation to illuminate the environment and detect signatures of interaction between the wave and object(s) of interest applies universally throughout the radiation spectrum. The ionosonde fits naturally in its own section of the EM spectrum for sensing the plasma structures. With the capability of building global maps of the ionospheric properties, however, yet another intuitive imaging capability of ionosondes emerged, resulting from the collaborative use of worldwide sensor networks.

It is hard to estimate the total number of ionosondes ever built. The most complete collection of foF2 measurements included data from 250 observatories [14], so the total ionosonde count may have reached several-hundred. It is known with certainly, however, that by 2020 a total of 167 ionosondes have been built in one city, Lowell, Massachusetts, by Bodo Reinisch’s group. Figure 3 displays a picture of Bodo in 1970 with Digisonde #128.

Figure 3. Bodo Reinisch with Digisonde 128 (photograph around 1970). (Reprinted with permission of B. Reinisch.)

The technology advances that amounted to the first Digitally-Integrating Gonio-metric Ionosonde (Digisonde) model 128 developed in 1969 are well documented [15, 16]. In the late 1960s, R&D groups were engaged in devising the next-generation "advanced" ionosonde [17, 18] that would extend the original set of signal measurements to include Doppler frequency, angle of arrival, and polarization. New requirements demanded *phase-aware* signal generation, transmission, reception, and processing. Rapid developments of the radar technology, including phased antenna arrays [19] and goniometry, were helpful in accomplishing this challenging task. Advanced ionosondes became instrumental in both academic research and practical applications. The number of science publications stemming from the ionosonde data reached 1,000/year in 1981 [20].

Significant progress in understanding the ionospheric plasma dynamics was made by Doppler skymap imaging [16]. During disturbed ionospheric conditions, the vertical-incidence ionosonde illuminates a wide area in the ionosphere to then receive a multitude of off-vertical echoes that are specularly reflected from a tilted ionosphere or irregular plasma structures. The Doppler skymap is a visual presentation of signals in polar coordinates, similar to optical all-sky images (Figure 4). Individual overlapping echoes are distinguished by their Doppler frequency and then evaluated for their angles of arrival. The line-of-sight velocities restored from the individual echoes are then collectively analyzed to obtain the vector velocity of predominant plasma drift.

As for more practical applications of advanced ionosondes to ionospheric monitoring, the new capability of automated extraction of the quantitative ionospheric properties from the ionogram images, called *autoscaling,* entered a new phase called ARTIST: Automated Real-Time Ionogram Scaling with True height [21]. Early ionogram autoscaling research [23, 24] had stirred a wide enthusiasm for the mighty computer vision replacing human subjectivity; however, the next two decades were spent in a

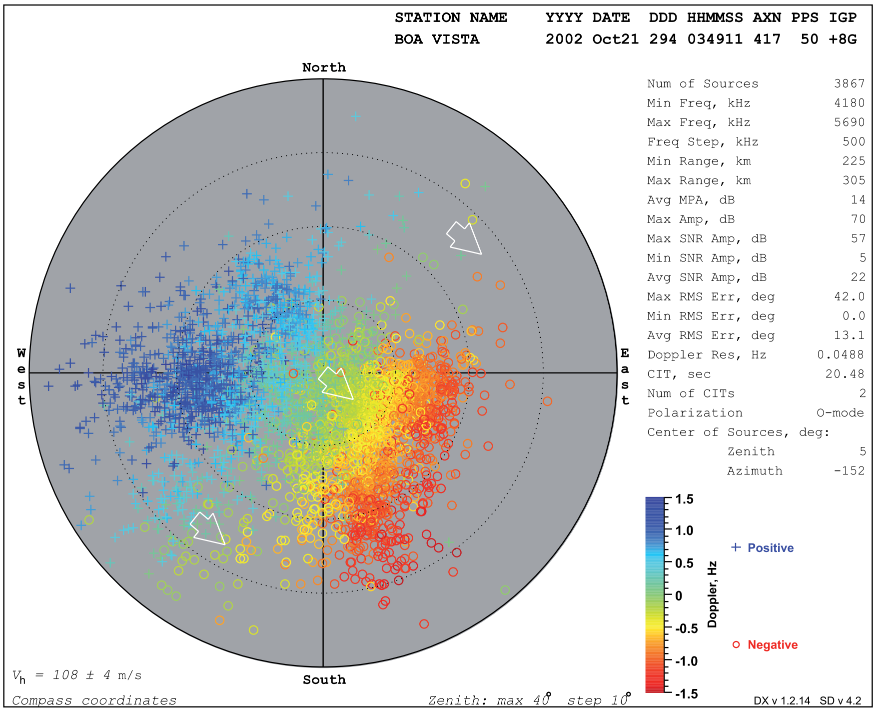

Figure 4. Digisonde skymaps show the (x, y) coordinates of the reflection points of all echoes received at a fixed frequency, within a 40° cone around the zenith. Colors indicate the Doppler frequency shift from negative (red) through zero (green). (Source: Adapted from [22].)

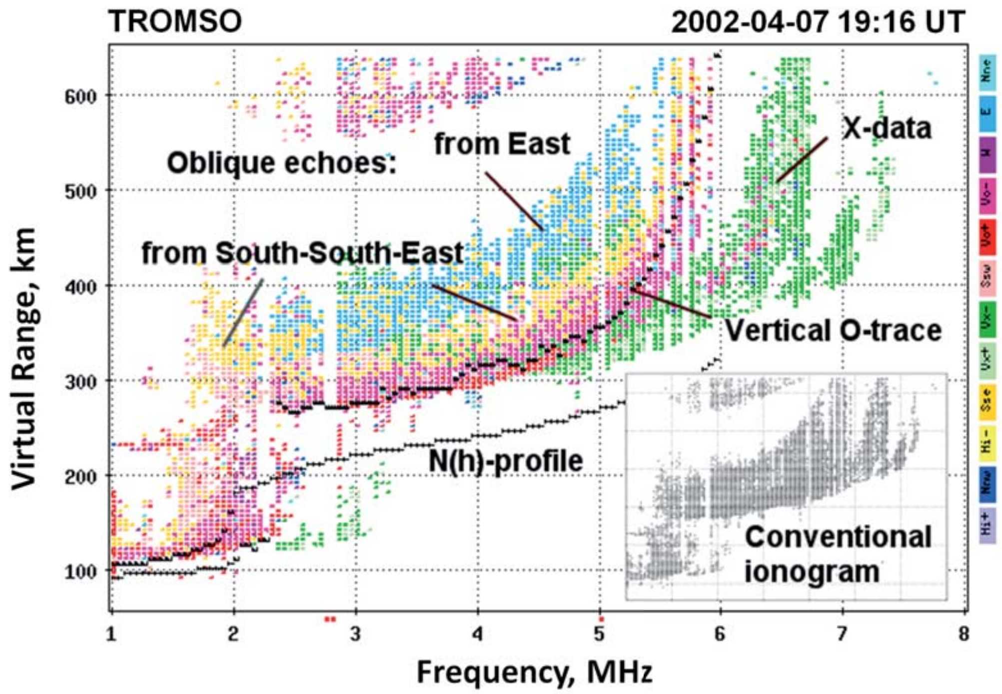

Figure 5. An ionogram taken by an advanced ionosonde with colors used to represent echo attributes (polarization, angle of arrival, and Doppler frequency). Insert: a conventional grey-scale ionogram would be harder to interpret. (Source: [25].)

thoughtful search for practical and reliable solutions. The advanced ionosonde added color to ionogram images (Figure 5). In color, ionograms became easier to autoscale. And with the advent of inexpensive 16-bit Intel microprocessors in the late 1970s, ionogram-autoscaling ionosondes had finally come into play. Today, about 93% of all acquired ionograms do not get to be seen; the actionable information is extracted automatically and forwarded for fusion with other measurements, assimilative models, and secondary analysis algorithms.

Operating a network of 100 ionosondes does not require 600 full-time personnel anymore, as it would in 1932. The first fully operational automatic ICED/PRISM system for ionospheric weather monitoring was established by the Air Weather Service (AWS) of the US Air Force [26, 27]. The ICED/PRISM model engines assimilated near-real-time (nRT) data feeds from the first unattended pre-Internet online network of 16 Digital Ionospheric Sounding Systems (DISS) [28] based on the Digisonde 256 [29] with the ARTIST autoscaler.

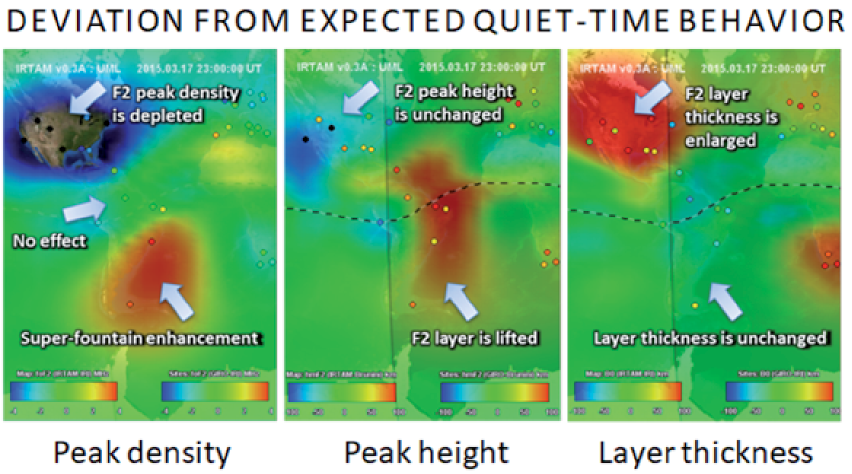

Figure 6. Weather-minus-climate maps that compare GIRO-driven IRTAM weather and IRI climate specifications Red and blue shades denote higher and lower than expected values, respectfully. Color dots are placed at GIRO site locations. (Source: Adapted from [22]).

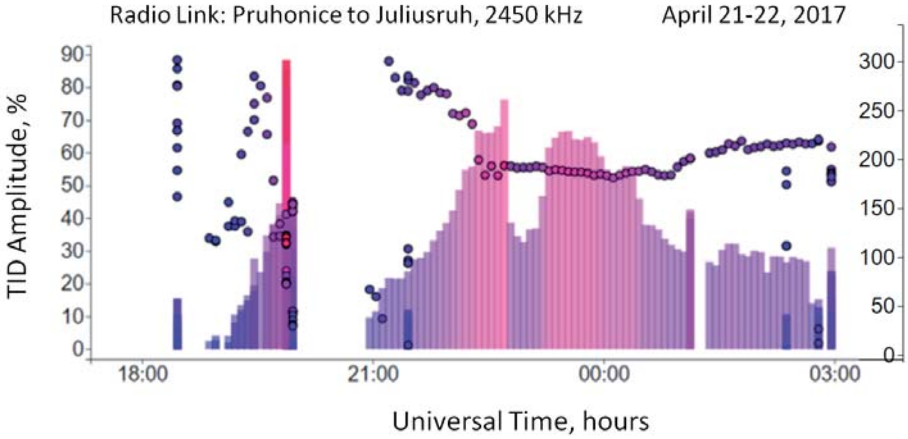

Figure 7. A major TID event with electron density modulation of up to 70% amplitude and traveling predominantly South-South-West direction detected on a Digisonde-to-Digisonde link between Pruhonice, in Czechia, and Juliusruh, in Germany. (Source: Adapted with data from [13].)

In 2005, the US National Science Foundation (NSF) announced a "quiet revolution" in sensor networks [30] that had fundamentally transformed the world of engineering and science. According to the criteria that NSF analysts formulated, the Digisonde network would have qualified as a "quiet revolution" twenty years earlier: it featured a fully unattended, real-time, self-diagnosed, intelligent-system distributed sensor network with prompt data feeds to a world data center and assimilative models for decision making. Built upon the early success of the AWS DISS, the Global Ionosphere Radio Observatory (GIRO) was established in 2005 [31], with international agreements for sharing real-time ionosonde data. GIRO measurements are assimilated by the next-generation models of the ionosphere [32-35]. Every 15 minutes, GIRO servers release the weather nowcast and publish weather-minus-climate maps for rapid insight into the current deviation of the ionosphere from its anticipated quiet-time behavior (Figure 6).

Availability of the new digital signal electronics, and in particular, Direct Digital Synthesizers (DDS), direct-sampling digital receivers (also known as software-defined radios, SDR), and digital steered antenna arrays, has transformed a fleet of ionosphere radars, both spaceborne and ground-based, into next generation, high-fidelity, phase-aware, miniaturized, and cost-effective instrumentation. Digital transceivers have long become the standard solution for ionosondes [36, 37], opening new possibilities for the angle-of-arrival measurements of sufficient precision to detect even slight wavelike plasma

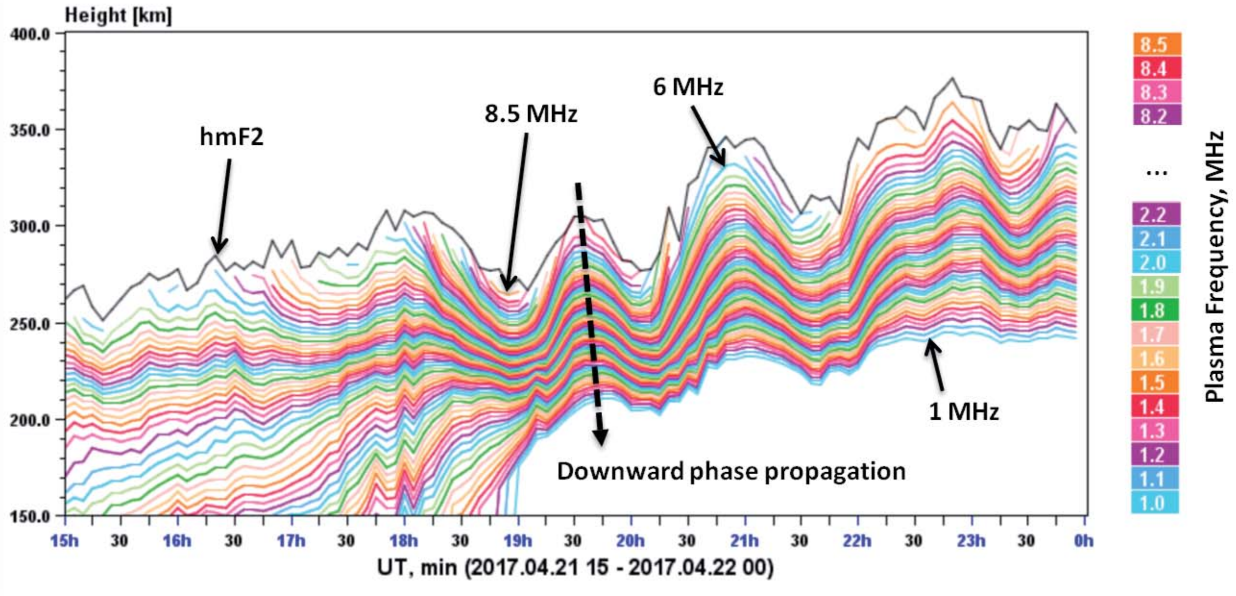

Figure 8. TIDs in electron isodensity contours derived from Digisonde data at the Ebro Observatory (Roquetes, Spain). Periodic variations of the plasma density reveal their dependence on the altitude in terms of both amplitude and phase of the modulation. (Source: Adapted from [37].)

perturbations attributed to the passage of traveling ionospheric disturbances (TID) [38-40] and evaluate their propagation characteristics, including amplitude, wavelength, and horizontal vector velocity (Figure 7).

While traveling disturbances leave only a small fraction of 1% imprint in the global navigation spacecraft system (GNSS) total electron content (TEC) measurement, the ionosonde observes an unmistakable 30-70% modulation amplitude as it pin-points the probing signal to specific plasma locations. Such high sensitivity to TIDs earned ionosondes a new place in the world of modern life applications that are adversely affected by ionospheric dynamics during disturbed conditions [41, 42]. One strong driver of renewed interest in ionosondes is the apparent susceptibility of operational systems for Precision Point Positioning (PPP) and HF transmitter geolocation to the overpassing TIDs that alter the signal path introducing unacceptable errors of positioning knowledge required for autonomous vehicles. Regarded as a “silent killer of accuracy” or “short-range catastrophe” in these domains, damaging TID effects have been evading detection by the affected systems themselves, though are clearly seen in ionograms and Doppler skymap images [39]. Additionally, stacked isodensity contour plots (Figure 8) obtained from the plasma density profile timeline reveal the altitude dependence of the amplitude and phase of TID and provide descriptive imaging of the TID travel in the vertical direction.

In future, high precision of the phase measurements that the digital transceiver affords will lead to a new generation of enhanced phase-aware computations and new signal waveforms, including precision radar ranging [43, 44], in particular in its implementation as the double-sideband suppressed-carrier waveform [37]; pseudo-random sequences for low-intercept sounding [44]; coded-continuous waves with frequency-hopping [46]; monostatic low-power CW chirp-sounders [47]; orthogonal waveforms for simultaneous vertical and oblique sounding [48], and a fleet of low-cost SDR-based ionosondes [49].

Digital transceiver and signal processing will allow sufficient miniaturization of the ionosonde to fit on a CubeSat platform [50] so it becomes possible to fly a constellation of the topside sounders [51]. Integration of the spaceborne Vector E-Field Instrument (VEFI) [52] and HF sounder into the same payload will allow simultaneous characterization of the electric field and plasma structures from a single platform, allowing the new capability of sensing the ionospheric plasma dynamics.

Ionosondes remain the workhorse of accurate and prompt ionospheric weather monitoring, providing measurements of high quality and resolution in near real-time from a global network of observatories. Modern HF systems have re-emerged as rapid-insight, high-sensitivity Ionosphere Disturbance Indicators (IDIs) that detect and specify adverse effects on trans-ionospheric signal propagation. They are autonomous systems that specify traveling ionospheric disturbances, ionospheric scintillation activity, elevated radio absorption, and other natural and man-made phenomena that still make modeling, mitigation, and forecast of the ionospheric dynamics a great challenge.

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3. Science and Discovery Through Incoherent Scatter Radar: Brief History, Development, and Future Directions

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3.1 Introduction

The technique of modified Thomson or incoherent scatter (IS) radar has been employed since the mid-1950s to provide comprehensive, fundamental insights into the state of the ionosphere and its thermal parameters in a way not matched by any other radio-based, remote-sensing technique. IS radar’s unique observation power stems from its use of a precise theoretical model derived from fundamental constants and first-principles plasma theory, applied to properly interpret very weak ionospheric backscatter measured using large aperture antennas and powerful microwave transmitters. Ultimately, this technique directly, and uniquely, measures full altitude profiles of the most fundamental ionospheric parameters including electron density, electron temperature, ion temperature, plasma velocity, and ion composition. These basic state variables with varying assumptions then allow further derivation of such key quantities as electric field strength,

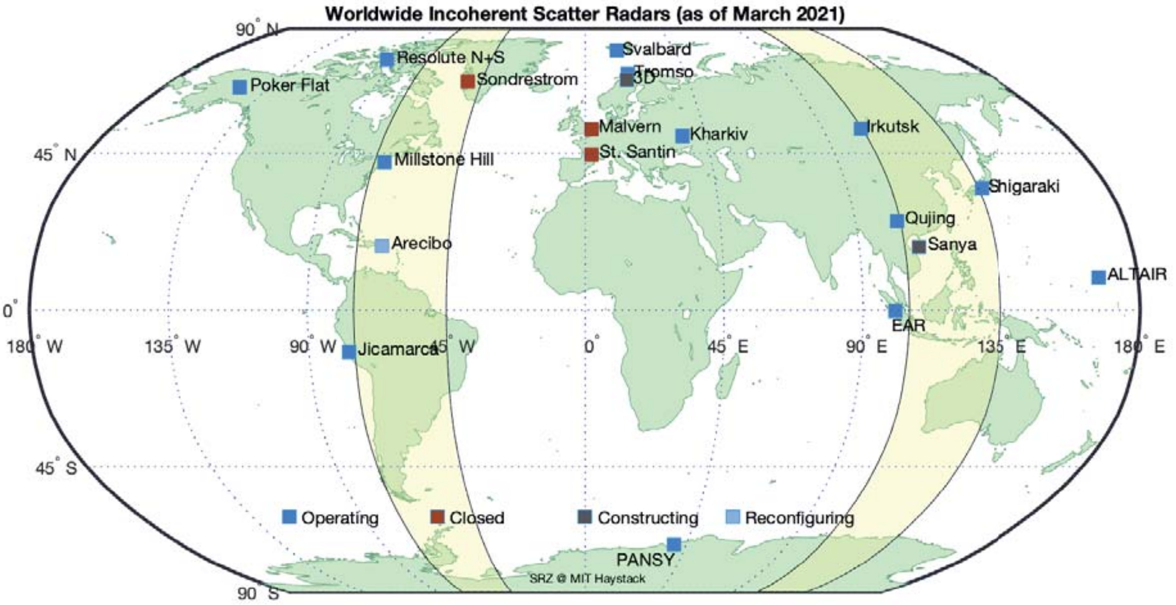

Figure 9. A world map of incoherent scatter radar systems, encompassing historical, current, and future sites. (Courtesy of Shunrong Zhang, MIT Haystack Observatory.)

conductivity, electric currents, neutral temperature, and neutral wind velocity. Taken in aggregate, no other technique is comparable in the range of ionospheric and thermospheric parameters provided for synoptic and detailed scientific studies.

IS measurements can be provided to users in near real-time, and historical data is available for many existing radars, in some cases extending back more than five solar cycles. IS measurements continue to play a critical role in community atmospheric and ionospheric model development and verification, helping to produce for example the widely used MSIS neutral atmosphere model [1] and the International Reference Ionosphere (IRI) [2]. In recent years, IS measurements have also been used to validate and amplify in-situ satellite measurements from a number of different missions in system scale studies (e.g. [3]). In general, IS radar characterizations of ionospheric and thermospheric dynamics are a mainstay of community knowledge and understanding of large and small scale processes and features within the tightly coupled magnetosphere-ionosphere-atmosphere system.

This article briefly reviews the history of IS radars, including those currently operational and those that are now closed, as a function of decade. It ends by looking toward the future, including a short description of new 21st century systems and scientific capabilities on the horizon. Figure 9 illustrates the world map of IS radars, encompassing historical, current and future sites.

3.2 Background

Due to the extremely small radar cross-section of free electron scatter from the ionosphere, incoherent scatter experiments require a challenging combination of large aperture antennas, very high power radar transmitters, and a very sensitive receiver near the thermal noise floor. This is necessary because in aggregate the ionosphere returns less than 10^{-19} of the transmitted power during a typical experiment (10s of femtowatts using megawatt transmitted pulses). Although J. J. Thomson inferred the possibility of this type of radiowave scatter from electrons in the first decade of the 20th century following his 1897 postulation of their existence [4], such weak signal radar experiments were not practical until the 1950s when sensitive receivers and efficient large-scale antenna construction techniques became available. In 1957, Professor W. E. Gordon of Cornell University noted these trends and did the first fundamental calculations which showed that Thomson scatter from electrons in the ionosphere was now detectable with the new high-power microwave transmitters available at that time. By Gordon's calculations, a very large antenna aperture was also needed whose dimensions were measured in hectares. The combination of the two at approximately 40 megawatt-hectares was deemed sufficient, and in spring 1958, Gordon began his plans to build a radar "sensitive enough to observe electron scatter in addition to various astronomical objects…" [5].

Although the assumption of pure electron scatter in Gordon's calculations led to the later building of the 305m diameter reflector Arecibo Observatory, commissioned in 1962, the initial detection of incoherent scatter was achieved first in 1958 on a much smaller radar. Dr. Ken Bowles, a former Cornell student employed by the US National Bureau of Standards (NBS) in Boulder, CO, knew of Gordon's calculations and, in only 6 weeks, connected a megawatt class VHF frequency transmitter to a large dipole antenna array in Long Branch, IL, forming a 20 megawatt-hectare system. On October 22, 1958, Bowles conducted experimental measurements with this setup [6], relaying news to Gordon of a successful incoherent scatter detection using an averaging oscilloscope and camera with a 4 second film exposure providing ~10 dB effective integration. Later that same day, Gordon presented these same results at a Penn State URSI meeting and used the phrase "…And then I want to tell you about a telephone call that I just had." [7] Bowles later wrote in his 1958 paper that"

> "The possibility that incoherent scattering from electrons in the ionosphere, vibrating independently, might be observed by radar techniques has apparently been considered by many workers, although seldom seriously because of the enormous sensitivity required…." [6]

History bears out this statement, since incoherent scatter from the ionosphere was previously observed in the mid-1950's by the large Ballistic Missile Early Warning System military radars (whose design was at the right power-aperture class), but the observed signals were discarded as "strange ubiquitous noise."

The initial detection by Bowles was later found to be contrary to theory, since the 20 megawatt-hectare system was not only 1/2 of the performance class Gordon predicted but also used a 41 MHz frequency, which suffered from a much larger amount of background noise due to galactic and atmospheric noise sources. This triggered a large amount of theoretical work by several authors (e.g. [8-12]) which showed that, due to collective plasma effects, the backscatter spectral width was characteristic of ion motions even though electrons were providing the scatter. This fact increased the detectability of the scatter by a large factor (~50), allowing a smaller operational system compared to original calculations assuming pure electron scatter.

Following these developments, several incoherent scatter radars were established. We note that all extant data from these systems, whether historical or current, is available for community use in the Madrigal distributed database system (cedar.openmadrigal.org) operated by MIT Haystack Observatory as part of the Millstone Hill Geospace Facility.

3.2.1 1960s

Jicamarca: The 50 MHz incoherent scatter radar at the Jicamarca Radio Observatory near Lima, Perú was constructed beginning in 1960 by K. L. Bowles, B. Balsley, G. Ochs, G. Miller, and J. Green (NBS), soon after the 1957 International Geophysical Year (IGY) [13]. Its purpose was to extend multiple latitude radio propagation and ionospheric studies near the magnetic equator; to see if a predicted ion gyro resonance signature at long correlation times could be used as an ionospheric mass spectrometer; and to continue and strengthen good US international collaborations with Perú that were initiated during the IGY. Jicamarca was designed as a large aperture VHF frequency radar system using 18,432 dipoles over an area of 300 m x 300 m, separated into 64 modular sections (8 x 8) each with 12 x 12 full polarization dipoles capable of observing ionospheric Faraday rotation. Four 1.25 MW peak power transmitters were connected to the array using open transmitter feedlines, with independently phased receivers using RG17 coax. The Jicamarca design was chosen based on previous Arecibo studies that showed arrays could be built for much less than the cost of then conventional antennas, with the cost for these arrays being proportional to f^2 for a constant area. The array was oriented so that the minimum sidelobe plane was coincident with the magnetic meridian in order to reject strong echoes from narrow sporadic E reflecting layers. Jicamarca has made many key contributions to knowledge of the equatorial ionosphere and its embedded irregularities, including very high altitude measurements [14], Faraday rotation based ionospheric electron density profiles [15], scattering perpendicular to the magnetic field [16], optimal full profile analysis approaches [17], and studies of the critically important spread F phenomenon [18]. It continues today as a multi-disciplinary incoherent scatter radar facility supported by the US National Science Foundation (NSF) with profiling ability to over 2,000 km altitude, and is currently being upgraded for full electronic beam steering ability.

Arecibo: The Arecibo Ionospheric Observatory was constructed by W. E. Gordon and commissioned in 1962 [19]. Built into a natural sinkhole in the karst landscape of Puerto Rico, the dish antenna was a 305 m spherical reflector, producing a very high 62 dB of gain at 430 MHz. Arecibo was designed with a cable-mounted steerable receiver and was later equipped with several radar transmitters for emitting signals, mounted on a suspended platform ~150 m above the dish. Incoherent scatter radar observations were made at 430 MHz frequency using the 305m reflector combined with a klystron based transmitter at 2.5 MW peak power. The spherical design of the antenna was deliberately chosen to provide flexibility by enabling the steering of the telescope feed and hence the main beam, although this required an innovative phased line feed design to fully exploit the return signals. The original platform weight was 700 tons with a maximum 430 MHz steering angle of ~18 degrees off vertical. From its beginnings, Arecibo's power-aperture product made it the most sensitive of all incoherent scatter radars in the world. In 1997, a major upgrade was completed consisting of a Gregorian focusing system in a radome alongside the 430 MHz ionospheric radar line feed. By providing precise correction for spherical ray focusing effects, the Gregorian system greatly improved performance for astronomical observations, and importantly also enabled dual beam incoherent scatter radar observations in two different directions when used in conjunction with the existing line feed. This latter capability enabled rapid and unique simultaneous measurements of ion velocity and neutral wind vectors at Arecibo on ~1 minute time scales [20]. Arecibo has provided numerous studies of the ionosphere and plasmasphere, including topside light ion studies [21], precise Langmuir mode and ion gyroscatter [22], and ion-neutral coupling information [23]. In November 2020, NSF announced that Arecibo would be decommissioned due to safety concerns after one of the main supporting cables snapped. On 1 December 2020, the 900 ton platform collapsed into the side of the dish when several additional cables gave way. As of 2021, NSF is currently conducting community workshops on ideas for future revival of Arecibo ionospheric observations including incoherent scatter radar.

Millstone Hill*:* The first experimental configuration of the Millstone Hill Incoherent Scatter Radar occurred in 1961 on the campus of MIT Haystack Observatory in eastern Massachusetts, when an existing UHF satellite tracking radar with a 26 meter class antenna was tasked for occasional incoherent scatter measurements by Dr. J. V. Evans and colleagues. The available 26 m satellite tracking antenna was not ideally suited for incoherent scatter work, and its aperture could only achieve marginal performance at the radar's 440 MHz center frequency. Nevertheless, it did allow Millstone to be the first to publish IS observations using a full incoherent scatter radar system [24]. In 1962, the 26 m satellite tracking radar was converted to L-band, freeing the UHF transmitter for other purposes. In 1962-63, Evans had a 68 m diameter fixed zenith pointing antenna built specifically for use in incoherent scatter measurements and the now spare megawatt class UHF transmitter was attached, forming the first dedicated Millstone Hill IS radar. In 1978, a 46 m fully-steerable antenna (MISA – Millstone Hill Steearable Antenna) and rapid transmit antenna switch was added to the radar configuration, providing ionospheric measurements over a wide spatial field encompassing the eastern US, Canadian border, and into the Caribbean. The MISA antenna was originally designed by SRI and moved from the Sagamore Hill Air Force facility where it was originally installed. Millstone Hill's key studies include Storm Enhanced Density (SED) [25] and Sub-Auroral Polarization Stream (SAPS) [26] velocity flows driven by strong magnetosphere-ionosphere coupling in the mid-latitude and subauroral ionosphere, empirical models of subauroral and high latitude electric fields [27], optimal full altitude signal processing [28], software radar approaches [29], ionosphere-thermosphere coupling [30], and mid-latitude E and F region electrodynamic coupling through Farley-Buneman two-stream instability diagnostics [31]. Millstone Hill has continued uninterrupted incoherent scatter radar observations of the mid-latitude and sub-auroral ionosphere for more than 60 years under NSF support, and is operated for the community as part of the multi-disciplinary Millstone Hill Geospace Facility.

St. Santin*:* The French incoherent scatter system at St. Santin started its operations in 1965 and was closed in 1987 [32]. The French system initially operated with one transmitting antenna located in St. Santin, 300 km south of the Nancay radio telescope. The St. Santin antenna illuminated a vertical column with a 140 kW continuous wave transmitter at 935 MHz. Because of its bistatic configuration and the use of continuous (i.e. not pulsed) transmissions, signals of excellent spectral quality were observable at effective and rapid integration times not available from all other contemporary IS radars (e.g. [33]). Different ionospheric parameters could be inferred with this approach as well with good measurement speed, including average ion mass, and empirical models of its observed ionospheric climatology are available [34]. Because of these features, the system was later extended into a unique quadristatic radar configuration with the intent of making ion drift vector measurements.

Malvern*:* The Malvern incoherent scatter radar in the United Kingdom began operations in 1968 and continued through 1975. It operated in two modes, both a monostatic mode using a pulsed radar and a multistatic mode that was established in 1971 using a CW transmitter with three receiving antennas. The main radar operated at 400.5 MHz with an antenna that was a fixed circular paraboloid that pointed vertically upward. In the pulsed mode the klystron could operate with a peak power of 7 MW. ([35], [36]). To overcome these limitations, a multistatic system was established in 1971 (MISCAT) with a 40 kW continuous-wave signal transmitted from Malvern, and the scattered signal was received at 3 receiving sites remote from Malvern. In Wardle, the Jodrell Bank Mark 111 telescope provided a fully steerable antenna with an ellipsoidal aperture 25 m x 36 m. The second antenna was at Chilbolton, an outstation of the Science Research Council Appleton Laboratory. This antenna was also fully steerable with a circular aperture 25 m in diameter. The third receiving antenna near Aberystwyth consisted of two parabolic troughs, each 12 m x 25 m, connected together to form a single aperture which was steerable in elevation ([37]). The first true ground-based measurements of plasma velocity were made with this system in September 1972 ([38]) and multistatic observations continued until August 1975, when the availability of the site for the transmitter came to an end. This multistatic radar system was the first IS radar to measure three-dimensional drift velocities.

3.2.2 1970's

***Kharkiv**:* The Kharkiv incoherent scatter radar facility was established in Kharkiv, Ukraine in the 1970s [39]. Its original 100-m diameter antenna is a zenith parabolic Cassegrain focus design operating at 158 MHz. The transmitter has a peak power of 3.6 MW, and the system now includes a later addition of a fully steerable 25 m diameter parabolic antenna. The Kharkiv location at mid-latitudes in the European sector provides an ideal location for detailed studies of longitude and latitude variations in the ionosphere together with the Millstone Hill IS radar, the Irkutsk IS radar, and the EISCAT Tromsø system. More details and milestones for the Kharkiv radar are provided by [40]. The Kharkiv radar continues operations today and participates frequently in international incoherent scatter URSI coordinated World Day observations. Observations from the Kharkiv IS radar were recently used to highlight the importance of neutral hydrogen dynamics for the midlatitude wintertime ionosphere [41,42], for ionosphere-plasmasphere studies [43,44], and for studies of traveling ionospheric disturbances [45-47].

***Chatanika**:* The Chatanika incoherent scatter radar was first constructed by SRI International at Stanford, California, and was later moved to Chatanika, Alaska, to study the effects of auroral structuring on the ionosphere, as part of a pilot project to investigate the possibility of IS studies in the auroral zone [48]. It was operational at that site from November 1971 to March 1982. The Chatanika system operated in a monostatic radar configuration using a steerable 27 m parabolic dish at a frequency of 1300 MHz with peak transmit power of ~5 MW. The Chatanika facility conducted numerous scientific studies focusing on auroral ionospheric dynamics, including magnetospheric electric fields [49]; ionospheric currents and related Joule heating, and magnetic activity [50]; morphology of the auroral ionosphere and the plasma trough [51]; D-region absorption [52]; auroral E layer [53]; spread-F irregularities [54]; particle precipitation (including photoelectron flux from the magnetic conjugate point in the southern hemisphere) [55]; and magnetic storm effects [56].

***ALTAIR**:* The Advanced Research Projects Agency (ARPA) Long-range Tracking And Instrumentation Radar (ALTAIR) is a dual UHF (422 MHz) and VHF (155-162 MHz) radar located on Roi-Namur (9.39°N, 167.47°E). The radar is at a power-aperture level rendering it capable of IS observations, and is equipped with a fully steerable parabolic dish antenna (45.72 m diameter, 2-way HPBW of 0.78^{o} at UHF). ALTAIR employs a focal point VHF feed and a multimode Cassegrain UHF feed in conjunction with a frequency selective sub-reflector (5.5 m diameter). The system is primarily used in defense and satellite tracking related applications. However, since 1978, it has been used occasionally for incoherent scatter radar measurements [57- 59]. ALTAIR can operate with 4 MW peak power at 5% duty cycle and can provide a range resolution as fine as 600 m extending from 65 to 755 km altitude. Its location in the South Pacific equatorial region makes its ionospheric measurements of considerable geophysical interest.

3.2.3 1980's

***Sondrestrom**:* In 1983, the 1300 MHz Chatanika Radar began its operation as the Sondrestrom radar after it was moved to Greenland. The most visible modification of the radar made following the move was the enlargement of the parabolic dish from 27 to 32 m. With a new shaped subreflector (for the existing Cassegrain feed), the net result was an improvement in both efficiency and gain – from 43 to 48 % and from 47 to 49 dB, respectively ([60]). The Sondrestrom IS radar was a central part of the Sondrestrom Upper Atmospheric Research Facility, situated about 15 km west of Kangerlussuaq, Greenland at a site commonly known as Kellyville. The intent of the move was to make ionospheric measurements in the vicinity of the polar cusp and polar cap, and the location was selected because the radar passed under the average auroral oval at noontime and was within the polar cap at midnight. Sondrestrom observations provided key community information on ionospheric convection and plasma conditions in the high-latitude ionosphere. The Sondrestrom radar was used to investigate the properties of the cusp [61], the auroral oval and the polar cap and the structures and dynamics of polar cap patches [62-65]. The radar was also used to investigate the seasonal dependence of high-latitude electric fields [66] and intensifications along the poleward auroral boundary [67]. In later years, Sondrestrom data was also used in modeling long-term ionospheric cooling effects [68]. In May 2018, the Sondrestrom site was closed by NSF.

Irkutsk: The Irkutsk incoherent scatter radar was established 120 km northwest of Irkutsk at the Siberian Institute of Earth Magnetism, Ionosphere and Radiowave Propagation (SibIZMIR), now the Institute of Solar-Terrestrial Physics. The first incoherent scatter spectra from this radar were obtained in 1981 [69], with early experiments done on an occasional basis. The system reuses an existing military "Dnepr" radar system (space surveillance and early warning radar system). Its unique linearly polarized 35 dB gain transmit/receive antenna at 149-163 MHz employs a complex system of steering and beam formation with a coverage sector width of ~45 degrees and a 246 x 12.2m horn aperture, divided into two symmetric half-horns (~0.5 deg beam width along long antenna axis using slotted waveguide). It operates on a frequency principle of scanning, with the radar pointing direction depending on frequency. In 1993, the transfer of one of the Dnepr system radars to the Institute was arranged to allow for its use as a dedicated IS radar. Full characteristics of the system are described by [70]. Irkutsk has conducted studies of different aspects of the Asian sector mid-latitude ionosphere [71-74]. Since 2011, the Irkutsk IS radar has also operated in a radio astronomy mode providing observations of solar radio emission and scintillations from space radio sources [75,76].

***MU**:* The middle and upper atmosphere (MU) radar was completed at Shigaraki, Japan (34.8°N, 136.1°E) in 1984 [77]. This radar has played an important role in the research of middle and upper atmospheric dynamics in Japan and is primarily used to observe coherent backscatter from irregularities in the troposphere, stratosphere, and mesosphere (the MST region). Ionospheric incoherent scatter observations commenced in December 1985 [78,79]. The radar is a pulsed Doppler radar operating at 46.5 MHz with 1 MW peak output power [80-82]. The MU radar was used to describe the turbulent upwelling of the mid-latitude ionosphere [83]. A system upgrade in 2004 added radar imaging capability with five frequencies across a 1 MHz bandwidth and 25 digital receivers [84].

***EISCAT Mainland**:* The European Incoherent Scatter (EISCAT) radar system was initially proposed in 1973 with a final agreement signed in 1975 between France, Germany, the UK, Norway, Sweden, and Finland. On the European mainland, EISCAT operates incoherent scatter radar systems north of the Arctic Circle at 224 MHz and 931 MHz in Northern Scandinavia. The first EISCAT mainland incoherent scatter radar system at 931 MHz began operations in 1981 as a steerable tristatic system. Each system (transmit-receive at Tromso, Norway; receive-only at Kiruna Sweden and Sodänkyla, Finland) operates with a fully steerable 32-m antenna. Radar pulses are transmitted from and received at Tromso and received simultaneously at Kiruna and Sodänklya, enabling three independent components of ion velocity by pointing all three systems at a common altitude. In 1985, an additional VHF incoherent scatter radar began operations at 224 MHz with a peak power of 3 MW, 12.5 % duty cycle and 1 μs – 2 ms pulse length with frequency and phase modulation capability. The VHF antenna is composed of four cylindrical parabolic sections with a total aperture of 120m x 40m, capable of steering in elevation in the magnetic meridian. In 2012, due to interference from telecommunications in the 930 MHz band, the remote 32 m parabolic antenna receivers at Kiruna and Sodankyla were converted to receive the VHF signal.

EISCAT Mainland radar observations have provided many important studies of the high latitude ionosphere and its variations, including ionospheric convection. In the first 10 years of operation, the VHF radar detected the flow of oxygen and hydrogen ions out of the ionosphere all the way up to altitudes in excess of 1000 km. Furthermore, O+ was found to remain the dominant ion up to the highest altitudes, and upward ion velocities exceeding 500 m/s were observed during disturbed conditions at heights above 500 km [85]. Ion inflow and outflow studies have remained a major research theme for the radars [86]. The EISCAT VHF radar has been used to analyze the structured plasma in the polar cap ionosphere, and for detailing the processes that produce cusp irregularity production [87]. Other research themes have included D- and E-region effects in the auroral zone [88]. The EISCAT system has also been used to study the effects of solar flares and large space weather events [89,90], and the VHF system has been used for many meteor research papers [91,92]. An entire community has also studied the impact of HF-modification on the ionosphere with Eiscat IS radar measurements, e.g. [93].

***EISCAT Svalbard**:* The EISCAT Svalbard radar (ESR) was officially inaugurated on August 22, 1996, initially with a 32-m mechanical fully steerable parabolic dish antenna. In contrast to previous incoherent scatter radars, the ESR system design was adapted to make use of commercial off-the-shelf TV transmitter hardware, reducing design risk, lead times, and cost. In 1999 a second, fixed, 42 m parabolic antenna was added aligned along the direction of the local geomagnetic field, allowing observations along the magnetic zenith simultaneously with the steerable antenna. ESR operates in the 500 MHz band with a transmitter peak power of 1000 kW, 25 % duty cycle and 1 μs – 2 ms pulse length with frequency and phase modulation capability. The high latitude location of this facility has proved optimal for ionospheric studies of the cusp and polar cap region [94-97]. This radar has also been used to support other missions such as rocket launches focused on ion outflow [98], the Cluster mission [99], and other coordinated incoherent scatter radar observations [100].

3.2.4 2000s

EAR: A VHF Doppler radar with an active phased-array antenna system, called the Equatorial Atmosphere Radar (EAR), was established at the equator near Bukittinggi, West Sumatra, Indonesia (0.20°S, 100.32°E, 865 m above sea level). The EAR is a large monostatic radar which operates at 47.0 MHz with peak output power of 100 kW. The EAR uses a circular antenna array, approximately 110 m in diameter, which consists of 560 three-element Yagi antennas. The EAR is approximately 10 dB less sensitive than the MU radar. Its main mode of operations for the ionosphere is primarily coherent backscattering from field aligned irregularities in the F-region associated with equatorial spread F, and in addition (to lesser) extent from E-region FAIs outside of the equatorial electrojet. However, as the ionospheric density is two-to-three times larger in the equatorial anomaly than at midlatitudes, the very weak incoherent scattering (IS) from free electrons is also detectable with the EAR. A few IS radar observations collected by this radar are shown in [101], while a study of the morphology of plasma bubbles measured with the EAR is described in [102].

***AMISR**:* The Advanced Modular Incoherent Scatter Radar (AMISR) design was created in 2000 by SRI International and funded in 2003 by NSF as a relocatable incoherent scatter class radar, becoming the first IS radar system purpose-built for basic ionospheric research. AMISR was designed as a UHF phased-array, solid-state incoherent scatter radar with modular and reconfigurable features for easy dismantling and relocation. AMISR's design provides electronic beam steering and allows for continuous, low duty cycle observations with remote operations capability without on-site personnel. SRI constructed three full-sized AMISR faces, each with approximately 128 panels covering a 32x28 meter surface. Each panel is made up of 32 Antenna Element Units (AEU) and is controlled by a Panel Control Unit (PCU) for AEU control and monitoring. The radar is powered by eight Utility Distribution Units (UDU), which provide aircraft-standard 400 Hz power. The system is driven from an Operation and Control Center (OCC) that houses general-purpose computers as well as low-level radiofrequency (RF) signal conditioning modules.

The first radar face of AMISR became operational in Poker Flat, Alaska (PFISR) in 2007, with the remaining two faces operational in Resolute Bay (RISR-N) in 2009 and Nunavut, Canada (RISR-C, operated by Canada) in 2015. PFISR provides subauroral and auroral zone ionospheric measurements and also supports rocket launch activities at the NASA Poker Flat Rocket Range in Alaska. The system has enabled many important studies, including 3D studies of traveling ionospheric disturbances [103], volumetric imaging of the auroral ionosphere [104], electron density during pulsating aurora [105], nightside ionospheric electrodynamics associated with substorms [106], fine scale auroral ion temperature dynamics [107], and intense ion upflows in near-cusp regions associated with storm enhanced density plume transport [108].

Both RISR locations satisfy the original scientific goals of the Polar Cap Observatory (proposed by an earlier scientific report) by enabling measurements in the region where coupling occurs between the solar wind and Earth's magnetosphere, ionosphere, and thermosphere. Together, RISR-N and RISR-C make routine measurements of polar cap electrodynamics and provide key information for understanding magnetosphere-ionosphere coupling and its global effects, including polar cap photoelectron heating [109], space-time variability of polar cap patches [110], and studies of polar cap potentials under interplanetary magnetic field changes [111].

3.2.5 2010s

***PANSY**:* The Program of the Antarctic Syowa Mesosphere–Stratosphere–Troposphere/Incoherent Scatter (PANSY) radar is a large atmospheric radar located in the Antarctic at Syowa Station (69.01°S, 39.59°E) [112,113]. It was installed in 2011, and in 2015, the PANSY radar performed the first incoherent scatter (IS) measurements in the Antarctic region at E, F, and topside ionospheric altitudes, operating at 47 MHz. The main array of the PANSY radar has 1045 three-element crossed-Yagi antennas arranged in a distributed manner, with a field-aligned irregularity (FAI) array consisting of a pair of peripheral linear arrays of 12 three-element Yagi antennas. Recent work has used this FAI array to help suppress interference which can contaminate the incoherent scatter signal from the main array. This is the first IS radar in Antarctica and one of the few incoherent scatter radars in the Southern Hemisphere. Because of its location, its measurements are of major geophysical interest.

***Qujing**:* The Qujing incoherent scatter radar, operational since the spring of 2014, reported on its initial operations in May 2018 [114]. This radar is a 500 MHz monostatic system with peak power of 2 MW and a 29-m steerable parabolic dish within a 44-m radome. The Qujing system is one of the key instruments in the Meridian Project which consists of diverse ground-based remote sensing facilities aligned near longitude 120 E for space environment monitoring and forecasting. Qujing's field of view allows unique observations of the northern crest of the equatorial ionization anomaly (EIA) in the Asian sector.

3.2.6 2020s

***Sanya**:* A state of the art phased array IS radar is being built at Sanya (18.3°N, 109.6°E). This location is in the low latitudes, on Hainan Island, and it will be named the Sanya ISR (SYISR). As a first step, a prototype radar system consisting of eight subarrays (SYIS radar-8) was built to reduce the technical risk of producing the entire large array [115]. Preliminary experimental results collected by this prototype were published in [116].

EISCAT 3D*:* EISCAT 3D is under construction at the time of this article and represents the next generation of incoherent scatter radars. EISCAT 3D will be a multistatic radar composed of five phased-array antenna fields. Each field will have around 10,000 crossed dipole-antennas elements. All five sites will act as receivers, with a single core site transmitting at 233 MHz (VHF band). Because EISCAT 3D will be steered electronically, it will be able to simultaneously monitor a hundred directions, collecting over a thousand measurements per second.

EISCAT 3D will have the capability to produce volumetric images of ionospheric plasma parameters using aperture synthesis radar imaging. It will be possible to make three-dimensional images of the movements of different ionospheric constituents, and to collect information about the temperature, density of different atmospheric species and about the intensity of electric fields. The estimated imaging performance indicates that the radar will be capable of detecting features down to approximately 90×90 m at a height of 100 km, corresponding to an angular resolution of approximately 0.05^{o}. Additional calculations indicate that high-resolution imaging of auroral precipitation is feasible. Overall, EISCAT 3D will open doors to the development of new signal processing techniques, and open a window for new scientific discoveries. An extensive science case for the instrument [117] includes a wide ranging set of topics utilizing measurements from the troposphere to the topside ionosphere providing parameters in three dimensions, not just along a single radar beam, with possibility of continuous operations. The location of the radar within the auroral oval and at the edge of the stratospheric polar vortex is also ideal for studies of high-latitude dynamics, long-term variability in the atmosphere, and global change.

3.3 The Way Forward: Future IS Radars as Community, Cross-Disciplinary Science Engines

We have described historical and current IS radar facilities and their capabilities. Future facilities, using further technical advances, will be ideally poised to even more expansively address topics that are a vital need for community science. At the core of these applications are IS radar's unique remote sensing qualities for key variables: scalars (temperature, composition, line-of-sight velocity, electron density), vectors (convection, electric field, ion momentum, neutral winds through ion-neutral coupling), and gradients (especially with regard to directions perpendicular and parallel to the magnetic field). Higher level synthesis of basic IS radar altitude profiles as a function of space and time can also produce additional quantities addressing fundamental physics with global impact. A partial and general list includes continuity equations (production vs. loss vs. transport parallel and cross-field), ion acceleration, current closure, ion-neutral coupling, Pedersen, Hall, and Cowling conductance and its electrodynamic influence, energy and momentum exchange between plasma and neutral species, and coupling of micro and macro scale phenomena.

At a larger level, future IS facilities will remain central to investigation into frontier geospace topics that are inherently cross-disciplinary. These include multi-scale geospace electrodynamic coupling, space weather monitoring, middle-atmosphere dynamic impacts on the ionosphere and magnetosphere, energy balance and heat flow between the ionosphere, plasmasphere, and magnetosphere, heavy ion outflows, outward acceleration, mass loading of the magnetosphere with impacts on global electrodynamics, and global / system scale implications of regional phenomena. Indeed, due to magnetic 'lensing' / mapping considerations, IS radar-based volumetric imaging studies of small-scale structures in the ionosphere can have an outsize impact on system understanding across the magnetosphere, plasmasphere, and heliosphere. Furthermore, the ground-based nature of the radar remote-sensing process combined with in-situ satellite observations can provide unique solutions to the classic 'slit camera' difficulty in disambiguating temporal versus spatial evolution of the ionospheric plasma. These qualities in aggregate make IS radar observations a core and essential part of the global community's Heliophysics System Observatory.

Future IS radars, with high sensitivity and associated fine scale observation capabilities, will also continue to expand discovery class science and instability physics studies as a natural plasma laboratory. Topics here include dispersion relations in the low beta, cold plasma case, especially k-space investigations using transmitter frequency diversity; Landau damping in geospace plasmas with extension to astrophysical plasmas; photoelectron fluxes through detailed examination of velocity distributions of the suprathermal plasma; theory of Langmuir mode resonances in a warm plasma; fundamental plasma instabilities such as Farley-Buneman two-stream, gradient drift, and gyrotropic; and coupling of kinetic and fluid / macroscale processes.

Finally, the megawatt-hectare power-aperture product necessary to conduct IS radar observations provides an exciting opportunity to build 21st century instruments as multidisciplinary generators of discovery science even beyond geospace applications. Future architectures will enable these qualities through practical use of multistatic geometries (separate transmitters and receivers), processing architectures optimized for multiple simultaneous applications of the received data, flexible and reconfigurable aperture arrays, and processing backends with flexible software pipelines including integration of machine learning / AI techniques. The resulting implementation landscape is exciting and offers vast new experimental possibilities. Technologies available in the last 2 to 3 decades have been transformative: mass production of wide field, high sensitivity phased arrays, large transport of sensor data within IS radar arrays for low power / large count transmit arrays, and greatly enhanced receiver processing capability. This is particularly true since network capacity, a key enabler, increases at a rate outpacing nearly all other technology.

Such capabilities will allow the IS radar facility of the future to serve not only the geospace community, but to simultaneously act as a science and technical discovery engine for a large palette of fields. These include radio astronomy (Epoch of Reionization, quasars, other generators of radio energy), planetary radar for multi-wavelength imaging of surface and subsurface features, solar and heliospheric plasma structure (dynamically driven by e.g. coronal mass ejections and coronal interaction regions), magnetospheric structure through examination of embedded irregularities as tracers, meteor and meteoroid mass flux atmospheric input from near Earth objects and dust, and turbulence in the magnetosphere and heliosphere.

In the end, the future is bright for this most capable of all ground-based radiowave remote-sensing techniques. Scientific discovery and progress for the whole heliospheric community will ultimately benefit in many ways, both known and yet to be revealed, by the continuation and expansion of this essential technique in the form of future, advanced, multi-purpose IS radar facilities.

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4. Active Experiments in Plasmas Using RF Waves

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The effect of powerful radio waves on the ionosphere was discovered in the early days of radio and is still a hot topic of investigation using modern HF facilities and diagnostics. URSI has played a major role in supporting the research facilities and honouring the scientists involved, as is outlined below.

Active experiments in the ionosphere using radio waves started unintentionally, soon after the first HF broadcast transmitters commenced operation in the early part of the 20th century. The broadcast from a powerful commercial AM station in Luxembourg could be heard by a receiver tuned to another medium frequency station [1]. This cross modulation, widely known as the Luxembourg effect, was soon explained by as little as a 5% change in electron temperature caused by the powerful modulating station, which resulted in the electron collision frequency and hence the absorption of any other radio waves passing through the modified region to have the modulation superimposed on it.

Figure 10. The EISCAT HF heating facility, in the foreground, and two incoherent scatter radars situated in Ramfjordmoen, near Tromsø, Norway. Visible are parts of three HF antenna arrays, covering 4-8 MHz, around the transmitter building housing 12 100-kW transmitters. The control building is on the right, the circular antenna is for the 933 MHz incoherent scatter radar, and the cylindrical parabolic antenna is for the 224 MHz incoherent scatter radar. (Source: Eiliv Lehren, Tromso [8].)

After World War II research into the effects of radio waves on the ionospheric plasma increased dramatically, fuelled both by innovations in high power radar systems, both coherent and incoherent, and the need to understand radio wave propagation during the cold war. The dramatic ionospheric modification effects observed by the Platteville HF facility built in Colorado, USA, in the late 1960s, resulted in several facilities being built in the former Soviet Union, USA and northern Scandinavia. Until recently there were four active facilities: Arecibo in Puerto Rico, HAARP in Alaska, EISCAT's HF facility in northern Norway, and Sura in Russia with only Arecibo and the EISCAT HF facility being co-located with an incoherent scatter radar (ISR), which is one of the most important but not the only diagnostic instrument. Figure 10 shows part of the HF antenna arrays in the foreground with the two incoherent scatter radars of EISCAT near Tromsø, Norway. After the collapse of the Arecibo antenna, this HF facility is unique in being co-located with an ISR. In common with other ionospheric research, optical cameras, radio receivers, coherent radars, rockets, and satellites are all important instruments used in measuring the effects of powerful HF wave injection. These facilities typically radiate about a megawatt of HF waves in the 2.7 to 10 MHz range through antenna arrays designed to radiate vertically with high gain resulting in effective radiated powers of several tens to a few thousand MW. The pointing direction of the radiated beam can usually be changed to off-zenith to a variable degree. Details of the present facilities and an overview of some of the exciting science topics are addressed in [2].

There is a plethora of phenomena that can be addressed by injecting powerful HF radio waves into the ionosphere. High power, HF radio transmitters can disturb plasma in the Earth's ionosphere and magnetosphere providing a unique opportunity to study the interaction between electromagnetic waves and particles without the limited spatial scale-size and chamber edge effects that can be encountered while performing plasma experiments in a laboratory. The powerful radio wave can exceed the threshold for several plasma-wave instabilities and can pump energy into electron and ion plasma waves. Electrons can be excited to high energies resulting in optical emissions, and artificial ionisation. Apart from studying plasma physics, the powerful radio waves can efficiently heat the electrons in the ionosphere changing chemical reaction rates allowing aeronomical studies. Electron heating in the mesosphere (D region) can both enhance and supress strong VHF radar echoes from the summer mesosphere, contributing to studies of the dusty plasma in this region. Because these active radio experiments are useful for both ionospheric and plasma physics studies, both Commisions G and H have an interest in this field and therefore have regular joint sessions on active experiments at URSI symposia.

An important early discovery was the detection of Stimulated Electromagnetic Emissions (SEE), a rich spectrum of sideband emissions produced in the ionosphere and detected by radio receivers on the ground (see [3] for a comprehensive description). These observations provide a complementary diagnostic of the various plasma waves and instabilities excited in the ionosphere to that provided by the much more complex ISR. Researchers in Russia have developed this technique to a high level as demonstrated by [4]. Recent work in this area has concentrated on narrow-band SEE related to ion cyclotron waves and stimulated Brillouin scattering [5, 6].

Other interesting results from HF-pumping experiments are the magnetic zenith effect, artificial ionisation, optical emissions in various spectral lines, and the production of fine scale structures. All these effects are shown in results from HAARP for example [7] but many similar effects have been seen at other facilities as well.

It was thought that only O-mode transmissions result in interesting plasma instabilities because the X-mode reflects at a lower altitude than the resonance heights for upper-hybrid wave and Langmuir wave excitation. But experiments at EISCAT have shown that this is not always the case [9, 10] but a satisfactory theory explaining how X-mode waves produce these results is still lacking.

Artificial electron heating is also used to investigate the dusty plasma in the mesopause [11] through heating the electrons there and changing the diffusion and charging rates of electrons on aerosols. Heating of electrons in the D and E region can also be used to modulate the conductivity and thereby currents in the lower ionosphere that, in turn, can radiate low frequency waves in the range from below 1 Hz to many kHz. Such waves can propagate into the magnetosphere and into the Earth-ionosphere waveguide, an effect which has been exploited extensively, especially at higher latitudes where auroral currents can be very strong.

Even after several decades of research using active radio wave injection into the ionosphere, exciting new results are still being obtained thanks to more modern facilities, diagnostics, and advances in computing allowing more sophisticated experimental techniques. A new generation of incoherent scatter radar should soon provide a new 3-dimensional view of the artificially perturbed ionospheric plasma. EISCAT-3D is a multi-static phased array system [12] with the main transmitting site being built in Skibotn, about 50 km from the Tromsø HF facility.

Several researchers who made important contributions to the field of active experiments, either through experiments or theory, have been honoured through URSI medals. Awards were made of the Balthasar Van der Pol Gold Medal to W. E.

Gordon and T. Hagfors, the John Howard Dellinger Medal to J. Fejer and P. Stubbe, the Appleton Prize to A. V. Gurevich, T. B. Jones, and D. T. Farley.

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5. Ionospheric Modelling

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The Earth's ionosphere is a layer of molecular and atomic ions (NO+, O2+, O+, N+, He+, H+) that surrounds the earth from about 50 to 1000 km. This plasma layer is responsible for retarding and refracting effects on traversing radio waves and enabled Marconi's groundbreaking radio link from Europe to the United States in 1902. Many of our modern space technologies depend on such propagating radio waves. It is understandable then, that the study and modelling of

Figure 11. Group photo from the 1989 IRI Workshop in Abingdon, UK. Participants include from bottom left to the top of the stairs: Larry Brace, Eurico de Paula, Peter Bradley, Bodo Reinisch, J. Taubenheim, Angela Vernon, Dieter Bilitza, Katarina Barbarati, Karl Rawer, Bill Hanson, Kyril Serafimov, Lucien Bossy, Gordon Wren, Sandro Radicella, Hervé Sizun, Mike Dick, Phil Wilkinson, Rachel Edwards. (Source [5].)

Earth's ionosphere is one of the core responsibilities of URSI. Specifically, URSI's Commission G was given the task to lead this endeavor with the goal to provide the broad understanding of the ionosphere necessary to support space and ground-based radio systems. When the Committee on Space Research (COSPAR) decided to follow the success of its

Figure 12. of the 1993 IRI Workshop in Trieste, Italy: (front row left to right:) Marta Mosert-Gonzalez, Klaus Bibl, Sandro Radicella, Karl Rawer, Dieter Bilitza, Lucien Bossy, Bodo Reinisch, Tamara Gulyaeva, (first back row left to right:) Dora Pancheva, K-I Oyama, S.P. Gupta, Jose Roberto Manzano, Bruno Zolesi, R.G. Rastogi, TBD, Y. Tulunay, Jacob Adeniyi, E.E. Ekuwen, (second back row:) Iwamoto Kimura, Peter Bradley, Werner Singer, Ljiljana Cander, TBD, R.A. Gulyaev, S. Kartel, Rudi Hanbaba, W. Zhen, Manlian Zhang, TBD (third back row:) TBD, Dave Anderson, Iwona Stanislawska, E. Kazimirovsky, Adolf Paul, Alexei Danilov, Reinhart Leitinger, S.S. Kouris, Andrei Mikhailov. (Source [6].)

COSPAR International Reference Atmosphere (CIRA) with a similar project for the ionosphere, URSI joined forces and an inter-union Working Group was established in 1969 under the leadership of Karl Rawer (Commission G Vice-Chair and then Chair 1966-1972). The new project was called International Reference Ionosphere (IRI) and, like CIRA, it was intended to combine approved experimental results so as to be a useful reference with no dependence on theoretical assumptions. The two organizations, URSI and COSPAR, were ideal partners bringing different data sets to the table. URSI, the decades-long record of ground-based measurements in particular by the world-wide network of at times over 100 ionosondes, and COSPAR, the much needed global coverage through space-based observations by the Alouette, ISIS, Atmosphere Explorer, and AEROS satellites to name just a few. They also had somewhat different goals and thus broadened the user communities of the model. While URSI's prime interest is in defining the background ionosphere for radiowave propagation studies and applications, COSPAR's prime interest is in a general description of the ionosphere for the evaluation of environmental effects on spacecraft and experiments in space.

A first set of tables with IRI parameters for selected conditions was presented at the URSI General Assembly 1975 in Lima, Peru. These reference data were well received and prompted URSI to agree to publish the next version of the model, IRI-78, as a special URSI report [1]. By now the IRI team had made two important decisions: (1) To use the global CCIR (1967) [2] model for determining the F-peak density and height; these parameters define the point of highest density in the ionosphere and are therefore of paramount importance for all applications. The CCIR maps are based on the work of Jones and Gallet [3, 4] who fitted a special set of geographic functions to data from over 150 ionosondes worldwide, from 1954 to 1958. This advance from parameter profiles at selected locations to a global model was a step of particular importance for Commission G because radio propagation studies require a global model. (2) Rather than thick books of tables and graphs like CIRA, the model was published and distributed in the form of a computer code, a foresightedness that contributed to the popularity and wide use of the IRI model with the advent and wide-spread use of personal computers a few years later.

The IRI Working Group grew in numbers and met regularly during URSI and COSPAR General Assemblies and during special bi-annual IRI Workshops. Group photos from the 1989 Workshop in Abington, UK, and from the 1993 IRI Workshop at ICTP, in Trieste, Italy, are displayed in Figures 11 and 12 [5, 6]. Commission G was always well represented at the IRI Workshops and supported the participation of young scientists from developing countries financially.

Bringing together ionospheric scientists from the ground-based and space-based communities, these meetings played an important role in comparing coincident observations from ground and space and helping to resolve existing discrepancies, so only the most reliable data would be used for the development of the model. In fact, critical comparison of different measuring methods turned out to become a major IRI task. For example, a special meeting on "Methods of Measurements and Results of Lower Ionosphere Structures" was initiated by the group and was held in 1973, at Konstanz, Federal Republic of Germany. With the guidelines established during the meeting in mind and in broad international cooperation, a great effort was started to gather relevant data from different techniques.

Ionosondes can only measure up to the F peak so a different data source had to be found for the region above the F peak (the topside). An accurate representation of the topside electron density is of particular importance because it contains the lion share of the ionosphere's electron content. Incoherent scatter radars can measure the whole ionospheric electron density profile from top to bottom but they are quite expensive to build and operate and only a few exist worldwide. Topside sounder satellites carried an instrument similar to an ionosonde into space and by measuring the electron density from the satellite orbit down to the F peak, their data are the ideal complement to the ground ionosonde data. The Alouette 1, 2 and ISIS 1, 2 satellites of the sixties and seventies had accumulated a wealth of topside data, too much for the limited computer resources at the time. With IRI backing, a data restoration project succeeded in making a large volume of these data accessible for modelers [7] and it became the prime data base for the IRI topside model [8]. In the region below the E-peak (at about 110 km) a different approach had to be chosen because this region is not accessible by ionosondes or satellites. Here rocket measurements are the main data source and with IRI assistance data from many different rocket missions were combined and served as basis for this part of the model [9].

Another Working Group of URSI Commission G was meanwhile working on the next generation of models for the F peak. Under the leadership of first Kenneth Davies, and then Charles Rush, this group of experts was tasked with investigating ways to improve the CCIR models that had been developed two decades earlier and were still heavily used. Various approaches were tested and a new model was presented in 1988, often called URSI-88 model [10]. The model was based on ionosonde data from 1975 to 1979 and used the same set of functions as the CCIR maps but a different method to fill data gaps over the oceans and other data sparse regions. The CCIR model had relied on the assumption that the diurnal variation of the F peak parameters is the same along lines of magnetic dip latitude and so could extrapolate from a known station to phantom stations on the same field line to cover ocean areas and data-sparse regions, while the new URSI-88 model used Dave Anderson's theoretical model to fill these gaps [11, 12]. Comparisons with topside sounder data from the ISS-b satellite documented the superiority of the new model, in particular, over the ocean areas [10] and IRI adopted the new model as its recommended choice for the F peak, especially over the ocean areas.

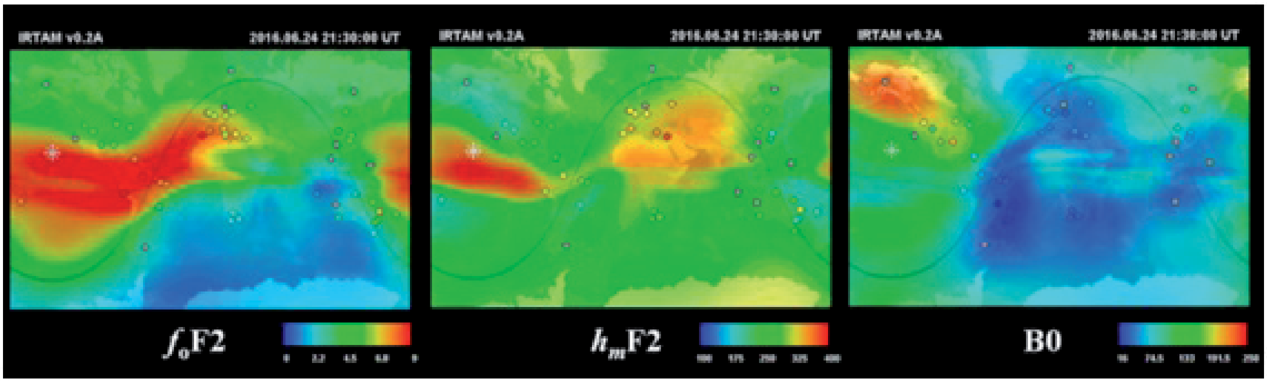

Fig. 13. IRTAM global predictions for the IRI parameters foF2, hmF2, and B0 for 24 June 2016, at 21:30:00 UT. The circles mark the locations of Digisonde stations that have been assimilated into IRTAM, and their color gives the magnitude of the measured parameters. The solid curve in all panels marks the terminator. (Source: Adapted from [19].)

With more and newer data, and by fully exploiting older data sets, and with better modelling techniques, the IRI model was steadily improved resulting in major releases of new version in roughly a 5-year sequence [13-19]. IRI-related sessions during the URSI General Assemblies supported this process with discussions and reports about model performance, shortcomings, successes, proposals for improvements, and applications. The result is a widely used and accepted international standard for the ionosphere and is recognized as such by URSI, COSPAR, the European Cooperation for Space Standardization (ECCS), and the International Telecommunication Union (ITU). But the most important endorsement came with the election of IRI to become the ISO standard for the ionosphere in April 2014. ISO is the International Organization for Standardization and ISO standards undergo a long vetting process whereby each country asks its ionospheric experts to review the standard proposal and to comment regarding the adoption of the proposed standard. Final voting by country then decides about the acceptance or rejection of a standard.

IRI did very well in model assessment studies like the series of such studies that was performed by NASA's Community Coordinated Modeling Center (CCMC) [20-24]. Up to 10 different models were evaluated using different data sources, event periods, and performance assessment parameters. IRI was almost always one of the top three models and often even outperformed theoretical models that assimilated real-time data. There is also a great number of published science papers that have evaluated IRI parameters by comparisons to a multitude of data sources. In fact, a comparison with IRI is often the first step when new satellite, rocket, or ground-based data become available. The great need for a model like IRI is documented by the fact that the IRI papers are highly cited in a wide range of journals covering geophysics, optics, computer science, astrophysics, geodesy, space weather and climate, solar and cosmic research, plasma physics, and more. In 2019, IRI usage was acknowledged in 16% of the papers in Radio Science, the preeminent journal on radiowave propagation and its applications and in 8% of the articles in Journal of Geophysics, the flagship publication of the American Geophysical Union.

The latest developments are focused on improving the accuracy of IRI predictions through assimilation of ionosonde data into the model. The Ionosphere Real-Time Assimilative Model (IRTAM) approach grew out of a collaboration with another Commission G Working Group, the Ionosonde Network Advisory Group (INAG). Figure 13 shows world-maps of the IRI F peak parameters foF2 and hmF2 and the layer thickness parameter B0 that have been brought closer to real-time condition through the assimilation of ionosonde data from the Global Ionospheric Radio Observatory (GIRO) network [25, 27]. A similar effort is now underway with the GNSS Working Group of Commission G to explore ways of assimilating GNSS Total Electron Content (TEC) data into IRI with the goal of improving the accuracy of the representation of the topside ionosphere in the model [27].

In honor of Rawer's leading role in bringing the IRI initiative to life and to fruition the Karl Rawer Gold Medal was created and is awarded during URSI General Assemblies.

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6. Radio Scintillation History

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6.1 Introduction

In 1933, Karl Jansky [1] determined that a persistent radio noise emission was coming from the direction of the center of our Milky Way galaxy. Evolving radio technology was used in World War 2 to detect attacking airplanes [2] and to intercept radio communications. In the post-war period a plethora of extraterrestrial radio emissions were detected, and Radio Astronomy was born. The first observation of radio scintillation was the *twinkling* of radio-star emissions [3]. A review paper by Jules Aarons [4], a major early scintillation contributor, described the first radio scintillation observations and identified structure in the Earth's ionosphere as their source.

On October 4, 1957, Russia launched the first artificial earth satellite, Sputnik-1. It broadcast a 40 MHz modulated signal for three weeks before it reentered the atmosphere and burned up on January 4, 1958 [5]. The impact of Sputnik in the United States was profound. The National Science Foundation (NSF) had been established in 1950. However, the development of additional agencies to stimulate technology and science was resisted by President Dwight Eisenhower, who was concerned about large permanent government agencies. Within a year of Sputnik's launch, the Advanced Research Projects Agency (ARPA) (February 7, 1958) and the National Aeronautics and Space Association (NASA) (October 1, 1958) were established.

Scientists at the Johns Hopkins Applied Physics Laboratory measured the Doppler shift of the Sputnik beacon to determine the satellite orbit. They realized that measuring the Doppler shift of a satellite with a known position could be used for position measurement [6]. Autonomous position determination was a critical need at the time for targeting submarine-launched ballistic missiles. Within a decade, Low-Earth-Orbiting (LEO) satellites were being used for navigation and communication. Dedicated, and satellite transmissions of opportunity, replaced radio stars as the primary sources for ionospheric scintillation observations.

Regarding theory, Maxwell's equations fully characterized the interaction of radio waves with transparent media. However, incorporating irregular structure required the introduction of stochastic processes whose Fourier transform does not exist. The sequential developments of the correlation theory of such processes by Norbert Wiener [7] and Alexander Khinchin [8], laid the mathematical foundations for the theory of wave propagation in random media, which included the theory of scintillation. The history of scintillation morphology is well documented in many excellent survey papers. The theory of scintillation still initiates lively debates. The remainder of this survey will trace the history of scintillation morphology followed by the history of scintillation theory, and a brief summary of the current status and challenges.

6.2 Scintillation Morphology

A theoretical paper by Briggs and Parkin [9], which is cited in the review by Jules Aarons [4], introduced four numbered statistical measures of scintillation intensity. The index S4, which is a normalized measure of intensity variance, has carried that name to this day. The seminal paper by Booker [10], provided a framework for combining plasma-physics, electromagnetics, and stochastic processes to interpret scintillation diagnostics. Booker's theory predicted scintillation coherence measures. Calculations were simplified with the introduction of an *equivalent* phase-screen model. The initiating field had constant intensity with a phase variation generated by integrating the electron density along the propagation path, formally, TEC. Intensity scintillation develops as the field propagates away from the phase screen. Plasma physics provided analytic relations between the ionospheric refractive index and the electron density. Statistical measures of the refractive index, particularly the power spectral density (PSD), are functionally related to statistical measures of the electron density structure.

The earliest systematic radio-star scintillation observations were attributed to Father Koster, a Catholic missionary and physicist, whose first assignment was Ghana, West Africa [12]. His obituary credits him with having first recorded Sputnik outside the Soviet Union. Africa was a propitious location because of the structure associated with ionospheric high-frequency (HF) sounder measurements at geomagnetic equator latitudes. The phenomenon came to be known as spread F or equatorial spread F (ESF) [13]. The high-latitude auroral zones were also known to be regions of ionospheric activity. Morphological studies of radio stars and early satellite scintillations were consolidated into probability-of-occurrence models. A morphology review [11] described an early occurrence model [14], which is still used.

The Wideband satellite, designated P76-5, was dedicated to scintillation measurements. The Defense Nuclear Agency sponsored the mission to measure the UHF frequency coherence of the disturbed ionosphere, hence the name Wideband satellite [15]. Narrow-band signals were transmitted at S-band (2891 MHz), L-band (1239 MHz), with seven UHF spectral frequencies from (378.6 to 445.5 MHz), and VHF (137.6 MHz). Receiving sites were operated at Poker Flat, Alaska, Ancon, Peru, and for a time at Roi Namur in the Kwajalein Atoll. Both the satellite and the Scout D launch vehicle were spare components of TRANSIT, the Navy Navigation Satellite program. They were available because of the high reliability of the Scout-D launch vehicle.

Multi-disciplinary studies of ionospheric structure, including satellites instrumented to measure ionospheric structure directly, rocket probes, and chemical releases were pursued from the late 1960s. Many morphological studies [16-23] refined the solar-cycle, seasonal, diurnal, and geographical dependencies of scintillation, and its association with solar-induced magnetic activity. ESF attracted considerable interest, in part because there was a well-developed theory [24, 25].

On July 23, 1979, a powerful rocket launched from the Kwajalein Atoll intercepted a fully developed ESF structure. The rocket carried plasma diagnostics and a radio beacon, which transmitted a UHF signal through the intercepted structure [26]. A comparative analysis of the beacon scintillation data and the in-situ probe [27], revealed a two-component power-law PSD through the peak of the F-layer. Later studies, which used in situ satellite measurements [28], and beacon data [29], confirmed the two-component structure.

The observation of equatorial scintillation on communication satellite transmissions at frequencies above one GHz [30] was unexpected, and unexplained by the weak scatter theory. By 1970, computational resources, including early super computers, were available. The introduction of strong-scatter theory can be traced back to the seminal survey paper by Yeh and Liu [31]. Simulations [32] showed that the two-component spectral model could reconcile the observed scintillation at S-Band. Parameter estimates that reconciled frequency-dependent measurements were also demonstrated [33]. Simulations of propagation in structured media were published [34-36]. The equivalent phase-screen model became more important when it was realized that the free-space propagation of the intensity PSD could be reduced to an analytic form with a small number of scale-free parameters. Carrano developed an efficient algorithm for computing the intensity SDF [37].

Every element of scintillation morphology and structure was refined with GNSS satellite observations [38]. When scintillation was strong enough to degrade, or disrupt GNSS operations, phase-screen models were refined and calibrated against high-quality data sets [39]. If the ionospheric gradients normal to the occultation paths are small, the path variation can be inverted to extract the ionospheric profile. Scintillation measurements have been interpreted accordingly [40].

6.3 Scintillation Theory

The conceptual geometric optics picture of rays guiding radio wave propagation led to applications by V. A. Krasil'nikov [41]. It worked reasonably well for optics and acoustics applications [42]. Corrections to accommodate diffraction by Obukhov [43] were based on the early work of Rytov [44], which led to the method of smooth perturbations by Chernov and others [45-50]. The *parabolic wave equation* evolved [51-54]. The challenge was finding a tractable means of characterizing stochastic field measures. The breakthrough came from the development of a hierarchy of differential equations for the complex field moments of all orders developed by V. I. Tatarskii [54]. This approach became widely known following an English translation of his book [48].

An international conference was held during August 1992 at the University of Washington, Seattle, and the papers summarizing numerous applications of the theory were published in a book [55]. Theoretical developments continued. Recent research, using moment equations, was reported [56-58]. A hybrid integral equation approach was developed [59,

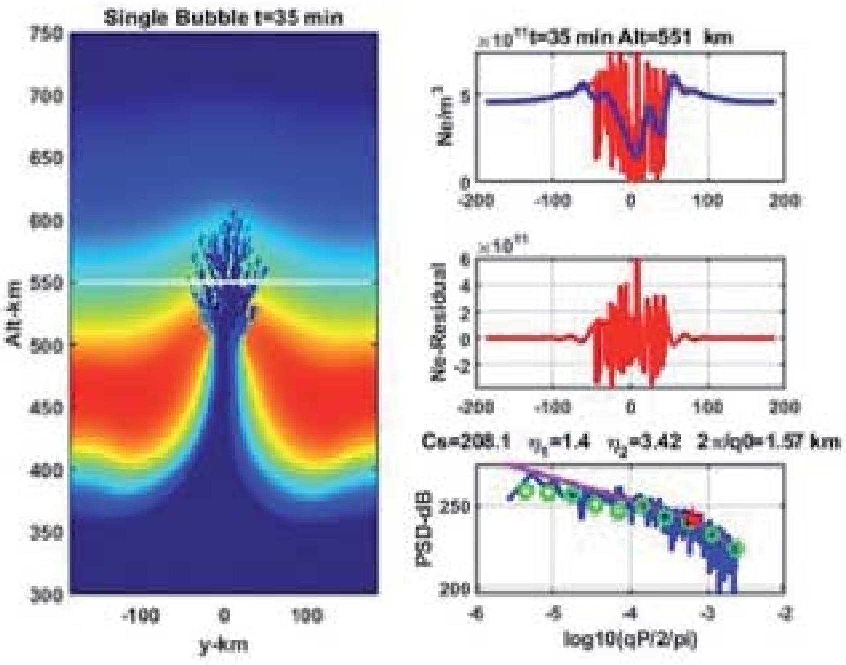

Figure 14. An example of the height-dependent spectral structure characterization from an EBP plume simulation. The middle frame is the structure residual. (Source: Adapted from [70].)

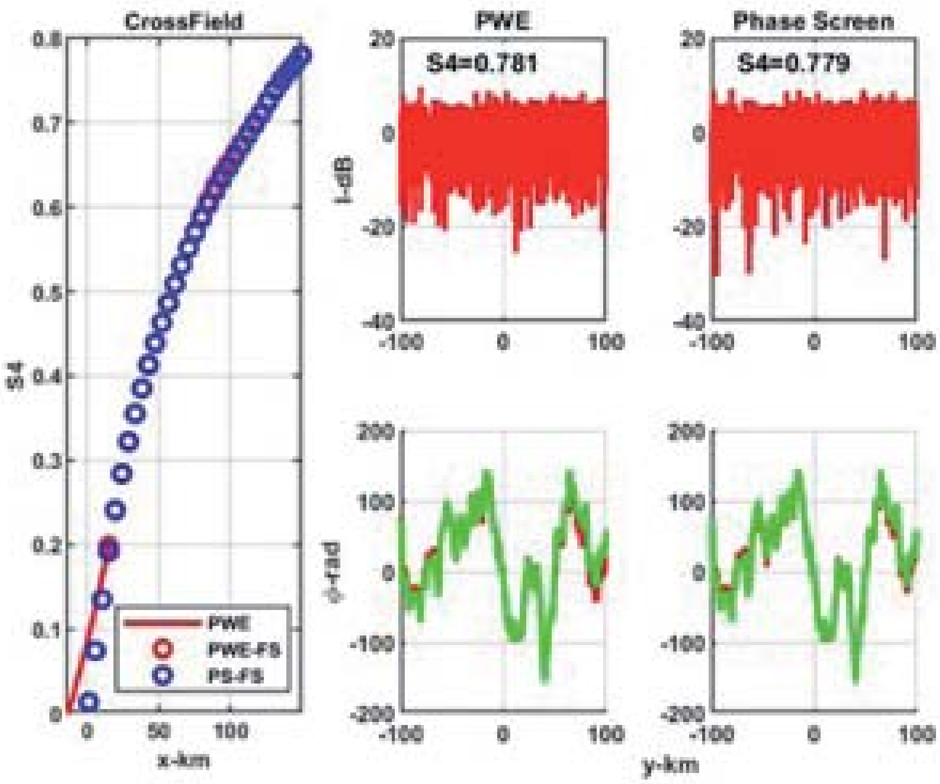

Figure 15. The left frame is the S4 index from a 3D calculation (red) and phase screen (blue). The right frames are intensity and phase in the observation plane. Green at phase screen. (Source: Adapted from [71]).

60], and incorporated into a global scintillation model [61]. An unbounded power-law phase screen supported a self-contained theory. The initiating phase screen is a realization of fractional Brownian motion as developed by Mandelbrot [62]. Scintillation structure at any distance from the phase screen admits scalable structure with caustic-like structure described as diffractals [63]. The scale-free parameters can be extracted with likelihood-based irregularity parameter estimation procedures [64].

Although the major theoretical effort has addressed coherence measures, intensity probability distribution functions (PDF) were introduced early in the history of scintillation. PDFs are defined by the statistical moments of the random variable. The earliest models were defined by two moments, which could be related to the intensity variance or gaussian models that assumed jointly Gaussian statistics for the complex components or the logarithm of intensity and phase. These were found to be deficient. Moreover, the only theoretical support came from strong-scatter limits [65]. The most interesting case was when the scintillation index exceeded unity. Following developments in optics, a universal distribution [66] included all the analytic distributions that have been used. Among them is the $\alpha-\mu$ distribution [67], which has been used to characterize GPS fading structure [68].

6.4 Current Status

The forward propagation equation, and its parabolic approximation, is the most general formulation of the theory. Numerical simulations supported by modern computational resources provide accurate realizations from megahertz to gigahertz frequencies. Similarly, physics-based simulations [69] have generated time-dependent realizations of equatorial plasma bubbles with cross-field resolution approaching meter scales. The simulations have been analyzed to determine the time and altitude variation of the power-law spectral parameters. An illustrative snapshot is shown in Figure 14. The analysis procedure is described in Rino et al [70]. Configuration-space realizations comprised of random collections of striations with appropriately scaled size distributions can be constructed to match the measured spectral characteristics. Figure 15 is an example using the procedures described in Rino et al [71]. For ESF, these results connect diagnostic and predictive procedures with structure characteristics measured both with in situ measurements and simulations.

The more diverse structure in the auroral zone remains to be characterized, along with sporadic-E, and structure induced by ionospheric heating. Beyond that, stochastic structure characterization needs to be integrated into the assimilation of data from evolving GNSS receiving networks. A recent collection of review articles "The Dynamic Ionosphere: A System Approach to Ionospheric Irregularity" treats the subject directly [72]. The paper "Scintillation Modeling" by Materrasi, Alfonsi, Spogli, and Forti is particularly relevant.

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7. Long Term Studies on Ionospheric Scintillation and Plasma Bubbles

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7.1 Introduction

In 1902, Kennelly and Heaviside suggested the existence of an ionized layer to explain long distance HF communication. Since then, this layer (the ionosphere) was the object of many experimental and theoretical studies. Presently, the ionospheric electrodynamics are reasonably well understood. The discovery of ionospheric plasma irregularities opened a new field of study, for scientific reasons and due to their substantial effects on radio waves crossing them, causing amplitude and phase scintillation. The generally theory for the irregularity generation is that after sunset, if the equatorial upward vertical plasma drift is enhanced [1], the ionospheric F layer is uplifted, generating a steep bottomside gradient. A sequence of plasma instability mechanism, acting on seeding mechanisms, create these irregularities, which rise to the topside equatorial ionosphere, while mapping along the magnetic field lines and reaching low latitudes away from the geomagnetic equator. These large density-depleted regions, populated with irregularities displaying a wide range of scale sizes (cm to km), are called Equatorial Plasma Bubbles (EPB). The EPBs can reach continental sizes along the magnetic field lines and hundreds of km in the zonal direction.

Booker and Wells (1938) [2] were the first to provide detailed studies of spread F (SF), the diffuse or spread appearance of F-layer echoes on Huancayo ionogram traces. Many different instruments were developed to explore the irregularities, considering their scale sizes [3, 4]. Additionally, sophisticated plasma irregularity computer simulation models [5] were developed. The irregularity occurrence and intensity depend on many factors including local time, season, solar flux, magnetic location, SSW (Sudden Stratospheric Warming), and geomagnetic conditions [6-8]. Numerous deleterious effects of signal scintillation on technological systems were observed: fringes in the remote sensing SAR (Synthetic Aperture Radar) satellite images; positioning errors and degradation on the availability and integrity of Global Navigation Satellite Systems and all other systems based on them [9, 10].

7.2 Historical Scintillation and Bubble Measurements in the Brazilian Territory

In 1967, the first C4 ionosonde was installed in the Brazilian territory. Later on, a network of ionosondes was established to study SF traces associated with irregularities. However, the first EPB manifestation over the Brazilian territory was observed using meridional profiles of OI 6300 Å nightglow emissions from a scanning photometer [11, 12] at Cachoeira Paulista (22,67° S, 45.00° W). Further, Sobral et al [13] made the largest statistical study up to present (2020) on plasma bubble occurrence over the same Brazilian station, using 22 years of airglow data. Starting in 1997, GNSS L1 band scintillation monitors (SCINTMON) were installed [14]. They measure amplitude scintillation represented by the S_4 index with 50 Hz data rate, and irregularity zonal drifts. A VHF (30 MHz) backscatter coherent radar was installed at the equatorial station of São Luís (02.53° S, 44.30° W) in 2000 [15], providing range-time-intensity maps of 5-m irregularities since then. Later, this system was upgraded in collaboration with the University of Texas at Dallas [16], providing interferometric capabilities. In 2006, arrays of spaced VHF receivers were installed at São Luís, Cuiabá (15.60 ° S, 56.90° W), and Cachoeira Paulista, providing the S_4 index and the irregularity zonal velocities of 960-m scale size irregularities.

More recently, new all-sky imagers provide global coverage of bubble signature images. The Cornell L1 frequency scintillation monitors were gradually replaced by 50-Hz dual frequency (L1, L2) LISN (Low-latitude Ionospheric Sensor network) scintillation monitors, which measure the amplitude and phase scintillation and the Total Electron Content (TEC) in real time. Nowadays, the LISN scintillation monitors are being replaced by more modern ones that also measure the new block IIF and IIR-M GPS frequencies L2C, L5 at rates 50 Hz-100 Hz [17], also receiving multi-constellations signals, enhancing the opportunity for multi-equipment and multi-frequency studies of irregularities over Brazilian territory. Data from payloads on-board rockets launched from Alcântara base on the magnetic equator complement these studies. Single frequency (L1) low-cost ionospheric scintillation monitors are currently under development as reported in [18]. Such an initiative opens the possibility of setting up dense arrays for Space Weather, education and research.

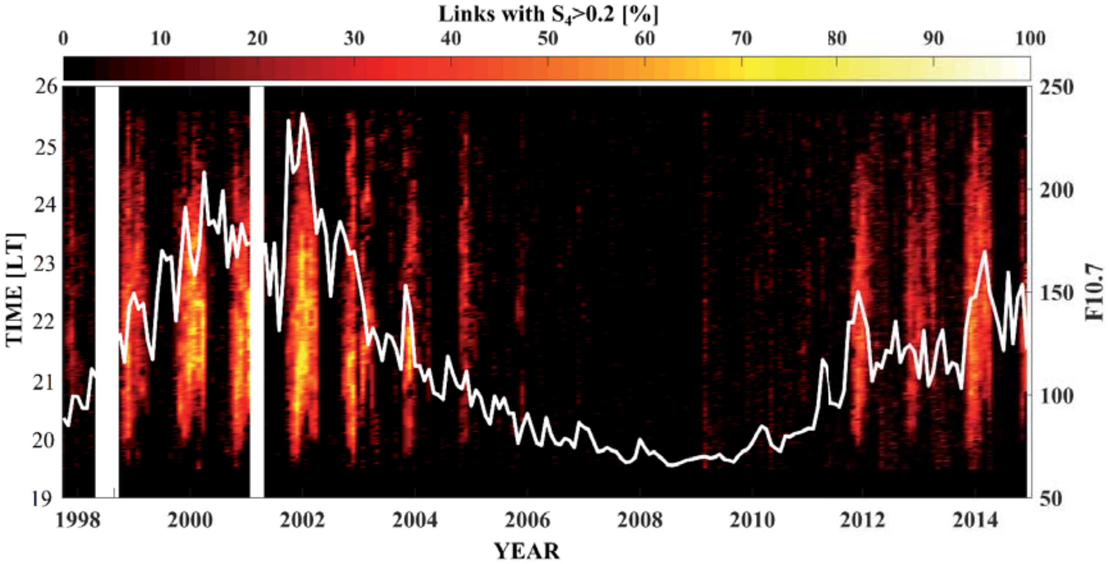

Figure 16. S4 data from the low-latitude Cachoeira Paulista station.

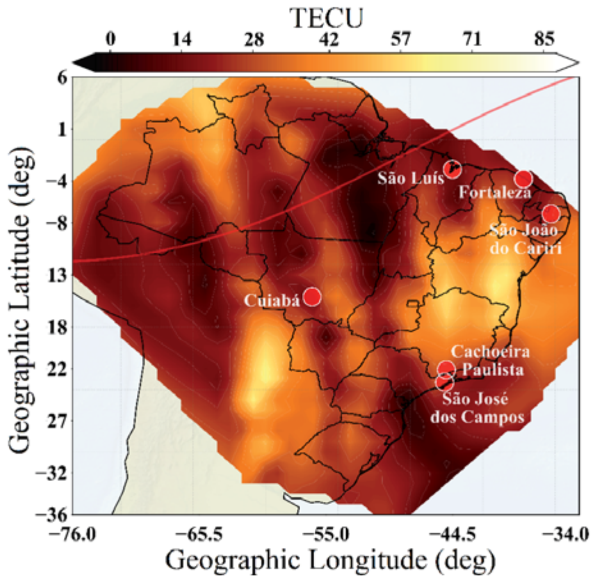

Figure 17. Global vTEC at 22:45 LT, February 15, 2014.

In the future, studies on new MC (Multi-Constellation) and MF (Multi-Frequency) GBAS (Ground Based Augmentation System), designed to overcome the challenge of being safely used even during plasma irregularity events, will be carried out. Real-time scintillation warning broadcast to the GNSS positioning and navigation system users, effective mitigation procedures, and ionospheric scintillation prediction/forecast are important goals to be reached. Also, receivers with signal processing techniques that consider the correlation between inter-frequency scintillation will be valuable to reduce its

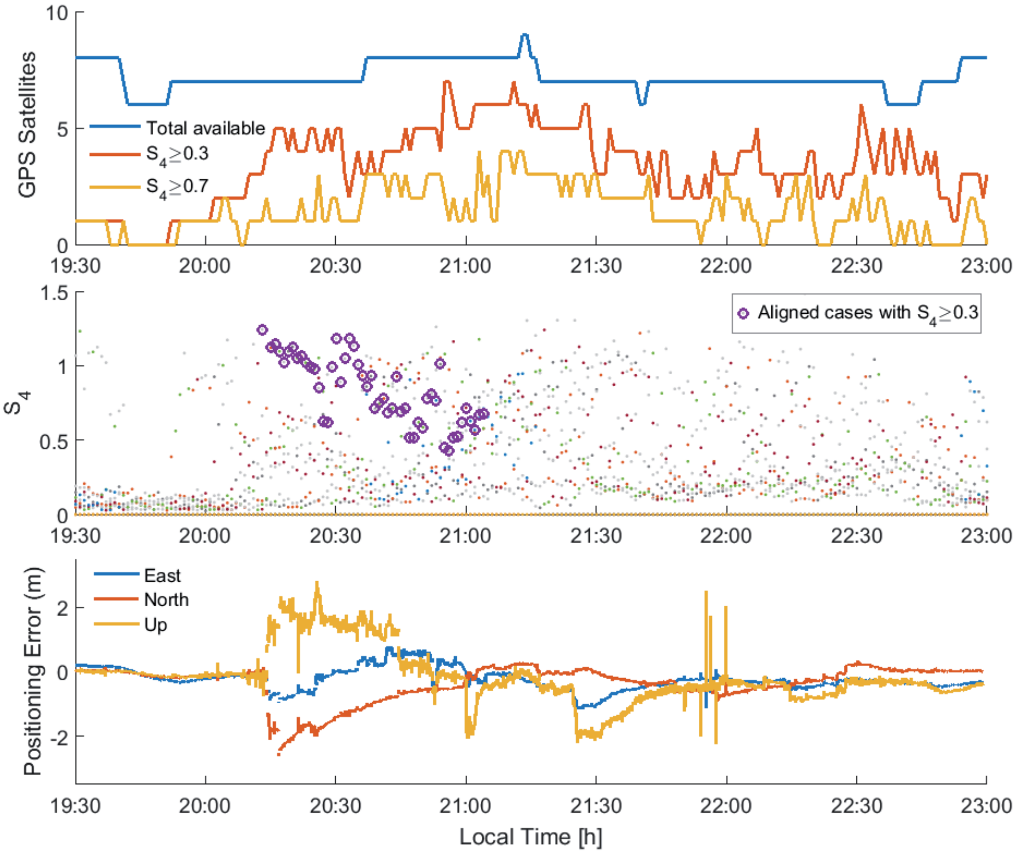

Figure 18. The number of available satellites (top plot), S_4 (middle plot), and positioning errors (lower plot). Bubble-aligned GNSS paths are highlighted by diamond symbols.

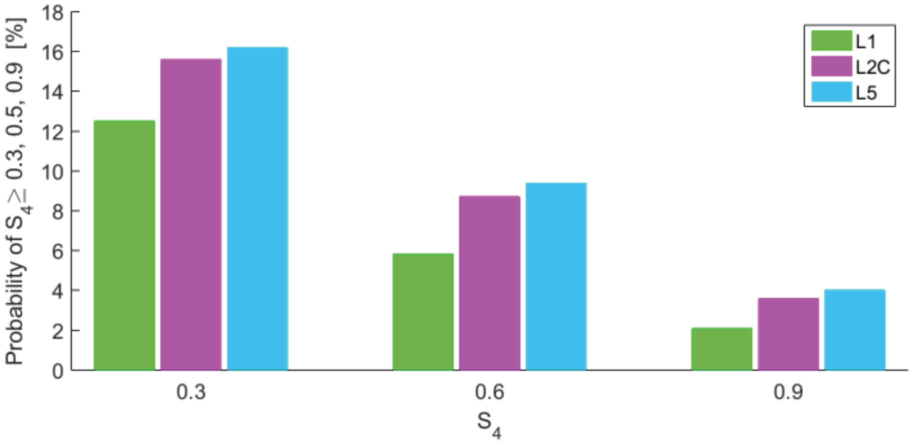

Figure 19. The probability of $S_4 \geq 0.3$, 0.6, and 0.9, for the GPS signals L1, L2C, and L5, recorded from 20:15 to 21:00 LT, at São José dos Campos (23.18° S, 45.88° W), from November 2014 to March 2015.

effects on positioning and navigation. Compact and portable ionospheric sounding systems with affordable and fast data transfer to the users are highly desirable.

7.3 Local Time, Solar Activity, Seasonal, Latitudinal, Longitudinal, Magnetic Activity and Propagation Path Effects on Equatorial and Low-Latitude Plasma Irregularities

Using data from one GNSS receiver installed at Cachoeira Paulista, a station located under the EIA (Equatorial Ionization Anomaly) crest, the climatology of the ionospheric irregularities represented by the amplitude scintillation index S_4 from 1997 up to 2014 is plotted in Figure 16, for $S_4 > 0.2$. The white continuous line represents the F10.7 cm solar radiation. These data show amplitude scintillation incidence from September to March/April in the local time interval 07:30 PM to 01:30 AM. The incidence and severity of the scintillation increase with increasing solar activity as reported in [7].

Using global TEC collected from a large array of GNSS receivers, plasma bubbles signatures were analyzed, as shown in the left panel of Figure 17 and the corresponding scintillation events [19, 20]. In this figure, the EPBs are the depletions areas (darker bands) extending from equatorial to low latitudes.

When radio signals have a large propagation path along the bubble (alignment), a potential threat to GNSS operation rises with large amplitude fading events as demonstrated by [21]. This environment might result in larger positioning errors as shown in Figure 18. This figure shows the total number of satellites and those affected by scintillation. The highlighted diamonds in the middle panel represent the alignment cases.

Recently, the new GNSS frequencies L2C and L5 were made available. Analyzing S_4 data from November 2014 to March 2015, Figure 19 shows the probability of events larger than the thresholds $S_4 \geq 0.3$, 0.6, and 0.9, pointing out that the L5 and L2C signals are more affected by ionospheric scintillation when compared to the L1 signal [17]. Indeed, [22], using data from São José dos Campos, pointed out a higher probability of losing lock on the lower frequency carriers (L2C and L5), despite the enhanced codes and advanced tracking techniques available for these modernization signals.

7.4 Conclusion

This brief and partial review pointed out the importance of using radio-sounding techniques to characterize and predict/forecast ionospheric irregularities, to improve the robustness of receivers, and to mitigate their effects on satellite-based telecommunication, navigation and positioning systems. More information and recent advances in this topic can be found in [23].

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URSI Commission H: Waves in Plasmas

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1. Introduction: History (1975-2011)

Commission H, *Waves in Plasmas*, originated in August, 1975, as a result of a reorganization of the URSI commissions at the XVIIIth General Assembly in Lima Peru [1]. It replaced the previous Commission IV, *On the Magnetosphere*. The motivation for the change was to emphasize URSI's role in radio science rather than geophysics. The first chair of the new commission was R. Gendrin of France; succeeding chairs are listed in Table 1 along with the earlier chairs of the prior commissions.

This history of Commission H will be followed by sections discussing contemporary activities (starting around the time of the XXXth URSI GASS in Istanbul, Turkey in 2011) and future plans. The history and contemporary discussions will be divided into the following five topics for waves in plasma: Spacecraft Observations and Active Experiments; Antennas and other Instruments for Space Plasma Experiments; Ground-Based Observations of ULF & VLF Phenomena; Laboratory Experiments; and Plasma Instabilities, Nonlinear Phenomena, and Wave-Particle Interactions.

1.2 Spacecraft Observations and Active Experiments

Radio sounders performed some of the first active plasma-wave experiments in space. The main purpose of radio sounders in space is to provide accurate measurements of the electron density (N_e) in the vicinity of the spacecraft and, for high-power sounders, to obtain profiles of N_e remote from the spacecraft. Those in Earth orbit out to a few thousand kilometers are often referred to as topside sounders because they generate electromagnetic (em) waves that reflect off

Table 1. The Chairs of URSI Commission H and predecessors.

Years	Commission	Chair	Country
1922-1928	Atmospheric Disturbances	E. V. Eccles	UK
1928-1946	Atmospheric Disturbances	E. V. Appleton	UK
1946-1948	Atmospheric Disturbances	R. Bureau	France
1948-1952	IV (On Terrestrial Atmospherics)	H. Norinden	Sweden
1952-1957	IV (On Radio Noise of Terrestrial Origin)	J. A. Ratcliffe	UK
1957-1963	IV (On Radio Noise of Terrestrial Origin)	R. A. Helliwell	USA
1963-1969	IV (On the Magnetosphere)	H. G. Booker	USA
1969-1972	IV (On the Magnetosphere)	J. W. Dungey	UK
1972-1975	IV (On the Magnetosphere)	F. L. Scarf	USA
1975-1978	H (Waves in Plasmas)	R. Gendrin	France
1978-1981	H (Waves in Plasmas)	F. W. Crawford	USA
1981-1984	H (Waves in Plasmas)	M. Petit	France
1984-1987	H (Waves in Plasmas)	R. L. Dowden	New Zealand
1987-1990	H (Waves in Plasmas)	H. Matsumoto	Japan
1990-1993	H (Waves in Plasmas)	R. F. Benson	USA
1993-1996	H (Waves in Plasmas)	F. Lefeuvre	France
1996-1999	H (Waves in Plasmas)	V. Fiala	Czech Republic
1999-2002	H (Waves in Plasmas)	H. G. James	Canada
2002-2005	H (Waves in Plasmas)	U. Inan	USA
2005-2008	H (Waves in Plasmas)	R. B. Horne	UK
2008-2011	H (Waves in Plasmas)	Y. Omura	Japan
2011-2017	H (Waves in Plasmas)	O. Santolik	Czech Republic
2017-2021	H (Waves in Plasmas)	J. Lichtenberger	Hungary

the denser ionosphere below the satellite. These reflections occur deeper into the ionosphere as the sounder frequency increases. The resulting em echoes can be converted into vertical electron density profiles $N_e(h)$ from the satellite altitude almost down to the altitude of the N_e maximum (typically between 200 and 400 km). Since the topside sounders are immersed in the ionospheric plasma they also generate electrostatic (es) waves. Some of these waves also echo, but from distances much closer to the satellite (hundreds to thousands of meters). They appear spike-like on the topside-sounder records (called ionograms) and have been given the name "plasma resonances." They occur at characteristic frequencies of the ambient plasma and their identification provides accurate diagnostics of the ambient N_e and the ambient magnetic field strength $|\mathbf{B}|$. These diagnostic capabilities make radio sounders ideal instruments for investigating plasma waves of natural origin, as well as sounder generated plasma waves, and sounder-stimulated emissions from the ambient plasma. Between 1961 and 2003 38 rocket, satellite, and planetary payloads from 8 countries were dedicated to radio sounding ranging from proof-of-concept flights to sophisticated instruments for the investigation of plasma resonances as well as the reception of long-range echoes in terrestrial and planetary plasmas [2].

The four topside sounders of the International Satellites for Ionospheric Studies (ISIS) program [3] were ideal for the investigation of sounder-stimulated plasma resonances in addition to the main objective of investigating the topside ionosphere. Some of these resonances are shown on the ionogram in Figure 1a. It presents the apparent range of ionospheric reflections resulting from the transmission of short radio pulses (0.1 ms) at frequencies varying from 0.2 to about 5 MHz (in this example). The apparent range, also called the virtual range, is equal to ct/2 where c is the free-space speed of light and t is the round-trip echo time. This range is greater than the true range because the em waves at these frequencies travel with a group velocity $v_g < c$ in the ionosphere as indicated in Figure 1b. The traces labeled "O" and "X" correspond to the free-space ordinary and extraordinary modes of propagation. The trace labeled "Z" corresponds to the slow branch of the X mode and it is often called the Z mode; it is confined to the ionospheric plasma. The cutoff frequencies of the Z and X reflection traces, at the satellite location in Figures 1a and b, are indicated by f_ZS and F_XS; in some papers they are written as f_Z and f_X or simply as Z and X. These frequencies are functions of N_e and $|\mathbf{B}|$. Thus once $|\mathbf{B}|$ is obtained, the f_ZS and F_XS values provide two independent determinations of the ambient N_e. The ambient $|\mathbf{B}|$ can be obtained from a magnetic-field model or, often more precisely, from the observed plasma resonances at the electron cyclotron frequency and its harmonic, labeled fH and 2fH in Figure 1a. Since fH is directly proportional to $|\mathbf{B}|$; in some papers fH is written as f_H, f_B, f_{ce} or 1 (if the harmonics are labeled as n; more than 20 have been observed). The cutoff frequency of the O trace occurs at the electron plasma frequency fN (often written as f_N, f_{pe} or simply as N or P) which is proportional to $(N_e)^{1/2}$. The plasma resonance at fN, in this example, merges with the high-frequency side of the plasma resonance at fH. Another large plasma resonance in Figure 1a occurs at the upper-hybrid frequency fT (also written as f_T,

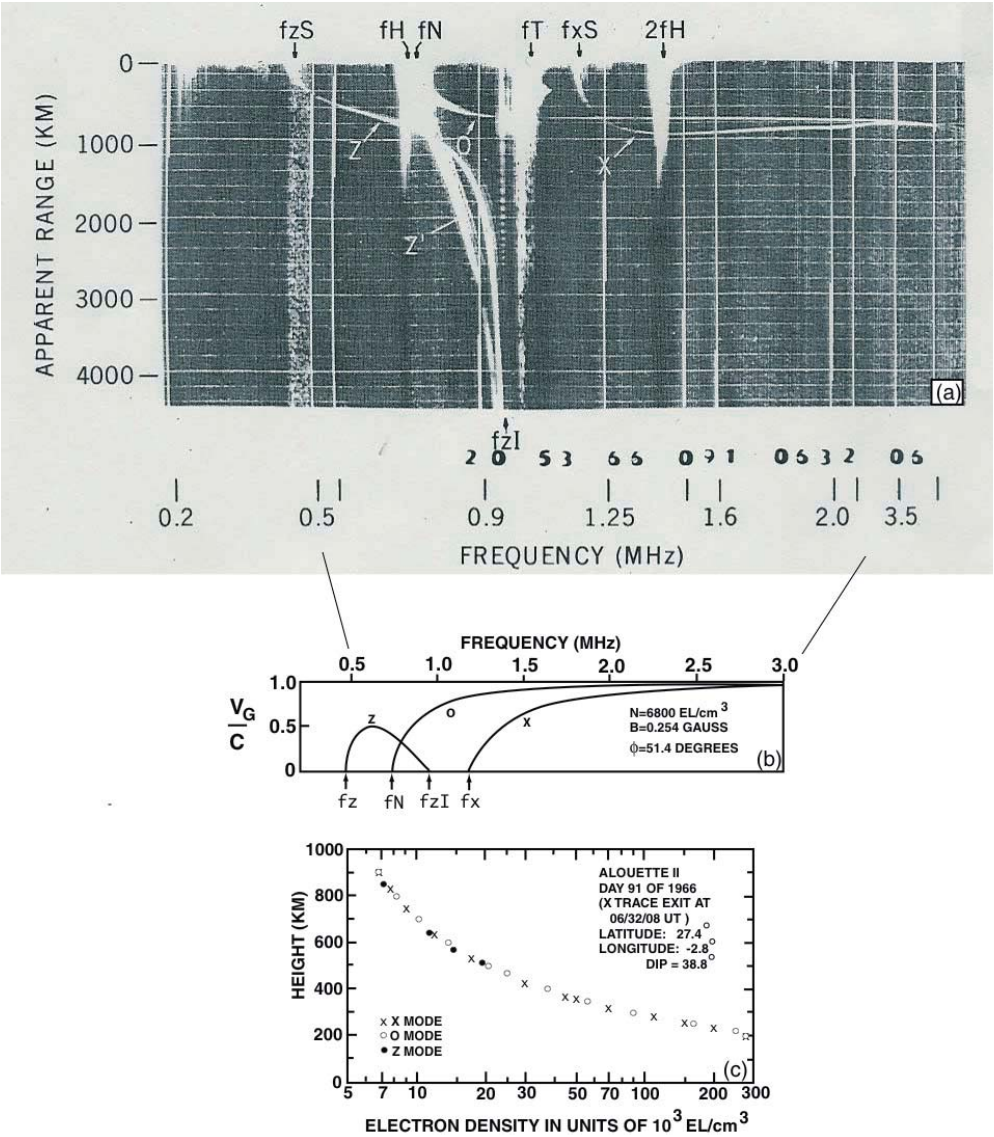

Figure 1a. An Alouette-2 mid-latitude ionogram in negative format (signal reception in white on a black background) showing Z, O and X ionospheric reflection traces, sounder-generated plasma resonances, and a natural noise band in a narrow band of frequencies greater than f_ZS. The fzI label and arrow below the ionogram (near the 0.9 MHz frequency marker) identifies a condition known as Z infinity (see text for descriptions of the other labels).

Figure 1b. The group velocities of the waves giving rise to the ionospheric reflections.

Figure 1c. The calculated electron density profile, $N_e(h)$, from each of the reflection traces (adapted from [2] and [4]).

f_{uh} or simply as T) where $fT^2 = fN^2 + fH^2$. Thus if the gradients in N_e and $|\mathbf{B}|$ along the satellite path are not significant, as it travels several tens of kilometers during the several seconds elapsed during the stimulation of the resonances and cutoffs of Figure 1a, f_ZS, f_N, f_T and f_XS provide four independent determinations of N_e once f_H is determined from the f_H and $2f_H$ resonances (f_H can also be determined from $f_X\mathrm{S} - f_Z\mathrm{S}$). The Z, O and X traces also provide independent determinations of $N_e(h)$ as illustrated in Figure 1c.

The sounder-generated plasma resonances described above, and illustrated in Figure 1a, have been the subject of extensive research as documented in many review papers [2, 5-10]. The clue to the proper interpretation of these resonances came via the effort to understand the origin of the slanting echo trace labeled Z' in Figure 1a. It, like the Z, O,

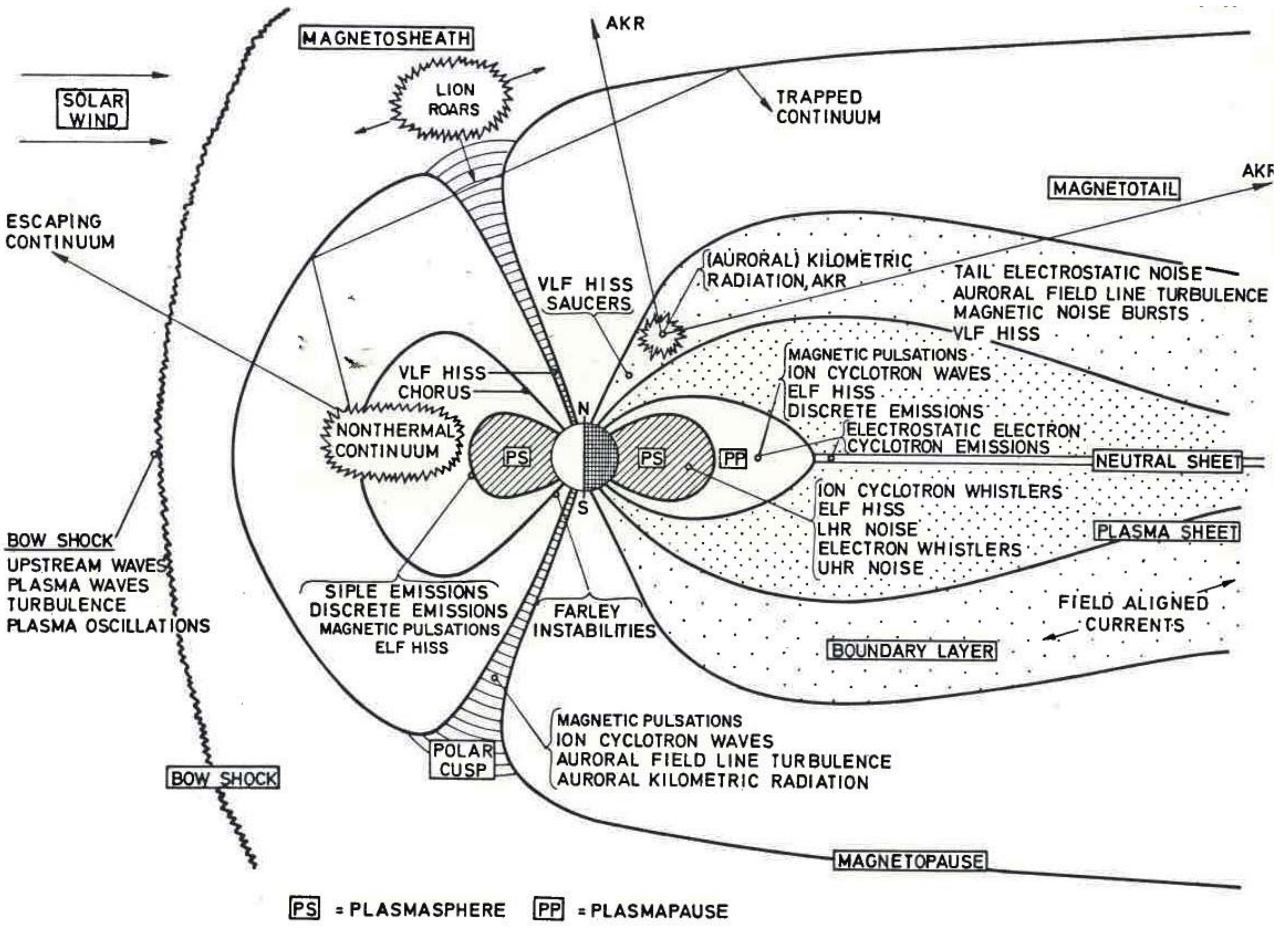

Figure 2. Regions of plasma wave occurrence located in a noon-midnight meridian cross section of the Earth's magnetosphere [21].

and X reflection traces in the figure, could be explained in terms of cold plasma dispersion theory. But, in the course of the investigation, echoes based on warm plasma dispersion theory, i.e., where the thermal motions of the electrons were included, were also considered. These echoes were electrostatic in nature and had delay times that were too long, so were discarded [11]. Later work, stimulated by these warm plasma solutions, found that the resonances at f_N, f_T and nf_H with $n > 1$ could be interpreted in terms of oblique echoes of slowly propagating sounder-generated es waves [8, 12, 13]. The interpretation for the case $n = 1$, i.e., for the f_H resonance, is more complicated and was presented several decades later; it involved highly damped waves radiated from the plane containing the antenna and $|\mathbf{B}|$ [14].

The above discussion concerned the interpretation of phenomena resulting from a radio sounder on a single spacecraft. Wave propagation experiments have also been performed between separated transmitters and receivers during high-latitude rendezvous between two ISIS topside-sounder satellites [15-17] and during high-latitude dual-payload rocket experiments [2], including the OEDIPUS tethered systems [18-20], enabling detailed studies of em wave propagation. These investigations indicated the importance of wave scattering from, and guiding along, N_e field-aligned irregularities (FAI), i.e., irregularities in N_e transverse to the direction of the background magnetic field **B** that are maintained for long distances along **B**. The observations from these experiments suggest that high-latitude FAI are common occurrences.

A large variety of natural emissions have been identified over decades of observations with plasma wave receivers on satellites [21-28] and on the ground [29]. The variations of these emissions often provide ideal indicators of spacecraft passages through the various magnetospheric boundaries illustrated in Figure 2. The proper identification of a received plasma wave can be challenging and is important for a proper determination of N_e as has been indicated in several investigations [30-32]. Combining active and passive observations have been used to confidently identify plasma emissions and source-region parameters [33, 34].

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1.3 Antennas and Other Instruments for Experiments in Space Plasma, 1919-2011

In the history of antennas, one finds a surprising variety of configurations designed 1_2_v2_NF to optimize the required communications. The concern of URSI Commission H about antennas in space plasmas often has led to small structures that can be accommodated on spacecraft. Although we will add a few sentences at the end of this section dealing with large terrestrial antennas needed for injecting into/detection in the ionosphere, this discussion is mostly about small, simple types that can be flown on spatial vehicles in low earth orbit. Before leaving this question, let us also note in passing the significant number of modern spacecraft that have been designed to completely characterize the E and B fields of waves by using electric and magnetic dipoles together.

First, small dipoles answer scientific objectives in space plasma physics better than small loops. In addition to ease of deployment, small dipoles offer superior performance. Kraus [1] shows that in active antennas, the electric dipole radiates as length/wavelength, whereas the magnetic loops radiates as (area/wavelengh)^2 in vacuo. The receiving dipole exhibits its superiority in related issues such as bandwidth.

In isoplasmas and magnetoplasmas, the situation is more complicated to work out. But for all frequencies, the dipole is usually superior. The dipole was first evaluated by Bunkin [2], and he was followed by Kogelnick [3], Kuehl [4], Arbel and Felsen [5], Ginzburg [6], and Andronov and Chugunov [7]. Many authors used the cold or hot plasma as a basic theory to deal with basic antenna attributes such as impedance, radiation, and related topics. See Balmain [8), Ament et al. [9], Staras [10], Seshadri [11], Wang and Bell [12], Nakatani and Kuehl [13], and Meyer-Vernet [14]. Attention was directed to the quadrupole probe as a four-point method for exploiting mutual impedance, in Storey et al. [15], Kolesnikova and Beghin [16], and Geiswiller et al. [17]. It was found that powerful active dipoles create charged-particle fluxes capable of modest aurorae, in Gal'perin et al. [18], James [19], Shuiskaya et al. [20], and Baranets et al. (21). Indeed, sounder-accelerated particles have roles to play in generating radio waves and visible emissions James, [22]. High-frequencies can serve as carrier of VLF intelligence, as will be seen in ionospheric heating, described later.

Passive dipoles have made an extensive contribution in space plasmas. Equivalent circuits [23] are made to include the effects when antennas are plunged into a plasma, for such properties as the capacitance of the vacuum sheath [24], the noise source generated by particle thermal motion [25], and phenomena related to propagation in the electrostatic modes [26].

It was found beneficial at, and below VLF, to use point-point, not distributed, dipoles. When a precise measurement of an electric field was needed, the distance between points was simpler to interpret than what a distributed dipole detected. Furthermore, point-point measurements avoided ion-sheath non-uniformity induced by orbital motion across field lines. For wave direction, discrete points were called upon as interferometers [27-29]. In these cases, designers had to find compromises between the dipole as a radio component and as a detector of dc fields.

There are few examples of loop antennas being applied for radiation. But it is found that by loading a many-turn receiving coil with high-permeability material at ELF and below, high magnetic sensitivity is achieved within small bandwidths.

Maxwell's equations have been used to good benefit in the conception of ganged dipoles for high power terrestrial radiation. Given the variety of terrain in question, a number of constraints had to be followed.

These included the carrier frequencies, local time of operations, and whether radiation polarization was to be vertical or horizontal. First, for urls on the leading ionospheric heaters that radiate vertically see [30-33].

For comparison, in VLF submarine communications that radiate at low elevations, see [34, 35]. Other medium-sized antennas for different radars, or public broadcast require various characteristics that would carry this short description much beyond its allotted space.

This section on antennas is largely an abbreviated version of the URSI GASS2011 invited lecture to Commission H [36].

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1.4 Ground-Based Observations of ULF and VLF Phenomena

The history of the ground-based observation of VLF (Very Low Frequency) phenomena between 1975 and 2011 can be divided into four areas: the "classic" whistler observations; the ground-based active VLF experiments; the monitoring of the man-made VLF signals; and lightning detection by VLF waves.

The routine observation and analysis of lightning-generated whistlers on the ground was practically discontinued in mid-1970, due to the tedious human labour required for the detection and analysis of whistler traces. The last important results were based on the analysis of two decades long whistler/VLF data at Stanford University. The analysis of whistler dispersion at 5 kHz and the equator electron density profile derived from it exhibits large seasonal and annual variations [1]

The routine measurement and analysis were re-animated by the development of the automatic whistler detector algorithm [1] and an enhanced whistler inversion method [2] that was based on recent experimental field aligned electron distribution models derived from satellite measurements. The two methods were combined and implemented in the global Automatic Whistler Detector and Analyzer Network (AWDANet) [3] (the map of the network can be seen in the figure in the Commission H pages of the Hungarian section in this volume). It operates ~25 stations, 15 of them are capable of near real-time whistler detection and inversion to provide cold electron density of the plasmasphere, a key parameter for modeling wave-particle interaction in the Radiation Belts.

The Siple Transmitter operated between 1973 and 1988. It was installed at L ~4.3 and included a 21.2 km dipole antenna located in Antarctica at 75.93 S, 84.25 W. The main aim of the experiment was to study VLF triggered emissions, that is, wave-particle interaction in the magnetosphere [5-6]. The data after transmission included many unexplained phenomena e.g. rising and falling emissions, wave growth, entrainment, and multiple-hop echoes. These controlled artificial wave injections provided a major contribution to understanding the wave-particle interaction in the magnetosphere. The injected VLF signals were recorded in the other hemisphere (Roberval, Canada) [7], on satellites (Explorer 45), Imp 6 [8] and on rockets (N-T rocket) [9]. An excellent review of the history and results of the Siple transmitter as well as the history of VLF research at Stanford University can be found in [10].

Many of the powerful transmitters in the VLF-LF band operated by the navies of various nations. The majority of transmitted power propagate in the Earth-Ionosphere waveguide (EIWG) and is thus sensitive to the position, shape and electron density of the D-region as well as the presence of charged particle columns associated with terrestrial lightnings. The changes in the lower boundary layer of the ionosphere due to the electron precipitation from the radiation belts – the Trimpi-effect – can be investigated by monitoring the amplitude and/or phase variations of the VLF transmitter signal. This effect is most pronounced around the polar circles. The Antarctic-Arctic Radiation-belt (Dynamic) Deposition VLF Atmospheric Research Konsortium (AARDDVARK) provides a network of continuous long-range observations of the

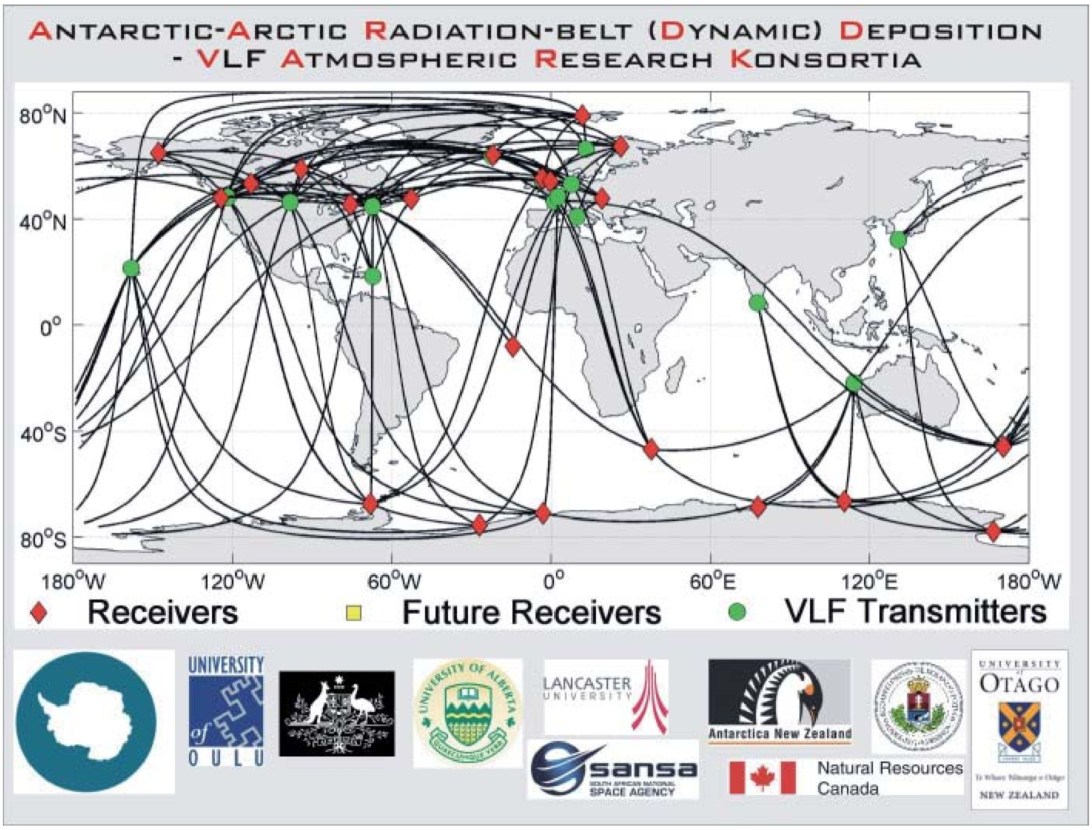

Figure 3. The AARDDVARK network (from http://www.physics.otago.ac.nz/space/AARDDVARK_homepage.htm).

lower ionosphere in the polar regions (Figure 3). It is a network of sensors to detect changes in ionization levels from ~30 - 90 km altitude, globally, continuously, and with high time resolution, with the goal of increasing the understanding of energy coupling between the Earth's atmosphere, the Sun, and space. This science area impacts our knowledge of space weather processes, global atmospheric change, communications, and navigation networks [11]. The enhanced losses of energetic electrons from the radiation belts into the atmosphere, both during a storm and also through the post-storm relaxation of enhanced radiation belt fluxes have a significant effect on middle atmosphere ozone chemistry and NOx production [12, 13].

Radio atmospherics, the VLF portion of electromagnetic waves emitted by terrestrial lightning, can propagate in the EIWG with small attenuation, thus it can be detected at many thousands of kilometers away from the lightning. The propagation in the EIWG is slightly dispersive and thus the time of group arrival can be used to estimate the propagation time of sferics and the distance between the source lightning and the receiver [14]. The World Wide Lightning Location Network (WWLLN, http://wwlln.net) is a chain of VLF receivers and it can locate the lightnings globally if at least four WWLLN sites detects the signal from a lightning-stroke [15]. The WWLLN, at the time of writing this paper, have over 70 sensors around the globe to detect sferic activity in the VLF band. Typically, only about 15 to 30% of strokes detected by one sensor are detected by 5 or more others. These strokes are usually the stronger ones. Recent research indicates WWLLN detection efficiency for strokes about 30 kA is approximately 30% globally [16].

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1.5 Laboratory Experiments

Many laboratory experiments have been performed to simulate wave propagation and excitation in space plasmas. Such experiments can overcome some of the challenges encountered when making *in-situ* space measurements such as the space-time ambiguity, lack of repeatability of measurements, and uncontrollable external factors. These challenges can be overcome in a controlled laboratory environment where the basic physics can be investigated if a reasonable scaling of key space parameters is achieved. Not every aspect of space plasma can be faithfully scaled in the laboratory, e.g., large MHD-scale phenomena are particularly challenging. Others, such as the cause and effect of waves and various coherent processes at meso and micro scales, are more amenable to laboratory scaling. Satellite clusters have recently been used to overcome some of the difficulties with resolution and space-time ambiguities. While they help, they are expensive, and there are limitations in measurements made from a moving platform. An area where laboratory experiments can contribute substantially is in understanding the effects of strong spatial variability that are often encountered in space localized over short distances and can be scaled reasonably well in the laboratory. Also, laboratory experiments can validate theoretical concepts relative to the interpretation of space wave phenomena. For example, the prediction of the existence of Force-Free Electro-Magnetic Field (FFEMF) waves and solitons [1] received support from a laboratory experiment [2]; in a separate theoretical work it was shown that the FFEMF can form oscillating bounded states [3, 4] that predict a frequency spectrum later observed in the sequence of ionospheric topside-sounder-stimulated plasma resonances known as the Dn resonances, discussed in the next section.

Several extensive reviews of laboratory experiments have been presented including reviews of geospace observations, theoretical models, and laboratory experiments involving sheared plasma flows [5], laboratory investigations of key wave modes observed in different regions of the geospace environment [6], and laboratory experiments on shear Alfvén waves [7].

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1.6 Plasma Instabilities, Nonlinear Phenomena, and Wave-Particle Interactions

The plasma resonances identified in Figure 1, except for the one at f_H, could be explained in terms of oblique echoes of slowly propagating sounder-generated es waves using linear warm plasma dispersion theory where ion motions could be neglected. This is not always the case. Figure 4 shows a topside ionogram where there are additional resonances that require different interpretations. The resonances labeled D1 and D1+ are members of a sequence of diffuse resonances, called Dn resonances, that appear at frequencies between the nf_H resonances and below f_N. As indicated in the insert, they have a hybrid relationship similar to the one between f_T, f_N and f_H (also shown in the insert). The resonance labeled Q2 is the first of a sequence of resonances, called Qn resonances, that appear at frequencies between the nf_H resonances and above f_N. These resonances sometimes float away from the zero apparent-range baseline (as in this example). A resonance that often floats in this manner is the one labeled F (for floating resonance); it is only observed during the special plasma conditions indicated in the figure insert. The spur observed on the low-frequency side of the $2f_H$ resonance near 500 km apparent range in Figure 4 corresponds to a time delay equal to the proton gyro period, i.e., about 3.3 ms in this example.

These resonances, which have been stimulated in the ionosphere and the magnetosphere, have been the subject of several review papers [1-3] and detailed review sections in additional papers related to the resonances [4, 5]. Of particular importance are the Dn and Qn resonances because they have also been related to natural emissions in space plasmas [4, 6, 7]. The warm-plasma dispersion theory can also be used to explain the Qn resonances but the dispersion solutions in this case are not as sensitive to slight gradients in N_e and **B**, as they are for the principle resonances at f_{pe}, f_{uh} and nf_{ce} ($n > 1$), and echoes are not returned to the sounder [8]. The proton spur on the $2f_H$ resonance is likely due to protons being modulated by the transmitter frequency as shown to be the case for proton echoes sometimes stimulated by topside sounders [9]

The Dn resonances, on the other hand, have been attributed to incoherent emissions stimulated by the sounder due to plasma-wave instabilities [10, 11], strong turbulence [12] and force-free em cylindrical oscillations [13]. The instability approach is supported by an observed $(T_e)_{\perp}/(T_e)_{||} >> 1$ electron temperature anisotropy following the sounder pulses

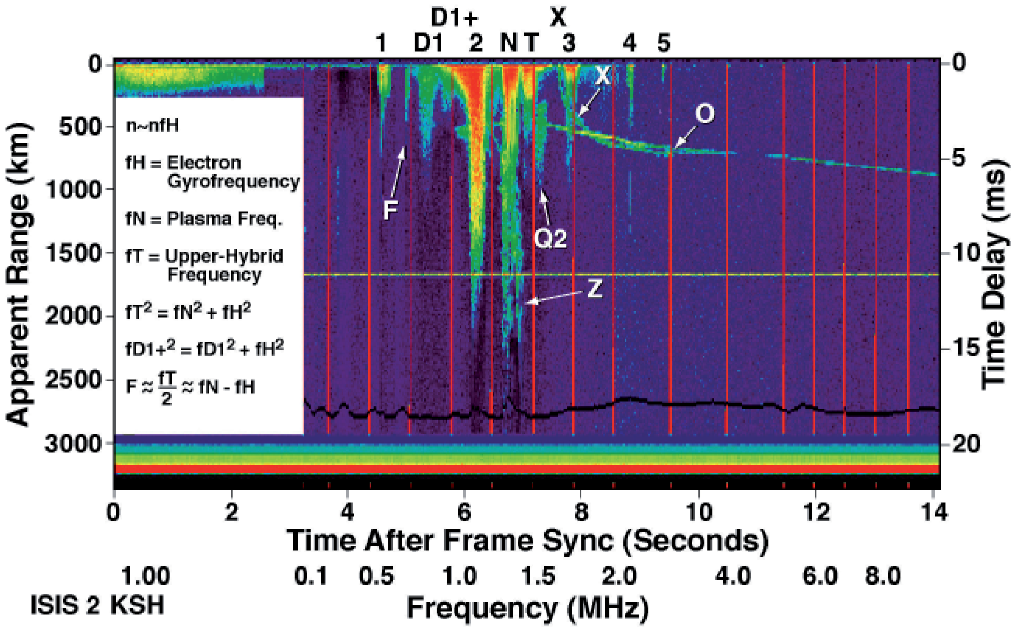

Figure 4. An ISIS-2 digital ionogram displaying the apparent range of the color-coded relative echo amplitude (blue to red) as a function of sounder sweep time and sounder frequency. In this example, the sounder frequency was fixed at 1.0 MHz for the first 3.3 s and then swept from 0.1 to 10.0 MHz; the total duration of the record was slightly more than 14 s. Ionospheric notation is given for the plasma resonances at the top and in the insert. The data were recorded at Kashima, Japan on 23 May 1979 at 1023:41 UT, when the satellite was at 18.5° latitude, 143.4° longitude, and 1377.1 km altitude, where $f_N/f_H = 2.34$ (after [1] and adapted from [2]).

[14-16], by the association of these Sounder Accelerated Electrons (SAE) to the Dn resonances [17, 18] and that SAE can be excited even by lower-power sounders [19], and by the diffuse low-frequency tails observed on the nfce resonances when $nf_{ce} < f_{pe}$ [20]. The strong turbulence approach is supported by the large electric fields (~ 100 V/m) near the satellite generated by the sounder antennas [21]. The force-free em cylindrical-oscillations approach is supported by the excellent agreement between the predicted and the observed spectral sequence of the Dn resonances and their subsidiary resonances [3] and by the prevalence of cylindrical structures known as N_e Field-Aligned Irregularities (FAI) [22, 23]. The long time durations (~ 10 ms) observed for some of the Dn resonances have been interpreted in terms of the propagation time of waves from a distant sounder-induced turbulent region either by a nonlinear wave-particle interaction and a nonlinear three-wave interaction process [11] or by a nonlinear Landau-damping mechanism [24]. This propagation concept has been supported by interpreting the observed splitting of the long-duration D1 resonance in mid-to-high latitudes in terms of a Doppler effect [25].

There is evidence that FAI, i.e., the structures in the cylindrical-oscillations approach to explain the Dn resonances, can be enhanced or created by topside sounders. This evidence is based on the enhanced Z-mode scattering from such FAI only when $f_N/f_H = f_{pe}/f_{ce} \approx n$ [26]. A sensitivity to such plasma conditions has been obtained theoretically by considering nonlinear cylindrical oscillations [27], which, for large amplitudes, leads to excessive negative space charge near the axis of the cylinder and an upward shift of fpe to a maximum of $\sqrt{2}$fpe [28]. Special plasma phenomena, particularly Stimulated Electromagnetic Emissions (SEE), have also been reported during ionospheric ground-based heating experiments when the frequency f_o of the high-power radio transmissions is near certain fundamental ionospheric frequencies [29]. The scattering cross section of FAI stimulated during such experiments was observed to be substantially enhanced when $f_o \approx 2f_{ce}$ [30] and all spectral SEE features were observed to be suppressed for $f_o \approx nf_{ce}$ with n = 4-7 [31].

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2. Contemporary Activities (2011-2019)

2.1 Spacecraft Observations and Active Experiments

Successful operations of a unique combination of magnetospheric spacecraft missions contributed to recently revived interest in experimental investigation of waves in space plasmas, especially in the region of the Van Allen radiation belts but also on the low-Earth orbit.

The CNES DEMETER mission was retired on December 9, 2010 after more than 6.5 years in orbit, but the exceptional data set collected by this mission still continues to serve as an excellent source of knowledge on different wave emissions observed on the low-Earth orbit: for instance, on lightning generated whistlers [1], low altitude equatorial noise [2], power line radiation [3], magnetospheric line radiation [4], quasi periodic emissions [5], although numerous DEMETER observations still remain unexplained [6].

The ESA Cluster four-spacecraft mission was put in an elliptical high-inclination orbit, in 2000, and since its launch it has provided an excellent, constantly growing data set of observations of waves in plasmas in the Earth’s magnetosphere, its boundary layers, and in the solar wind. With an anticipated deorbiting of Cluster spacecraft between 2024 and 2026 this important era of space research will come to an end. Cluster still continues to generate unprecedented results thanks to its orbit and multi-point capabilities. Examples of the many results of this successful mission are: the characterization of discrete EMIC emissions [7]; contributions to research on the origin of plasmaspheric hiss [8]; on properties of equatorial noise [9]; quasiperiodic emissions [10]; and wave emissions in the solar wind [11]. Cluster measurements also contributed to investigation of whistler mode chorus [12-14], which has been proven to play a significant role in the dynamics of the outer Van Allen radiation belts [15].

This important wave emission has also been systematically studied using measurements of the NASA THEMIS mission [16-17], which was put in orbit in 2007. This five-spacecraft constellation also contributed to the development of new analysis methods [18], and to the research of other wave phenomena, for example: equatorial noise [19]. Another important set of studies of chorus emissions was based on the exceptional NASA Van Allen Probes spacecraft pair data set [20-22] collected systematically since its launch in 2012. This very successful mission, which ceased its operations in 2019, also contributed to extensive studies of other types of waves, for example: plasmaspheric hiss [23-24]. Chorus has been recently analyzed in detail using the NASA Magnetospheric Multiscale (MMS) mission data [25], launched in

2015. Chorus has also been a subject of initial studies based on the measurements of the newly launched (2016) JAXA Arase spacecraft [26].

Other spacecraft missions contributed to investigations of electromagnetic waves in the solar wind close to the Earth's orbit, and in the vicinity of other Solar system planets. For example: the NASA Stereo mission measured the solar radio bursts [27]; the NASA-ESA Cassini-Huygens mission to Saturn provided the first lion roar observations in Saturn's magnetosheath [28]; observations of Kronian Z-mode emissions [29]; and plasma wave phenomena linked to Saturn's moons [30]. Finally, NASA Juno mission, launched in 2011, started its operations on a polar orbit around Jupiter in 2016. Measurements onboard this spacecraft lead to many discoveries, related, for example, to Jovian lightning and its electromagnetic radiation [31,32].

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2.2 Ground-Based Observations of ULF and VLF Phenomena

2.2.1 VLF Observations

The operation of the AWDANet VLF network (Section 1.4) has continued. It was significantly enhanced in a European Union FP7-Space project [1]. Based on the huge number of whistlers detected by the network between 2002-2018, the source regions of whistlers were identified [2].

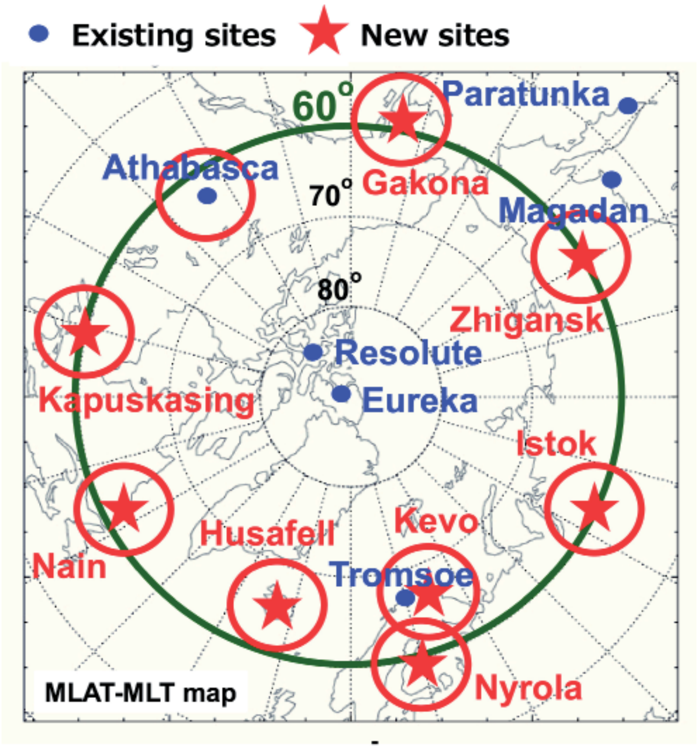

Figure 5. The PWING stations in a magnetic local time-magnetic latitude map. Blue dots and red stars, respectively, indicate pre-existing and new sites deployed by the PWING project. The red circles indicate the rough area of the field of view for each all-sky imager [6].

ELF-VLF observations started in Finland in August 1970 [3]. In the early 1970s M. Rycroft, from the U.K., made ELF-VLF observations in Sodankylä, but there were no Finnish partners. The second activity occurred at the end of the 1970s when M. Rycroft, P. Cannon, and T. Turunen made ELF-VLF recordings in Northern Finland and Northern Norway. At that time, a very compact battery-powered portable ELF-VLF receiver was used. The most important observation was the generation of ELF radio signals in the auroral ionosphere by non-linear demodulation of LF transmissions [4-5].

First recordings, in the late 1980s and early 1990s, were made in Inari and Sodankylä. These observations were related to the Russian Activnyij (Interkosmos-24) satellite, although, no signal from the satellite was received. Wideband ELF-VLF observations were carried out at different locations using two vertical 126 m^2 “Aktivnyij” aerials. Before 1993, they were used either as orthogonal loops or as a configuration of three antennae integrated per direction, which gave $\sqrt{3}$-times better signal-to-noise ratio. The next generation of ELF-VLF receivers was designed in summer 1992, and the first test campaign was in September at Sodankylä. Antennas were 10-by-10 m squares with 10 turns, which means 1000 m^2 effective area.

ELF-VLF data were recorded on the stereo audio tracks of VHS videotapes until 2005. The time code was simultaneously recorded together with auroral TV data on the video track of the same tape. Afterwards, one-hour blocks of ELF-VLF data were digitised in the post processing phase using 16-bit resolution. The instrumental noise level is usually in the 4-6 least significant bits.

Since 2005, recordings were made digitally with 24-bit dynamic resolution and the frequency band is 0.1–39 kHz. This allows for a much larger dynamic range of the input signal than before. This larger dynamic range gave some crucial information about the phenomena, which are just above the background noise level, or even below it. The threshold of the receiver sensitivity is about 0.1 fT (i.e., $\sim 10^{-14}$ nT^2 Hz^{-1}) making the KAN receiver the most sensitive in the world. For the last 13 years the Finnish ELF-VLF receiver has been at Kannuslehto (KAN). Since the Japanese ERG/Arase satellite started operations, KAN has received waves continuously from early September to late April.

Based on the Japanese Arase satellite a new network PWING (study of dynamical variation of Particles and Waves in the INner magnetosphere using Ground-based network observations) was established, led by Nagoya University. The PWING project (Figure 5) provides a longitudinal network of ground-based instruments that monitor ULF/ELF/VLF

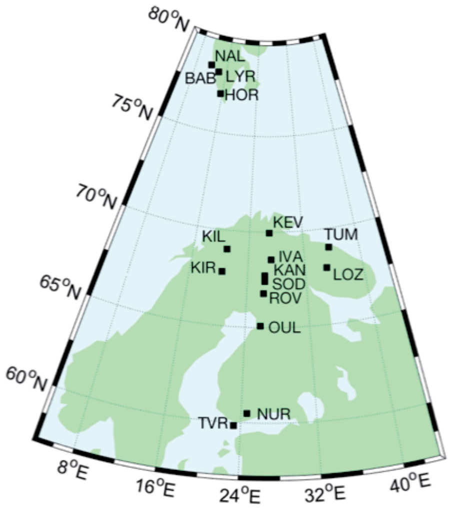

Figure 6a. The Finnish search-coil magnetometer network (including also the location of KAN, and TVR AWDA).

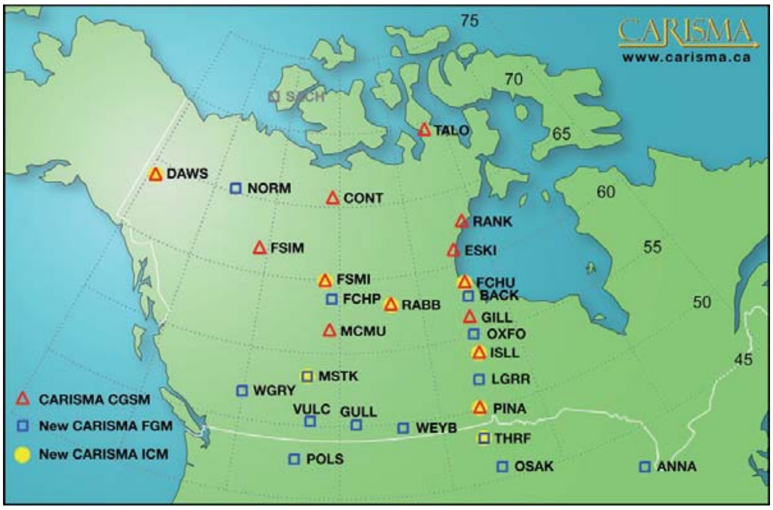

Figure 6b. The Canadian CARISMA network (the yellow marks are search-coil magnetometers).

waves and high- and low-energy plasmas at eight stations at geomagnetic latitudes (MLATs) of ~ 60° in the northern hemisphere. The 60° MLAT was chosen because it is connected to the magnetic field line of L = 4, which is the key radial distance for studying the wave–particle interaction in the vicinity of the plasmapause [6].

2.2.2 ULF Observations

Although the study of ULF wave phenomena was historically associated more with IAGA (Division III 'Magnetospheric phenomena' had a dedicated Working Group III-1. for ULF Pulsations) rather than URSI, there have been trials from time to time to bring the ULF and VLF research communities together. Following the URSI General Assembly at Lima in 1975, a joint URSI/IAGA working group on Passive Electromagnetic Probing of the Magnetosphere was formed. Since 1989, the joint group has been known as VERSIM (VLF/ELF Remote Sensing of the Ionosphere and Magnetosphere). The working group has organized several joint sessions at IAGA and URSI meetings. ULF waves already appeared as a topic in the 1980s, e.g. at the XXI URSI General Assembly ("ULF and VLF Waves", a symposium on multipoint and multispectral wave techniques and their application to ionosphere/magnetosphere studies proposed by K. Tsuruda, and co-convened by W. J. Hughes) was held in Florence in 1984.

The communication and interactions between the ULF and VLF communities intensified after the 3rd VERSIM Workshop held in Tihany (Hungary) in 2008, and consolidated on the course of the EU FP7 funded PLASMON project in which VLF and ULF experts worked together to develop a global ground-based plasmasphere monitoring system [1]. Beyond several VLF experts of the VERSIM community, PLASMON also involved ULF wave researchers from the University of L'Aquila, Italy (M. Vellante), and from the Eötvös Loránd Geophysical Institute, Hungary (B. Heilig). They developed an autonomous system capable of monitoring plasmaspheric mass density in near real time. The mass densities are inferred from the observed eigenfrequencies of geomagnetic field lines by solving the MHD wave equation in a realistic magnetic field configuration. The field line resonance (FLR) frequency is a function of the geomagnetic latitude of the footprint of the resonating field line (i.e. of the field line length), the magnetic tension (known from field models) and the density of the plasma frozen to the field lines.

The needs of the PLASMON project implied the establishment of the European quasi-Meridional magnetometer Array (EMMA). EMMA was formed by merging and complementing existing European networks (Finnish stations of IMAGE, Polish, Slovakian and Hungarian stations of MM100, and the Italian SEGMA). EMMA covers the L-shell range L = 1.5-6.1, thus the whole plasmasphere under quiet geomagnetic conditions and also a part of the plasma trough under disturbed conditions. EMMA data was used to monitor plasmaspheric dynamics, with an emphasis on the refilling process, and developed an empirical model for the plasmaspheric mass density [7-8]. The Dynamic Global Core Plasma Model loss and refill rates have to be revised in order to have a good fit between observations and the model [9], while the FLR inversion was improved by replacing the centred dipole model of the geomagnetic field by an eccentric dipole or the IGRF model [10].

The joint effort of the VLF and ULF researchers to improve the plasmasphere remote sensing techniques and understanding plasmaspheric dynamics continues in joint sessions at URSI and IAGA meetings, as well as at VERSIM workshops.

ULF waves are measured by search coil (or induction coil or pulsation) magnetometers. One network for ULF measurements was already mentioned PWING. One latitudinal network is located in Finland (7 stations from 60.5°N to 69.8°N) and has operationed since 1999. All these search coil magnetometers have 3 orthogonal components. The Finnish network is run by Sodankylä Geophysical Observatory.

Another search coil magnetometer network is in Canada. This is part of CARISMA (Canadian Array for Realtime Investigations of Magnetic Activity), which is the magnetometer element of the Geospace Observatory Canada project. It is the continuation and expansion of an original magnetometer array that was part of the CANOPUS ground-based instrumentation array. Search coil magnetometers are co-located (Figure 6) at 8 CARISMA station locations (DAWS, FSMI, FCHU, RABB, ISLL, MSTK, PINA, THRF).

There are also several search coil magnetometers in Russia. They are run by different institutes. Currently, at least, 11 search coil magnetometers are in operation in different parts of Russia (from Kola Peninsula to Kamchatka Peninsula). One of them is located at Barentsburg on Svalbard.

Augsburg College, and the University of New Hampshire, operate three search coil magnetometers on Svalbard (Ny Ålesund, Longyearbyen, and Hornsund) [11], and three others at Sondrestromfjord (Kangerlussuaq), Greenland, Iqaluit, Canada, and South Pole Station, Antarctica.

The British Geological Survey has installed search coil magnetometers at Eskdalemuir Geophysical Observatory in the Scottish Borders.

Schumann resonance (SR) is one of the best-known ELF phenomena. The fundamental resonance mode is ~8 Hz and has a corresponding wavelength equal to the circumference of the Earth. The overall frequency band runs from 3 Hz to 50 Hz, as part of the lower ELF range. There are presently about 30 ELF receivers now in operation worldwide, in more than 20 countries, with the great majority running independently. Now the MIT is offering , Supercloud for archiving the world-wide SR data.

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2.3 Laboratory Experiments

There have been two recent reviews of laboratory experiments related to whistlers. The first concerned helicon modes, i.e., whistlers with helical propagation [1]. The second dealt with the excitation of whistler-mode waves by antennas [2]. It showed how the research of the last few decades covered nonlinear effects, instabilities, non-uniform fields, whistler modes with orbital angular momentum, wave-field topologies, and more. The focus was on laboratory experiments but the results were related to whistler waves in space plasmas, laboratory helicon sources, and the findings of other research groups. The review covered antenna radiation patterns, radiation efficiencies, the topology of the emitted wave packets, and the propagation of whistler modes in highly non-uniform ambient magnetic fields. New phenomena discovered in the whistler mode, even in the linear regime, nonlinear effects, instabilities, and advances in wave diagnostic techniques were also reviewed.

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2.4 Plasma Instabilities, Nonlinear Phenomena, and Wave-Particle Interactions

Stimulated by new spacecraft observations (THEMIS, Van Allen Probes, ARASE, and MMS), simulation studies have been rigorously conducted, resulting in theoretical analyses and new understanding of the nonlinear processes embedded in the observed wave phenomena.

Whistler-mode chorus emissions have been reproduced in electromagnetic simulations not only by one-dimensional models [1-3] but also by two-different dimensional models based on electron hybrid codes [4-5]. The analysis demonstrated the formation of rising tone emissions from equatorial regions, turning into oblique propagation in higher latitudes. The wave-particle interaction with obliquely propagating whistler mode waves was formulated [6-7], and particle simulation for acceleration of resonant electrons were conducted to clarify the highly efficient Landau resonance acceleration process [8]. The efficient acceleration, on the other hand, caused effective damping of the whistler mode wave, especially at half the cyclotron frequency where the group velocity and the phase velocity of whistler mode wave in quasi-parallel propagation coincide, resulting in the effective damping of the wave packet. A recent review of oblique whistler-mode waves was given by [9].

The generation process for electromagnetic ion cyclotron rising-tone emissions was studied with an ion hybrid code [10]. Unlike simulations of chorus emissions, more realistic parameters were used in the simulation, making it possible to make comparison with observations. A single rising-tone emission consisted of several sub-packets generated at slightly different locations near the magnetic equator.

These sub-packets were also found in the generation process of whistler-mode chorus emissions. When the amplitude of a triggering wave exceeded the threshold applied, the waves started to grow at a fixed position near the magnetic equator. The nonlinear growth process is due to the frequency increase induced by the formation of a nonlinear resonant current. The wave amplitude of the sub-packets were determined by the optimum wave amplitudes for the nonlinear wave growth process [11]. A sub-packet generated near the equator undergoes convective wave growth due to the gradient of the background magnetic field [12].

The nonlinear wave growth occurred in two stages, the absolute instability with frequency variation followed by the convective instability through propagation to the higher latitude. Around the equator, the depletion of resonant electrons form an electron hole in the velocity phase space that can grow with a rising-tone frequency, while enhancement of resonant electrons form an electron hill that can grow with a falling-tone frequency. The process of nonlinear wave growth was applied to explain the appearance of short coherent wave packets forming plasma spherical hiss emissions [13-15].

EMIC rising-tone emissions can also interact with relativistic electron in the radiation belts, and they can precipitate a substantial number of electrons from the radiation belts [16-17].

Energetic electrons are effectively accelerated by chorus emissions. To simulate the long-time evolution of the relativistic electron flux, a new nonlinear method was based on massive test particle simulations with the formulation of numerical Green's functions [18]. The acceleration by chorus waves was modeled for a specific L-shell. The ULF waves modified the trajectories of relativistic electrons in the radial directions by trapping electrons with a wide energy range [19]. The comprehensive review on the ULF wave particle interaction was given by [20].

As one of the nonlinear wave phenomena frequently observed in space plasmas, electrostatic solitary waves, or electron holes, were observed and analyzed in recent spacecraft observations. A recent review on electrostatic electron holes was given by [21]. Some of the electron holes were accompanied by electromagnetic fields.

Electromagnetic electron hole radiating whistler mode wave were studied theoretically [22]. Nonlinear theory of electrostatic oscillations was developed by [23], treating cold plasma cylindrical oscillations both along and transverse to the cylinder axis along B, and obtained a spectrum resulting from nonlinear beating between the electron plasma frequency f_p along B and (2) $1/2f_p$ transverse to B.

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3 Future Activities

Predicting future activities is always a difficult task, but it is particularly risky in the case of a rapidly changing and evolving science phenomena like plasma waves, that is further "complicated" with its strong interlocking to space research. Therefore, what we can try to do is a kind of extrapolation of the recent activities combined with the known plasma wave instruments on near-future space missions.

3.1 Plasma Wave Instruments on Space Missions

3.1.1 Transition from Research to Services

The majority of historical and recent plasma wave measurements were operated on geospace satellites (see Section 2.1) and most of them served for research purposes in the area of (what we call now as) space weather. Based on the accumulated data and model development, we are now in a transition phase from Space Weather related research – where various plasma waves and related processes play key roles – to operational services. These *Space Situational Awareness* (SSA) services are under intensive development by the major space-faring nations, including USA, EU (ESA [1, 2]), Russia, China, India, etc., and are already partially implemented. Space weather is an important part of SSA services, where various space and ground-based operational plasma-wave measurements are, or will be the part of the inputs to space weather models (Radiation Belts, Ring Current, Ionospheric Space Weather, etc.). The present research infrastructure is expected to be converted to an operational service, complementing the existing services on GEO and LEO polar satellites. Single point/single satellite measurements (on large satellites) will certainly be replaced by multi-point/multi-satellite measurements on constellations of small (down to cubesat-size) satellites.

3.1.2 Transition from Geospace to Lunar/Planetary/Solar Research

Although geospace will remain the most important area of plasma wave instrumentation (and thus plasma wave related activities), as noted in the previous section, the emphases will mostly be shifted from research to operational services. Thus, the research emphases will also be shifted from geospace missions to lunar/planetary/solar missions, well aligned with the renewed plans of human flights to Moon and Mars.

3.1.3 Operating/Planned to be Operational Plasma Wave Instrument in the Near-Future

In this section we briefly list the most important plasma wave instrument, including active and passive ones, that are either in an operational phase, or under development and planned to be launched and operated in the next 10-15 years.

1. Arase Plasma Wave Instrument (PWI) [3]. PWI measures the DC electric field and plasma waves, covering the frequency range from DC to 10 MHz for electric field and from a few Hz to 100 kHz for the magnetic field. It consists of an orthogonal electric field sensor (WPT; wire probe antenna), a triaxial magnetic sensor (MSC; magnetic search coil), and receivers named electric field detector (EFD), waveform capture and onboard frequency analyzer (WFC/OFA), and high-frequency analyzer (HFA). Arase was launched on 20 December 2016 by Japan Aerospace Exploration Agency (JAXA) to explore the Earth's Radiation Belts (perigee: about 440 km, apogee: about 32,000 km, inclination: about 32°).

2. BepiColombo Mio (Mercury Magnetospheric Orbiter, MMO) PWI [4]. PWI has two-axis electric field sensors (WPT and MEFISTO) deployed in the spin plane, and three-axis magnetic sensors (LF-SC and DB-SC) at the top of the MAST. Those sensors are connected to a sophisticated receiver system for measuring electric field, plasma waves, and radio waves. The PWI covers a very wide frequency range, DC to 10 MHz for electric field and 0.1 Hz to 640 kHz for magnetic field. PWI measures the electromagnetic waves near the Mercury, either in the solar wind or in the magnetosphere of the planet. The BepiColombo is a joint mission of ESA and JAXA and was launched on 20 October 2018. It is expected to arrive at Mercury on, December 2025. The planned orbit for the Mio probe is highly elliptical (590x11640km).

3. Demonstration and Science Experiments (DSX) Wave Particle Interaction Experiment (WPIx) [5]. The WPIx experiment consists of a broadband receiver (100 Hz-50 kHz), a narrowband receiver (covering the 3 kHz-750 kHz range) and a VLF transmitter, operating in two modes, high power (i.e. Whistler mode waves) at 3 – 50 kHz at up to 500 W (900 W at end of life), and low power mode (i.e. Boomerang mode waves) at 50 – 750 kHz at 1 W. The top-level objectives for the DSX space flight experiment are to investigate the electromagnetic wave-particle (electron, proton, ion) interaction in the MEO region of space between the Van Allen radiation belts. DSX was launched on 25 June 2019 and its orbit is a 6000 x 12 000 km MEO Slot Orbit. This is the only known active space experiment for the near-future.

4. Solar Orbiter (SO) Radio and Plasma Wave Instrument (RPW) [6]. The RPW instrument consists of a sophisticated plasma/radio wave receiver system connected to high sensitivity electric and magnetic sensors. Since the receiver system covers a very wide frequency range (quasi-DC to 20 MHz for electric, and 0.1 Hz to 1 MHz for magnetic), different kinds of sensors are used for the measurements. SO is a joint ESA/NASA collaboration that will address a central question of heliophysics: how does the sun create and control the giant bubble of magnetic fields around it: the heliosphere? SO will be placed into an elliptical orbit around the sun coming as close as 26 million miles from the star every five months. The planned launch date of SO is February 2020.

5. JUpiter ICy moons Explorer (JUICE) Radio and Plasma Wave Investigation (RPWI) [7]. RPWI is to characterize the radio emission and plasma environment of Jupiter and its icy moons. It will use a set of sensors, including two Langmuir probes to measure DC electric field vectors up to a frequency of 1.6 MHz and to characterize thermal plasma and medium- and high-frequency receivers, and antennas to measure electric and magnetic fields in radio emission in the frequency range 80 kHz- 45 MHz. JUICE, an ESA mission, is planned to be launched in June 2022 and it will reach the Jovian system after a 7.6 years cruise, where it will spend 3.5 years.

6. The launch of the French space agency CNES TARANIS spacecraft is scheduled for 2020. This successor to the successful DEMETER spacecraft will aim at investigating phenomena linked to thunderstorms, especially to transient luminous events, and terrestrial gamma ray flashes. The spacecraft will carry state-of-the-art instrumentation including a suite of instruments for electromagnetic wave measurements. Preparatory experimental [8,9] and modeling [10] studies are underway using the ground-based measurements, which will also be used for comparison with spacecraft data during the operational phase of the mission.

7. After electromagnetic wave measurements by the Mars Express and Maven missions, in orbit around Mars, ExoMars 2020 will, for the first time, attempt to measure electromagnetic waves in a broad range of frequencies directly on the surface of Mars [11]. We hope to obtain new results on penetration of waves from outer space to the surface, and possibly also signatures of hypothesized electric discharges in Martian dust storms, and dust devils.

8. Cluster, MMS, THEMIS: these missions have been operational for years and are expected to operate for several more years – see section 2.1 for details.

3.2 Plasma Wave Instruments on the Ground

In the future, in-situ measurements will also be accompanied/complemented by ground-based network measurements. As there are currently numerous networks operating, and will surely be operating in the near future, here we only refer to section 2.2 where those networks were listed among the contemporary activities.

3.3 Theoretical Achievements of Plasma Wave Theory

Similar to recent theoretical achievements described in Section 2.4, further significant development are expected in the theory of wave-particle interaction in space plasmas. The other large area, where we may also expect significant development is the area of plasma instabilities in hot plasmas. The major driver for the development here is expected to be the progress of ITER, the world's largest Tokamak, a magnetic fusion device, under construction in France since 2007 as a combined effort of China, the European Union, India, Japan, Korea, Russia and the United States.

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URSI Commission J: Radio Astronomy

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Preface

The organization and operation of URSI can be seen as a sailing trip around the world by ten boats, each representing one of the ten Commissions of URSI, that gather at three-year intervals in a place on Earth decided by the central overseers, the Council. At these General Assemblies the captains of the Commission ships meet with the Council to discuss the experiences of the recent period and make plans for the next. The crews of the ten boats set up their individual meetings to present the scientific discoveries of the last three years to their colleagues who could not fit on the ship and travelled to the harbor to hear the news. Occasionally, crews from more than one boat find common interest in holding joint meetings. Also, individual captains may make landfall by invitation at a suitable place for a conference on a special subject of interest.

This procedure was in place for a hundred years, to the great satisfaction of the URSI community, and with considerable success. It is not unusual to accompany such a centennial with the publication of a book on the history of the organization. The URSI Centenary Book, of which this chapter is a part, will do just that. However, how to write a history of a journey with short highlights every three years, and intermediate years of calm? In addition, the highlights, the General Assemblies, tend to be rather similar in structure and there is a danger that the story will become repetitive and rather boring. I have faced this dilemma during the writing of this chapter.

The history of the Commission proper, its terms of reference and organizational and political activity within URSI, demonstrated by its proposals and resolutions, is given the needed attention. The development of the technical means for making radio astronomical observations of increasing breadth and depth has been the mainstay of Commission J sessions at the General Assemblies and in specialized Symposia. I have tried to summarize the main aspects of these developments while being aware that it is not an encyclopedic listing. The astronomical discoveries made possible by the new telescopes have always been part of the program of Commission J sessions. They are treated rather more in passing than in detail in this chapter. A small number of photos, most provided by colleagues, and some personal anecdotal memories are added to give the reader some light relief.

1. Introduction

In the first half of the nineteenth century the experimental work by Oersted, Coulomb and notably Ampère and Faraday demonstrated a close relationship between electric currents and magnetic fields. Faraday's (1791-1867) discovery in 1845 of the rotation of the plane of polarization of light under the influence of a magnetic field established an intimate relationship between light, considered a wave phenomenon, and electric and magnetic fields. On the basis of this groundwork James Clerk Maxwell (1831-1879) developed the dynamical theory of the electromagnetic field, published in 1865. He unified electricity, magnetism, and light into the concept of electromagnetic (EM) waves travelling through the "ether" with the speed of light.

The electromagnetic waves originating from Maxwell's equations are not limited to the wavelengths of light. The theory predicts the existence of EM-waves at other wavelengths. Heinrich Hertz (1857-1894) demonstrated these radio waves with his experiments in Karlsruhe, published in 1888. Hertz's experiments aroused considerable interest in the new field of electromagnetic waves. It led to wireless telegraphy, and to radio broadcasting. These developments used long

Figure 1. Wilbur (Chris) Christiansen, on the left, showing the Pott's Hill radio telescope to high URSI officials: Sir Edward Appleton (far right), and, next to him, Professor B. van der Pol, famous Dutch radio scientist, during the URSI General Assembly, in Sydney, in August 1952 (courtesy of ATNF Historical Photographic Archive B2842; Image Credit: CSIRO Radio Astronomy Image Archive).

wavelength (order of meters or longer) radiation transmitted and received by dipole and wire antennas. The term radio (from the Latin radius - beam) appears in the 1890s as radio-waves, radio-telegraphy, radio-receiver. By 1910 radio had replaced the term wireless in the USA and the European continent, but the latter remained the favoured term in Britain until after the Second World War. The establishment of URSI (Union international de radiotélégraphie scientifique in the original document) in 1919 could be considered as the official acceptance of radio as the indicator of EM-waves at wavelengths well beyond that of light.

Hertz's demonstration induced several investigations into the possibility of detecting radio waves emitted by the sun. However, all experiments carried out in the USA, England, Germany, and France between 1890 and 1901 were unsuccessful due to the low sensitivity of the receiving equipment and because the observations were performed over a period of minimum solar activity. Only a major solar outburst at the maximum of the 11-year solar cycle might have been detectable. With growing commercial interest in long-distance radio-communication at very long wavelengths, no further efforts in detecting the sun were undertaken for several decades.

2. The Birth of Radio Astronomy

About a decade after the creation of URSI, radio emission at a frequency of 20 MHz was detected by Karl G. Jansky, at the Bell Telephone Laboratories in Holmdel, USA, and its origin identified as the central region of our Galaxy. The first public presentation of his discovery occurred on 27 April 1933 at the USA URSI Meeting in Washington, DC, followed by a paper at the national convention of the IRE in Chicago on 27 June. The impact of this momentous discovery was extremely limited. In a letter to his father Jansky noted "not a word was said about my paper by the handful of old college professors, members of this almost defunct organization". Astronomers showed no interest in this new source of "cosmic" radiation. However, an engineer and Ham-radio-amateur, Grote Reber, constructed a 10 m diameter parabolic reflector and mapped a large part of the sky at a wavelength of about 2 m. With some difficulty, he managed to get his results published in the Astrophysical Journal in the early 1940s. At the close of WWII physicists and radar engineers started to use their wartime equipment to observe the sky, notably in Australia, Britain, and USA. In the Netherlands, in 1944 Hendrik van de Hulst predicted that a spectral line of atomic hydrogen, the most abundant element in the Universe, at 21 cm wavelength could be detectable. The goal to achieve this became the major driver for the development of radio astronomy in the Netherlands.

The early observations, mostly made at frequencies of a few hundred MHz, produced a small catalogue of individual sources of emission, the celestial positions of which were determined with the use of interferometry to such accuracy that comparison with optical objects was feasible. The identification of the strongest radio sources with supernova remnants (Cassiopeia A and Taurus A) in our Galaxy, and extragalactic objects (Cygnus A, Virgo A) convinced the community of optical astronomers that these "radio engineers" were expanding the realm of astronomy beyond the optical wavelength domain.

3. Radio Astronomy Enters URSI

At the first URSI meeting, after the war, in 1946, in Paris, President Edward Appleton established a Sub-commission on "Radio Noise of extraterrestrial Origin". At the 1948 General Assembly, in Stockholm, its status was upgraded to a full Commission V (five) – "Extra-terrestrial Radio Noise". The name was changed to "Commission V – Radio Astronomy" at the Zürich General Assembly in 1950.

We should note here that the early radio observations, particularly those of the sun, had also drawn the interest of the International Astronomical Union, established in 1919, the same year as URSI. At its General Assembly in Zürich, in 1948, Commission 40 on Radio Astronomy was established with 20 members, among them a few optical astronomers. The year 1952 was particularly exciting for the small group of radio astronomers. At the General Assemblies of both IAU in Rome, and URSI in Sydney, the optical identification of several radio sources was announced and Galactic structure was revealed by the 21-cm hydrogen line observations (e.g., Figure 1). These events established radio astronomy as a bona fide branch of astronomy that was accepted by the community of optical and theoretical astronomers and astrophysicists.

At the URSI Assembly, in Sydney, Commission V was represented by a strong delegation of about 15 radio astronomers from outside Australia: about a third of all foreign participants (e.g., Figure 2). In the following years URSI-Commission V published a number of Special Reports with detailed reviews of the state of radio astronomy: Report 1 (1950) on "Solar and galactic radio noise", edited by E. Appleton [1]; Rep. 3 (1954) "Discrete sources of extra-terrestrial radio noise", by J. Bolton [2]; Rep. 4 (1954) "The distribution of radio brightness on the solar disk", by W. Christiansen [3] and Rep. 5 (1954) "Interstellar hydrogen" by J. Oort [4]. Obviously, URSI Commission V was determined to play an active role in the development of technology for, and the dissemination of results in the new field of Radio Astronomy.

The existence of "Radio Astronomy" Commissions in both IAU (Comm. 40) and URSI (Comm. V) led to considerable discussions within and between the two groups by the mid-fifties. How would the work by radio astronomers be divided over the two Commissions? Should URSI be limited to instrumental, and technical aspects, and astronomical results be presented and discussed through IAU? This question was discussed at the high levels of both organisations, and the tendency was to answer the question in the affirmative. The great majority of the individual commission members, i.e., the active radio astronomers, did not accept the implementation of this idea. Here we should remember that at the time URSI did not offer membership to individual scientists. One could become member of the National Committee in one's country and all radio astronomers in these were counted to belong to Commission V – Radio Astronomy of URSI. Most of these had also joined Commission 40 of IAU. In 1955, the membership of Commission 40 was 49 persons, 32 from the five most active countries (UK, USA, Australia, Canada, and the Netherlands). By 1961, these numbers had climbed to 105, and 70 in the five countries. There was a large overlap between Commission 40 and URSI commission V, so similar numbers apply roughly to the membership of Commission V.

While the leaders of IAU and URSI deliberated about division of responsibilities, and URSI published its Reports, mentioned above, both organisations agreed to hold a few Symposia specifically devoted to Radio Astronomy. The first took place at Jodrell Bank in 1955; it was IAU Symposium 4, early in the new series of published IAU Symposia. It was followed by a large and highly successful joint IAU/URSI Symposium in Paris in 1958. During this period URSI and IAU jointly worked on mundane but essential aspects, such as the definition of terms and quantities, as well as naming the quickly increasing number of radio sources. In 1959, the third Cambridge source survey used the simple source designation 3Cnnn, for third Cambridge catalogue, with the number increasing with right ascension. This numbering was the de facto system until the Parkes survey with several thousands of sources used the designation e.g., PKS1925+416 for the Parkes Catalogue PKS, right ascension in hours, and minutes (19^h25^m), and declination in degrees to one tenth of a degree (+41.6). This system was widely adopted, where the lettering identifies the observatory.

The great majority of radio astronomers in URSI welcomed the connections with IAU Commission 40, but maintained their desire for a structure within URSI that would embody both instrumental aspects and astronomical results. A resolution at the General Assembly in 1960 was passed that confirmed this "hybrid" character of Commission V.

Its terms of reference should be (in a somewhat condensed form):

1. The activities of the Commission shall be concerned with:
    (a) Radio sources in space, particularly sun, solar system, Galaxy, discrete sources in the Universe.
    (b) Study of meteors, sun, moon, planets, and other solar system object by radio echo technique (radar).

2. Study and promotion of the development of technical methods in relation to the above. Take strong efforts to protect observations from interference.

3. In connection with (1) the Commission will aim:
    (a) to work jointly with other URSI Commissions where common interests exist.
    (b) to work jointly with Commission 40 of IAU in convening symposia on Radio Astronomy.
    (c) to cooperate with Commission 40 of IAU on the choice of topics for discussion in order to prevent any undesirable overlapping.

4. The Commission shall formulate appropriate recommendations to URSI on any subject in relation to the above for consideration by other URSI Commissions and other international bodies [5].

Over the course of time the URSI Council, or other Commissions, have taken issue with this charge without having resulted in a significant change. Its core functions satisfactorily despite some adjustments. At the URSI reorganization, in 1975, Commission V was designated Commission J.

Figure 2. Australian radio astronomers with foreign guests at the URSI Assembly in Sydney in 1952.
(l-r) (first row): W.N. Christiansen, F.G. Smith (UK), J.P. Wild, B.Y. Mills, J.L. Steinberg (France), C.F. Smerd, C.A. Slain, R. Hanbury-Brown (UK), R. Payne-Scott, A.G. Little, M. Laffineur (France), G.B. Slee, J.G. Bolton.
(second row): C.S. Higgins, J.P. Hagen (USA), J.V. Hindman (France), H.J. Ewen (USA), F.J. Kerr, C.A. Muller (Netherlands).
(third row): J.H. Piddington, E.R. Hill, L.W. Davies.
(Courtesy of ATNF Historical Photographic Archive 2842-43, 8 August 1952; Image Credit: CSIRO Radio Astronomy Image Archive.)

Table 1. Major new radio telescopes of the 1960s.

Location	Type	Dim. (m)	Wavel. (cm)	Year - Remark
Parkes, Australia	Paraboloid	64	6	1961
Arecibo, Puerto Rico	Spherical, fixed	305	75	1963, tracking line feed
Nançay, France	Spherical, fixed	300	21	1967, coelostat ('Kraus')
Bologna, Italy	Parabolic cylinder	600	75	1967, 'Northern Cross'
Ooty, India	Parabolic cylinder	530	90	1969, NS, tracking
Algonquin, Canada	Paraboloid	46	3	1966
Green Bank, US	Paraboloid	98	20	1962, transit telescope
Green Bank, US	Paraboloid	43	2	1965
Kitt Peak, US	Paraboloid	11	0.1	1967, mm-waves
Culgoora, Australia	Annular array	3000	375	1967, heliograph 96 parabs
Cambridge, UK	Synthesis array	1500	21, 75	1964, 3 parabs, 18 m
Westerbork, NL	Synthesis array	1600	21, 6	1969, 12 parabs, 25 m

From the beginning of its existence Commission V actively pursued the protection of frequencies for the exclusive use by radio astronomy. The first was, of course, the 21 cm HI-line, for which the frequency band 1400 – 1427 MHz was designated by the International Telecommunications Union in 1959. In 1960, URSI, IAU, and COSPAR jointly established IUCAF (Inter Union Committee on the Allocation of Frequencies) to deal with the field of spectrum management on behalf of the passive radio sciences, such as radio astronomy, remote sensing, space research, and meteorological sensing. IUCAF's brief is to study and coordinate the requirements for radio frequency allocations established by the afore-mentioned sciences and to make these requirements known to the national and international bodies responsible for frequency allocations. IUCAF has official standing as a non-voting organization at the ITU, the International Telecommunication Union. URSI provided three to four delegates to IUCAF, who were nominated by Commission V. While fighting an uphill battle against the ever-encroaching needs of the communication industry, IUCAF was effective in defending existing allocations and implanting awareness of the delicate position the radio astronomer is faced with. Also, effective schemes for excision of interference from the observations have helped to co-exist in the crowded radio spectrum with the concurrent drawback of decreasing the weight of our arguments in defense of the existing allocations to passive use of the spectrum. In Appendix 1 of this chapter the current chairman has provided more information on IUCAF.

In the second half of the 1950s several new radio telescopes came into operation, notably the relatively large 15-25 m diameter reflectors in Dwingeloo, Bonn; NRL (Naval Research Laboratory), Harvard; Jodrell Bank (76 m!); and the Cross Antennas and Interferometers in Australia, Cambridge and the USSR. At the 1958 Paris Symposium a host of new results from these new telescopes was presented. While significant progress in the identification of radio sources with optical objects was presented, it was also clear that larger, more sensitive telescopes, capable of extending the wavelength range into the short centimeter regime, were needed. Also, significant progress in the identification of radio sources with optical objects could only be expected from more accurate radio source positions, of the order of one arc second.

4. The Golden Years of Radio Astronomy and Commission V

The period 1960-1975 has been called the 'golden years' of radio astronomy. Indeed, the number of new telescopes of increasing power enabled an enormous increase in production of accurate observations. In the USA, several universities obtained antennas of the 25-30 m class. The Caltech interferometer provided accurate positions that helped the identification process significantly. The National Radio Astronomy Observatory was established in 1957, and by 1965 offered open access to its two major telescopes of 300 and 140 feet diameter, as well as a three-element variable baseline interferometer. A 64 m dish in Australia became operational in 1961, and the "one mile" synthesis telescope at Cambridge produced the first fully sampled source maps with 23 arc seconds resolution and 1 arc second position precision in 1963. First results from these new telescopes were presented at the 1963 URSI Assembly in Tokyo. The discovery of Quasars was a beautiful result of close collaboration between radio and optical astronomers.

In 1964, URSI published a book entitled "URSI Golden Jubilee Memorial 1964" [6]. The title speaks for itself. Reviews of activities up to the early 1960s are presented for each of the Commissions. That of Commission V – Radio Astronomie – was written by R. Coutrez and R. Agonze, both from the Observatoire Royal de Belgique. It is the only contribution to this book written in the French language. The official languages of URSI are French and English and it is not surprising that these French-speaking authors chose their mother tongue. The review is heavy on the sun, planets, and meteors, but the Galactic and extra-galactic results are mentioned in an optimistic tone for further research, but for one

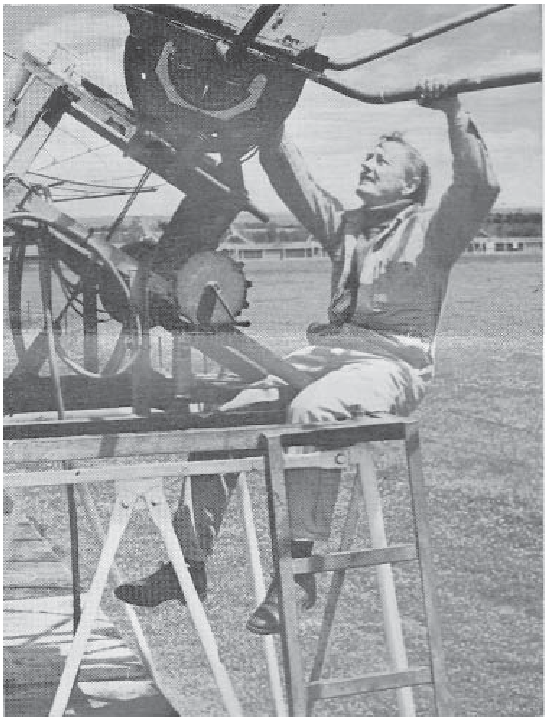

Figure 3. Wilbur (Chris) Christiansen was Chair of Commission V from 1963-1966 and President of URSI from 1978-1981. Here he is adjusting one of the antennas of the Fleurs Synthesis Telescope (Australia) in 1973 (QV, 6, no. 4, p.9, 1973).

interesting exception. On the subject of discrete sources, they write: "the majority of discrete radio sources show however a clear extragalactic character: most of these have not been identified with optical objects and probably never will be in view of their distance". This was written in 1963; a few years later we knew a lot more.

During the 1966 General Assembly, in Munich, a large number of recent and future telescopes were presented. The most important ones are listed in Table 1.

[The 1966 GA, in Munich, was my first General Assembly. The eldest French delegate, Professor Laffineur, read his paper in French, thereby obeying the official state requirement for conference contributions and enabling his younger French colleagues to speak English. I received some good advice from Gart Westerhout: "Always take a seat rather up front and somewhat to the side. Ask a question often, stand up and mention your name. You will be well-known after a few conferences!" Actually, I was already favoured company to my American colleagues because I could translate the German menu card in the restaurant. However, I was not always sure what would appear on our plates.]

The commission V sessions during the General Assemblies in the sixties were crowded with descriptions of these new instruments, and the astronomical data (e.g., Figure 3). There were a few singular discoveries at Nobel Prize level. The determination of the Cosmic Microwave Background, by Arno Penzias and Robert Wilson, in 1965, brought them a Nobel in 1978. Jocelyn Bell and Tony Hewish discovered pulsars in 1967. In 1974 a Nobel was bestowed on Martin Ryle and Tony Hewish (but not Jocelyn Bell) for the development of aperture synthesis, and the pulsar discovery, respectively. Later, radio astronomy related Nobel Prizes went in 1993 to Joseph Taylor and

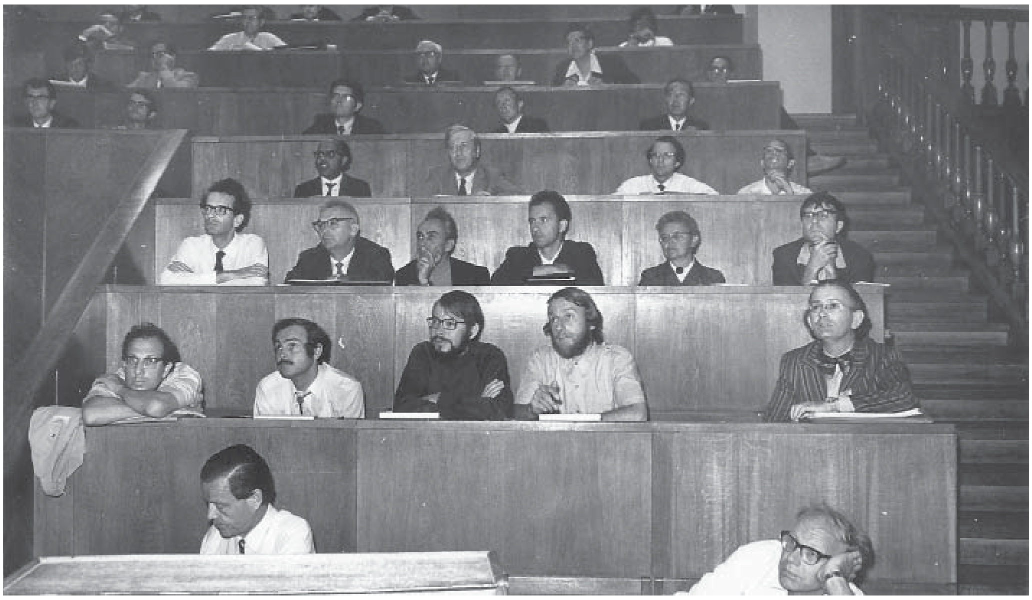

Figure 4. A session during GA in Warsaw 1972; most can be identified. From bottom row up, left to right: 1 - John Findlay, F. Graham Smith, 2 - Ken Kellermann, Johann Schraml, Ard Hartsuijker, Jaap Baars, Gart Westerhout, 3 - NN, Stanislaw Gorgolewski (Toruń), Jósef Maslowski (Kraków), NN, Ms. Wilhelmina Iwanowska (Director Totuń Obs., Zygmunt Turlo (?) (Toruń), 4 - Govind Swarup, Sam Goldstein, Al Moffet, Kochu Menon, 5 - Lout Sondaar, Kel Wellington, NN, NN, Tanaka, 6 - Jack Welch, NN, Mayo Greenberg (?), NN, George Swenson, 7 - NN, Harry van der Laan, NN (NN = No Name).

Figure 5. A picnic during the General Assembly in Lima, in 1975, with John Findlay standing right and Ivan Pauliny-Toth on the left in yellow shirt.

Russell Hulse for the demonstration of gravitational waves emanating from a double pulsar, and in 2006 to John Mather and George Smoot for their achievements with the COsmic Background Explorer, COBE.

By the mid-seventies radio astronomy had solidly established itself as an essential component of astronomy. For many radio astronomers the involvement, or at least close contact with the technical aspects: telescope, receiver, data reduction, operation, remained an essential part of their activity. Thus, the participation of Commission V in the URSI general assemblies continued to be intense. In addition, the Commission increasingly proposed and organized symposia in the area of its concern. Often these were planned and organized in close cooperation with Commission 40 (radio astronomy) of IAU. Examples of these are: the 1966 Noordwijk Symposium on the Galactic System; the 1978 Heidelberg VLBI (very long baseline interferometry) Symposium; and the 1980 Grenoble Symposium on Millimeter Technology in Radio astronomy.

> [In 1972, the GA was held in Warsaw (e.g., Figure 4). At the suggestion of our Polish colleagues about a dozen radio astronomers set out for a restaurant, famous for its kitchen and, in particular, the “Polish duck.” We were handed a large menu card with many dishes. After unsuccessfully trying to order from the card (“not available”) we asked what was available. The answer was duck, only duck! So, we ordered duck. When it arrived at our table, it was so lightly cooked that it was barely edible. One remarked: “my duck wanted to fly off my plate,” and another retorted, “you should have let it.”]

5. Renamed Commission J – Radio Astronomy Solidly Settled in URSI

The extensive reorganization of URSI, at the 1975 General Assembly, in Lima (e.g., Figure 5), left the status quo of the Radio Astronomy commission essentially unchanged. From that time onwards the designation became Commission J – Radio Astronomy. Around this time Commission J decided to reserve at least one full day at every GA for short “Reports of Observatories.” These were successful in their democratic and inclusive character; regardless of the observatory’s size, each gets their time slot.

The arsenal of powerful radio telescopes grew in the early seventies with the Effelsberg 100 m telescope, operating between 2 and 75 cm wavelength, and the Westerbork Synthesis Radio Telescope (WSRT) at 6, 21 and 50 cm. A new “window” at millimeter wavelengths was opened by the detection of carbon monoxide (CO) in the Galaxy at 2.6 mm with the NRAO 36 ft mm-telescope in 1970. Between 1972 and 1978 Brazil, Finland, Sweden, Spain, Korea, and the Five College Radio Astronomical Observatory (FCRAO, Univ. Massachusetts) acquired radome enclosed antennas of 14 m diameter (20 m in Sweden) that could be used at 3 mm, the FCRAO at 1.3 mm.

At the 1978 Helsinki General Assembly much attention was devoted to aspects of mm-astronomy. The NRAO 36 ft operated at full swing and many new molecules were found. A major emphasis was on presentation and discussion

Table 2. Millimeter wavelength telescopes of the 1980s and 1990s.

Institute	Location	Year	Diameter m	Rms µm	Protection	Altitude m
Caltech array of 4 antennas	Owens Valley, California	1979	10.4	60	open	900
NRAO	Kitt Peak, Arizona	1980	12	75	astrodome-open	1940
NRO	Nobeyama, Japan	1982	45	120	open	1350
IRAM	Pico Veleta, Spain	1984	30	70	open	2850
BIMA – array	Hatcreek, California	1985	6	50	open	1280
NRO – array of 5 antennas	Nobeyama, Japan	1985	10	75	open	1350
Caltech - CSO	Mauna Kea, Hawaii	1986	10.4	25	astrodome-open	4140
JIA- JCMT	Mauna Kea, Hawaii	1986	15	30	astrodome skin	4140
Daeduk Astron. Obs.	Korea	1989	13.7	150	radome	
IRAM – array of 3 antennas	Plateau de Bure, France	1989	15	65	open	2550
ESO-OSO, SEST	La Silla, Chile	1990	15	55	open	2400
Purple Mountain Obs.	Nanjing, China	1992	13.7	180	radome	3200
ATNF	Mopra, Australia	1995	20	100	open	860
SMTO MPIfR-Steward Obs.	Mt. Graham, Arizona	1995	10	15	astrodome-open	3200
SMA array of 6 antennas	Mauna Kea, Hawaii	2002	8	20	open	4070
LMT - UMass/ INAOE	Cerro la Negra, Mexico	2012/17	50	75	open	4640
ALMA – global poject.	Chajnantor, Chile	2005/13	12	22	open	5000
NOEMA-IRAM 12 element array	Plateau de Bure France	2018/21	15	60	open	2550

of developments for larger telescopes for short mm-wavelengths (<3 mm), and low-noise receivers. Plans for dedicated mm-telescopes, between 10 and 45 m in size, to be located at suitably high sites, were presented by Germany, France, England, Japan, and the USA. Further highlights were the successful VLBI observations at cm-wavelengths, and plans to extend baselines by antennas located in space.

In the "business session" time in the overall program for general review papers by each Commission was proposed. This has led to the three General Lectures during the GA at dedicated time slots outside the regular Commission meetings. Commission J was successful in providing lecturers. A list is given in Appendix 2.

Moreover, there was strong support for joint sessions with other commissions. This indeed became a clear part of future General Assemblies. There was also support for separate, URSI sponsored symposia, organized by individual institutes. Commission J organized and sponsored several as mentioned above.

The full operation of the Very Large Array (VLA), in New Mexico, in 1980, opened another "golden decade" for radio astronomy. This synthesis array of 27 antennas, moveable over rail tracks, with a 'Y' configuration, and a 21 km arm length, delivered high quality "pictures", with arcsecond angular resolution, at several wavelengths. Its performance and ongoing improvements were presented at the 1981 Washington DC General Assembly.

The second major development of the decade was progress in the construction and operation of the large millimeter and sub-mm telescopes that were discussed at Helsinki, as mentioned above. This is summarized in Table 2. For completeness four major (sub)millimeter telescopes completed after 2000 were added to the Table.

The design and construction of these highly accurate reflector antennas was mainly realised by industry under guidance of the Institutes. However, the extension of sensitive receivers into this wavelength domain was, at the time, not of primary industrial interest. Consequently, almost every institute aiming at mm-wavelength activity expanded its electronics department with development of appropriate receiver systems. This involved, in particular, low-noise mixers based first on Schottky diodes, and soon SIS-devices and local oscillators of sufficient power. These subjects were extensively reviewed, and discussed at the Washington General Assembly, and several dedicated symposia were held in the decade, such as: URSI Symposium on Millimeter Technology in Radio Astronomy in Grenoble in 1980; and URSI International Symposium on Millimeter and Submillimeter Wave Radio Astronomy in Granada, Spain in 1984. The proceedings of the latter symposium present a good review of the status and promise of current observations, and future work with the telescopes still under construction, or just beginning to produce results. The success of the new mm-telescopes was demonstrated during sessions on the subject during the Assemblies of 1984 in Florence, and 1987 in Tel Aviv. Clearly at the shortest wavelengths, where the atmosphere allows earthbound observations from high and dry sites, the sky had much to offer, and was intensely observed.

At the two Assemblies just mentioned there was however no lack of new initiatives for more telescopes. In Florence, NRAO presented the plan for the Very Long Baseline Array (VLBA) consisting of ten antennas of 25 m diameter to be located on suitable sites from Hawaii in the far west, to the Virgin Islands in the Caribbean. The technique of VLBI was constantly being upgraded ,particularly in the area of bandwidth, data collection, and archiving. Studies of "Space VLBI" concepts involving an orbiting radio telescope observing in conjunction with the ground arrays were underway in ESA, NASA, and in IKI in the Soviet Union. Richard Schilizzi described the developments in VLBI in one of the 1984 General Lectures.

In the area of mm-astronomy, Sweden announced a plan for a 15 m mm-telescope in the southern hemisphere that resulted in SEST (Southern ESO Swedish Telescope) located on the ESO site La Silla, in Chile. NRAO reported the refurbishing of its original 36 ft mm-telescope to a slightly larger (12 m) and significantly better antenna. Also, NRAO worked on the design of a 25 m antenna for operation to 0.8 mm wavelength. CSIRO announced the plan to build a powerful synthesis array in Australia. By the time of the Tel Aviv Assembly, the Australia Telescope was under construction near Narrabri, the site of the original circular radio heliograph built there for solar work by Paul Wild.

In Florence, Commission J drafted a letter of strong support for the essential work by IUCAF in the area of frequency protection that was submitted to the URSI Board, for support.

More new telescopes were introduced during the 1987 General Assembly in Tel Aviv. A major subject was the potential move of radio astronomy into space with telescopes orbiting the Earth. A report was given on the ESA-NASA Space VLBI concept, QUASAT, a large antenna of at least 15 m diameter operating at 1.6, 5, and 22 GHz. NASA made studies of a similar system, called the Large Deployable Reflector, of 10-30 m diameter aiming at far-infrared wavelengths. Neither of these was realised. The Japanese proposal, VSOP, for an 8 m telescope for VLBI at 1.6, 5, and 22 GHz was launched in 1997 and successfully operated for 8 years (the 22 GHz receiver malfunctioned). ESA launched a project for a large space-telescope at far-infrared wavelengths in 1984, named FIRST for Far InfraRed Space Telescope. After a long and tedious technical, organizational, and financial development cycle, a 3.5 m diameter mirror with three detectors in the 60-670 µm wavelength range was launched in 2009, named the Herschel Space Telescope. Finally, India introduced a major new telescope, the Giant Metre-wave Radio Telescope (GMRT): an array of 30 antennas of 45 m diameter of an original design. It came into operation in 1999.

Commission J again discussed its Terms of Reference in Tel Aviv. It was decided to add "space radio astronomy" and infrared - and optical-interferometry to its fields of interest. As usual, a few specialized symposia were suggested, which led to URSI sponsored meetings such as: a VLBI Summer School, in Bologna, Italy, in September 1988; a Millimeter Astronomy Symposium, in Hawaii, November 1988; the Symposium on Radio-Astronomical Seeing, in China, in May 1989; and URSI/IAU sponsored meeting on Limits of Observational Astronomy, in Sydney in September 1989.
(An anecdote on the Tel Aviv Assembly is the extensive interrogation by the border police on departure of Commission J Chairman, Richard Wielebinski. Fostering contact with our colleagues from the Soviet Union he had invited the USSR group of radio astronomers for drinks in his hotel room. This was obviously a highly suspect activity!)

The next GA took place in Prague in 1990, after the collapse of the Berlin Wall, and the de facto "decommunization" of the Eastern European countries. Commission J held productive Business Meetings, where some adjustments to the term of reference were made leading to the following statement:

(a) the activities of the Commission are concerned with observation and interpretation of all radio emissions and reflections from celestial objects.

Figure 6. The Global VLBI Working Group meeting in Onsala, Sweden in May 1993.
Squatting: Hisashi Hirabayashi, Roy Booth (Chair), Anton Zensus, Joel Smith.
Standing, left to right: Peter Dewdney, Fujun Zhang, Robert Preston, Richard Porcas, Junji Inatani, Peter McCulloch, Paul Goldsmith, Chidi Akujor (guest), Valery Altunin, Lucia Padrielli, David Jauncey, Masaki Morimoto, Jim Ulvestad, Dennis Walsh, secretary Margareta Mattsson, Andrzej Kus, secretary Karin Brunzell, Richard Schilizzi, Ron Ekers, Leonid Gurvits, David Meier.

(b) Emphasis is placed on:

(i) the promotion of technical means for making radio-astronomical observations, and data analysis,
(ii) support of activities to protect radio-astronomical observations from harmful interference.

(At the 1990 Prague GA, Richard Schilizzi was elected Commission J vice-chair. However, Council overturned this in favour of a representative from the Soviet Union. Yuri Parijskij became vice-chairman. This was at the time of perestroika and glasnost.)

The continuing expansion of VLBI observations, and space VLBI in particular, led to the establishment of an URSI Global VLBI Working Group (GVWG), soon to be a joint WG with IAU. The objectives of GVWG were:

i) to develop a concept for an International VLBI network, comprising existing or future national and regional networks;
ii) to promote compatibility of technology in VLBI instrumentation;
iii) to serve as liaison between ground-based observatories, and national or international space agencies, for coordination of participation by ground radio telescopes in Space VLBI missions.

Commission J proposed a number of inter-assembly symposia for sponsorship by URSI (e.g., Figure 6), and the importance of the work of IUCAF was confirmed. One of the "founding fathers" of IUCAF, since its inception in 1960, John Findlay, retired from IUCAF and was thanked by the Commission for his contributions to the work of IUCAF. Commission J also expressed its sympathy for the intent of a document, tabled by some of its members, entitled "Declaration of Principles concerning Activities following the Detection of Extraterrestrial Intelligence." This declaration is attached to this Chapter more for its historic interest than for its actual current use (Appendix 3).

The science and technology sessions were filled with reports on progress with recently completed instruments, such as: the mm-telescopes, announced in Tel Aviv, and the description of new telescopes; a plan for the Green Bank Telescope, a 100 m clear aperture dish, certainly a worthy improvement on the collapsed 300 ft telescope; the big upgrade of the Arecibo telescope with point-feeds at several frequencies; the extension of the MERLIN array in England; as well as progress on GMRT in India. With VLA in full operation, and several arrays at mm-wavelengths in operation, there were lively sessions on the issues of data handling, interferometer calibration, and imaging processes.

In connection with the GA, URSI sponsored two specialist workshops proposed and organized by the radio astronomy groups at the University of Riga, Latvia, and the Special Astrophysical Observatory in Nizhnij Arkhyz, home of the RATAN 600 radio telescope in Russia. About a dozen western GA participants flew from Prague to Riga for a four-day workshop on Reflector Antenna Technologies. With the aid of excellent simultaneous translators, stimulating, and pleasant discussions ensued with about 25 scientists and engineers from the USSR, including Latvia, Russia, and other Soviet republics. The meeting at RATAN was devoted to "Holographic testing of large radio telescopes." It was held in English, and included a visit to the 600 m diameter RATAN variable profile antenna system.

> [During the transfer from the airport to the hotel in Riga, the Latvian secretary turned to us and announced: "Gentlemen, I want you to be aware that you are now in a free country, named Latvia." The trip to Nizhnij went via Moscow and finished with a three-hour drive to the Observatory. It was late at night and since leaving Riga we only had a sweet on the Russian plane. We were told there would be food upon arrival. This turned out to be a stack of large circular loaves of bread and a dozen bottles of apple cider. We finished it all before going to bed.]

6. Towards ALMA and SKA

At the 1993 GA, in Kyoto (e.g., Figure 7), Commission J proposed two Working Groups. The Millimeter-Submillimeter Array WG recognised the need for international collaboration and can be considered as the seed for the creation of ALMA (Atacama Large Millimeter/submillimeter Array). The Large Telescope WG had a goal of defining instruments one to two orders of magnitude more sensitive than any existing or planned facility at centimeter and meter wavelengths, and to explore the required international collaboration for such a project. The SKA (Square Kilometer Array) is the result of these considerations. Presentations and discussion of these two major future projects occupied a significant part of the activity of the Commission during this Assembly.

A resolution from Commission J urging the ITU (International Telecommunications Union) to avoid spectrum allocation to services that can be realised by guided waves (cable and optical fiber) was accepted by the URSI Council and submitted to the ITU. The extent to which this request was followed is hard to assess.

During the next General Assembly in Lille, Commission J resolved to continue the Working Groups for the mm array and large telescope. The work and composition of IUCAF was discussed and new members from Commission J were

Figure 7. An encounter of radio astronomers (from left) Ron Ekers, Richard Schilizzi and Peter Shaver with one of the many temples in Kyoto during the URSI GA in 1993 (the lady is unknown).

elected. Its chairman, Willem Baan, presented an extensive report of IUCAF activities over the triennium 1996 to 1999 to the Toronto General Assembly. It can be found on the URSI website under 'Records of General Assemblies'.

The effectiveness of Working Groups was demonstrated at the 1999 Assembly in Toronto. Progress on the establishment of an international mm array, soon to be named ALMA, was such that Commission J abandoned the working group set up 6 years earlier. Similarly, the prospects for the SKA had also reached a point where it did not need the support from a separate working group, which consequently also ceased its work. It was decided to continue the activities of the Global VLBI Working Group in view of the increasing number of participating countries, and the addition of the Japanese and Russian Space VLBI Telescopes, VCOP-HALCA and RadioAstron, respectively. Further it was proposed to set up a working group to provide support to the OECD Task Force on safeguarding radio astronomy use of the spectrum, and a working group to study the effect of halting leap second insertions into UTC.

The 1999-2002 triennium saw great progress in the development of new radio astronomy facilities, and the expansion of existing ones. The Giant Metrewave Radio Telescope (GMRT), in India, representing an important step forward in low frequencies sensitivity, became fully operational.

The year 2002 was marked by the operational start of the Green Bank Telescope (GBT), the 105 m diameter clear aperture replacement of the venerable 300 ft that had collapsed in 1988.

Also, the international efforts to establish a global large mm- and submm-array culminated in the establishment of ALMA, by ESO, and NSF, representing Europe, and North America (USA and Canada), respectively. East Asia (Japan, Korea, and Taiwan) joined as an associate partner providing enhancements to the basic instrument. ALMA is located at the 5000 m high Chajnantor plane, in the Atacama Desert of Chile. At the time of the official agreement in April 2002, all parties were engaged in instrumental development work, such as prototype antenna evaluation, receiver construction, and software development.

In the following triennium VLBI reached a milestone with the detection of fringes at 2 mm wavelength, representing, at the time, the highest angular resolution in astronomical observations ever made. The stations involved were at Haystack Observatory, Steward Observatory, and the Max-Planck-Institut für Radioastronomie with its new APEX submm telescope in Chile, and IRAM.

In the Netherlands ASTRON engaged in the design and development of LOFAR, an array that is expected to improve the sensitivity and resolution of low-frequency radio astronomy by two orders of magnitude. Development of concepts and designs for the Square Kilometer Array continued as an international effort with active groups in Australia, Canada, China, Europe, and the United States.

The preparations for the SKA advanced sufficiently to issue a request for proposals of sites in 2004. Four viable proposals were subjected to scrutiny in 2006 leaving two, Australia, and Southern Africa, on the short list. Eventually, it was decided, in 2012, to divide the SKA over both sites: the low frequency telescope to be located in Western Australia, and the mid/high frequency telescope in Southern Africa.

Aspects of the technical realisation of these large instruments became a recurring feature of the Commission J presentations and discussions during General Assemblies up to this day.

During 2006-7 a major discussion point became the proposed URSI White Paper on Solar Power Satellite Systems as URSI's reaction to proposals to build space-borne solar light collectors, transfer the power to microwaves, and beam these to receiving antennas on the Earth. Commission J took the position that all statements in the White Paper and Appendices advocating SPS should be removed, and that considerable revision of the remainder of the material was required for this paper to reach the standard expected from URSI. The resulting URSI Council statement at the Chicago GA read:

> the URSI White Paper on Solar Power Satellite Systems should be used as a reference to undertake world-wide coordinated studies to investigate the potential of Solar Power Satellites as an alternative energy source, taking into account all relevant scientific aspects, the environmental and societal impact, the impact on other radio services, and the technical and economic feasibility.

The White Paper was issued in June 2007, and can be found on the URSI web pages.

At the 2008 GA, in Chicago, Commission J resolved to discontinue the Working Group on the Leap Second because its irrelevance for radio astronomy. The WG on Global VLBI continued with adjusted terms of reference and several new members. The WG concentrated on Space VLBI and seeking contact with more ground-based telescopes, in particular, in relation to the RadioAstron space telescope mission. In the following years discussions identified GVWG as struggling to play a role of relevance in the modern world of global VLBI. A conclusion of this discussion was that GVWG should be disbanded under both URSI and IAU umbrellas. Thus, GVWG was formally closed as an URSI Working Group at the GA in Istanbul in 2011.

The terms of reference for Commission J underwent another small revision at the Chicago meeting to reflect changes in the overall activities of radio astronomical research. The new text was:

Commission J - Radio Astronomy Terms of Reference:

- The activities of the Commission are concerned with observation and interpretation of all radio emissions from the early universe to the present epoch.
- Emphasis is placed on:
- The promotion of science-driven techniques for making radio-astronomical observations and data analysis;
- Support of activities to protect radio-astronomical observations from harmful interference.

Highlights of the Chicago meeting were: reports on the progress on construction of the GBT; the extended VLA; ALMA; and LOFAR. Future telescopes in the pipeline were described, including: the SKA, and its Pathfinders in South Africa (MeerKAT), and Australia (ASKAP); and the 500 m diameter FAST fixed bowl in China. Fast fiber-optic connections were enabling the European VLBI Network to operate in a real-time observing mode, called eVLBI.

7. More New, Big Radio Telescopes

The 2011 General Assembly in Istanbul offered a dense program of progress and results from the large new projects begun in the foregoing years. Emphasis was given to the new telescopes for low frequencies of order of 100 MHz. The status of LOFAR in the Netherlands, GMRT in India, MWA (Murchison Wide field Array) in Western Australia, and LWA (long wavelength array) in New Mexico USA, were presented and discussed. Many aspects of the plans for the SKA (Square Kilometer Array) were described and discussed from mundane points such as power needs and signal transport, to critical issues such as array configuration, choice of elements (reflector antennas or phased array), and signal processing, calibration, and imaging methods.

A second highlight was the reports from ALMA, which was nearing completion. A full overview of the ALMA system and performance was presented, including beautiful results obtained with a partial array.

A joint session with Commissions A and G was devoted to: Pulsar Timing and Time Transfer.

The terms of Reference for Commission J were slightly adjusted with respect to the Chicago version to:

The activities of the Commission are concerned with:

- Observation and interpretation cosmic radio emissions from the early universe to the present epoch and
- radio reflections from solar system bodies.

Emphasis is placed on:

- The promotion of science-driven techniques for making radio-astronomical observations and data analysis;
- Support of activities to protect radio-astronomical observations from harmful interference.

During the triennium to the 2014 GA in Beijing, substantial progress was made in the completion and upgrade of large telescopes such as MeerKAT, FAST, GMRT, LOFAR with a growing number of stations spread over Europe, and the Russian RadioAstron Space VLBI satellite. These were reported at the Beijing meeting, where also extensive attention was given to the developments around the SKA. Its Director, Phil Diamond, summarized the SKA Project at one of the General Lectures during the Assembly. ALMA, now fully completed, was also featured extensively along with reports from other (sub) millimeter telescopes APEX, SMA, and the space observatory Herschel.

The complexity of the new, large instruments, and the enormous data stream they produce, require intensive efforts in the area of data handling and analysis. Several sessions were devoted to “Correlation, calibration and imaging across all wavelengths” and “Time Domain Radio Astronomy: An Example of Big Data in astronomy”.

During the Business Meetings in Beijing there was a lively discussion on the way the General Assemblies were structured. The attractiveness of URSI is strengthened by the potential of cross-fertilization between Commissions. However, it was regrettable that there were so few inter-Commission sessions at this particular URSI GA, and all Commissions, including J, were urged to give priority to more coordination between Commissions (inter-Commission sessions).

At the same time the participants argued for shorter papers to accommodate more oral presentations. There should be more flexibility in assigning timeslots during some sessions, in particular for the Commission J standard sessions on "Observatory Reports" and "Latest Results."

It was not immediately clear how all these wishes could be realised within the overall duration of the General Assembly.

While Commission J no longer had any internal Working Groups, it participated in several Intra- and Inter-Union Working Groups:

- URSI Commissions: EFGHJ on 'RFI Mitigation and Characterization', represented for Comm. J by Willem Baan and Rich Bradley,
- Comm. HJ on 'Computer Simulations in Space Plasmas', K. Shibata (Japan) for Comm. J,
- URSI Inter-Commission 'Data Committee', Chair: S. Wijnholds (Comm. J, the Netherlands),
- URSI/IUCAF Inter-Commission Working Group on 'Radio Science Services', Chair for IUCAF: W. Van Driel (France) (ex officio),
- URSI/IAU Inter-Union Working Group on 'Historic Radio Astronomy', Chair: R. Wielebinski (Germany) (IAU), R. Schilizzi (UK) (URSI).

A proposal to participate in a recently established Working Group of the IAU for Historic Radio Astronomy was welcomed by Commission J, and URSI Council, and the WG became an IAU-URSI Working Group. The WG has national reporters in various countries that report to the WG chair on events.

The purpose of the WG Historic Radio Astronomy was reviewed at the Beijing GA along with its three major tasks:

1) assemble a master list of surviving historically-significant radio telescopes and associated instrumentation found worldwide, and document the technical specifications and scientific achievements of these instruments,
2) maintain an on-going bibliography of publications on the history of radio astronomy, and
3) assemble biographies and memoirs of deceased radio astronomers.

At each GA, new books and published papers in this area would be listed together with active projects. In addition, the WG planned to organize sessions on Historic Radio Astronomy at URSI and IAU General Assemblies. NRAO maintains a webpage for the WG (rahist.nrao.edu).

The last General Assembly of URSI in its first century of existence took place in Montreal, in 2017. The meeting had a large attendance; almost 1500 papers were submitted, and the organizers deemed parallel sessions necessary. Commission J communicated its objection to this to the URSI Council. During the Business Session there was some discussion regarding how to stimulate local URSI meetings in various countries. The concept of workshops affiliated with the URSI meetings was strongly supported.

The Commission J program at the Assembly leaned heavily on the success of (sub)millimeter instrumentation, both new telescopes, e.g., ALMA, and upgrades of existing ones. There was a large session on receivers and calibration and another on digital processing of huge data flows. Both subjects are of the greatest importance for the emerging large telescopes, both interferometer arrays, and multi-beam phased array feeds (PAF) for single reflectors with their enormous data streams. The APERTIF system on the Westerbork Radio Synthesis Telescope combines PAFs on a 12-element synthesis array. Presentations on the status and outlook of ALMA, the SMA, and NOEMA (NOrthern Extended Mm Array) of IRAM promised a bright future. Lars-Åke Nyman gave the tutorial lecture with title "The Atacama Large Millimeter/submillimeter Array (ALMA)."

Other subjects that received considerable attention were aspects of the SKA, from design issues to first experiences with MeerKAT, and observations of transient signals (bursts), and pulsars. The first session at an URSI GA on historic radio astronomy focused on the histories of a number of venerable interferometers and arrays. This highlighted the importance of the knowledge of history in understanding the present need for making sensible predictions of the future.

8. Conclusion

To return to the metaphor of the Preface, with the publication of the Centenary Book URSI has collected the summary logbook of each Commission. The one for Commission J was not written by any of the captains during the 70 years of its existence. I have been for more than 50 years an active and enthusiastic crewmember. Writing this chapter has entailed sometimes-frustrating searches in the archives, but always-pleasant recollections in memory. Commission V-J has occasionally been characterised by the "old guard" URSI officials as a raucous group. We had however one defender among the officials: Chris Christiansen. He told his colleagues in Council: "let the blokes do their thing. They are good at it." I believe that over time the radio astronomers in Commission J have not disappointed him. Commission J is, and remains, an active participant in URSI.

Recently URSI, in a continuous internal discussion about its means and ways, has instituted a few significant changes. Since 2017 individual radio scientists are eligible for Individual Membership. This entails some benefits, such as reduced fees for conferences and publications, but perhaps is more important for its strengthening of the link between the individual and the URSI Organisation.

Also, URSI has expanded its global reach with the establishment of so-called Flagship Meetings: the triennial Regional Radio Science Conferences in the Asian-Pacific and Atlantic regions. Thus, together with the triennial GA we now have a big URSI meeting every year. This will arguably have a negative influence on URSI initiated or sponsored specialised Symposia in the years between the General Assemblies, a development that perhaps is regrettable. There is a risk that an annual meeting encompassing the whole of URSI will lead to overfeeding, or a loss of appetite, and excitement. It would also appear to have a negative influence on the national URSI meetings that have been advocated repeatedly at Business Meetings during the General Assemblies.

Whatever these developments may bring, it appears certain that Commission J will remain a highly active component of URSI that will continue to demonstrate its relevance for URSI and Radio Astronomy through its achievements in a bright future.

9. Acknowledgement

In April 2019 I was careless enough to accept a request to write the Commission J chapter for the URSI Centenary Book. At times it was hard going, mainly because archival material was hard to come by. I managed to write this chapter with invaluable help from URSI secretary Inge Heleu and the URSI Document Depository that she is still improving on the web. Knowing that she had nine other authors breathing down her neck, I have been blessed with useful and timely information. My thanks to her are deep. A few of the earlier chairmen of Commission J provided material and other information. I extend my thanks to past-chairmen Richard Schilizzi, Subra Ananthakrishnan, and Richard Wielebinski, and to Miller Goss, Harvey Liszt, and Leonid Gurvits. A lot of information I gathered from my own notes written during the Assemblies. That I still have those is thankfully due to my wife, Marja, who let me keep them despite our move to a smaller domicile.

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3. W. Christiansen, "The distribution of radio brightness on the solar disk", URSI Report 4,1954.

4. J. Oort, "Interstellar hydrogen", URSI Report 5, 1954.

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Appendix 1: Contribution by the IUCAF (Chair: Harvey Liszt)

IUCAF - The Scientific Committee for the Allocation of Frequencies for Radio Astronomy and Space Science (http://www.iucaf.org).

Discovery of ubiquitous Galactic emission from the 21-cm line of neutral atomic hydrogen in 1953 at a frequency of 1420.40575 MHz spurred the realization by URSI radio scientists that observations at certain key frequencies would need to be protected in the face of burgeoning commercial and military use of the radio spectrum. Facing the prospect of an impending rearrangement of the radio spectrum at the CCIR World Administrative Radio Conference in Geneva in 1959-1960, the Inter Union Committee for the Allocation of Frequencies (IUCAF) was formed from IAU, URSI and COSPAR to make the case for radio astronomy protection.

The history of IUCAF up to 1999 is discussed in the papers by Findlay [1, 2], and Robinson [3]. The passing of the first chairman of IUCAF, J-F Denisse (France), was noted at the opening ceremony of the 2017 URSI GA in Montreal.

IUCAF's activities at the WARC of 1959 and 1963 formed the basis of the modern spectrum management scheme that protects all passive radio science: observations of the Earth from space by the Earth exploration satellite service that contributes vitally to weather forecasting and climate studies, and observations of the cosmos by the radio astronomy service, and the space research service. Full recognition of purely passive use of the radio spectrum, receiving emission solely from the natural world and the wider Universe, required rewriting some of the most basic rules for radio spectrum use (the ITU-R Radio Regulations) and is still a work in progress. The most important innovation accruing from this effort was the creation of internationally-recognized purely passive spectrum bands in which all ITU-R regulated emissions are forbidden, enabling uncontaminated global mapping of terrestrial natural radiation from space. Many nations embody similar spectrum protections in their domestic rules but keeping the passive bands free of harmful RFI is a constant struggle.

Several of the special frequencies identified in the 1950's as needing spectrum protection were related to study of the hydroxyl radical OH that was discovered in interstellar space in 1963. Early generations of various nations' global positioning satellites harmfully interfered with radio astronomy observations of cosmic OH beginning in 1979, and IUCAF led a long struggle to eliminate this interference that was only brought to a successful conclusion in Geneva in 2007. Today, IUCAF is still fighting to keep some of the same OH bands free of interference from a mobile satellite system providing satellite phone services. Spectrum management for radio astronomy is a long game, requiring constant engagement.

With several vacancies, IUCAF is composed of 4 members from each of the adhering scientific Unions, with committee members from the US, France, Sweden, South Africa, Australia, Japan, and China. Its finances are managed by URSI and its annual reports appear in the URSI Radio Science Bulletin. Current activities mainly center around IUCAF's longstanding and highly-respected role as a Sector Member of the ITU-R, where it leads the international effort to maintain protection of the spectrum bands allocated to radio astronomy. Since 2000, IUCAF has held a series of international spectrum management schools in the US, Italy, Japan, and Chile, with the next planned for South Africa, in 2020.

As URSI celebrates its centenary, IUCAF has just turned 60. This is an especially fraught time for radio astronomy as long-unused spectrum allocations to radar, mobile applications (vehicles and 5G), and satellite broadband internet services are enabled by technological advances well into the mm-wave and sub-mm domains. Spectrum management is more important than ever to the continued success of radio astronomy, and URSI should be especially proud of its foresight, its foundational role, and its continuing support that have made it all possible.

"Be Kind to Radio Astronomy" (http://www.nrao.edu/~hlizt/RFI/).

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2. also in International Astronomical Union Colloquium No. **112**, pp. 194-197, 1991.

3. Brian Robinson, "Frequency Allocation: the First Forty Years", *Ann. Rev. Astron. Astrophys*. **37**, pp. 65–96, 1999.

Appendix 2: URSI Award Winners, Lecturers, and Chairs of Commission J

The highest award bestowed by URSI is the Balthasar van der Pol Gold Medal. It was awarded to: Martin Ryle, in 1963, for development of aperture synthesis, Paul Wild, in 1969, for the development of the Culgoora Radio Heliograph, and Jack Welch, in 2008, for contributions to millimeter-wavelength interferometry.

The John Howard Dellinger Gold Medal was awarded to: Anthony Hewish, in 1972, Imke de Pater in 1984, Govind Swarup in 1990, Alan Roger in 2008, and Dave Staelin in 2011.

At each GA there are three General Lectures selected by Council from suggestions by the ten Commissions. Commission J contributed to these with the following speakers (a few names could not be traced, not even in the URSI secretariat):

1984 - Very-Long Baseline Interferometry - R. Schilizzi
1987 - The Encounters with Comet Halley in March 1986 - ?
1990 - Revealing the Invisible Universe – Ron Ekers
1993 - Radio and Radar Exploration from Spacecraft: Highlights of Magellan at Venus, G. Pettengill
1996 - none from Commission J
1999 - Space-to-Ground Interferometry for Radio Astronomy - H. Hirabayashi
2002 - Microwave background Radiation - J. Carlstrom
2005 - Impacts of Extreme Solar Disturbances on the Earth’s Near-Space Environment - S. Basu
2008 - Pulsars, General Relativity and Gravitational Waves - J. Cordes
2011 - The Radio Physics of Meteors: High Resolution Radar Methods Offering New Insights - A. Pellinen-Wannberg
2014 - Square Kilometer Array - P. Diamond
2017 - Exploring Gravity - M. Kramer

Also each Commission presents one Tutorial Lecture on its subject during the GA.

1984 - Quasi-Optical Techniques at mm and sub-mm Wavelengths - P Goldsmith
1987 - Radio Astronomy - New Horizons - ?
1990 - Polarization - V. Radhakrishnan
1993 - Charm of Radio Astronomy and its protection - M. Morimoto
1996 - Cosmic Masers - a Useful Tool in Radio Astronomy - J. Moran
1999 - Radio Stars: The High Sensitivity Frontier - ?
2002 - Radio Astronomy on the Move Toward Microarcsecond Accuracy from Geodesy to Cosmology - L. Gurvits and A. Nothnagel
2005 - Low-Frequency Imaging - A. Pramesh Rao
2008 - Phased Arrays in Radio Astronomy - A. van Ardenne
2011 - Exploring the Epoch of Reionization with Low-Frequency Radio Telescopes - A. Parsons
2014 - Enabling Technologies for Modern Radio Astronomy - R. Ekers
2017 - The Atacama Large Millimeter Array (ALMA) - Lars-Åke Nyman

Chairs of Commission J:

1948-53	D. F. Martyn	Australia
1953-57	M. Laffineur	France
1957-62	A. C. B. Lovell	U.K.
1963-65	W N. Christiansen	Australia
1966-68	E. J. Blum	France
1969-72	C. A. Muller	Netherlands
1972-74	J. L. Locke	Canada
1975-77	G. Westerhout	USA
1978-80	H. Tanaka	Japan
1981-83	V. Radhakrishnan	India
1984-86	R. Wielebinski	Germany
1987-89	R. H. Frater	Australia
1990-92	R. Ekers	USA
1993-95	Y. N. Parijskij	Russia

1996-98	R. S. Booth	Sweden
1999-2002	Jacky N. Hewitt	USA
2003-05	M. Inoue	Japan
2005-08	R. T. Schilizzi	Netherlands
2008-11	S. Ananthakrishnan	India
2011-14	J. Jonas	South Africa
2014-17	W. Baan	Netherlands
2017-20	R. Bradley	USA

Appendix 3: Declaration of Principles Concerning Activities Following the Detection of Extraterrestrial Intelligence

We, the institutions and individuals participating in the search for extraterrestrial intelligence,

Recognizing that the search for extraterrestrial intelligence is an integral part of space exploration and is being undertaken for peaceful purposes, and for the common interest of all mankind,

Inspired by the profound significance for mankind of detecting evidence of extraterrestrial intelligence, even though the probability of detection may be low,

Recalling the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon, and Other Celestial Bodies, which commits States Parties to that Treaty "to inform the Secretary General of the United Nations as well as the public, and the international scientific community, to the greatest feasible and practicable, of the nature, conduct, locations, and results" of their space exploration activities (Article XI),

Recognizing that any initial detection may be incomplete or ambiguous and thus require careful examination as well as confirmation, and that it is essential to maintain the highest standards of scientific responsibility and credibility,

Agree to observe the following principles for disseminating information about the detection of extraterrestrial intelligence:

1. Any individual, public or private research institution, or governmental agency that believes it has detected a signal from or other evidence of extraterrestrial intelligence (the discoverer) should seek to verify that the most plausible explanation for the evidence is the existence of extraterrestrial intelligence rather than some other natural phenomenon or anthropogenic phenomenon before making any public announcement. If the evidence cannot be confirmed as indicating the existence of extraterrestrial intelligence, the discoverer may disseminate the information as appropriate to the discovery of any unknown phenomenon.

2. Prior to making a public announcement that evidence of extraterrestrial intelligence has been detected, the discoverer should promptly inform all other observers or research organizations that are parties to this declaration, so that those other parties may seek to confirm the discovery by independent observations at other sites and so that a network can be established to enable continuous monitoring of the signal or phenomenon. Parties to this declaration should not make any public announcement of this information until it is determined whether this information is or is not credible evidence of the existence of extraterrestrial intelligence. The discoverer should inform his/her or its relevant national authorities.

3. After concluding that the discovery appears to be credible evidence of extraterrestrial intelligence, and after informing other parties to this declaration, the discoverer should inform observers throughout the world through the Central Bureau for Astronomical Telegrams of the International Astronomical Union, and should inform the Secretary General of the United Nations in accordance with Article XI of the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon, and Other Celestial Bodies. Because of their demonstrated interest in and expertise concerning the question of the existence of extraterrestrial intelligence, the discoverer should simultaneously inform the following international institutions of the discovery and should provide them with all pertinent data, and recorded information concerning the evidence: the International Telecommunication Union, the Committee on Space Research of the International Council of Scientific Unions, the International Astronautical Federation, the International Academy of Astronautics, the International Institute of Space Law, Commission 51 of the International Astronomical Union, and Commission J of the International Radio Science Union.

4. A confirmed detection of extraterrestrial intelligence should be disseminated promptly, openly, and widely through scientific channels, and public media, observing the procedures in this declaration. The discoverer should have the privilege of making the first public announcement.

5. All data necessary for confirmation of detection should be made available to the international scientific community through publications, meetings, conferences, and other appropriate means.

6. The discovery should be confirmed and monitored, and any data bearing on the evidence of extraterrestrial intelligence should be recorded and stored permanently to the greatest extent feasible and practicable, in a form that will make it available for further analysis and interpretation. These recordings should be made available to the international institutions listed above and to members of the scientific community for further objective analysis and interpretation.

7. If the evidence of detection is in the form of electromagnetic signals, the parties to this declaration should seek international agreement to protect the appropriate frequencies by exercising the extraordinary procedures established within the World Administrative Radio Council of the International Telecommunication Union.

8. No response to a signal or other evidence of extraterrestrial intelligence should be sent until appropriate international consultations have taken place. The procedures for such consultations will be the subject of a separate agreement, declaration or arrangement.

9. The SETI Committee of the International Academy of Astronautics, in coordination with Commission 51 of the International Astronomical Union, will conduct a continuing review of procedures for the detection of extraterrestrial intelligence and the subsequent handling of the data. Should credible evidence of extraterrestrial intelligence be discovered, an international committee of scientists and other experts should be established to serve as a focal point for continuing analysis of all observational evidence collected in the aftermath of the discovery, and also to provide advice on the release of information to the public. This committee should be constituted from representatives of each of the international institutions listed above and such other members as the committee may deem necessary. To facilitate the convocation of such as committee at some unknown time in the future, the SETI Committee of the International Academy of Astronautics should initiate and maintain a current list of willing representatives from each of the international institutions listed above, as well as other individuals with relevant skills, and should make that list continuously available through the Secretariat of the International Academy of Astronautics. The International Academy of Astronautics will act as the Depository for this declaration and will annually provide a current list of parties to all the parties to this declaration.

Commission K and Bioelectromagnetics: Thirty Years of a New Discipline

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1. Introduction

Compared to the other URSI commissions, Commission K was formed recently. The idea of a bioelectromagnetics commission dates back to the 1970's with its official creation in 1991. This was a very active period for the discipline with the creation of the Bioelectromagnetics Society (BEMS) in 1978 and the creation of the European Bioelectromagnetics Association (EBEA) contemporaneously with that of URSI Commission K. BEMS and EBEA remain the most important learned societies in bioelectromagnetic science.

Of course, there were good reasons for the emergence of this discipline. This includes the rapid development of the relevant biology and the emergence of precise medical diagnostic tools using various types of non-ionizing electromagnetic radiation (and later on, of new therapeutic tools using electric and electromagnetic fields).

In addition, there were public safety concerns regarding human exposure to electromagnetic fields associated with the various fast-developing wireless communications systems, and also with low frequency fields from power distribution systems. One of the most important issues was the increasing use of the mobile phones using 1G, 2G, 3G, 4G and now 5G systems. When Commission K was created, only 1G mobile phones were available and smartphones were still to be developed. Thirty years later, more than two thirds of the inhabitants on Earth have their own smartphone and their use is still increasing, even in the most remote regions. The frequencies used, signal shapes, and power emitted from both the mobiles phones and base stations were studied in detail to address societal, health, and industrial issues. However, there are still open questions and the debate about the potential health risks continues.

Since its inception, Commission K was strongly linked to both the fundamental understanding of biological interactions and medical applications of electromagnetic fields. Consequently, Commission K is interdisciplinary, able to promote international research cooperation among biologists, physicists, engineers, and physicians.

Table 1. Chairs and Vice Chairs of Commission K.

1990–1991	Jorgen Bach Andersen (Denmark) (founder and interim chair)	Maria Stuchly (Canada) (founder and interim vice-chair)
1991-1993:	Maria Stuchly (Canada)	Paolo Bernardi (Italy)
1993-1996:	Paolo Bernardi (Italy)	James Lin (USA)
1996-1999:	James Lin (USA)	Shoogo Ueno (Japan)
1999-2002:	Shoogo Ueno (Japan)	Bernard Veyret (France)
2002-2005:	Bernard Veyret (France)	Frank Prato (Canada)
2005-2008:	Frank Prato (Canada)	Gugliemo D'Inzeo (Italy)
2008-2011:	Guglielmo D'Inzeo (Italy)	Masao Taki (Japan)
2011-2014:	Masao Taki (Japan)	Joe Wiart (France)
2014-2017:	Joe Wiart (France)	Samyoung Chung (Korea)
2017-2020:	Joe Wiart (France)	Koichi Ito (Japan)

2. Short Overview of URSI Commission K on Electromagnetics in Biology and Medicine

In the 1970's it became evident that it was necessary to study and understand the interactions of electromagnetic fields with biological systems. In URSI, this new field of investigations was first addressed by an Inter-Commission Working Group of Commissions A and B [1]. A working group on "Measurements Related to the Interaction of Electromagnetic Fields with Biological Systems," was established in 1975 and it organized an International Symposium on Biological Effects of Electromagnetic Waves, in Airlie House, Virginia, USA, in 1977. Following this Symposium, several other meetings were organized in collaboration with BEMS. It should be noted that the US National Committee of URSI Commissions A and B were co-sponsors of the BEMS first official meeting held jointly with the URSI National Radio Science Meeting.

In 1990, during the Prague General Assembly, the URSI Council decided to create Commission K. Saul Rosenthal, James C. Lin, Paolo Bernardi and Jorgen Bach Andersen took an important role in its creation. The terms of reference for the newly created Commission K included interactions between electromagnetic radiation and living systems over the entire electromagnetic frequency spectrum (namely, DC to optical frequencies), and applications in medicine. The URSI Council designated Jorgen Bach Andersen (Denmark) as Interim Chair of the new Commission, and Maria Stuchly (Canada) as Interim Vice Chair. In 1991, in Kyoto, Japan, Maria Stuchly and Paolo Bernardi were elected as the first Chair and Vice Chair of Commission K. Table 1 presents the Chairs and Vice Chairs of Commission K since its creation in 1991.

The initial terms of reference [1], not only included the study of interactions of electromagnetic radiation from DC to optical frequencies with living systems and applications in medicine, but, also the promotion of research and development in the domains of: (a) physical interactions of electromagnetic fields with biological systems; (b) biological effects of electromagnetic fields; (c) interaction mechanisms; (d) human exposure assessment; (e) experimental exposure systems; (f) medical applications.

From its start, due to its interdisciplinary character, Commission K actively participated and co-sponsored international conferences with other relevant organizations such as BEMS, EBEA, the IEEE Engineering in Medicine and Biology Society, the International Symposium on Electromagnetic Compatibility (EMC) and others.

3. Commission K and Wireless Communication

Over the past 30 years, the provision of personal mobile wireless communications systems has grown quickly to the point where there are now more than 6 billion cellular phone users globally. The emergence of 5G and of pervasive wireless communication systems, such as machine-to-machine communications, is further strengthening this tendency (Figure 1). Notably, despite the increasing use of wireless communications, public concern about possible health impacts from exposure to radio frequency (RF) electromagnetic fields (EMF) remains, even if no risk has been proven to date.

In this context the monitoring and management of EMF exposure has become a key issue. Based on scientific knowledge, international organizations such as the International Commission on Non-Ionizing Radio Protection (ICNIRP), and the

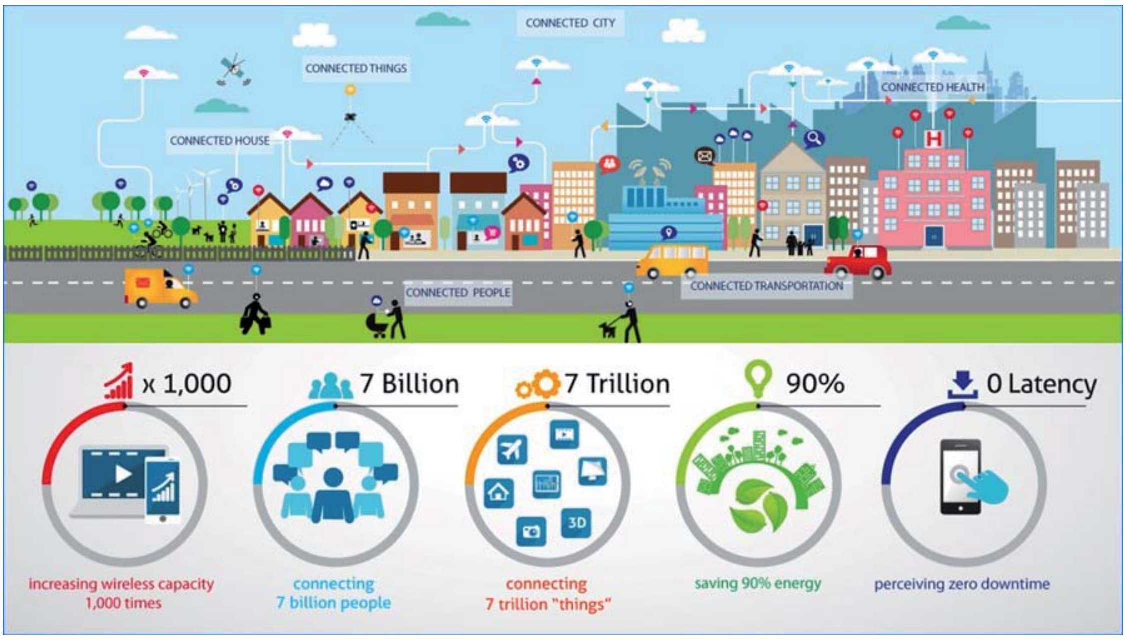

Figure 1. Massively connected infrastructure and society, made possible by a huge increase in wireless capacity (Source: EU commission, Brussels, Belgium).

Institute of Electrical and Electronics Engineers (IEEE), have established limits to protect the public and professional users against known and unknown biological effects linked to exposure from electromagnetic fields.

To protect humans from adverse biological effects of the electromagnetic fields, ICNIRP and the International Committee on Electromagnetic Safety (ICES) have recommended limits that are now almost harmonized. ICNIRP limits have two components: fundamental basic restrictions and derived reference levels [2, 3]. The basic restrictions are based on established health effects and, depending upon the frequency of the field, the physical quantities used to specify these restrictions are induced electric field (E_{ind}), specific energy absorption rate (SAR), absorbed power density (S_{ab}), specific energy absorption (SA), and absorbed energy density (U_{ab}). Reference levels are provided for practical exposure assessment purposes to determine whether the basic restrictions are likely to be exceeded; these derived quantities are electric field

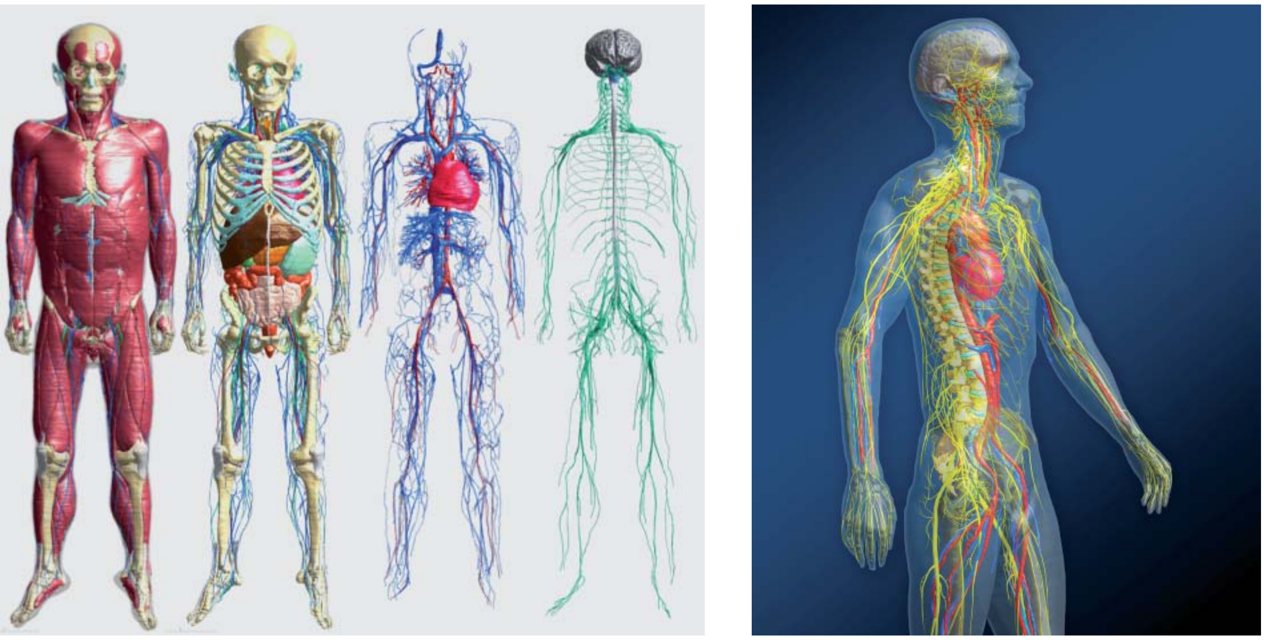

Figure 2. Anatomical human body models for dosimetric simulations, a) human models with different tissues and organs, b) functionalized human body model displaying nerve trajectories (Source: IT'IS Foundation, Zurich, Switzerland).

strength (E), magnetic field strength (H), magnetic flux density (B), and power density (S). Compliance with the reference level will ensure compliance with the relevant basic restriction. As stated in the ICNIRP guidelines within the RF domain, the exposure thermal effects can induce a rise of human body temperature, with possibly associated adverse biological effects. Basically, the exposure limits were determined (and thus recommended) in order to protect the human body from such thermal effects.

Commission K has organized specific sessions in GASS, AP RASC, and AT RASC dedicated to methods and protocols applicable to the assessment of SAR. Methodological issues are important in this regard. In 2010 Commission K co-organized, in conjunction with EBEA and COST BM0704, (Emerging EMF Technologies and Health Risk Management) a meeting on fundamental issues related to exposure limits, dosimetry, exposure assessment, risk perception and management, and epidemiology. In 2013 a workshop was co-organized by ICNIRP and Commission K. It is important to note that Commission K is part of the International Advisory Council (IAC) of the International EMF project of the World Health Organization (WHO).

To understand the potential interactions of the electromagnetic fields with living objects, modeling is important at all levels, including cells, tissues, and full bodies. High performance electromagnetic models of biological targets, in particular of human beings, were designed, and entire model families were developed to consider age-related and sex-related differences, including pregnancy [4-7].

Contemporary models are complex, and detailed, including different tissues types such as nerves. Each tissue is specified with its electromagnetic characteristics, to the limits of present knowledge. Human and also animal anatomical models have established themselves as crucial components for dosimetric assessment of non-ionizing radiation and, more recently, these highly sophisticated human body models were crucial in the development of novel therapies and medical devices. Figure 2a describes anatomical representations of the human body with detailed geometric descriptions of the distribution of different tissues in the body. In Figure 2b the human body model is functionalized, with nerve trajectories and neuron electrophysiology models to add extensive tracing of the peripheral nervous system to the model. Recently, sessions dedicated to dosimetry were convened at all of the URSI scientific symposia.

The wireless communication issues discussed in Commission K include epidemiology, and sophisticated tools, able to inform about the biological effects of mobile telephones and base stations, were developed. The epidemiological aspects of the exposure, and the biological consequences of that exposure, mean the biology and technology cannot be dissociated. Since its creation, Commission K has dedicated sessions and workshops to epidemiology in all the URSI scientific symposia. The management of big data offers new possibilities, making epidemiology a rich and complex discipline. New (maybe definitive) conclusions to 30 years-old controversies may be expected thanks to the feasibility of considering, as a whole, complex information from different electromagnetic signals, different exposure durations, different assessment methods, etc.

Epidemiology studies are particularly important with respect to the possible promotion, or acceleration of cancers. Despite the large number of review reports, of national and international studies (such as Interphone, Mobikids, Geronimo and Cosmo), and despite the classification of EMFs as carcinogens 2B by the International Agency of Research on Cancer (IARC) of the World Health Organisation (WHO), final conclusions are lacking. However, most experts consider that there is no health risk from mobile communications devices (phones, smartphones, base stations), including 5G, providing that the present exposure limits dictated by the ICNIRP are respected.

It is necessary to qualify this statement. For example, we do not know yet how the Internet of Things and other novel radio science developments will revolutionize human relations with the physical world. There are also open questions, such as the impact on the learning capabilities of young people exposed to smartphones and tablets from a young age, and the development of age-related mental deficiencies.

4. Bioelectromagnetics: a Multiscale Scenario Gathering Macroscopic and Microscopic Dosimetry to Mechanisms of Interaction

Our understanding of the interaction of electromagnetic fields with living organisms was hotly debated over the last five decades, with particular reference to so-called non-thermal or specific effects. The core of the dispute is whether the interaction of RF, including microwave fields, with biological tissues is limited to the energy transfer to the water polar solvent of the tissue (dielectric heating), or if some other molecular targets and/or mechanisms can be identified. Many studies have tried to suggest possible mechanisms and a critical review was reported in [8].

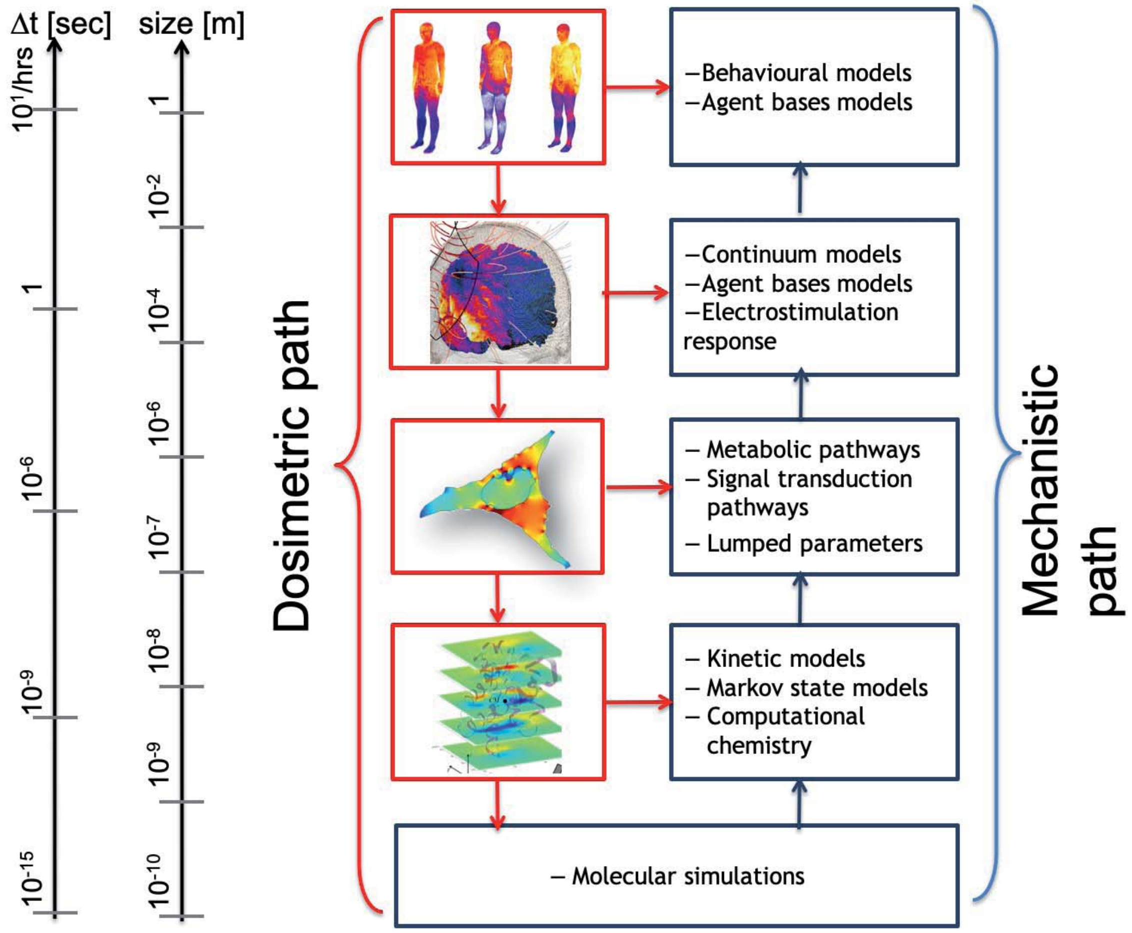

Figure 3. The multiscale approach that makes bioelectromagnetism a unique discipline. This is a representation of the schematic view of the ideas underlined in [8].

In general, one can say that to initiate or promote effects in biological systems, EM fields must give rise to a series of events that ultimately lead to some outcomes. This chain of events must originate with a field acting on molecules, altering their charge distribution, chemical state, or energy. Such a change, often named the first transduction step, can be sensed and amplified through the biological scale of complexity to produce responses that might have consequences for the organism. Therefore, bioelectromagnetics has to fulfill investigations able to study the complex organization typical of living systems. All biological systems may be considered as a stratification of different levels of biological organization, each with its own complexity, size, timing, structure, and function.

In order to describe quantitatively the behavior of a biological system, interaction models are needed. If one considers the scales from molecules to the whole organism, they range from nanometers to meters in length and from nanoseconds to years in time. To overcome the difficulty of developing models spanning spatial scales of 10^9 and time scales of 10^{17} a hierarchical set of models, valid in a limited range of scales and linked together through suitable parameters, were developed. This multiscale approach is typical of systems biology, but when applied to bioelectromagnetics it must be expanded to address dosimetric models and mechanistic models (Figure 3).

Regarding the dosimetry path, at the microscopic level we cannot consider average and uniform tissue and organ exposure, since the permittivity and conductivity of the individual biological (sub)structures must be considered. Microstructured materials and inhomogeneities due to cellular and subcellular structures have to be considered. Therefore, microdosimetric techniques are needed for calculating the real distribution of the field on cells, membranes, and organs. At the nanoscopic scale, the electric properties cannot be separated from the molecular components of the tissues.

Mechanism modeling explores the link between the EM dose and the biological effects and, incorporates several mathematical tools and simulation techniques because of the different time and space scales involved. One of the main challenges of the multiscale approach is the problem of efficiently coupling different models at adjacent spatial scales, that is, the issue of the bridging domains.

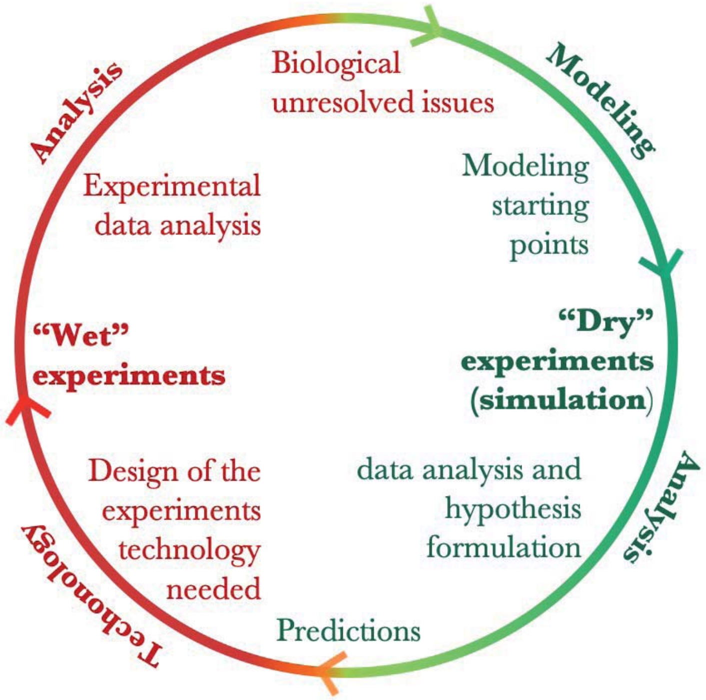

Figure 4. The virtuous bioelectromagnetic circle integrating experiments (wet) and modelling (dry), readapted from [9].

The whole framework can only progress through cooperation between experiment (wet) and simulation or modeling (dry), in a virtuous circle (Figure 4) and [9].

5. Commission K and Medical Applications

A wide variety of bioelectromagnetics medical applications were developed, or emerged within the 30 years existence of the Commission K, but the use of electric and electromagnetic fields for the treatment of diseases started as soon as we first started to understand electricity, at the beginning of the 18th century.

Reaching further back in time, humans were treated using natural electricity. Indeed, in 2400 BC (that is close to 5 millennia ago) the Egyptians used electric fishes (the Nile electric Catfish - *Malapterurus electricus*) to treat epilepsy. We know this from the paintings and hieroglyphs in the tomb of Mastaba of Ty at Saqqara (Egypt) which show an important individual of the 5th dynasty and depict the oldest known exposure of living cells to short and intense electric pulses, with the purpose of treating patients.

The legacy of Romans also includes the use of various electrical marine animals for several types of treatments. For example, Scribonius Largus wrote in 47 CE, that

> "For any type of gout a live black torpedo should, when the pain begins, be placed under the feet. The patient must stand on a moist shore washed by the sea and he should stay like this until his whole foot and leg up to the knee is numb. This takes away present pain and prevents pain from coming on if it has not already arisen. In this way Anteros, a freeman of Tiberius, was cured…".

Another example is provided by Claudius Galen (129–200 CE):

> "The whole torpedo, I mean the sea-torpedo, is said by some to cure headache and prolapsus ani when applied. I indeed tried both of these things and found neither to be true. Therefore, I thought that the torpedo should be applied alive to the person who has the headache, and that it could be that this remedy is anodyne and could free the patient from pain as do other remedies which numb the senses: this I found to be so."

Today, bio-inspiration is a recognized research approach, which in the field of the bioelectromagnetism, started more than 200 years ago, when Alessandro Volta invented the DC battery based on his work on electrical eels. This fish has stacks of specialized electrocytes (electro-plax) each heavily laden with ion transporters capable of providing an intermittent discharge of ~150mV at ~1 pA, resulting in a total power for the organ of ~600W (~600V and ~1A). Dissection of electric eels led Alessandro Volta to experiments with isolated galvanic cells of copper and zinc to form voltaic piles.

Bioelectromagnetics surged at the end of the 1980's with various experimental treatments. Unfortunately, some of the treatments, mainly deriving from the period between the two world wars, had no scientific basis and undermined the discipline. For example, antitumor electrotherapy, promoted by Dr Norderstrom from Sweden, resulted in more failures than successes. Electrotherapy of cancer was, however, successfully applied on tens of thousands of patients in China in the 1990s, in areas of the country where surgery, radiotherapy, and even chemotherapy were not available at that time. By inserting an adequate number of needles in a tumor and connecting them to a 9V battery, over a few hours, the chemical changes around the electrified needles, including changes in pH, the production of chlorine and radical species, are sufficient to kill the tumor cells.

Numerous waveforms and radio science considerations need to be considered in the development of such systems, e.g., sinusoidal or not, monopolar or bipolar, frequency (from DC to GHz), amplitude, burst waveform or single, repetition frequencies, etc. Commission K seeks to understand these issues, alert the health authorities to new developments, and help them set regulatory limits. Notably when the ratio of benefit to risk is high, it may be appropriate to exceed the safety limits.

Using ionizing radiation is well known both as a diagnostic tool and as a therapeutic agent. The therapeutic uses of ionizing radiation are, however, restricted to ablative approaches, as the main effect of ionizing radiation used in its therapeutic applications relies on the destruction of the cells by X rays, gamma rays, and beams of particles (hadron therapy), including beams of protons (proton therapy). It is envisaged that bioelectromagnetics will lead to the development of new, non-ionizing radiation approaches that are safer. Diverse applications can be envisaged based on the multitude of effects that the electric and magnetic fields can have on biological objects. The efficacy of these approaches will depend not only on the knowledge of field interaction with the cells and tissues, but also on a determination of the appropriate dosimetry.

6. Achievements of Commission K Members Recognized by URSI

Bioelectromagnetic applications in medicine are already extensive and this chapter is not intended as a comprehensive review. We have chosen to describe here the achievements of the members of Commission K who have received an URSI award.

6.1. The 2005 Issac Koga Gold Medal Award to Prof. Susan C. Hagness

> Citation: "For contributions to the development of enhanced finite-difference time-domain methods in computational electromagnetics, and ultrawideband microwave imaging techniques for early breast cancer detection."

Microwave imaging is based on the use of low-power microwaves to sense the dielectric properties of human tissues [10]. This technique was successfully applied to breast cancer detection at microwave frequencies, where there is a significant difference between the dielectric properties of normal and malignant tissues. This is a low-cost technique that does not pose health risks to the patient [10-11]. Microwave technology offers exceptionally high contrast with respect to physical or physiological factors of clinical interest in spite of a reduced spatial resolution compared to that provided by X-rays. The award recognized the work of Prof. Susan C. Hagness in developing enhanced finite-difference time-domain methods in computational electromagnetics leading to the development of imaging methods, for the microwave detection of breast tumors [10, 12, 13]. Such confocal microwave imaging starts from the assumption that tumors are strong scattering objects in a background environment that generates a relatively weak level of signal; therefore, the aim is to spatially focus the received scattered signals to locate the strong scatterers.

6.2. The 2017 Balthazar van der Pol Gold Medal to Pr. Dr. Lluis M. Mir

> Citation: "For leadership in Pulsed Electric Fields Applications in Biology and Medicine: fundamentals of cell electroporation in vitro and in vivo, and development of anti-tumor electro-chemotherapy, from inception to clinical use."

The first article with this term and concept was published in January 1991 [14] and the results of the first clinical trials of this new anti-tumor approach were published in December 1991 [15]. Lluis M. Mir and his group developed the concept of using cytotoxic drugs, which are unable to enter cells (termed non-permeant), in combination with short and

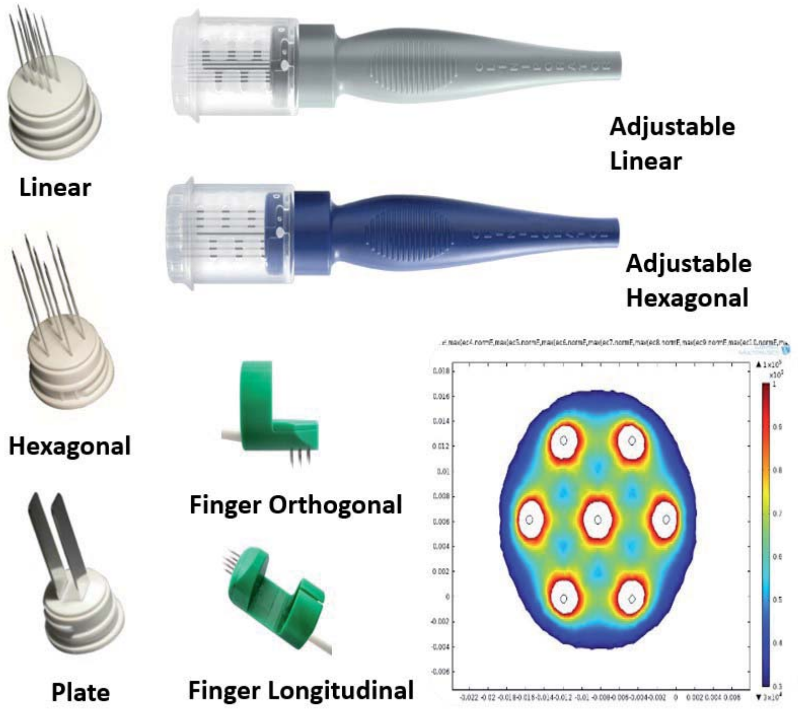

Figure 5. Various fixed geometry electrodes for electrochemotherapy (Courtesy of IGEA, Carpi (Mo), Italy).

intense electric pulses delivered to the tumor (8 DC pulses of 100 µs duration and 100 to 130 kV/m delivered at a repetition frequency between 1 and 5000 Hz).

The entire volume of the tumor has to be exposed to the electric pulses and this requires an understanding of how to place the electrodes. This is simple for superficial (cutaneous or subcutaneous) visible tumors as well as for internal tumors using treatment planning procedures developed thanks to phantoms. Interestingly, the need for a good coverage of the tumor also means that the cytotoxic drug is active in the treated volume only, and therefore, chemotherapy side-effects are minimal. Since the electric pulses applied provoke a reversible electroporation of the cells, cells are not killed by the electric pulses and the proliferating tumor cells are selectively killed by the cytotoxic drug, in particular in the case of bleomycin, the ideal drug to be used in electrochemotherapy. Electrochemotherapy is thus safe and it has already been applied to tens of thousands of patients, particularly in Europe, as palliative treatment but also with curative intents (and achievements). Many different electrodes were developed, for example with fixed geometries (Figure 5).

The standard operating procedures for this treatment were developed in 2006, and an updated version, that takes into account the experience accumulated on thousands of patients, was published recently [16]. Electrochemotherapy is efficient on all types of tumors, with response rates varying from 50 to 100%. Electrochemotherapy is also rapidly growing in veterinary medicine, where it is replacing surgery, in particular, because the treatment follow-up is much simpler than that of surgery (no suture points, no bleeding, no wound dressing even in the case of superficial tumors, e.g., Figure 6).

It is important to note that Lluis M. Mir also participated in the inception and development of other medical applications of cell electroporation. The first, already established in the clinics, ablates tumors with electric pulses alone, using pulses of the same duration but of higher intensity, and in higher number than those used for electrochemotherapy, which cause cell death by irreversible electroporation [17]. The second approach is a gene therapy approach that does not require the use of viruses, which is particularly interesting for vaccination purposes using stable nucleic acids instead of unstable proteins [18].

In all these applications, the safety limits for the electric pulses delivery to the patients are surpassed (the pulses applied have a significant biological impact on the cells of the target tissues). However, in all these cases, the benefit to risk benefit ratio is high, such that the safety limits can be violated because there is a clear benefit for the patient. The pain associated with the electric pulse delivery can be avoided by anaesthesia [16].

Figure 6. Results from a single treatment by electrochemotherapy of a hemorrhagic malignant melanoma metastasis in the skull of a patient. An immediate arrest of the bleeding was observed. The healing time was approximately ten weeks and no regrowth was observed (right panel). Needle marks in normal tissue show selectivity of the method (middle panel) (courtesy of Dr. J. Gehl).

6.3. The 2020 Balthazar van der Pol Gold Medal to Prof. Koichi Ito

Citation: "For contributions to research and development in the fields of medical applications of electromagnetic waves and their evaluation using human-equivalent phantoms."

There are a number of different approaches for cancer treatment, such as surgery, radiotherapy, chemotherapy, gene therapy, immunotherapy, ablative procedures, and hyperthermia. Practically, two or more different ways are sometimes combined for a better clinical outcome. Hyperthermia is considered to be a promising modality, gently employing the thermal effects of electromagnetic waves. It utilizes the difference of thermal sensitivity between a tumor and normal tissue. Generally, the target tumor is heated up to the therapeutic temperature, between 42 and 45°C, without overheating the surrounding normal tissues. Typical heating time is 0.5 to 1 hour for each treatment, which is repeated a few times at weekly intervals. When combined with hyperthermia, the efficacy of other cancer treatments such as radiotherapy and chemotherapy can be enhanced, and the dose can be reduced.

Microwave energy is one of the heating sources used for localized hyperthermia, and research and development of microwave hyperthermia was active in the 1980s and 1990s. Heating schemes can be divided into two types: external heating, and internal heating. For localized and deep-seated tumors, internal interstitial microwave heating seems to be an

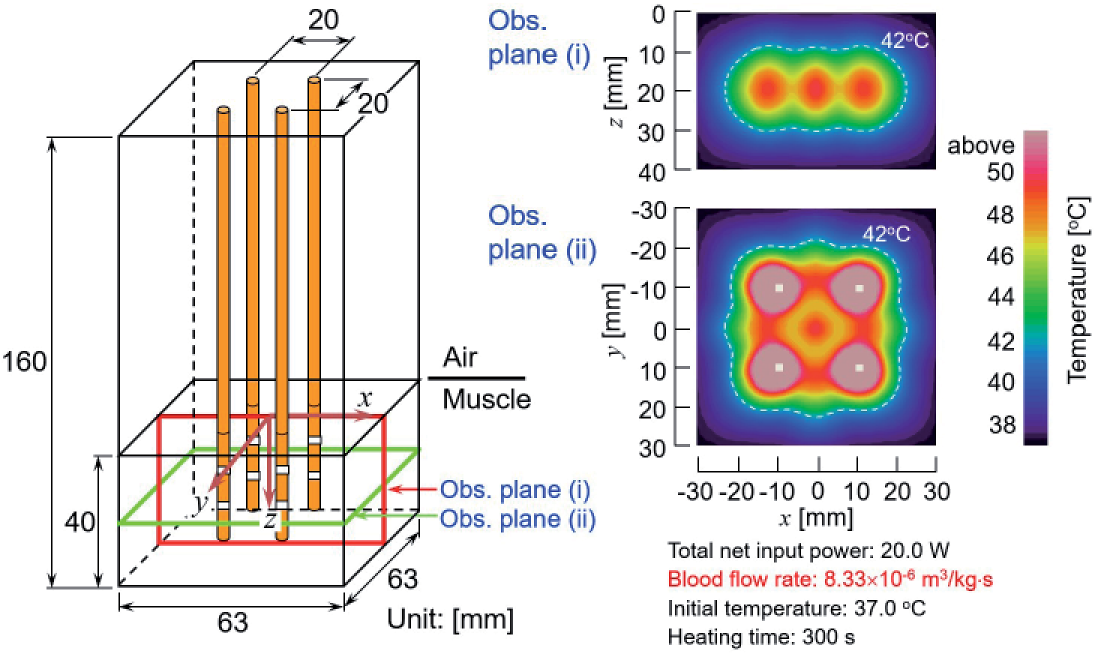

Figure 7. Structure and simulated temperature distributions of an interstitial array applicator (a case of 4 antennas).

appropriate method. With this technique, an array of thin microwave antennas is inserted into the tumor, which radiate microwave energy directly into the target [19], permitting effective and reliable heating of the tumor. Koichi Ito and his group developed so-called coaxial-slot antennas [20], which were used for clinical treatments in collaboration with doctors. Figure 7 shows the structure and simulated temperature distributions of an interstitial array applicator composed of four coaxial-slot antennas [21]. This particular applicator may treat a tumor of about 4 cm in size.

It is almost impossible to utilize real human bodies to experimentally evaluate the performances of implantable medical devices such as the coaxial-slot antennas mentioned above. Instead, computer simulations are usually performed with numerical phantoms as shown in Figure 7, and as discussed earlier in this chapter (Figure 3). However, experiments with human-body physical phantoms are indispensable to validate the results of numerical simulations, or to avoid animal experiments (see also Figure 4).

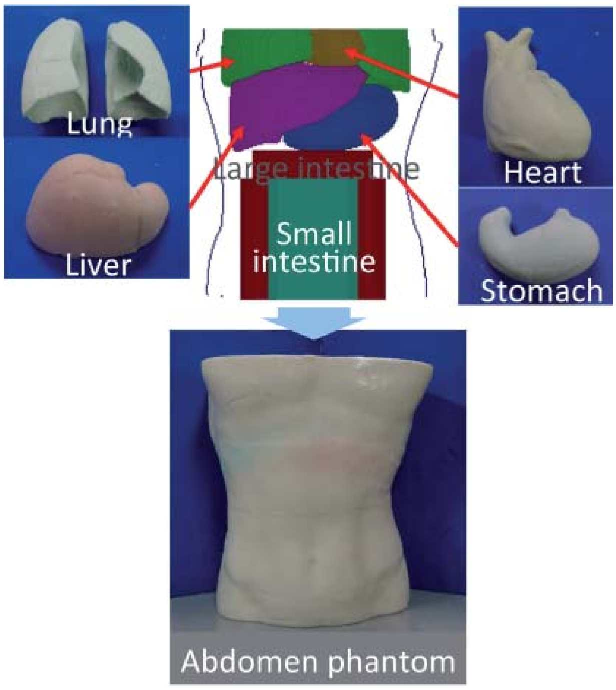

Figure 8. A fabricated abdomen semi-solid phantom, including different organ phantoms.

Human-equivalent physical phantoms should have nearly the same relative permittivity and conductivity as human tissues. Many different types of physical phantoms were developed and utilized for different purposes in experimental investigations. Typical physical human phantoms are liquid, gel, semi-solid, or solid. Koichi Ito and his group developed and provided various semi-solid phantoms, which proved to be suitable for experiments on implantable medical devices because it is easy to embed devices at the right position in those phantoms and to fix them without any support [22]. Figure 8 shows an example of a realistic abdomen phantom fabricated to evaluate the performance of a built-in antenna for a new type of wireless capsule endoscope. The phantom includes different organ phantoms, namely, muscle, lung, heart, liver, stomach, large intestine, and small intestine [21].

7. Conclusions

Commission K is the fruit of visionary people responding to a new societal challenge and the Commission has consequently become an essential element of URSI. Commission K relies on the interdisciplinarity nature of bioelectromagnetics, which is a strength and also a challenge because it requires radio scientists who are specialized and expert in several domains at the same time.

Commission K is connected to health and society, not only because of the medical applications of its radio science for medical diagnostics and therapeutics, but also because it seeks to provide the underpinning science that guides the regulations and limits on electromagnetic fields from a plethora of mobile and fixed wireless devices and power system distribution networks. URSI Commission K radio scientists seek to inform and reassure the general public worldwide, without obligation to those regulatory bodies.

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In 1919, shortly after the end of World War I, a small number of countries created the International Research Council and, with it, four scientific Unions, of which one was the Union Internationale de Radiotélégraphie Scientifique. The first General Assembly was held in 1922, and in 1928 the Union changed its name to the Union Radioscientifique Internationale (URSI) or the International Union of Radio Science. Since then URSI has grown from its original three members to over forty members and its areas of research have substantially evolved. This centennial publication presents an eclectic compendium of articles from twenty Member Committees and all ten Commissions, plus one overview historical article. Each article has a different emphasis, with some focused on individuals and others on particular topics. Together we hope they provide a valuable historical narrative and much interesting reading.

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