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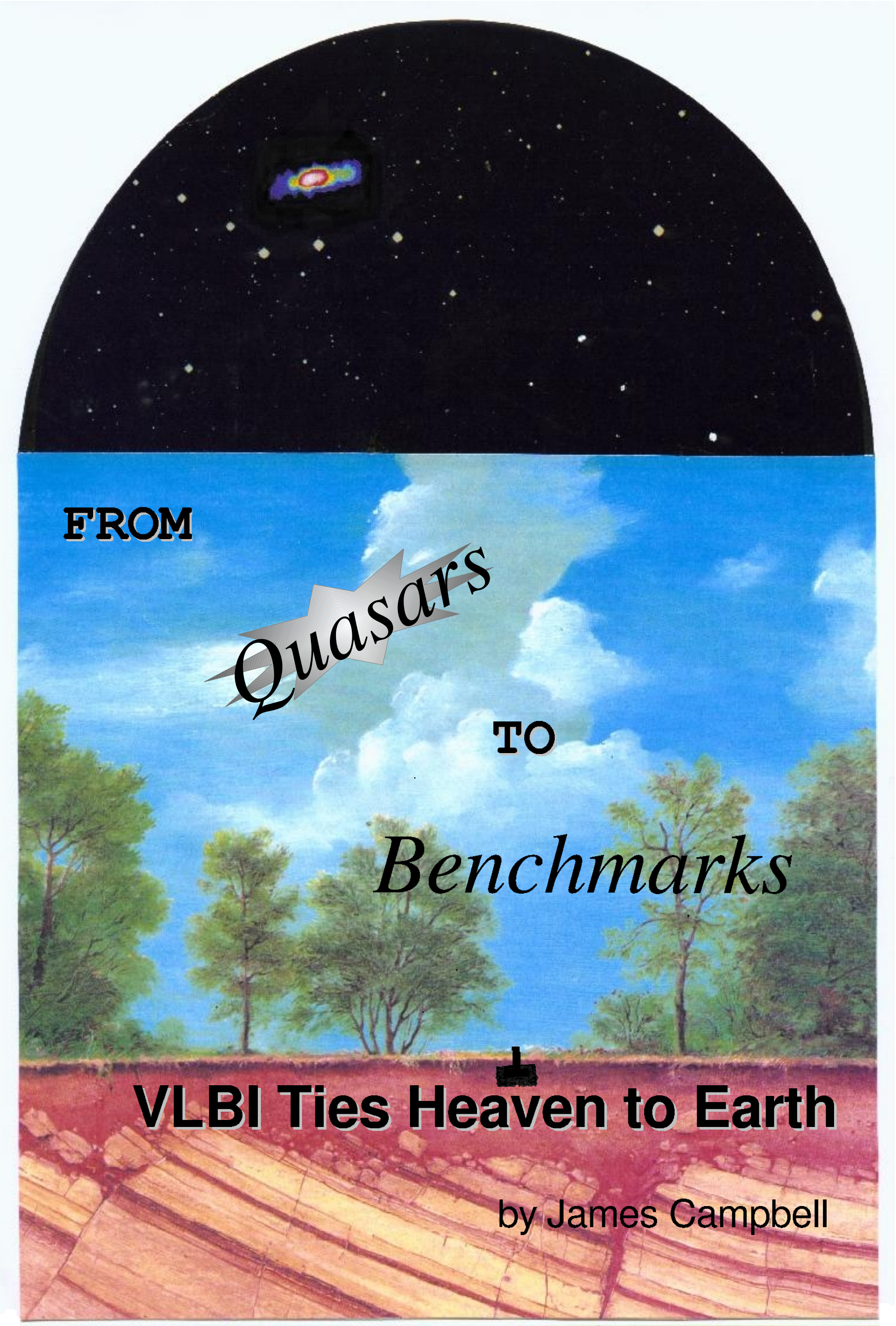

From Quasars to Benchmarks: VLBI Links Heaven and Earth

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Abstract

Very Long Baseline Interferometry is able to provide a direct geometrical tie to the extragalactic radio sources which represent the best possible realization of an inertial system. By this token, VLBI can measure Earth rotation and orientation as well as precise station positions and their velocities without involving the gravity field of the Earth. In the broader context of Earth observation and the monitoring of geodynamic processes, these and many more unique features have allowed the VLBI technique to achieve pioneering feats such as the determination of present-day plate tectonic motions, post glacial rebound, sub-daily Earth rotation variations and parameters of general relativity. In this contribution, some of the highlights of the history of VLBI will be passed in review and directions of future developments will be pointed out.

1. Introduction

At first glance it may seem rather bold to establish—as the title picture suggests—a direct link between two objects as disparate as the solid crust-fixed benchmark near our feet and the elusive quasi-stellar object at the ultimate confines of the universe. Yet, if we substitute the benchmark by a concrete foundation topped with a radio telescope and tune in to the wide bandwidth noise emanating from the tiny dots in the sky, radio astronomy is born and the way is opened for the concept of VLBI: adding in more telescopes and comparing the timed signals received at the different places on the Earth bestows us with an almost perfect tool for measuring angles and distances with extremely high precision on a global scale.

The geometric principle of VLBI is surprisingly simple and straightforward. It even precedes satellite geodesy, because the incoming radiation has plane wavefronts, thereby eliminating the parallactic angle and the distance to the emitter. The basic triangle for the determination of the baseline vector reduces to a rectangular one providing a direct relation between the baseline vector and the direction to the radio source, i.e. the scalar product representing the observed delay (Fig. 1 and Tab. 1). The interferometer being glued to the Earth's surface follows its diurnal rotation and in this way allows us to sample the radiation from all quasars coming into view.

If we leave abstract Euclidian geometry in empty space and return to the real world with curved space, flickering quasars, billowing atmospheres, wobbling axes and drifting continents, we have to delve into layers of complexity, fortunately not only as a chore but also as an opportunity to gain a wealth of new knowledge about our system Earth (Fig. 2).

Very Long Baseline Interferometry, initially named less ambitiously "Long Baseline Interferometry" is an outgrowth of radio interferometry with cable-connected elements designed to overcome the limited resolution power of single dish radio telescopes (Cohen et al. 1968).

In its simplest form, a radio interferometer consists of two antennas separated by a given distance and connected via the receivers, the down conversion systems and a phase stable electrical link to a phase (and amplitude) meter. To separate the actual radio signals from the unwanted

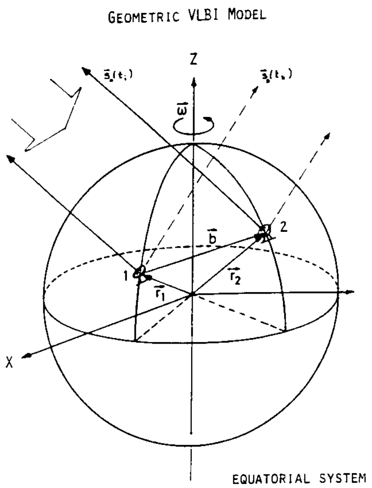


Fig. 1: Geometric VLBI model

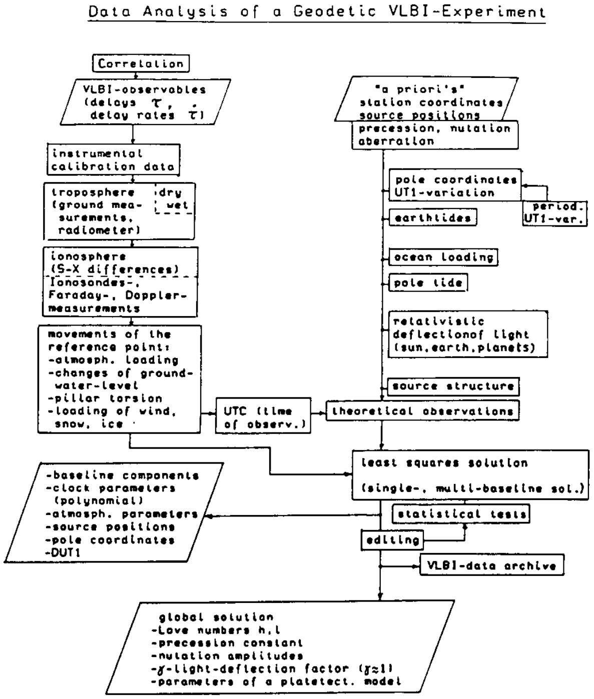


Fig. 3: Geodetic VLBI data analysis

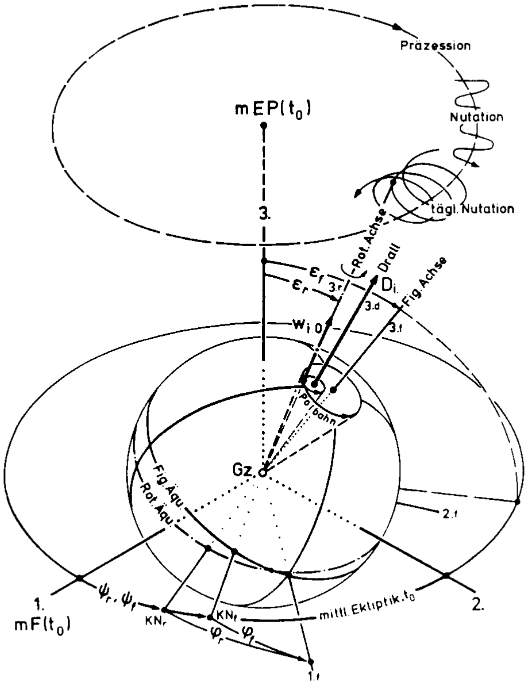


Fig. 2: Earth rotation in the space-fixed body-fixed systems (Heitz 1976)

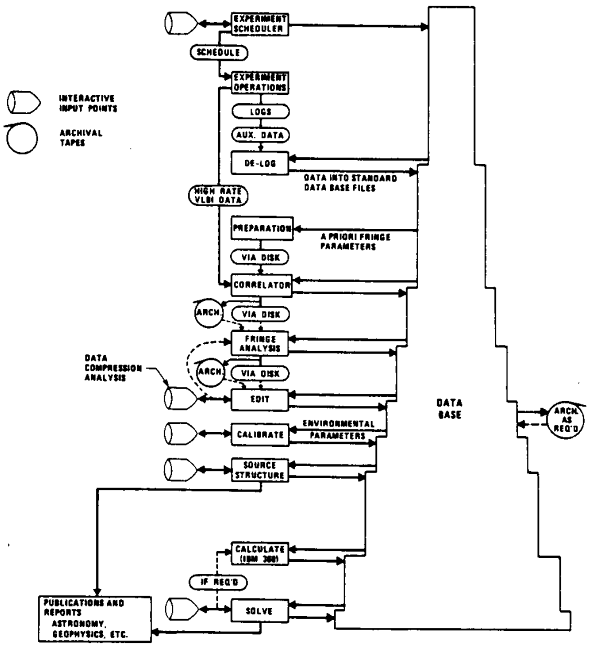


Fig. 4: The MkIII VLBI data analysis system

noise the correlation technique is normally used as the most efficient realisation of a phase meter. The response of such a system to the observed radio source carries information on its angular size and structure which are of prime interest to the astronomer.

To reveal the structure of extremely compact radio sources, the resolving power of Connected Element Radio Interferometers (CERI) was insufficient even at higher frequencies. A major breakthrough was made in the late sixties, when independent radio observatories in Canada and in the US were able to record their data on tapes using highly stable oscillators, and fringes were found during playback of the tapes at a correlator center, thus eliminating the need for a phase stable connection between the telescopes (Broten et al. 1967, Bare et al. 1967).

2. Phase or Group Delay in Geodetic VLBI?

The first experiments that were explicitly aimed at achieving geodetic accuracy on long baselines were conducted by the Haystack/MIT group on the 845-km baseline between the Haystack Observatory in the north of Massachusetts and the National Radio Astronomy Observatory of Green Bank, West Virginia (Hinteregger et al. 1972). The key to the high group delay resolution of ±1 nanosecond attained in these experiments was the invention of the so-called bandwidth synthesis technique (Rogers 1970), which helped to overcome the limitations of tape recording equipment in terms of recordable bandwidth.

Considering the successful use of the phase observable in GPS, one could wonder why it is so important to strive for high bandwidth. After all, the fringe phase is among the VLBI observables that are derived from the correlator output. One 2-MHz channel would be enough to detect and measure the phase of a source (observing strong sources with large dishes and cooled receivers). Two channels in two different bands would take care of the ionospheric phase delay, so one would just have to follow the GPS recipe and solve the ambiguities by forming double differences.

Obviously this is not the way taken in geodetic VLBI. One important reason is that sources in different parts of the sky cannot be observed simultaneously. Radio telescopes have to be steered and pointed at the sources one after the other to collect enough signal strength to permit their detection during correlation. During telescope slewing, several instrumental and environmental effects have ample time to destroy the phase coherence between scans.

This situation evidences an intrinsic division between VLBI and GPS: no double differencing means no elimination of timing errors between receiving stations. Therefore VLBI has to rely on "error-free" time keepers at the stations to bind the sequential observations of the radio sources together. The tempting idea to use omnidirectional antennas at the VLBI stations and forget about H-maser oscillators has to remain a dream because quasars are at least six orders of magnitude weaker than the signals emitted by the GPS satellites (MacDoran et al. 1982).

Thus several factors are joining to hamper and obstruct the use of the phase observable in geodetic VLBI (Herring 1992, Petrov 1999). In any case, the natural ultra-wide band continuum radiation is offered free of charge by the majority of the compact radio sources and provides the means to use the essentially unambiguous wide band group delay as the prime geodetic VLBI observable.

The group delay resolution is proportional to the inverse of the SNR and the spanned bandwidth (Rogers 1970), so, if we increase the spanned bandwidth at a given SNR by a factor of ten, the group delay uncertainty will be reduced by the same factor, a relation with tremendous consequences. There are virtually no limitations to further improve the geodetic group delay performance, except (evolving) technological constraints and costs. Phase delay, on the other hand, is still an issue of research and does provide very high accuracy on very short baselines (Herring 1992, Hase and Petrov 1999).

Before going into more details about the technical side of VLBI we have to take up the thread from the basic VLBI model to the fully grown analysis systems of the present day.

3. Models vs. Observations in Geodetic VLBI Data Analysis

The most commonly used way to extract significant and meaningful information from nature's ongoing processes is to try to model these processes by applying the laws of physics to the best of our knowledge. The less well known parts of our model will be equipped with a set of well seasoned unknown parameters. The least squares adjustment will then reveal the degree of correspondence we have achieved between theory and observation.

In VLBI, just like most other measuring techniques, the data analysis system has two main branches, one that takes in the raw observations and provides a number of instrumental and environmental corrections and the other that produces the "model observations" or "theoreticals" (Fig. 3).

The **fundamental geometric model** of the time delay forms the heart of the system. This model has evolved from its simple initial form in a geocentric system to the highly complex relativistic formulation in the solar system barycenter (Tab. 1). The complete formulation includes both the effects of **special relativity** (part of what is known as aberration in spherical astronomy) and of **general relativity**, which describes the curvature of space-time. The effect of gravity on the propagation of electromagnetic waves is considerable: even at an angle of 180° away from the sun the differential delay effect (for a 6000 km baseline) is still 0.4 ns. VLBI observations have been used to verify Einstein's theory (PPN formulation) to an accuracy of 0.1% (Counselman et al. 1974; Robertson and Carter 1984).

Table 1. Models for the geocentric (observed) time delay

Basic geocentric formulation		**Solar system barycentric formulation**
Cohen–Shaffer (1971) $\tau_0 = -\frac{\mathbf{b}\cdot\mathbf{k}}{c}$ **+ retarded baseline effect (or diurnal aberration at station 2)** **+ annual aberration**	**Thomas (1972)** $\tau_g = \tau_0 \left(1 - \frac{\dot{\mathbf{r}}_2\cdot\mathbf{k}}{c}\right)^{-1}$ $\dot{\mathbf{r}}_2 = \mathbf{\Omega}\times\mathbf{r}_2$ **+ annual aberration**	**Robertson (1975)** $\tau_g = \tau_0 \{1 - (\dot{\mathbf{R}}+\dot{\mathbf{r}}_2)\,\mathbf{k}/c$ $[(\dot{\mathbf{R}}\cdot\mathbf{k})^2 + 2\,(\dot{\mathbf{R}}\cdot\mathbf{k})\,(\dot{\mathbf{r}}_2\cdot\mathbf{k})]/c^2\}$ $+(\mathbf{b}\cdot\dot{\mathbf{R}})\,[(\dot{\mathbf{R}}\cdot\mathbf{k})/2 + (\dot{\mathbf{r}}_2\cdot\mathbf{k})]/c^3$ $-\tau_0(U + \dot{R}^2/2 + \dot{\mathbf{R}}\cdot\dot{\mathbf{r}}_2)/c^2$ $-(\mathbf{b}\cdot\dot{\mathbf{R}})/c^2$
	+ relativistic light deflection $\Delta\phi_{\mathrm{grav}} = 2r_{\mathrm{g}}^{\odot}/d$	**+ General relativity** $\tau_{\mathrm{grav}}^{\odot} = \frac{r_{\mathrm{g}}^{\odot}\mathbf{b}(\mathbf{k}+\mathbf{R}_0)}{Rc(1+\mathbf{k}\cdot\mathbf{R}_0)}$

In principle, the description of the Earth's orientation with respect to the celestial system (**precession, nutation**) and the motion of the Earth's axis with respect to the crust (**polar motion**) has to reach the same level of accuracy as all the other model components, which means roughly better than one milliarcsecond. The same holds for the rotational speed of the Earth about its axis: to compute the phase angle of the Earth's rotation at any epoch to better than 1 mas, the **UT1-variations** have to be known to better than 0.1 msec of time. Of course, our understanding of the origin of all these variations is still far behind these levels of accuracy and this is why at present we still have to regard all angles involved in the transformation between the terrestrial and the celestial systems as unknown parameters in our solution (Herring et al. 1986, Herring, this volume). It is due to the intrinsic strength of the geodetic VLBI observing strategy that we are still able to solve the system of observation equations, without ending up in singularity. Of course, if we stop the Earth, the instantaneous rotation axis vanishes and the system degenerates: we are left with three Eulerian angles between two non-aligned systems.

Already in the early seventies the periodic deformations of the Earth's crust could be seen in the VLBI observations: **solid Earth tides** cause diurnal and semidiurnal oscillations with vertical amplitudes of about 40 cm and horizontal displacements of up to 10% of the vertical effect. Although good models are available, the relevant parameters can be estimated from larger sets of data (Herring et al. 1983). More difficult to model are the **tidal loading** effects of the oceans, which amount to as much as a decimeter on some coastal or island sites (Scherneck 1991).

The fact that the VLBI stations are tied to the solid crust reveals itself alas as a rather deceptive assumption. Apart from the periodic convulsions of the Earth there are all sorts of aperiodic motions, the most prominent of which are the horizontal and vertical motions associated with **plate tectonics** (Minster and Jordan 1978). The obvious problem that arises for the definition of a terrestrial reference frame is akin to the problem of proper motions in the optical celestial reference frames: how do we fix the origin? Here we have to resort to the concept of a priori constraints, e.g. the "no net (to) rotation" (NNR), "no net translation" (NNT) constraints (Argus and Gordon 1996), but rigorously speaking there is no solution to this problem if we have different sets of defining stations in the global networks (Altamimi, this volume).

In global solutions with large data sets precise **source positions** can be determined simultaneously with the other parameters (Ma et al. 1993). The accuracy of the celestial reference frame may now be estimated to be around 0.3 milliarcsec on short as well as on longer time scales, although individual sources show greater variations (Feissel, this volume). The physical nature of quasars is still under debate, although models have been developed that are able to explain several of the observed features, such as the core-jet structure (Walker, this volume). For the geodesist the bitter fact remains that most of the observed compact sources are indeed showing **structure** at the level of several mas (Fey, this volume). This effect, in particular any changes in the structure, poses a limit on the accuracy of the radio reference system. However, permanent monitoring of the structure, which is accomplished in part by the same VLBI data, can be done in parallel to the geodetic analysis, thus providing a means to correct for the structure effects (Charlot and Fey 1999).

The systematic **instrumental effects** include clock instabilities, electronic delays in cables and circuitry and deformations of the telescope structure. Usually as a clock model a second order polynomial is introduced and occasionally a break has to be allowed for. Clock modelling is still very much an interactive procedure and belongs to the editing session. The instrumental delay changes are, or at least should be, monitored by the phase and delay calibration system, which is part of the MkIII system (Petrov, this issue). In the telescope the distance between the feed horn and the axis intersection should be constant; in this case it becomes part of the clock offset parameter. Large telescopes such as the Effelsberg 100-m antenna exhibit direction dependent changes that have to be measured by local geodetic surveying techniques (Nothnagel 1999).

The effect of the **atmosphere** on VLBI observations is considered to be the most serious problem, because at widely separated stations the elevations of the telescopes during a scan differ greatly as well as the meteorological conditions themselves (Mathur et al. 1970). But while the **ionosphere** can be readily eliminated to first order by using two different observing frequencies, the neutral atmosphere, essentially the troposphere, presents the same problems in VLBI as in GPS observations. Its influence on radio signals adds up to an extra zenith path of 1.8 to 2.5 meters. The contribution of the dry part is rather stable, although care has to be taken to choose a proper mapping function for the lower elevations (Davis et al. 1985, Niell, this volume). The **wet component**, although the smaller part of the total tropospheric effect, changes rapidly and has to be monitored by some external means. Still today the only promising—albeit costly—method appears to be the radiometer technique, which consists of measuring the microwave thermal emission from water vapour near 22 GHz in the line-of-sight (Elgered et al. 1982, Resch, this volume).

In VLBI data processing there are two levels of least squares solutions, one in which only the "local" unknowns are estimated (such as clocks, atmospheric parameters, and Earth rotation parameters) thus creating a first data base version of a particular experiment, and another one which collects all available experiments for a comprehensive solution including the "global" unknowns (such as station and source positions, etc.). Among the various VLBI software systems the MkIII Data Analysis System (Fig. 4) should be mentioned, which is built around the CALC/SOLVE software system developed jointly by the US East Coast VLBI groups including additional improvements made at Bonn and has become a standard against which the other systems can be compared (Ma et al. 1989). Of course, modelling does not end here: a holistic approach of the system "Earth" still remains a task for the future.

4. Geodetic Observing Programs and Milestone Results

A detailed description of the great potential of VLBI for geophysical applications was presented as early as 1969 at a conference held in London, Canada on "Earthquake displacement fields and the rotation of the Earth" (Shapiro and Knight 1970). In subsequent years virtually all of the goals mentioned there were to be achieved. We cite the original list from page 295 of the proceedings:

(1) Global Geodesy.

(2) Tidal Oscillations.

(3) Crustal-Block Motions (including continental drift).

(4) Polar Motion.

(5) Earth Rotation.

(6) Precession and Nutation (including a test of general relativity).

(7) Obliquity of Ecliptic.

(8) Shape of Sea Surface.

(9) Geopotential.

(10) Global Time and Frequency Synchronisation.

Referring to item (1), the text reads "...improvements in geodetic ties, especially over long baselines, by several orders of magnitude. For example, the relative positions of the stations of the world-wide net of Baker-Nunn satellite-tracking cameras have uncertainties of the order of 10-20m. Interferometry offers the possibility of reducing such uncertainties to a few centimeters."

In the meantime, uncertainties at the cm level and even less have been demonstrated by thousands of VLBI experiments in networks connecting almost all major continents of the globe. In order to realise the initial goals and many more, the efforts in different countries around the world have been combined in setting up several programs that include international cooperation. Here, we can name only two of the most important ones:

The NASA Crustal Dynamics Project (CDP, 1979–1993)

This project is part of a US Federal program involving several government agencies for the application of space technology to crustal dynamics and earthquake research (Coates 1985). Under its predecessor, the "Pacific Plate Motion Experiment" (PPME, 1976-1979) the first geodetic intercontinental baseline measurements with the MkI VLBI system were carried out in September 1977 and February and May 1978 on the baseline Haystack-Onsala (Ryan et al. 1986).

A milestone was reached when the first significant estimates of the length change on the transatlantic baseline Haystack-Onsala were announced. A baseline rate of 17 ± 2 mm/y derived from 31 experiments observed with the newly installed MkIII system beween Sept. 1980 and Aug. 1984 was published by Herring et al. in 1986 (Fig. 5). This value agrees extremely well with today's best estimates for that same baseline.

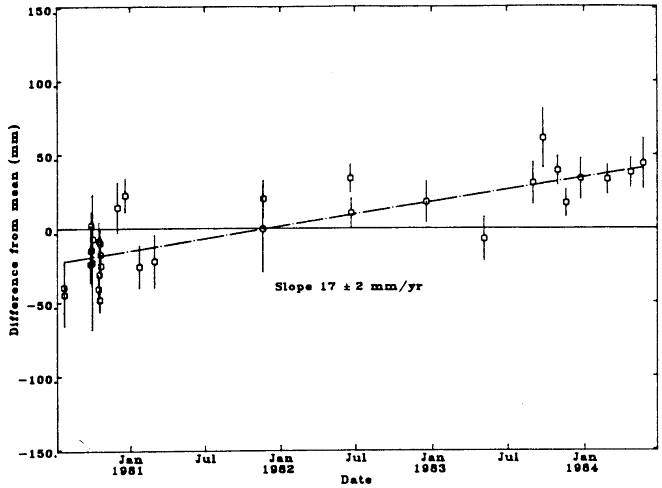


Figure 5. First estimate of intercontinental baseline rate Haystack - Onsala (Herring et al. 1986).

Cooperative arrangements had been made with several other countries extending the project to a truly international global research program. The VLBI part of the CDP comprised regular experiments (10–20 each year) of one to three days duration between all major geodetic VLBI facilities in the US, Europe, Asia, Australia, South Africa and South America. The annual reports of the CDP VLBI program constitute a detailed history of the successful application of the VLBI technique for the measurement of global tectonic motions (Ryan et al. 1993).

Project IRIS (International Radio Interferometric Surveying 1983-1990)

In contrast to the earlier VLBI programs which were based on the experiment-by-experiment philosophy (due to the limited correlator resources), the aim of the IRIS program was to increase the frequency of observing sessions to a level that permitted a quasi-continuous monitoring of the Earth rotation parameters. The monitoring concept was introduced at the IAG Symposium

No. 82 "Time and the Earth's Rotation" at San Fernando, Spain in 1978 under the acronym of POLARIS by the National Geodetic Survey, Rockville, MD (Carter et al. 1979). Observations began during the MERIT (Monitor Earth Rotation and Intercompare the Techniques) preliminary campaign (Wilkins and Mueller 1986) in the fall of 1980 with only one baseline (Westford-Ft.Davis) observing on a weekly basis. Later, the Swedish station of Onsala joined once per month to extend the POLARIS interferometer across the Atlantic. It soon became obvious that the long baselines across the Atlantic were essential to exploit the full accuracy of VLBI for Earth rotation monitoring, and at the end of 1983 the newly built geodetic radiotelescope at Wettzell in the southeast of Germany (Fig. 6) became an essential part of the IRIS network. Since 1984 this network has been routinely observing at a 5-day interval until 1990, when organisational and financial restructuring caused the Project to be taken over by the US Naval Observatory under the acronym of NEOS (National Earth Orientation Service). The IRIS Intensive campaigns, which were additional short daily measurements on the baseline Westford-Wettzell, were used to monitor the rapid UT1 variations between the 5-day epochs (Robertson et al. 1985).

Figure 6. Wettzell Geodetic Fundamental Station (1983, after completion of 20 m radio telescope).

In Wettzell, the construction of a dedicated geodetic radio telescope was part of the broader concept of a geodynamic "Fundamental Station" that would assemble the different space techniques such as Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), Optical, Doppler and GPS systems, as well as supplementary geophysical monitoring intrumentation at one site to be able to compare and combine the data gathered as well as the results obtained from the different networks (Schneider et al. 1982). In recent years, the idea has been extended to build a transportable duplicate of the Fundamental Station, the TIGO (Transportable Integrated Geodetic Observatory) and operate the system at a site in the southern hemisphere, in order to improve the global coverage (Hase, Petrov 1999). Unfortunately, there are even today only very few stations in the world that have reached the status of a true Fundamental Station.

In the past decades, Wettzell has become a pivotal point for several global and regional networks and has provided some of the longest and most densely spaced time series of interstation distances and Earth orientation parameters. It is interesting to compare the Wettzell-Westford baseline length evolution from one of the most recent global solutions (L. Petrov, personal communication) (Fig. 7) with the earliest determinations of the transatlantic baseline rates (Fig. 5). The extraordinary smoothness and linearity of the length evolution postulates an absolutely uniform crustal motion, and by the same token a perfectly uniform spreading process at the oceanic ridges. In their extensive analysis of the global baseline changes and site motions observed by VLBI, Argus and Gordon (1996) find no really significant departures from **continuous** motion, except of course the coseismic displacements in very locally defined areas (Clark et al. 1990).

Another example of the potential of VLBI on longer time scales is the observed time series of the nutation angles appearing as corrections to the IAU 1980 reference model (Herring, this volume). After some twenty years of intensive theoretical work by many groups in different parts of the world, the resulting new and thoroughly improved model will soon be published. It is quite certain that the continued time series of VLBI observations at well defined stations will contribute by their integrity to the solution of many more of the very intriguing and challenging questions in geodynamic research.

At the other extreme, VLBI observations have also lent themselves to investigate very short period, even down to sub-diurnal phenomena, such as the ocean tide induced variations in Earth rotation (Brosche et al. 1992, Clark et al. 1998). In this respect, the ultimate goal is of course a truly continuous observation program which will optimise the resolution power at the short periods down to a few hours. To achieve this goal, the CORE project has been devised at NASA/GSFC to combine the strengths of different station configurations on the globe and cover the seven days of a week without placing too much observational burden on any single one of the VLBI stations (Clark et al. 1998). This project has begun in an initial phase with on the average only two days per week and will be stepped up with the full deployment of the capabilities of the new MkIV VLBI system.

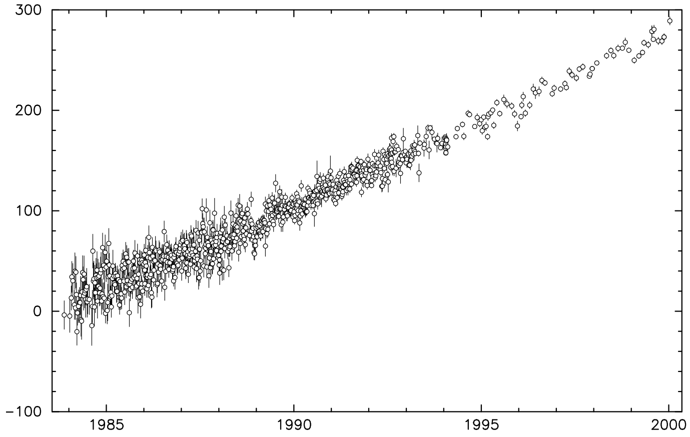


Figure 7. Wettzell-Westford baseline length evolution from recent solution (scale in mm)(Petrov, pers. comm.). The slope is 18.3 ± 0.1 mm/y with a WRMS of 8.5 mm.

There is just not enough space in this publication to present the many other projects in different parts of the world, such as China with two shared VLBI facilities for astronomy and geodesy (Tongshan et al. 1987); Japan with the Key Stone Project (Koyama et al. 1998) and several other domestic and international VLBI activities; Canada continuing its long tradition of VLBI both for astronomy and geodesy (Cannon et al. 1979, Klatt et al., this issue); Australia with an early involvement in geodetic VLBI (Harvey et al. 1983) and the long performance record of the stations of Tidbinbilla and Hobart; South Africa with the uniquely important station of Hartebeesthoek (Carter et al. 1980), and many more. Most of the presently active observing stations, analysis groups and technical development centers are listed and described in the first Annual Report (Vandenberg 1999) of the newly created:

IVS (International VLBI Service for Geodesy and Astrometry)

A strong incentive to introduce a more formal organisation that would provide the means for a better coordination of the activities in the global geodetic VLBI community towards a common goal and a more production-oriented approach, was given by the example of the GPS community in their International GPS Service for Geodynamics (IGS). The IVS was set up during 1998 and began its operations on the 1st of March 1999 (Campbell and Vandenberg 1999). The present first General Meeting at Kötzting gives proof of the successful start of a new, more internationally oriented phase of VLBI with even closer cooperation between its members (Schlüter, this volume).

5. From Bits to Gigabits/s: Progress in the Technical Realization of VLBI

The technical realization of VLBI is a perfect example of the concurrence of ingenious inventions and developments from many widely different sectors of electrical engineering, radar technology and communications technology, to name only a few. As mentioned earlier, the requirement for wide bandwidth and high sensitivity meant that there would be no way around the need to transfer extremely high data rates between the telescopes and the correlator center. Technically this is perhaps the most challenging part in the story of VLBI, i.e. to find cost-effective ways to perform this transfer. In consequence, the early phase of the technical development of VLBI is characterized by intensive experimentation with different ways to record the data on tapes.

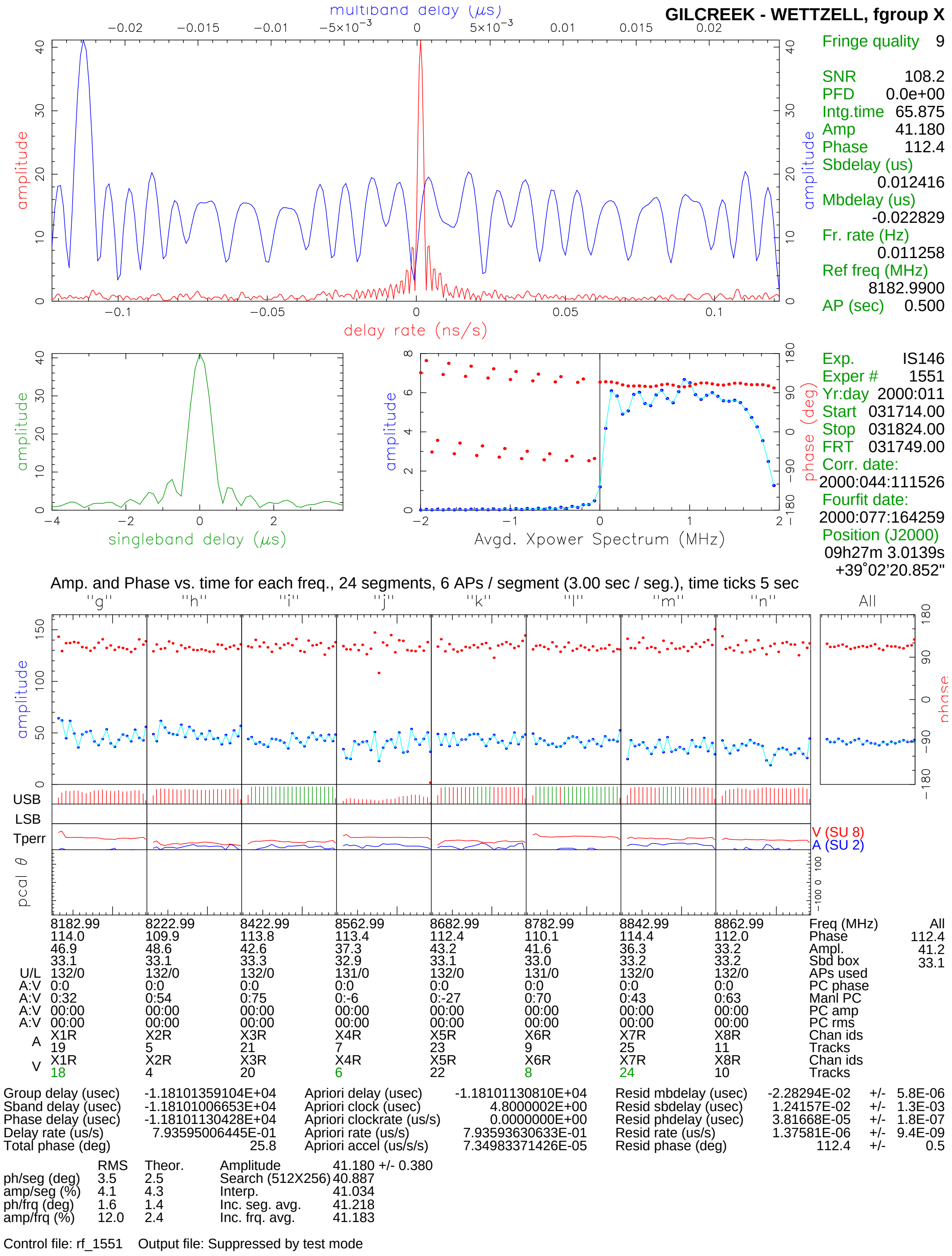
The MkI system used standard computer tapes of 360 kHz bandwidth. The paper about the first VLBI experiment to prove general relativity (Sept–Oct. 1972 on the baseline Haystack-Green Bank) gives a vivid impression about the giant effort involved: for about 120 hours of observation $\sim$5000 tapes had to be correlated (Counselman et al. 1974).

The MkII system was developed at the National Radio Astronomy Observatory (NRAO) on the basis of TV tape recorders with 2 MHz bandwidth (Clark 1973). The initial Ampex studio recorders were soon replaced by commercial cassette recorders opening the way for relatively cheap recordings. The wide spanned bandwidth was implemented in MkII just as in MkI by sequential switching of the IF to the different frequency channels in the band (Thomas 1972).

A turning point for geodetic VLBI was reached by the decision of NASA to support the development at Haystack of the multi-channel MkIII system that was designed to record 28 parallel tracks of 2 MHz bandwidth each, i.e. a maximum bit rate of 112 Mb/s. The geodetic setup included the dual S/X-band receiving with 14 channels recorded in one direction (forward pass), 6 channels for the S-band and 8 for the X-band. In this mode, a 1-inch wide instrumentation tape could carry about one to two hours of data in forward and reverse. If we add the successful upgrade of the hydrogen maser frequency standards to a level of 1 part in 10^{14} over many hours of operation, the preconditions for a quantum leap in geodetic accuracy were fulfilled (Clark et al. 1986). The first years of MkIII observations have given ample proof of the great success of the MkIII concept in geodetic VLBI.

However, also outside the US the momentum for technical developments in the field of VLBI was taken up, in particular of course in Canada, where the initial work (Broten et al. 1967) was pursued to debouch into the cassette-based S2 system (Cannon et al. 1997, Cannon, Petrachenko, this volume) and in Japan, where in the early 80s the MkIII-compatible K3 system was developed at the Radio Research Laboratories (Kunimori et al. 1993). As a follow-up system, a totally new concept based on cassettes was implemented with the K4 system which is being used now in the Key Stone project (Koyama et al. 1998). The 4-station network in the Tokyo area has been designed to run in a fully automated fashion, including a quasi-real-time transfer of the wide-band RF-signals. This development clearly paves the way for future e-VLBI systems that would make tape recordings obsolete.

Already in the early days of VLBI, hopes were high to be able to replace the cumbersome tape based systems by satellite-linked systems. A test experiment by Canadian and US groups on the communications satellite ANIK-B (Yen et al. 1977) proved the concept, while at the European Space Agency a project study on satellite linked VLBI went into great detail (ESA 1979), but was finally abandoned after being faced with the fact that the running costs at the required wide bandwidths would be prohibitive. At a recent meeting on the possibilities of e-VLBI (real time



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Mbdelay (us)
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Fr. rate (Hz)
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Ref freq (MHz)
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AP (sec)     0.500

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     114.0    109.9    113.8    113.4    112.4    110.1    114.4    112.0    Phase      112.4
     46.9     48.6     42.6     37.3     43.2     41.6     36.3     33.2     Ampl.       41.2
     33.1     33.1     33.3     32.9     33.1     33.0     33.2     33.2     Sbd box     33.1
U/L  132/0    132/0    132/0    131/0    132/0    131/0    132/0    132/0    APs used
A:V  0:0      0:0      0:0      0:0      0:0      0:0      0:0      0:0      PC phase
A:V  0:32     0:54     0:75     0:-6     0:-27    0:70     0:43     0:63     Manl PC
A:V  00:00    00:00    00:00    00:00    00:00    00:00    00:00    00:00    PC amp
A:V  00:00    00:00    00:00    00:00    00:00    00:00    00:00    00:00    PC rms
A    X1R      X2R      X3R      X4R      X5R      X6R      X7R      X8R      Chan ids
     19       5        21       7        23       9        25       11       Tracks
V    X1R      X2R      X3R      X4R      X5R      X6R      X7R      X8R      Chan ids
     18       4        20       6        22       8        24       10       Tracks

Group delay (usec)  -1.18101359104E+04  Apriori delay (usec)      -1.18101130810E+04  Resid mbdelay (usec)  -2.28294E-02  +/-  5.8E-06
Sband delay (usec)  -1.18101006653E+04  Apriori clock (usec)           4.8000002E+00  Resid sbdelay (usec)   1.24157E-02  +/-  1.3E-03
Phase delay (usec)  -1.18101130428E+04  Apriori clockrate (us/s)       0.0000000E+00  Resid phdelay (usec)   3.81668E-05  +/-  1.8E-07
Delay rate (us/s)     7.93595006445E-01  Apriori rate (us/s)        7.93593630633E-01  Resid rate (us/s)      1.37581E-06  +/-  9.4E-09
Total phase (deg)                 25.8  Apriori accel (us/s/s)     7.34983371426E-05  Resid phase (deg)            112.4  +/-      0.5

               RMS   Theor.   Amplitude          41.180 +/- 0.380
ph/seg (deg)   3.5   2.5      Search (512X256)  40.887
amp/seg (%)    4.1   4.3      Interp.           41.034
ph/frq (deg)   1.6   1.4      Inc. seg. avg.    41.218
amp/frq (%)    12.0  2.4      Inc. frq. avg.    41.183

Control file: rf_1551    Output file: Suppressed by test mode
```

Figure 8. Mark IV fringe plot

VLBI forum at Haystack, Ray 1999) the feeling was that although it would be important to prepare the new systems for the day when e-VLBI would become feasible, the tape based systems would have to stay in place for a number of years to come.

In this situation, the development of the MkIV system as a natural follow-up of the MkIII and MkIIIA systems is a consistent and consequent step to maintain as well as improve the operational capabilities of VLBI (Whitney, this volume). It seems appropriate to conclude this overview with a closer look at one of the most recent fringe plots obtained at the new Bonn version of the MkIV correlator (Alef, this volume) to illustrate the state of development (Fig. 8). A beautiful coloured version now replaces the ~25-year old alphanumeric fringe plot (Whitney 1976), that has served generations to find fringes and sort out problems. The 8-channel 700 MHz multiband delay function shown in blue in the upper plot has a main peak halfwidth of 1.4 ns, which at an SNR of 108.2 (4C39.25 is a strong source) leads to a group delay resolution of 5.8 ps (first of the bottom lines) or 1.5 millimeter.

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