Listening to the Cradle of Radio: Long Wave Radio Then and Now

Guglielmo Marconi got across the Atlantic in December 1901 on a frequency of about 800 kHz. Then he figured the longer the wavelength, the longer the distance. Soon, spark as a source of radio frequency was replaced by the arc, then by the Alexanderson alternator, then by vacuum tubes. Frequencies got lower and distances longer. Soon radio amateurs discovered that higher frequencies could go further distances with lower power and smaller antennas. Very low frequencies are still, however, best suited for some tasks in the ether. This article discusses many of them, then and now.

I. Radio Came of Age More Than a Century Ago—Growing Up in the Part of the Spectrum We Call the Long Waves—and We Can Still Listen

Guglielmo Marconi ("Bill" to his friends) got across the Atlantic in December 1901 on a frequency of about 800 kHz, or a wavelength of about 400 meters. Then he figured the longer the wavelength, the longer the distance. The idea was that longer waves would sort of walk along the curvature of the earth. Most everyone agreed: e.g., Reginald Fessenden and Karl Braun. So stations went to longer and longer wavelengths at lower and lower frequencies, as low as around 13 kHz, for commercial and naval long-distance circuits. All of these required expensive, high power installations, involving lots of wire for extensive antennas.

Noted radio authority Jack Belrose summarized: "Using 420-foot umbrella top-loaded antennas … tuned to about 88 kHz, [Fessenden] successfully communicated two-ways across the Atlantic in January 1906, between Brant Rock, MA and Machrihanish, Scotland. Marconi in the meantime had not succeeded in transmitting a complete message, even one way across the Atlantic. Marconi was however building bigger antenna systems, and hence moving down in frequency. By 1904, his English antenna had become a pyramidal monopole with umbrella wire, and the frequency was 70 kHz. In 1905 his Canadian antenna, installed at Glace Bay, NS, was a capacitive top-loaded structure, with 200 horizontal radial wires each 1,000 feet long, at a height of 180 feet, and the frequency was 82 kHz."[1]

The higher frequencies, and the shorter wavelengths that are today associated with radio, came into play in the mid-1920s. Long wave radio then died—but it didn't really. The Cradle of Radio is rockin' today.

Radio in today's long wave bands presents, every night, historical resonances, ranging from Marconi to unlicensed amateurs. This episodic history of long wave radio, and its current uses, may provide some insight into these frequencies and these legacy bands. These bands are accessible on modern equipment with simple antennas. And now, despite the ancient (1912) law of only "200 meters and down" for amateur radio operators, they are now once again welcome on the long waves on two licensed bands.

From a historical point of view, one of the most interesting, albeit irregular, signals on long wave is station SAQ in Sweden on 17.2 kHz. It still fires up its 1923 Alexanderson alternator to transmit a few times a year. The VLF Special Interest Group of the California Historical Radio Society continues to pursue this signal as the Holy Grail of long wave radio. (Despite it being very far away!)

In the VLF group, John Staples, Ph.D., W6BM, has focused on WWVB on 60 kHz as a beacon for experimentation, and research into small loop antennas, including the mathematics of loops and resonance. John initially used a Collins R-389 long wave receiver of WWII vintage, and SpectrumLab software to process (and see) the audio output. An image of his equipment appears in Fig. 1.

John Stuart, P.E., KM6QX, implemented a soundcard, SpectrumLab software, and a PC receiver, making

Fig. 1. The VLF receiving post of John Staples on Mt. Shinn, near Lodi, California in 2012, with his Collins R-389 VLF receiver. (John Staples)

a bicycle-wheel diameter and quite an effective loop on a stand. A diagram of his equipment appears in Fig. 2.

Dennis Monticelli, AE6C, provided engineering assistance throughout. Scott Robinson put together one of the VLF group's first working loop antennas. Paul Shinn, K6FRC hosted the 2012 Dxpedition to Mt. Shinn for the group's first try at logging SAQ. Paul had earlier received and verified SAQ. Gilles Vrignaud discovered long wave radio from Europe on the internet by way of remote receivers, for some very interesting broadcast programming and other signals.

My station K6VK used the WinRadio® G33 Software Defined Radio (SDR), and at first a Hustler® 6BTV 33 foot vertical over an extensive ground system, then several iterations of a very large loop, two turns of shielded coax about 50 square meters in capture area, then two 40+ foot tall vertical wire antennas with an impedance-improver circuit from John Staples. The WinRadio SDR provides extensive visualizations of received signals and spectra, by which K6VK first detected the cryptic Russian Alpha radio-navigation stations on 11+, 12+, and 14+ kHz.

Thus, in several ways, long wave signals can be heard *and seen* with today's radios and computers and simple loop or wire antennas—even the Russian "Alpha" stations. See Fig. 3 and Fig. 4.

These long wave signals communicate with submarines and other naval vessels; they aid air and sea navigation; they supplement GPS, and they alert vessels to weather and maritime dangers. A few European long wave broadcasting stations also still vibrate the "ether," although they are almost impossible to hear in California. Radio in today's long wave bands resonates still with historical uses. The long waves (from around 10 kHz to 530 kHz) continue to convey signals from around the world and of local interest. The usual ionospheric variation of propagation of the shorter waves matters little.

A 10 kHz signal has a very long wavelength indeed, some 30,000 meters, or

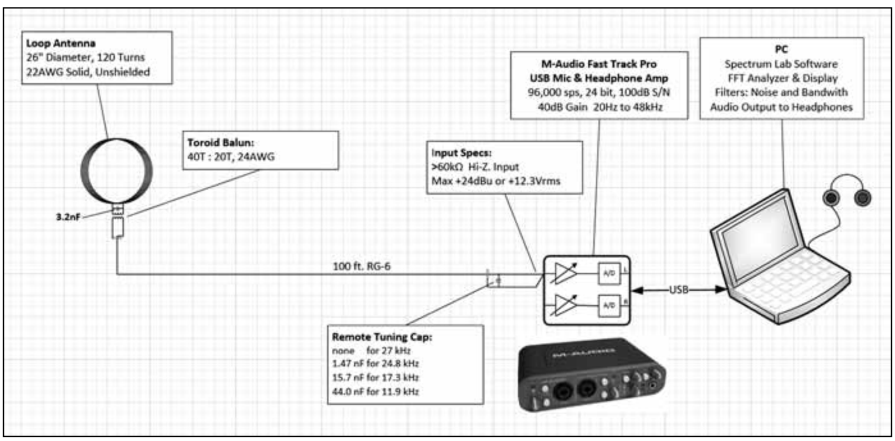

Fig. 2. John Stuart's VLF receiving system, PC-centered. (John Stuart)

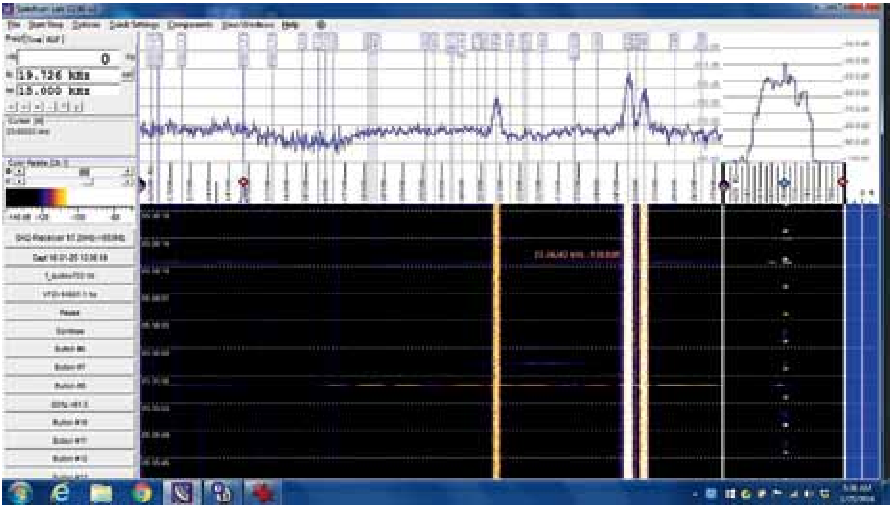

Fig. 3. John Stuart's reception of several VLF stations including a Russian Alpha "RSDN" at 14.881 kHz, its audio on the right using SpectrumLab software. (John Stuart)

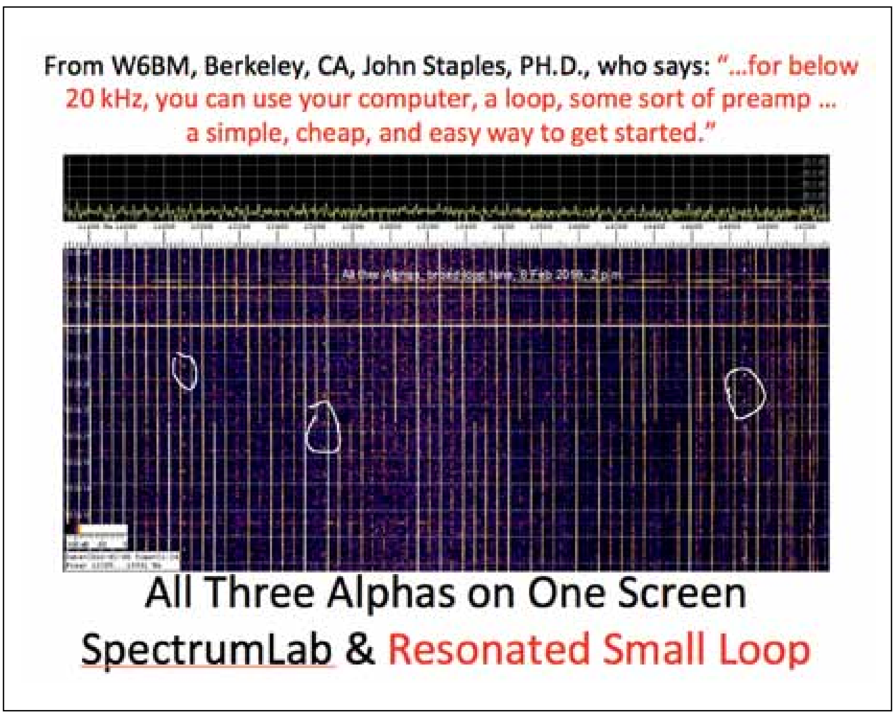

Fig. 4. John Staples' record of receiving three Russian Alpha stations at once using SpectrumLab software and a resonated small loop. (John Staples)

30 km, or about 19 miles. That means that the signal moving at the speed of light is vibrating its electric and magnetic fields at such a rate that it has moved on 19 miles before it returns to the initial states of its electric and magnetic fields (one cycle). By contrast, in the two meter band popular with today's amateur radio operators, at about 146 MHz, the signal moves on only two meters before it reaches its initial field values. In terms of photons, these energy bundles for low frequency radio each carry relatively little energy and hence "vibrate" slowly, at, say, 10 kHz. Conversely, the two meter band photons "vibrate" much faster because they carry more energy at 144 MHz. (The photons of light "vibrate" at 400 to 800 Terahertz). If a 10 kHz signal were audio, some (younger) people could actually hear it.

Despite the wavelength in kilometers, a low-cost up-converter permits a regular shortwave radio to hear these signals; the 0–500 kHz band is up-converted to 3.5–4 MHz (80 meter ham band). An image of such a converter appears in Fig. 5. A loop antenna and soundcard connected to a PC provide both visual and aural reception, especially with audio visualization software such as SpectrumLab. Several software defined radios (SDRs) work well as low as 11 kHz. Many short wave and amateur radio receivers reach down to 100 kHz, or even 30 kHz.

Early radio broadcasters on AM in the 1920s contested the maritime wavelengths, especially 300 meters and 600 meters, or 1 MHz and 500 kHz. Maritime communications settled down to 600 meters, more or less, usually more, i.e., lower frequencies at 500 kHz and below. Maritime services first utilized what we call the long waves, the only wavelengths the equipment of the day could receive or use to transmit. Commercial interests went to longer and longer wavelengths for more and more distance. The U.S. government had banished the radio amateurs to the then considered useless shorter wavelengths, "200

Fig. 5. A commercial VLF converter, where the 0–500 kHz band is up-converted to 3.5–4 MHz (80 meter ham band). Paul Shinn used such a converter to capture SAQ. (Internet sourced)

meters and down" (i.e., 1,500 kHz and up) in 1912.

The "hams" made the best of that challenge within a decade. Almost exactly a century ago, they discovered that communications with wavelengths less than 200 meters, or frequencies above 1,500 kHz, could match the long wave stations for distance (e.g., across the Atlantic). Relatively tiny but sophisticated "homebrew" vacuum tube radios led the way, with the Marconi company and the rest to follow. The professionals had long despised the "hams," but the enthusiastic experimental amateurs had wrong-footed the pros. So, most of what we know today as radio resonates at more than 500 kHz, up to 5 GHz and experimentally much higher.

Looking back a hundred years, that now-ancient wireless telegraphy era from a little after 1900 to about 1922 saw commercial companies, and military and naval forces, adopt the nascent technology. It then worked in the long wave part of the radio spectrum. They drove the technology quickly into a worldwide industry. Although the industry of international communications has flourished for more than a century, the long wave point-to-point technology died very quickly.

The efficiency and lower cost of short wave radio put an end, for example, to most long wave commercial radio point-to-point communications circuits. RCA at "Radio Central" on Long Island, NY dominated these circuits using Alexanderson GE alternators for European traffic. Only one, however, remains: station SAQ in Sweden. It operates as a museum station several times a year. Both Paul Shinn and Dennis Kidder, W6DQ, have copied SAQ signals in California. In quest of this historical station SAQ, several CHRS members, as a CHRS program, have recently explored many aspects of long wave radio, as the VLF Special Interest Group.

II. The Technologies of Early Long Wave Radio: Sparks, Arcs, Alternators and Then Vacuum Tubes

(A) Sparking Away

In 1901 Marconi used his new Poldhu, Cornwall, UK, station as a pulse transmitter with a double spark circuit. As stations went up in wavelength and down in frequency, the spark employed to emit the radio frequency energy got longer and longer in time as well as higher in amperage. By about 1912, the Marconi stations used large rotary spark gaps to generate an almost (but not quite) continuous wave. A large telegraph key then interrupted this energy with Morse code. The Marconi rotary spark gap in Bolinas, California quickly got the nickname "The Rock Crusher" for both the strength of its signal at more than 250 kW and the sound it generated, literally deafening. See the comparable 1914 Marconi Station ZZ rotary spark gap, Fig. 6.

Most wireless communications reached out locally and regionally, at less power. A "quenched gap" spark system could produce a thousand watts (1 kW) or much more. Standard receivers for long waves proliferated. Several companies on the West Coast, such as the early United Wireless Company (and successors) and Federal Telephone

Fig. 6. A Marconi high power rotary spark gap in action August 1914 at 300 kW. (Image from MarconiHeritage.org)

and Telegraph Company, competed for marine and inland traffic, before and after WWI. The Marconi company dominated on the East Coast. An image of a spark station of the era appears in Fig. 7.

(B) Whirling away

The only long wave station that has survived, SAQ in Sweden, still operates its 1922 Alexanderson alternator on 17.2 kHz. An image appears in Fig. 8; the alternator idea originated with Fessenden. At the alternator's heart rotates a five foot by three inch steel disk, spinning at 2,000 rpm. Some 488 brass slots interrupt the magnetic fields around the wheel. These pulses generate the long wave radio frequency energy to be emitted. Alexanderson alternators could reach 100 kHz, but in service ranged around 20 kHz. Power ran upwards of

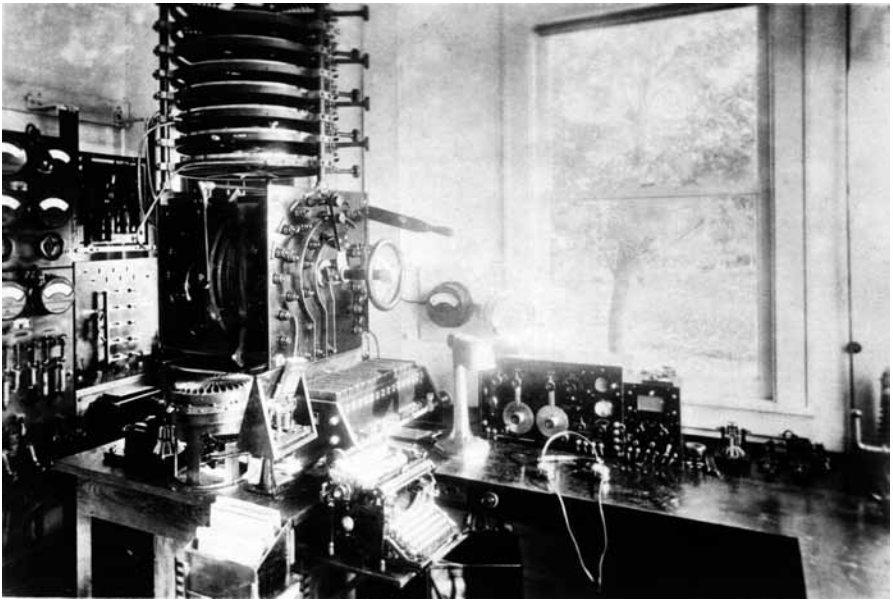

Fig. 7. A spark station, Navy or commercial dating from around WWI. This photo comes from the family of John Staples, and is known only as "Uncle Adrian's Radio Station." (John Staples)

Fig. 8. The alternator at SAQ today. (Bart Lee photo, 2017 at SAQ)

200 kW. Other alternators operated in this frequency range as well. In Bolinas, California, KET (known as "Bolinas High Power") operated at about 23 kHz. Ruins of this station may be seen at the KPH site in Bolinas, maintained by the Maritime Radio Historical Society (MHRS).

The long wave alternator stations required vast antenna arrays to communicate reliably. A series of six radiating high tower vertical antennas (127 meters tall, each with tuned grounds) had to point in the desired direction for each international circuit. RCA laid out its proposed twelve Radio Central arrays in a giant circle on a Long Island property of about ten square miles. The Europe, Japan, and South America circuits each required antenna arrays almost perpendicular to each other. A diagram of the proposal appears in Fig. 9.

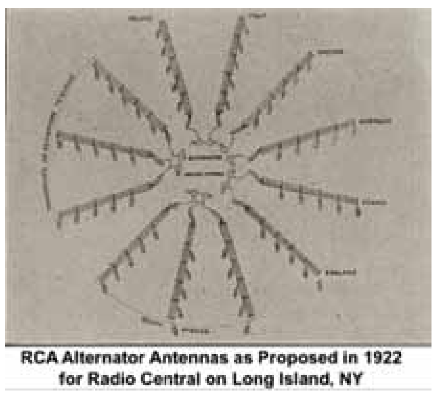

Fig. 9. The proposed, circa 1922, antenna arrays for the alternators to be used by RCA for world-wide VLF communications circuits at Radio Central on Long Island, NY.

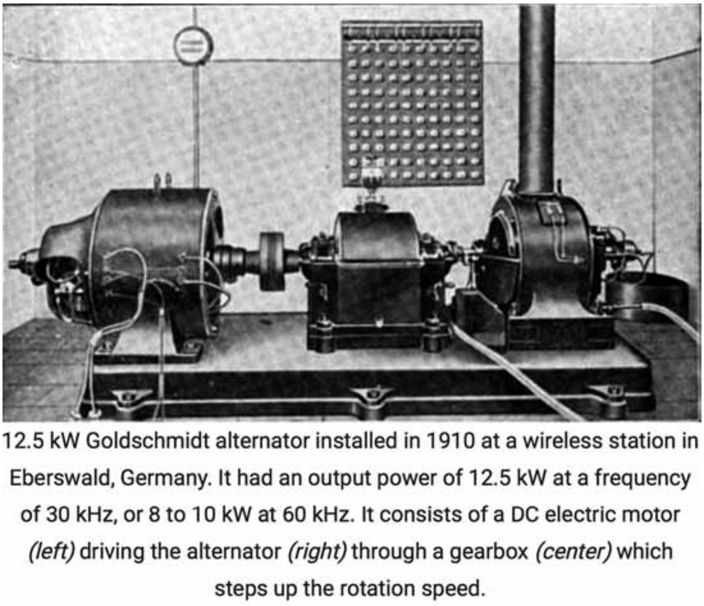

Fig. 10. Goldschmidt alternator installed in 1910 at a wireless station in Eberswalde, Germany. It had an output power of 12.5 kW at a frequency of 30 kHz, or 8 to 10 kW at 60 kHz. It consists of a DC electric motor (left) driving the alternator (right) through a gearbox (center) which steps up the rotation speed.

The German engineer Alfred Goldschmidt developed a similar alternator before WWI, although it operated at lower power. An image appears in Fig. 10. It worked with a frequency multiplier circuit, perhaps as high as 94 kHz.

The Germans put together a worldwide network including Eilvese near Hanover in Germany, at least one station on the U.S. East Coast (Tuckerton, NJ), and at *Lomé*, in the African nation of Togo, then a German colony. Ruins of the Togo station survive, including what may well be the interior disks of a Tesla bladeless disk steam turbine. The British in WWI put a quick end to the German long wave (VLF) network.

(C) Arcing away

Around 1910, Federal Telephone and Telegraph of Palo Alto, California put the first commercial arc station on the air from San Francisco's Ocean Beach. Its logo appears in Fig. 11. Oscillations between the arc and the antenna because of the arc's negative resistance generated a continuous wave (albeit with lots of spurious emissions). This too created low

Fig. 11. The logo of Federal Telephone and Telegraph, Palo Alto, California.

frequency, long wave signals. The arc, however, did so with greater efficiency than spark. As early as 1915, the continuous wave arc had shown itself superior to the spark systems.

The arc technology lent itself to very high powers, many multiples of Marconi's biggest spark systems. By 1918, the U.S. Navy had contracted with Federal for two 500 kW arcs for station NSS at Annapolis, Maryland for transatlantic service below 17.5 kHz, and for several other shore stations around the world. The navy installed a one megawatt Federal arc in France about 1918 for the other end of the transatlantic circuit. The navy bought many Federal arcs, especially the 30 kW set for ships. History San Jose preserves most of a five kilowatt arc inherited from Federal via the Perham Foundation. A schematic diagram and a drawing appear in Fig. 12 and Fig. 13.

An eight foot tall, 65 ton electromagnet made for a Federal high power arc transmitter sits outside the Lawrence Hall of Science at the University

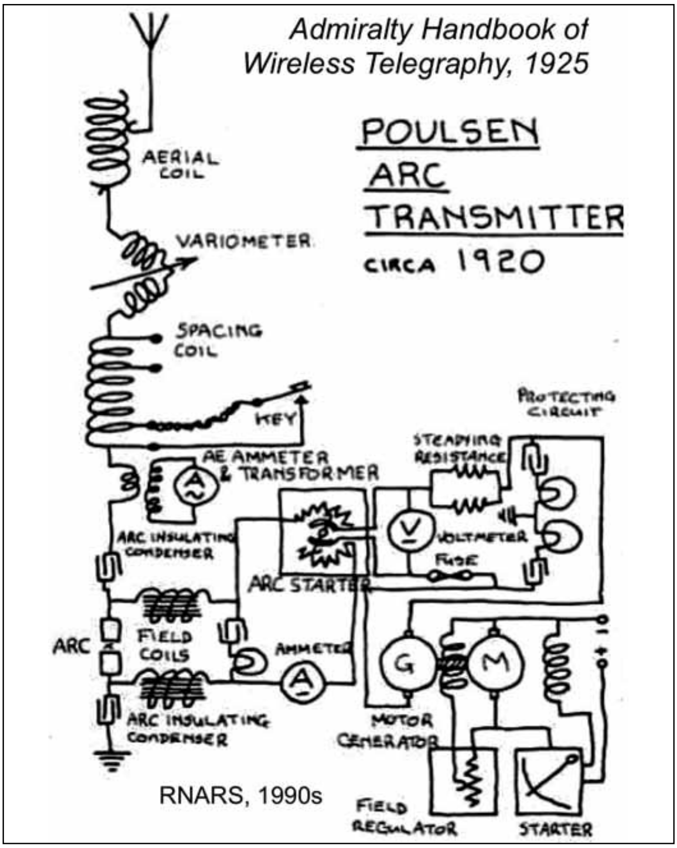

Fig. 12. A schematic diagram of Poulsen arc transmitter, circa 1920. (Cover of a 1994 Royal Navy Amateur Radio Society (RNARS) *Communicator,* 1994; schematic from the *Admiralty Handbook of Wireless Telegraphy*, 1925).

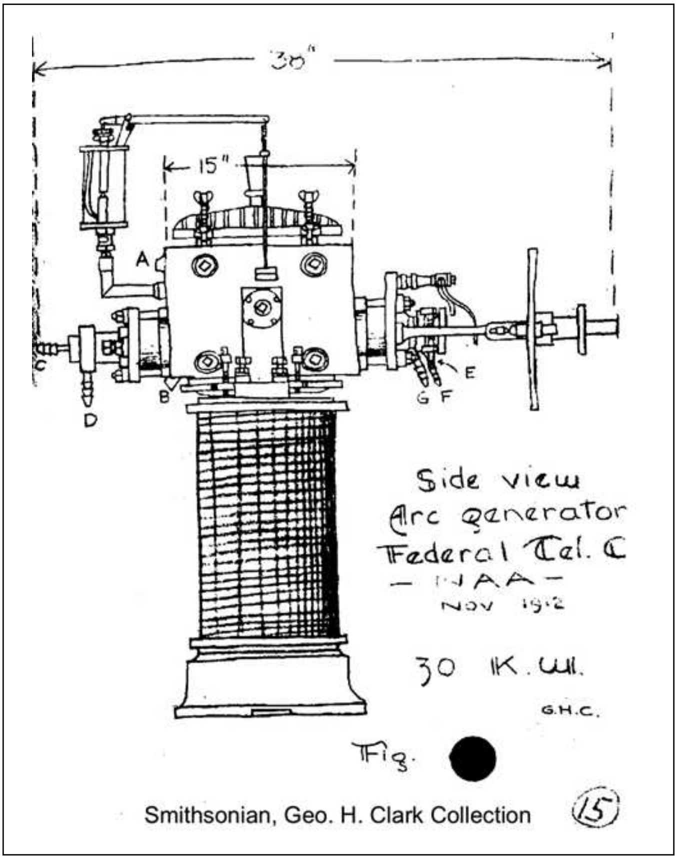

Fig. 13. A drawing by radio historian George H. Clark of a navy 30 kW arc as of 1912. (Smithsonian, Clark Collection, Bart Lee copy)

of California at Berkeley. It once provided a strong magnetic field for Professor Ernest Lawrence's 27 inch cyclotron, as early as 1932. The high power arcs remained in navy service until about 1934. An image of a high power arc appears in Fig. 14. Thereafter the navy used 500 kW vacuum tube transmitters.

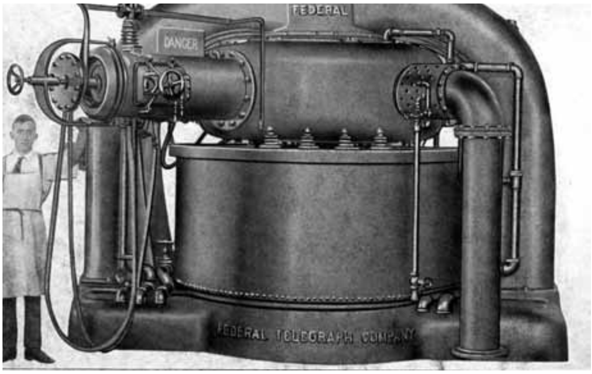

Fig. 14. A one megawatt large Federal arc, circa 1918, which operated in France circa 1920.

(D) Tubes of Nothing

By 1913, Lee de Forest had gotten his little Audion vacuum tube to oscillate at radio frequencies, on behalf of Federal Telephone and Telegraph in Palo Alto. Edwin Howard Armstrong had used the same sort of vacuum tube operation to create the regenerative receiver at about the same time. By 1916, the U.S. Navy used multiple paralleled vacuum tubes, producing a continuous wave that could be modulated by audio, for transoceanic tests of voice transmissions.

Radiomen heard these voice transmissions across the Atlantic in Paris, as intended—but also in Hawaii. Armstrong's regenerative receiving circuit had made worldwide radio possible as of 1914. Vacuum tube transmitters soon replaced all other modes of generation of radio frequency energy, although it took a couple of decades to achieve the high powers of arcs.

III. The Evolution of Effective Techniques for Long Wave Communications

Long wave radio did work long distances. But any transmitter for these wavelengths required massive amounts of electrical power, long lengths of copper-bronze antenna wire in arrays, and an industrial-scale plant. Some of today's working long wave transmitters run at less than a hundred watts (and amateurs are restricted to very low power). But to communicate with U.S. submarines, the navy today operates a network of high power, giant "capacity-hat" antenna digital stations. The mode is Multiple Shift Frequency Keying, MFSK. These stations can range into the megawatts. Their long wave roots go back as far as 1912.

(A) Hearing Long Waves

The U.S. Navy between 1904 and the 1920s learned to use high power long wave radiotelegraph transmitters to reach ships at sea from shore stations. Most early communications with its vessels took place between 175 and 550 kHz. U.S Navy shore stations used receivers designed to receive down to 10 and 12 kHz. An image of a navy long wave receiving installation, circa the 1930s, appears in Fig. 15.

Of the 36 U.S. Navy receivers listed by naval radio historian Captain L. Howeth[2] as normally used by naval ship and shore stations (excluding direction finder stations) during the period 1912 to 1928, 30 covered the long wave bands, nine of them down to 10 kHz. Two of the earliest were the models A and B, down to 60 kHz and 30 kHz respectively. Two of the latest of the period, the models RAA (for "general service") and the RCC (for "shore stations") went down to 10 kHz and 12 kHz respectively. Long wave radio provided the navy with reliable fleet communications until well after WWII. An image of a WWII-era navy long wave receiver appears in Fig. 16.

A great deal of the progress in the early radio art focused on improving antennas to hear longer wavelengths. One example is Harold Beverage's "wave antenna" for receiving, now known as the "Beverage antenna." One long wire, of at least a wavelength, pointed at the signal source, could gather enough energy for the signal to be heard, while much

Fig. 15. The Navy long wave receiving station in the Washington, DC area, 1930s. (U.S. Navy photo)

Fig. 16. A Navy WWII era long wave receiver. (Internet sourced)

diminishing all energy from other directions, especially noise, thus improving the signal-to-noise ratio.

Loop antennas, picking up the magnetic component of the radio wave, work in proportion to their electrical characteristics and their size—size matters, but not as much as one might expect. Quite small loops can capture VLF signals. On submarines, a loop antenna less than a meter or so wide seems to work just fine, even 15 meters undersea.

(B) Transmitting VLF

Early transmitters (after Marconi's wire arrays) took on a vertical aspect. Instead of horizontal arrays of great length, relatively short vertical elements got the signals out at very low frequencies and emitted very long waves. But they had to resonate at the intended frequency. A vertical antenna has a given inductance, which can be varied (usually at its base; Marconi's "jigger" coil did this). But capacitance to ground also determines resonance.

The vertical long wave antennas, sometimes arrays of vertical elements, got to dress up in "capacity hats." These capacity hats put a lot of wire, sometimes like umbrellas, sometimes as horizontal arrays, above the antenna to form a capacitor to the ground. That added capacitance counteracted the antenna's intrinsic inductance to control the frequency of resonance. The length of the long waves translates to a need for very long antennas for these very long wavelengths, or some shorter antennas "loaded" with extra capacitance, to capture or emit the radio energy. Really long antennas cost a lot, are hard to maintain, and hard to site. Shorter antennas for lower frequencies, however, present challenges because they compromise performance in various ways. Much innovation went into compensation for these challenges.

As early as August 1899, in San Francisco, the experimenters put a large laboratory Ruhmkorff induction spark coil into the *Lightship 70* out in the fog. They wired a "capacity hat"—one of the first—at the top of their vertical wire antenna. Their Morse code signal that the troopship "Sherman is sighted," got through to the Cliff House onshore as the first radio traffic in America. Similarly, Doc Herrold in San Jose around 1916 put a massive capacity hat between buildings at the top of his antennas. He operated an arc transmitter at perhaps 40 kHz. So too, did young William Dubilier in Seattle put an enormous amount of wire atop his very tall antenna in 1909. The experimenters of the day thought that this wire topping did the radiating. Actually the vertical wire "lead," energized by most of the radio frequency current, radiated at the lower frequency of resonance.

By 1918, the radio engineers had managed long wave radio, often using wire arrays above radiating vertical elements. This is still the design of most high power VLF stations.

One history of navy radio in the Pacific[3] reports: "The most important broadcast was the Primary Fleet (FOX) broadcast which was transmitted on the frequency of 26.1 kHz using the 500 kW VLF transmitter at Lualualei. Navy ships at sea and a majority of naval activities ashore copied the entire FOX broadcast. The Wailupe FOX was the most rapid way to get messages to ships."

The Lualualei transmitter, at 100 kW, came on the air in 1932. The alternator from Bolinas arrived for WWII, so the navy's earlier FOX broadcasts may have gone out on a Federal arc.

On the Atlantic side, Arlington, Virginia (call sign NAA) handled the fleet communications. The navy first (in 1913) used a Fessenden 100 kW rotary spark, then a Federal 30 kW arc, then by 1925 a vacuum tube transmitter.[4]

(C) The Short Waves Cometh

WWI both advanced and retarded the development of the radio art. The need for high and reliable traffic volume across the Atlantic locked long wave technology into place, at least for a while. The hope for better radio: cheaper, faster, frequency agile, even portable—drove experimenters to the short waves, above 2 MHz, soon as high as 25 Mhz. These short wavelengths got out fine with way shorter antennas, even as dipole and other fractional wavelength configurations. Amazing (then and now) ionospheric propagation got signals to the antipodes. An early instance, Marconi's Beam Wireless Service, saw short wave signals get from Cornwall, UK, to Australia, as early as 1927. The Beam Wireless signals, at about 9 MHz or 32 meters wavelength, radiated from large vertical parabolic array antennas.

The great short wave revolution in communications drove long wave communications into the dustbin of history by the end of the 1920s. After 1919, the experimenters, amateurs, and professionals like Marconi, even RCA, soon came to see advantages in the higher frequency ranges of what we now think of as the radio spectrum. RCA had planned for many alternators at VLF, with vertical antennas under wire arrays, to cover the world. But by 1923, RCA abandoned the long waves.

Nations soon broadcast directly to each other on shortwave radio by the late 1920s. Armies and navies communicated among themselves and over long distances with relatively small short wave radio systems. After initial success in 1921, amateur radio operators talked across the Atlantic in 1923 on a 110 meter wavelength, and soon to the world on 40 meters and then on 20 meters. The then not-well-understood eleven-year sunspot cycle provided miraculous ionospheric worldwide propagation of radio signals every few years, well enough to maintain various enthusiasms.

Abandoned by RCA, abandoned by Marconi, Telefunken long out of the game, what was left of long wave? As it happens, quite a lot persisted, especially for naval communications, and then more came along.

IV. Long Wave Radio and Nuclear War (Not to Mention Maritime Convenience)

As early as 1918, the U.S. Navy realized that long wave radio could reach its submarines without them having to surface. In WWII, Japanese radar could spot a periscope, but not an underwater trailed antenna. In order to provide safe communications with U.S. vessels throughout the Pacific, the navy turned to a high power long wave alternator. In its last use, one of the "Bolinas High Power" RCA Alexanderson alternators took up residence in the crater just north of Waikiki, on the Island of Oahu in Hawaii. From there it covered the Pacific theater of wartime operations.

The utility of very long waves, very low frequencies, for communicating with submarines became exponentially more important with the advent of the Polaris class nuclear submarines armed with nuclear weapons (the "Boomer" subs).[5] Both command and control as to launch, and fail-safe to prevent an erroneous launch, came to the fore. Only reliable communications could be trusted to authorize a launch and only reliable communications could prevent a bad launch, likely precipitating full-scale nuclear war by error.

The United States put in place worldwide the 10 kHz to 14 kHz OMEGA stations in the 1970s to provide a reliable fix of position almost anywhere in the world, initially for polar bombers and then for navy vessels. So, too, the Russians created their own Omega-like system (known to us as the Alpha stations), for their own purposes. Both systems featured not direction finding, but "hyperbolic navigation." While this sounds very mathematical (and it is), it's pretty simple at the receiving end. Two curves on the appropriate map intersect at two points, and other information eliminates one of the two. (That other information can be a third related signal). These now 50 year old radio systems pioneered modern "Position, Navigation and Time" (PNT) services. The United States turned off the OMEGA system in 1997 in favor of GPS, the multi-satellite Global Positioning System, for PNT services.

Some of the U.S. OMEGA stations may have converted to submarine communications stations in the range of 15 kHz to 77 kHz. The U.S. Navy and U.S. allies may well have built several of the others from Japan to Europe for this special purpose. At least six such navy VLF stations operate from Australia, Hawaii, the continental United States (three stations), and Puerto Rico.

The question arises: If long waves don't bounce off the upper ionosphere as do short waves, and if ground wave propagation is so limited, how do the signals get around the world? The answer is surprising. The ionospheric D-layer is ionized at night, but of course, not by the sun. These D-layer ions provide the reflective surface (something like a waveguide) that send the long wave signals back down to earth, for the submarines and others. The full-sky energy that sufficiently ionizes the nighttime D-layer for VLF likely comes from cosmic radiation.[6]

Two diagrams of the short day and long night range of the 60 kHz time signal of WWVB, from the National Institutes of Standards and Technology, are shown in Fig. 17 and Fig. 18. So, what may be resonances of the Big Bang (or not), or the results of lesser galactic collisions or stellar bangs, may help to provide some important communications capabilities up to 14 billion years later.

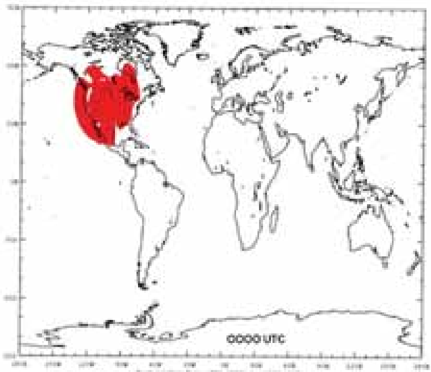

Fig. 17. Day range, WWVB, 60 kHz. (NIST)

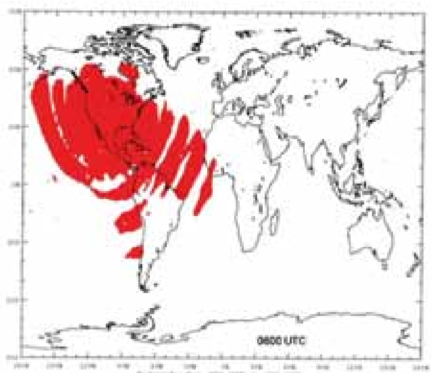

Fig. 18. Night range, WWVB, 60 kHz. (NIST)

Navy VLF stations have used frequency shift radioteletype (FSK) modulation since 1951, and traffic is also encrypted. In California, some of these navy stations are heard and seen all day: e.g., North Dakota, NML (ex-OMEGA); Washington State, NLK; Maine, NAA (honoring the navy's most distinguished old callsign at two megawatts); and Hawaii, NPM. A screen capture of many of the VLF stations as received here, appears in Fig. 19. Others in Australia (NWC) and Puerto Rico (NAU) are night-only catches. They each operate four channels with a total bandwidth of 200 Hz. NATO western Canadian station CKN operates at 76.2 kHz with a wider bandwidth, about 400 Hz.

Russia, China, Japan, and France also operate VLF stations heard in California on winter nights. A map of most known VLF stations appears in Fig. 20.

Russia operates its main worldwide communications network from Moscow

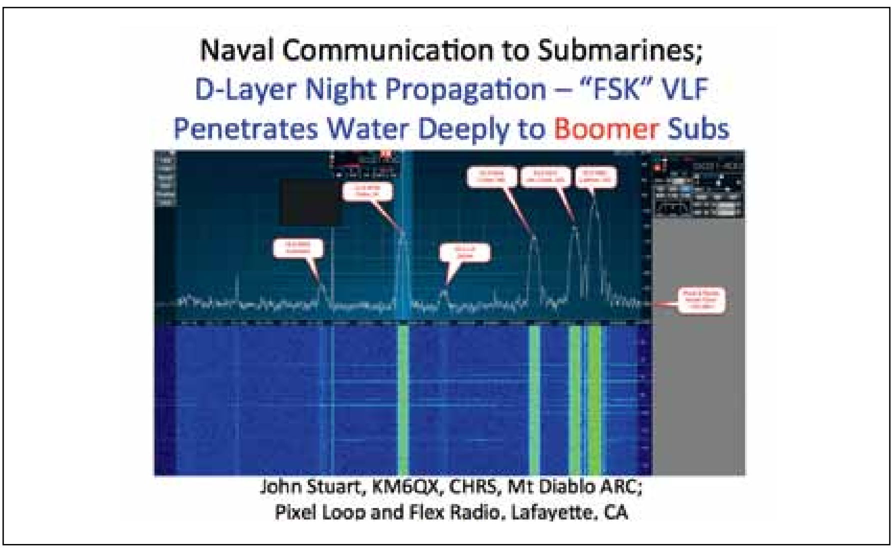

Fig. 19. Some of the more powerful VLF stations seen and heard in California. (John Stuart)

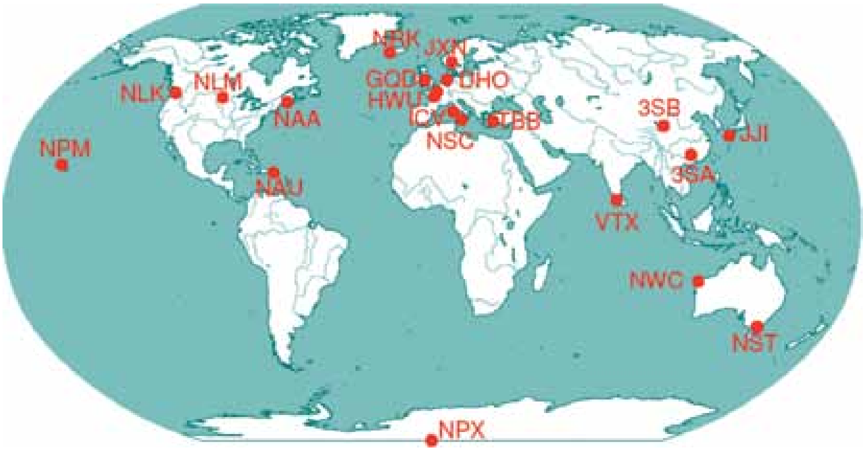

Fig. 20. Most of the VLF stations of the world appear on this map; NPX in Antarctica is perhaps notional.

as RDL on 21.1 kHz, often heard and seen at night. A screen capture of California reception of RDL appears in Fig. 21. The Russians also operate the frequently heard VLF "Beta" data stations and the "Alpha" navigation stations.

Some decades ago, the U.S. Navy operated a transmitter at 76 Hz (a wavelength of about 4,000 kilometers). At this frequency and wavelength, the sea-and-atmosphere interface is just a big waveguide. The capacity of the 76 Hz signal to convey information was limited by its frequency, efficiency, and narrow bandwidth. But that was not its purpose. It was a Fail-Safe. If, but only if, that transmitter went off the air could a submarine launch its ballistic missiles, no matter what other orders it had. Yet that extremely long wave radio system shut down about 1997 (as did OMEGA). The Soviets implemented a similar system at 82 Hz, now long gone also. The British Navy used a similar long wave fail-safe for its nuclear-armed submarines, using the presence of BBC Radio Four on 198 kHz.

The navy has said that its network of VLF stations rendered the 76 Hertz fail-safe station obsolete. Presumably, in the event of war, someone, somewhere, can pull the plug on these stations, just as would have been done on the 76 Hz station. The complexity of the network and its encrypted data would make a spoof impossible, so a false set of signals could not be substituted for the turned-off stations. Russia, on the other hand, seems only to have one around-the-clock worldwide VLF system operating, the navigational (PNT) Alpha stations. Perhaps this is the Russian fail-safe system. Inasmuch as the hyperbolic nature of the positioning is reciprocal, this network cannot be spoofed either. This is so because a submarine navigator would know that the received spoofing signals do not emanate from Russia. Thus, these VLF signals, all of which can be heard and seen in California, may be keeping the world safe.

The Russians broadcast the "Alpha" signals from at least three sites, and at three frequencies between about 12 kHz and 15 kHz. See Fig. 22, a Russian Alpha station. John Staples, as a principal of the VLF Special Interest Group, put the sharp directional null of his homemade loop to work to determine the signals

Fig. 21. The Russian worldwide VLF station RDL on 21.1 kHz, a screencap from the WinRadio G33 at K6VK. (Author's photo)

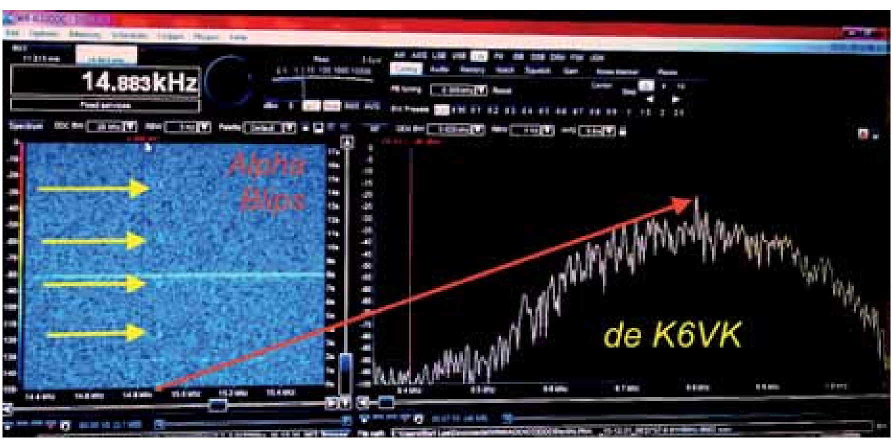

Fig. 22. Audio analysis of the Russian Alpha VLF station at 14.881 kHz on December 31, 2015, at 14:57 UTC at K6VK. (Author's annotated screen cap photo)

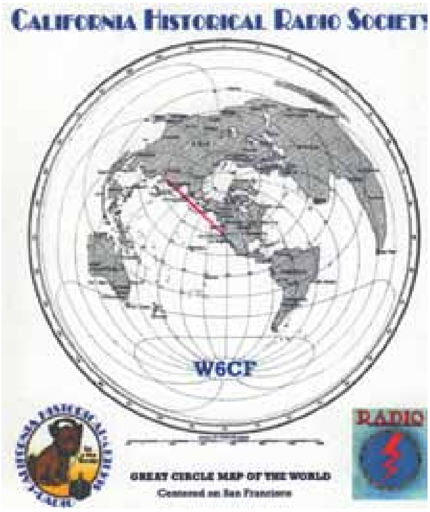

Fig. 23. John Staples' bearing for the Russian Alpha station in Siberia. (Bart Lee and John Staples)

heard here come from the North West. That means the Siberian station North of Beijing. A map appears in Fig. 23.

V. Air and Sea Navigation Aids

Navigation aids developed on long wave, and remained at these frequencies because of long wave's stability. These 24/7 stations are the easiest to hear (and see). From about 200 kHz to over 520 kHz, these airport and shoreside navigational beacons throughout the world for decades sent out two or three letter Morse code identifications (ID) signals, by which aircraft and ships can determine their positions. Only rarely if ever did ionospheric complications ("the night effect") develop for these ground wave systems. Ships at sea could take bearings on shore stations and other ships. Aircraft could determine position by direction finding of airport beacons (as well as city broadcasting stations at considerable range). Coastal and inland stations have long announced themselves with simple two or three letter identifiers, as they do to this day. Until recently, in Northern California, a listener on a radio with a long wave band could hear several of these AM Morse code-identified beacons; for example "CC" at Buchanan Field in Contra Costa County on 335 kHz. An image appears in Fig. 24.

In the 1930s, American console radios often featured a long wave band, as shown in Fig. 25. Yet European long wave broadcast stations rarely got into the American ether. But the aeronautical long wave stations also broadcast AM reports for pilots, around the country. Radio companies made the long wave band a selling feature, like the weather band, in an era when current weather information—and warnings—might otherwise be hard to get.

In winter, stations from Canada to Mexico, and as far east as Montana, mostly in the 200 kHz to 400 kHz range, beeped away into California. The Canadian beacon stations cover considerable distances because they operate at higher power than the U.S. stations. They also send a distinctive "long-dash," and they are still on the air.

The government converted many of the existing or planned long wave transmitters (such as OMEGA and GWEN facilities) into very high power digital beacons in the range of 300 kHz to 400 kHz (but dropped their Morse code identifications). These beacons supplemented the received digital GPS, the

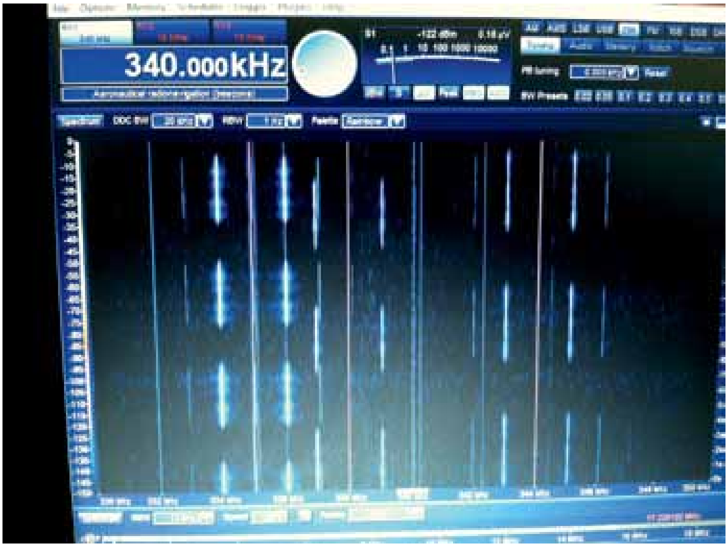

Fig. 24. Station CC in Contra Costa County, CA at 335 kHz, a typical LF beacon for an airfield. (Author's screen cap)

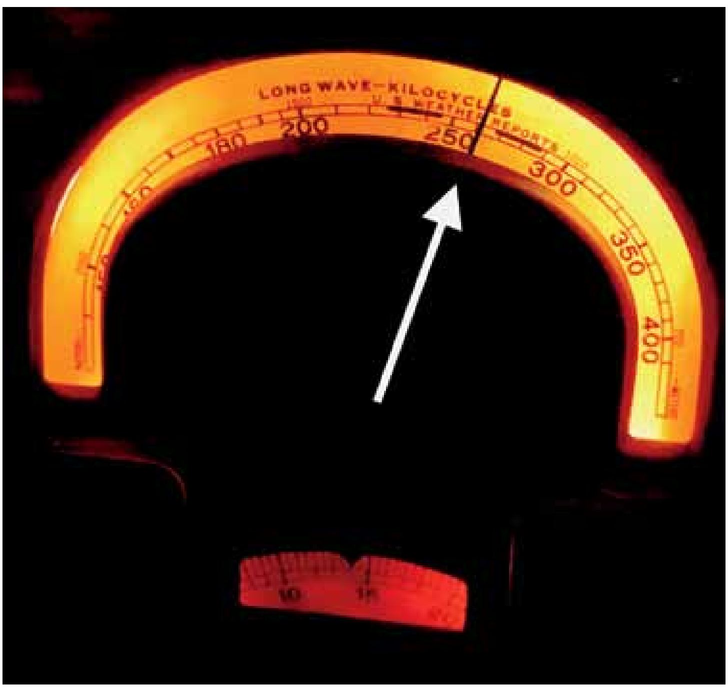

Fig. 25. The dial showing the "Weather Band" around 250 kHz, on a 1936 RCA 10K console radio. (Author's collection)

Global Positioning System, signals from satellites. A fixed-position long wave beacon on the ground provided correctional data about GPS satellite signal discrepancies. (The satellite signals are subject to many propagation and other vagaries that limit precision). These ground beacons were operated by the Coast Guard (usually former coastwise beacon sites), the Department of Transportation (one or more of the GWEN sites among others) and in the Mississippi Valley, the U.S. Army Corps of Engineers. A now-dated map appears in Fig. 26.[7] Many of the non-marine DGPS stations are now closed, because GPS-related FAA Wide Area Augmentation System (WAAS) provided by satellites replaced their functions.

After WWII, utilities and governments otherwise continued with long wave radio services for special medium and long distance advantages. United States navigation at sea depended on the powerful Loran stations (LOng RAnge Navigation) operating at around 100 kHz, or 3,000 meters. This too was a hyperbolic system. Loran no longer operates, but a new version, "eLoran" is in the works. This may back up the GPS system, which could be subject to many issues (e.g., bad space weather and malicious interference from Russia). GPS is especially vulnerable in wartime to jamming and spoofing. Tests suggest that eLoran works well even deep inside steel and concrete in the big city, where GPS cannot reach. Its high power signals would be very hard to jam or spoof. Out of concern that their GPS can be spoofed or disabled, the Russians themselves are now returning to long wave Loran equivalents.

VI. Time Signals

Long wave provided reliable time broadcasts. The navy station NAA (from around 1913), as well as the French Eifel Tower station (as early as 1910), sent out time signals for decades on long wave. Two postcards celebrating these stations are shown in Fig. 27 and Fig. 28.

Fig. 26. A map of the late system of the U.S. DGPS high-powered stations. (DGPS)

Fig. 27. Navy station NAA near Washington, DC on a 1920 postcard; the note says "These broadcast the Arlington time signals." (Author's collection)

Precise timing became a military, naval, scientific, and commercial necessity, especially for longitudinal navigation. Today, several nations operate such time and frequency standard stations, such as WWVB in Colorado on 60 kHz, JJY in Japan on 40 kHz and 60 kHz, and UK station MSF on 60 kHz. A screen capture of such stations regularly heard and seen in California appears in Fig. 29. China transmits time on station BPC, on 68.5 kHz (along with spread-spectrum traffic; this may well be a naval communications station as well, and perhaps a Fail-Safe station). Long wave time signals (e.g., WWVB) are more precise than the short wave ones (e.g., WWV), because of almost no disturbances in the pathways.

The ubiquitous "Atomic Clocks" reset themselves by WWVB at about midnight. SDRs and PC-enabled receivers

Fig. 28. Postcard showing the Paris Eifel Tower, used for radio since 1910, including time signals. (Author's collection)

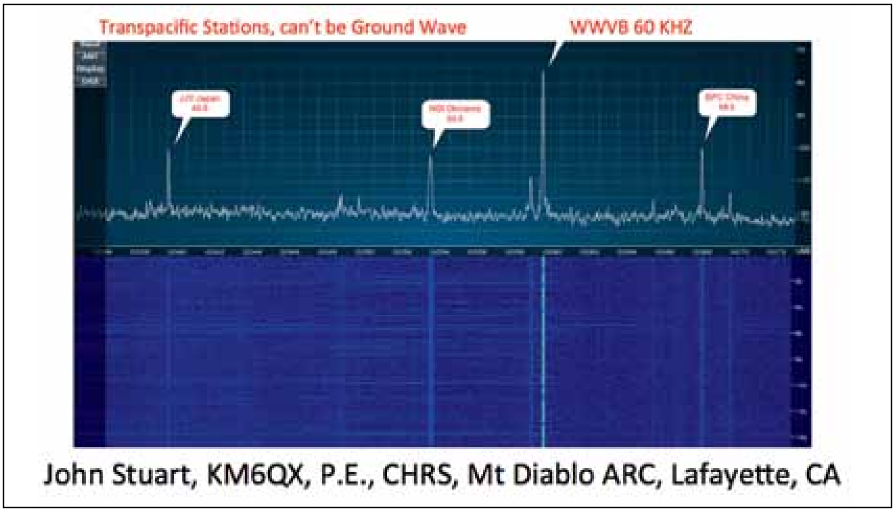

Fig. 29. John Stuart's capture of Asian and U.S. VLF time signals. (John Stuart)

can demodulate and record all of these stations just about every night, at least in winter. A small loop antenna or a longish vertical antenna suffices for WWVB and often for the other stations as well. John Staples has analyzed the WWVB signals in great depth.

VII. Marine Communications

Marine communications continued to use long waves for many decades. The calling frequency remained 500 kHz from the beginning. The frequency of 500 kHz, or 600 meters, permitted vessels' transmitters to operate effectively with relatively short, mostly horizontal antennas, constrained by the length of the vessel. An efficient antenna could make the difference between life and death on the high seas, as well as effect adequate marine communications and minimize received noise. This frequency resonated just below what became the AM broadcast band, but it remained largely the private preserve of the marine and naval shore stations and the ships at sea. These vessels ran relatively low power, other than the naval vessels. Moreover, 600 meters offered the reliability that short wave propagation conditions frequently compromised. Marine communications, however, have now transited through short wave radio and then to satellites.

Until recently, the only marine long wave signals came from the international NAVTEX stations, on 518 kHz. But in the United States, the Coast Guard no longer sends out these regional FSK broadcasts about weather and safety at sea. A second frequency, 490 kHz is in the works and is in use in Europe. San Francisco stations could regularly hear (and demodulate) NAVTEX from as far north as Alaska. Some SDRs provide a NAVTEX software plug-in. An image of a NAVTEX reception appears in Fig. 30.

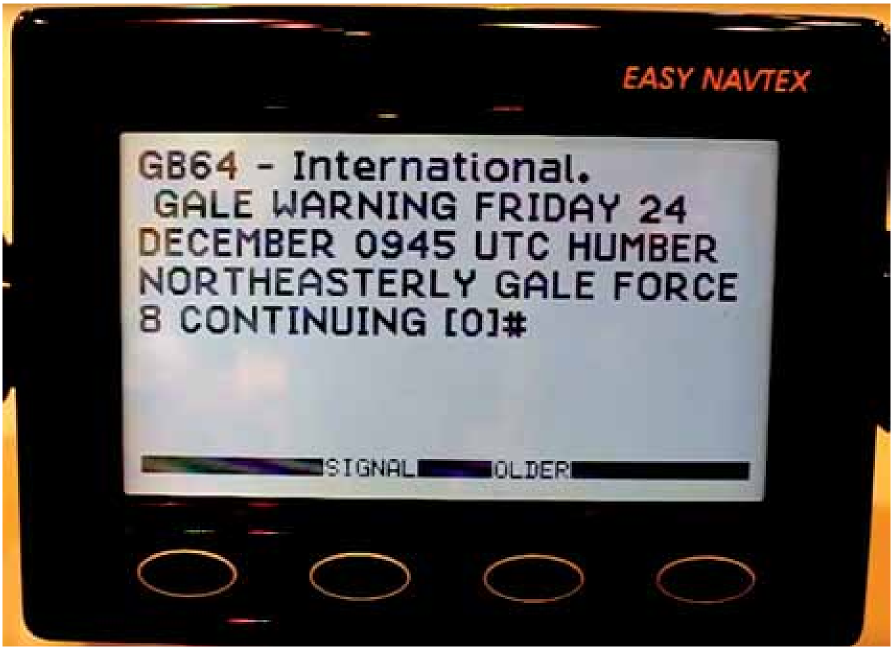

Fig. 30. A NAVTEX reception in England. (Internet sourced)

VIII. National Broadcasting

Broadcasters in Europe from the 1930s on continued to appreciate the stability of long wave signals for listeners, many of whom were too far away for regular AM broadcasting in the new internationally standardized band between 600 kHz and 1500 kHz. Many European countries have maintained AM broadcast facilities on long wave, between 150 and 300 kHz for decades. Some few are still broadcasting long wave to this day. Some commercial stations also appeared in the 1980s. An (old) commercial logo appears in Fig. 31.

These signals escaped ionospheric disturbance, and their listeners heard them by reliable ground-wave propagation. Sure, massive power remained required, often more than a megawatt. But the programs, usually government-sponsored, got through to the people (for better or worse). Some such stations that have been heard in Manitoba, Canada[8] appear in Table 1.

Fig. 31. The logo of the now-gone long wave broadcaster Atlantic 252; the 252 kHz frequency may still be used for broadcasting. The logo reads "More Music Radio Atlantic 252 Long Wave." (Internet sourced)

Table 1. Frequencies of high-power European stations on long wave that have been heard in Manitoba, Canada.

Frequency, kHz	Station	Location	Power, kW
162	Radio France	Allouis, France	2000
183	Europe 1	Felsberg, Germany	2000
189	Rikisutvarpid	Gufuskalar, Iceland	300
198	Radio 4 UK	Droitwich, England	500

It would be a rare catch to hear one of these stations in California, and then it would only be possible at O'Dark:30 around the winter solstice. Canadian and East Coast enthusiasts do log them, however. A decade ago, Radio Rossi from Siberia reached California on 279 kHz under ideal conditions. Then it went out of business in 2013. A modern UK portable radio featuring the long wave band and the two stations most easily heard appears in Fig. 32.

Gilles Vrignaud of the VLF Special Interest Group has discovered internet long wave radio. With his smartphone, through Wi-Fi and the internet, he can connect to dedicated SDR radios mostly in Europe. They tune in long wave (and other) broadcasting stations. They then make these signals available on the internet.[9]

In the United States, above the 100 kHz range, the Federal Emergency Management Agency's (FEMA) predecessor set out to create a hardened emergency communications network known as GWEN[10] in the 1970s. That acronym came from Ground Wave Emergency Network. It ranged in frequency up to about 200 kHz. Only GWEN WGU-20 on 179 kHz in Maryland got on the air. It opened in 1973 and closed in 1990.

Fig. 32. A modern English "Roberts" portable radio covering long wave as well as AM and FM; note BBC "Radio 4." (Author's collection; radio from the late Alan Carter, BVWS)

Fig. 33. The QSL card of the only GWEN station to operate, WGU 20, near Washington, DC. The card reads "Defense Civil Preparedness Agency Radio Station / WGU 20 / 179 Kilohertz 1st 50 KW / All Solid State AM Transmitter Chase, Maryland." (Internet sourced)

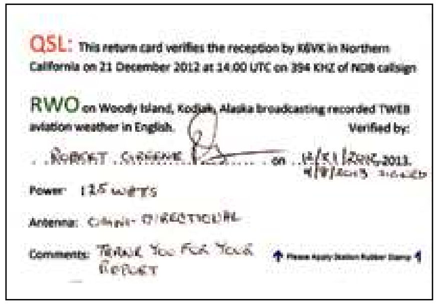

Fig. 34. A "prepared" QSL verification of station RWO in Alaska transmitting voice weather broadcasts, returned to K6VK. (Author's correspondence)

Its QSL card appears in Fig. 33. Much of what the GWEN stations were supposed to do at long wave is now done by the regional NOAA stations on VHF, including emergency notifications, around 162.5 MHz.

Today many cities benefit from low power local-only "emergency broadcast stations" on 530 kHz, just below the broadcast band.

IX. Air Traffic Management

Aviation early took advantage of the stability and the (usually) limited range of low power long wave signals to manage air traffic. Each airport on its unique local frequency provided terminal weather and Notices to Airmen (NAMs) about runways, hazards, and the like. In the San Francisco Bay area, Oakland airport (station WCY) starting in 1929, provided reliable information to airmen, and continued well into the 1970s on 362 kHz. Some home radios, especially consoles and imports, also picked up some long wave in those days. So casual listeners, along with radio amateurs, tuned in as well. Airports in Alaska until recently used long wave for voice Transcribed Weather Broadcasts (TWeB) from the airport beacon stations to report terminal aviation weather. It may be that aurora effects on other wavelengths and frequencies make long wave more reliable that far north. A QSL card for RWO in Alaska on 394 kHz appears in Fig. 34. Today, airports broadcast regular weather and other information locally on AM VHF between 118 MHz and 135 MHz.

X. Long Wave Amateur Radio

For many years, amateur experimenters have been authorized by the Federal Communications Commission (FCC) to transmit unlicensed in the 160 kHz to 190 kHz range, the 1750 meter band, at very low power, less than one watt. These "LowFers" also have occasionally been authorized at higher powers (five watts under Part 5 of the FCC regulations). At least one, WH2XVN (Dave Curry), regularly operated in California on 183.5 kHz. See screen capture shown in Fig. 35.

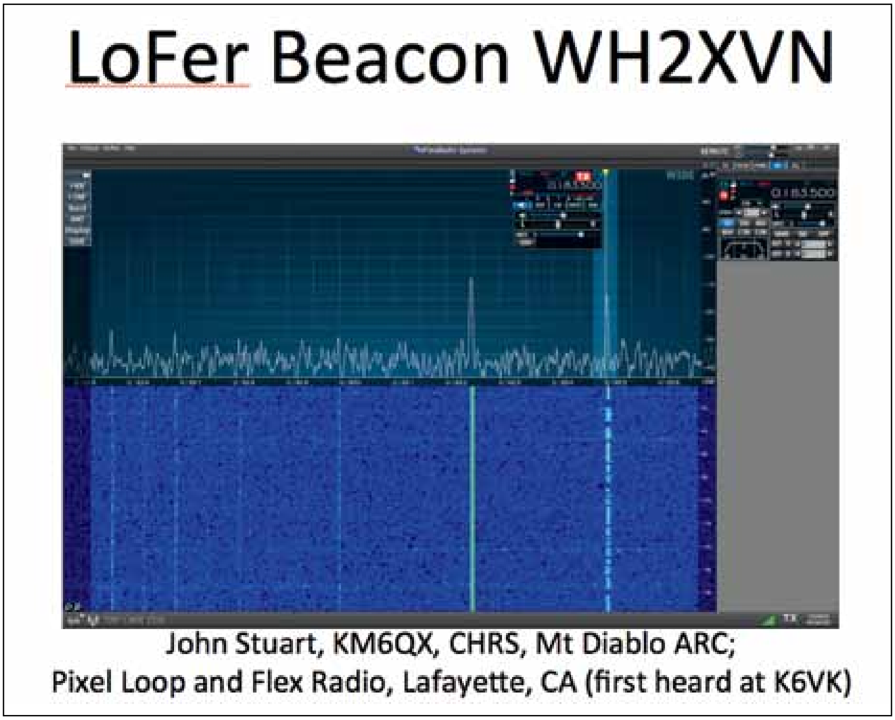

Fig. 35. A record of receiving the Part 5 LoFer beacon WH2XVN on 183.5 kHz. (John Stuart)

At the other end of the power spectrum, the FCC has also authorized marine historical radio in Morse code on the old 600 meter marine frequencies from 425 kHz to 512 kHz. The Maritime Radio Historical Society (MRHS) does so at Bolinas, California. Its principal and Chief Radio Operator is Richard Dillman, whose marine radio "sine" is RD and who is known as "Sparks," amateur radio call sign W6AWO. With the sponsorship of the U.S. National Park Service, MRHS operates KPH/KSM. MRHS has explored these frequencies for several years, with the help of commercial WLO in New Orleans and regional U.S. Coast Guard stations. The Maritime Radio Historical Society seeks to reactivate marine frequencies between 425 kHz and 500 kHz several times a year; see Fig. 36 and Fig. 37. These operations memorialize the great era of long wave marine communications. The operators hold the required commercial FCC First Class Radio-Telegraph licenses. They work their transmit and receive desks as true amateurs, for the love of radio. "Sparks" RD, along with dedicated colleagues, revived and reenact this aspect of radio history (on the short waves as well as long wave).

Starting in 2006, the ARRL operated a 600 meter experimental group as authorized by the FCC under the collective callsign WD2XSH. The ARRL noted over 200,000 hours of

Fig. 36. Morse code from KSM at Bolinas on 426 kHz November 2, 2014, from the WinRadio G33 receiver at K6VK. (Author's screen cap photo)

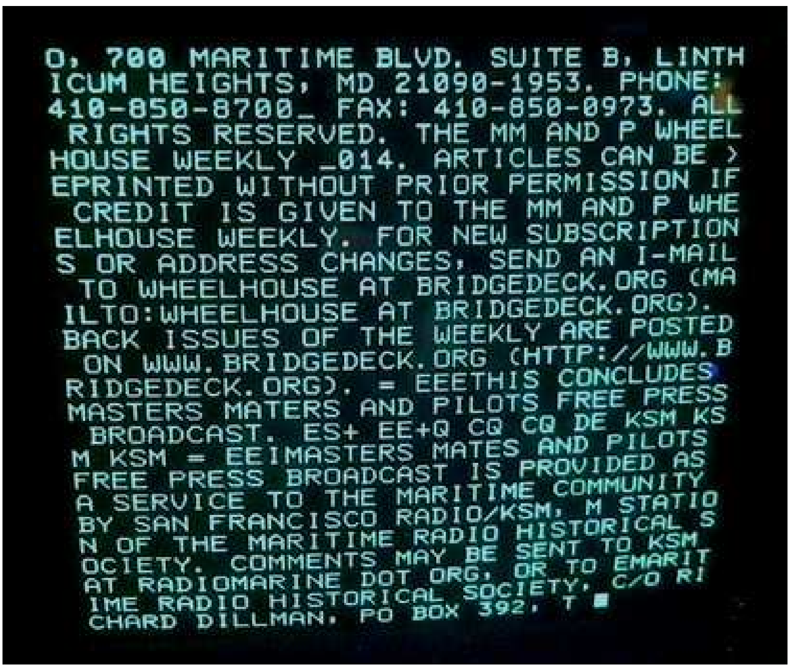

Fig. 37. Readout of the KSM text on 426 kHz November 2, 2014, from the WinRadio G33 by way of the HAL Telereader at K6VK. (Author's screen cap photo)

experimental communications on these frequencies. The 2016 amateur radio Field Day in June featured the operation of a number of the new-pioneering long wave stations,[11] which are shown in Table 2.

The FCC then authorized limited amateur radio activity on the 630 meter band at 472–479 kHz, as well as the 2200 meter band at 136 kHz. (This wavelength was once used for mobile communications by the U.S Army in France in WWI). These 136 kHz or close frequencies were already in amateur use in Europe and Canada. Joe Craig, VO1NA, got both a 2200 meter signal and an 8 kHz QSSS (slow speed Morse code) signal from Newfoundland across the pond to Europe some years ago. With his very long antenna, he also earlier had acted as the Newfoundland receiving station for the 160 meter Poldhu, UK Marconi beacon experiment of 2006.

Both the 630 meter band and the 2200 meter band are now active amateur radio bands, for WSPR beaconing, Morse code CW, and in Southern California, single sideband voice on 630 meters (according to Dave Curry, a Low-Fer pioneer). All U.S. states (but one) have enjoyed active long wave amateur communications. Some 21 California stations have activated, and some 180 altogether (according to Ralph Wallio, WØRPK / WD2XSH/34).

Table 2. Callsigns of low power amateur radio stations communicating on long wave frequencies during the amateur radio Field Day in June of 2016.

Callsign	State	Frequency, kHz	Mode	Power, watts
WG2XIQ	TX	474.5	CW	5-7
WG2XSV	WA	475.5	CW	1
WH2XAR	AZ	474.9	CW	½
WD2XSH	WA	475.7	WSPR	
VE7CNF	BC	477.5	CW	2
VO1MRC [VO1NA]	NL	477.7	CW	2

XI. A Mystery VLF Signal Identified

Surprises often appear on long wave bands, especially the very low frequencies. Now these wavelengths mostly communicate from land to deeply submerged submarines. In 2019 a BIG signal appeared "out-of-nowhere" in the long wave VLF band. A SDR full screen capture shown in Fig. 38 of the WinRadio G33 shows the signal. At about 22.7 kHz and with an 800 Hz bandwidth, it does not come from any of the operating U.S. Navy VLF land station transmitters (four of which appear in the screenshot).

The navy has for many years standardized its submarine communications at a 200 Hz bandwidth, MFSK (Multiple Frequency Shift Keying), with multiple carrier frequencies sometimes seen. There is no listed or observed navy VLF land station signal at more than 200 Hz bandwidth. One aeronautical signal is, however, listed: the U.S. Navy airborne TACAMO system at the observed 800 Hz bandwidth: "00022.6:unid:US NAVY TACAMO mobile worldwide, F1B-50Hz/190Hz/MSK 400Hz/800Hz BW. TACAMO is an acronym for TAke Charge And Move Out."[12]

The navy has operated TACAMO for several decades, since 1962. The wiki says: "TACAMO (Take Charge And Move

Fig. 38. A strong (32 microvolt), 800 Hz bandwidth MFSK VLF signal appeared at 22.7 kHz on May 1, 2020 at about 03:00 UTC, early evening local time, on the WinRadio G33 using a Very Large Folded Loop antenna. (Author's screen cap)

Out) is a United States military system of survivable communications links designed to be used in nuclear warfare to maintain communications between the decision makers (the National Command Authority) and the triad of strategic nuclear weapon delivery systems. Its primary mission is to serve as a signals relay, where it receives orders from a command plane such as Operation Looking Glass, and verifies and retransmits their Emergency Action Messages (EAMs) to U.S. strategic forces. As it is a dedicated communications post, it features the ability to communicate on virtually every radio frequency band from very low frequency (VLF) up through super high frequency (SHF) using a variety of modulations, encryptions, and networks, minimizing the likelihood that an emergency message will be jammed by the enemy."[13]

The wiki adds that "a west coast alert base at Travis AFB, California" near Sacramento, hosts some of the operating aircraft. So, too, other sources.[14] Popular Mechanics[15] recently ran an article titled: "This Unarmed Plane Is the Deadliest in the U.S Arsenal. The E-6 Mercury doesn't carry any weapons, but it could end civilization as we know it."

A Russian website conveniently collects some 20 of the TACAMO VLF frequencies from 19.7 kHz to 29.6 kHz.[16] Other sources also list 27 kHz.[17]

Each TACAMO aircraft, (in this case an E-6 "Mercury"— a modified Boeing 707, in December 2019) flies a unique spiral pattern (Fig. 39) above the sea, with a 200 kilowatt VLF transmitter.

This aeronautical event was reported in *The War Zone*,[18] titled "Here's Why An E-6B Doomsday Plane Was Flying Tight Circles Off The Jersey Shore Today." Part

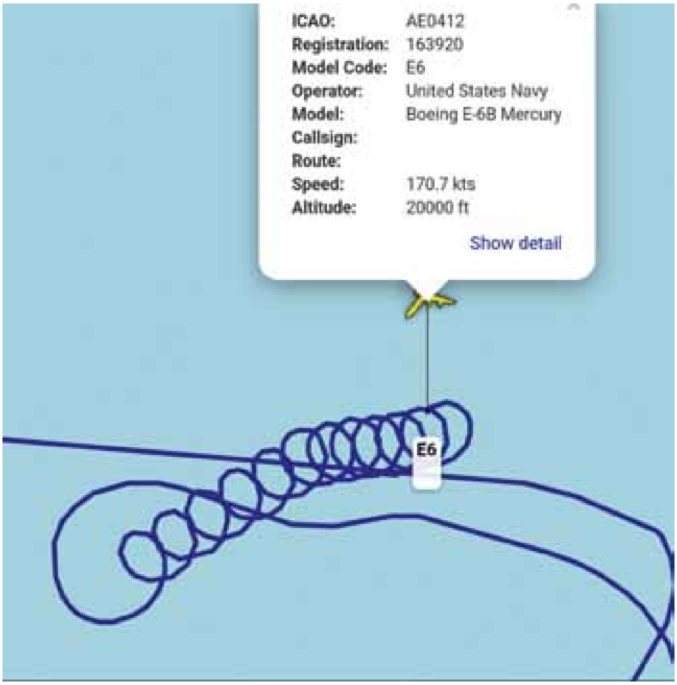

Fig. 39. As plane-spotting goes, this is as good as it gets; this diagram with data was posted by "Evergreen Intel @vcdgf555" on Twitter on December 12, 2019. The note reads "ICAO: AE0412, Registration: 163920, Model Code: E6, Operator: United States Navy, Model: Boeing E-6B Mercury, Callsign: (blank), Route: (blank), Speed: 170.7 kts , Altitude: 20000 ft. (Evergreen Intel @vcdgf555)

of the E-6B's critical mission is to fly aerobatic-like maneuvers that allow them to send messages to ballistic missile submarines hiding below.

The article reports: "The E-6B's primary VLF antenna is just over five miles long. It also has a shorter one that is deployed via a trapdoor arrangement in its tail. The VLF antennas are stabilized with a drogue on its trailing end. The idea is to get the antennas as close to vertical as possible for maximum transmission effectiveness. This is done by putting the aircraft into a very steep and tight banking turn at a slow speed and above 20,000 feet, not far above the aircraft's stall speed. These turns are repeated, oftentimes for hours at a time, as messages are sent."

Given the strength of the signals received here in the San Francisco Bay Area, the transmitter likely flew just off the West Coast. The observed signals often (but not always) seem to end at about 03:00 UTC.[19]

Almost all VLF transmissions, by our navy and other countries, are long range and strategic in nature. The VLF TACAMO system, on the other hand, is tactical. An alphanumeric single sideband voiced Emergency Action Message, as heard for years as "Sky King" on HF

Air Force frequencies, is relatively short. As data, it would be minuscule. But the MFSK bandwidth of 800 Hz suggests a great deal of digital data going down to one or more submarines. This is likely not email for sailors. It may well be a drill (or not) of retargeting data for the Boomer subs. Sometimes a much narrower signal appears; in this case several minutes before the wide signal; see Fig. 37.

The nearby navy MFSK stations at 200 Hz bandwidth, for comparison, are shown in Table 3. Note the 2.6 kHz gap between the navy's NPM and NAA center frequencies. This leaves plenty of bandwidth into which the navy can slot an 800 Hz wide MFSK signal if needed.[20] No intentional interference from any foreign land station is likely because of the difficulty of retuning VLF transmitters.

Sometimes this signal appears with perhaps two internal carrier frequencies (see the screen capture graphic of Fig. 40), at time 02:41:31. The signal approximates a 100 Hz bandwidth. TACAMO has been listed at sometimes 50 Hz and 190 Hz bandwidths in F1B modulation. F1B is frequency modulation, one channel, radioteletype or digital. Perhaps this

Table 3. Navy MFSK stations operating at 200 Hz bandwidth.

Station	Frequency (kHz)	Location
NPM	21.4	Lualualei, Hawaii
NAA	24.0	Cutler, Maine
NLK	24.8	Seattle, Washington
NML	25.2	LaMoure, N. Dakota

Fig. 40. This initial 22.7 kHz signal's bandwidth may be 100+ Hz, early in the evening of May 1, 2020. This signal is stronger than NLK in Washington state ("Jim Creek") at 24.8 kHz, bandwidth 200 Hz. (Author's screen cap)

trace shows two such signals in parallel. Shortly after this capture, the signal ended and then came up at 800 Hz bandwidth, as shown in Fig. 41.

Available receiving antennas can provide some directionality. The paired verticals at 40+ feet high at K6VK are omnidirectional. Their signals appear at the top of the next capture, Fig. 42.

The next level down is a large, single wire loop about an average 10 feet high and 120+ feet long, in an "L", first North/

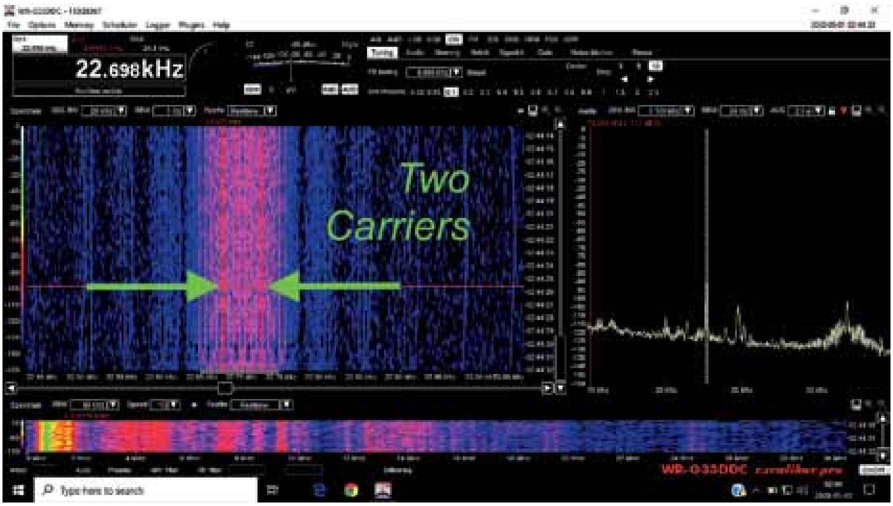

Fig. 41. The signal's bandwidth grows to 800 Hz with two internal carriers at 02:44 UTC. (Author's screen cap)

Fig. 42. The signal on 22.7 kHz at 02:56 UTC by way of four differentially directional antennas, the north-south VLFL loop was strongest at 46 microvolts on the WinRadio G33 at K6VK. (Author's screen cap)

South then East/West. It returns the strongest signals from the West. In this case, the signal is stronger than that received by the verticals. The North and East stations are weaker than on the verticals. Hawaii NPM is about the same strength. The third level down is a single turn (somewhat kinked) copper pipe large loop. It receives the best North/South. Only the 22.7 kHz signal appears. The lower band is a multiturn Very Large Folded Loop. It sees the 22.7 kHz signal as strongest (at 46 microvolts and -74 dBm) and NLK Jim Creek is comparable (and due North). One can infer from this rough data that this signal comes roughly from the North.

The signal of Fig. 43 was first observed at K6VK in November 2019. Its strength was comparable to NPM in Hawaii. Perhaps the aircraft then flew in that area. The aircraft usually fly at least at 20,000 feet altitude and NPM is not much above sea level.

The navy has hardened the TACAMO aircraft (Fig. 44) against nuclear blast and atomic-bomb-created electromagnetic pulse radiation (EMP). In

Fig. 43. The mystery signal as first logged at K6VK on November 8, 2019, at 22.7 kHz about 04:00 UTC (local late evening), on the WinRadio G33. (Author's screen cap photo)

Fig. 44. From "The War Zone"— a TACAMO aircraft in flight.

the event of a war, a TACAMO aircraft would be a very safe place to be—for a while.

XII. Long Wave Citizen Science: A Simple and Successful VLF Radio Eclipse Experiment

On August 21, 2017, many radio enthusiasts became Eclipsians, to monitor the effects of the total solar eclipse on radio reception. CHRS radiomen in the VLF interest group, John Staples, John Stuart, Paul Shinn, and the present writer did so. Another total eclipse for North America will happen in 2024.

The U.S. Navy VLF station NML in North Dakota transmits data at 25.2 kHz at high power. Its signal path to California crosses the path of totality shown in Fig. 45. The intersection would occur in the morning at about quarter to eleven, as shown on the map. A simple setup at K6VK produced the results recorded in the graph in Fig. 46.

The signal strength of NML doubled when the path of totality came between the transmitter and the K6VK SDR receiver. Before this intersection, about 1.5 microvolts came down the antenna (the usual daytime strength). At the maximum cross of the paths, that shot up to 3.1 microvolts (about a 6 dB increase); see Fig. 47. That strength then decayed back to normal at about the same rate it had increased.

To record the data, an Apple® iPhone sat in a stable jig, pointed at the screen of the WinRadio® G33 SDR (software-defined radio). Set to time lapse, it recorded about 4 hours of display in 30 seconds of video. The numbers in the graph derive from that video.

Fig. 45. The 2017 Solar Eclipse and VLF station NML signal at 25.2 kHz path Intersection.

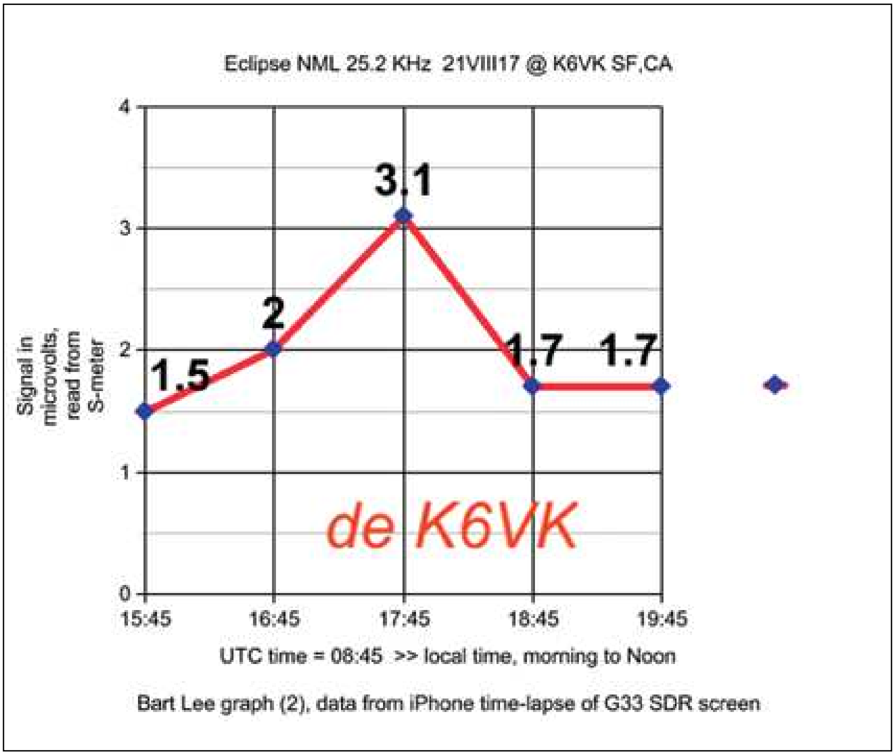

Fig. 46. Graph of increase in VLF station NML (ND) signal strength in California during the eclipse, 6dB+. (Author)

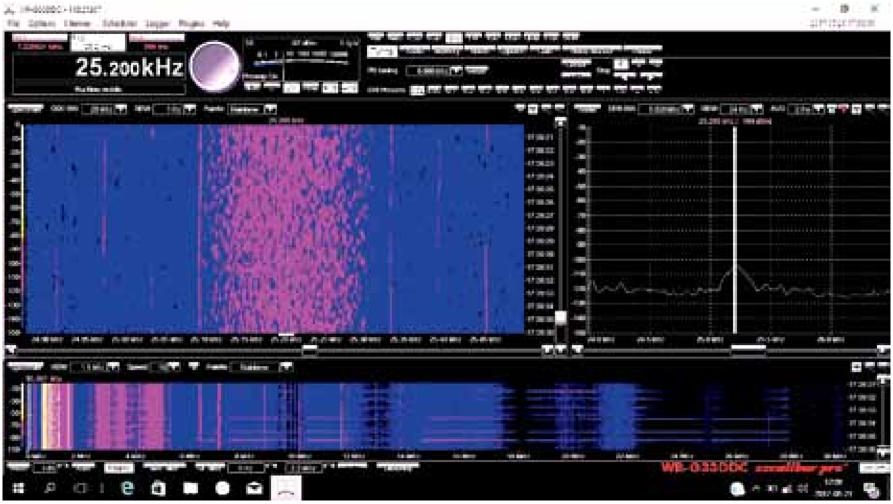

Fig. 47. Maximum signal strength at K6VK at maximum umbra intersection, 3.1 microvolts. (Author's screen cap)

John Stuart also recorded a jump in signal strength for NML, but with more precision. Ionospheric research during the eclipse[21] discovered a "bow-wave" (Fig. 48), which is consistent with the signal strength data for NML as received in San Francisco.

John Staples and John Stuart also recorded WWVB on 60 kHz. Although that signal path was south of totality, major effects appeared. John Stuart observed and recorded these effects on WWVB in the graph in Fig. 49.

Paul Shinn, K6FRC, monitored a long wave beacon some distance away from his home near Lodi, California, both south of totality, and also noted an increase in signal strength. Gilles

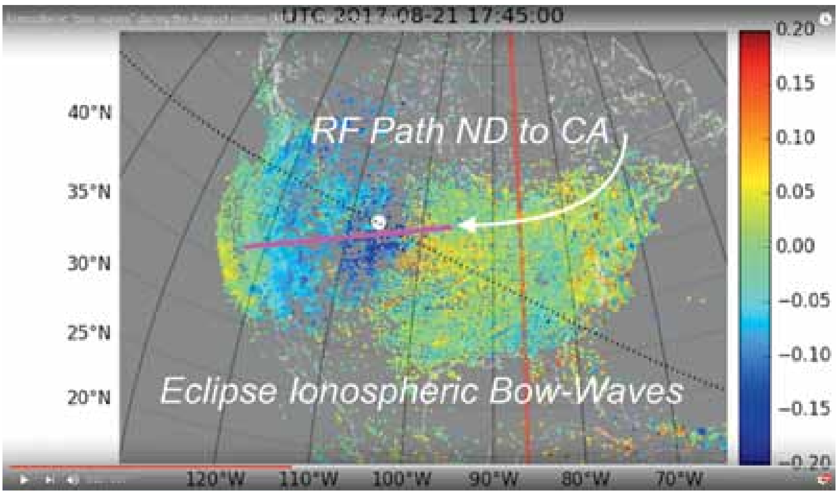

Fig. 48. The ionospheric bow wave (in blue) of the eclipse and the NML signal path. (Source: http://www.skyandtelescope.com/astronomy-news/solar-eclipse-made-bow-waves-earths-atmosphere)

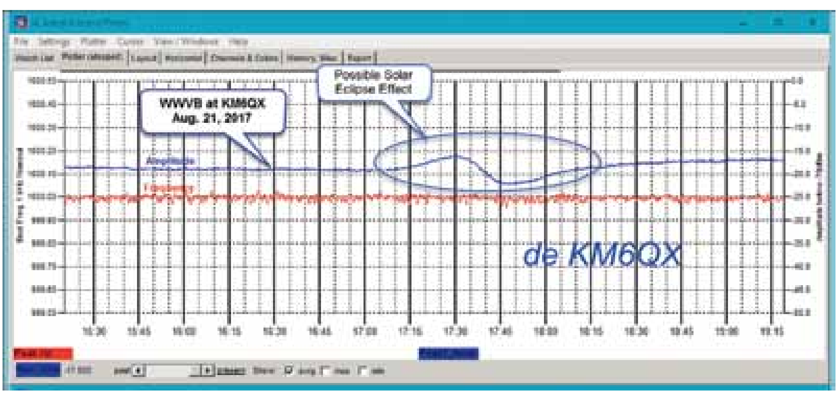

Fig. 49. WWVB at 60 kHz amplitude variation during the eclipse at KM6QX. (John Stuart)

Vrignaud noted that the ARRL's *QST* magazine reported amateur radio experiments during a 1932 eclipse. European amateurs did long wave reception experiments in the 1970s. The consistent result is significant changes in signal strength during an eclipse. The ionized layer high above us, first postulated by Oliver Heaviside in 1902, seems still to be working just fine, even when challenged by a solar eclipse.

XIII. Conclusion: Do It!

Long wave radio is alive and well. All are welcome, as radio receiving stations and even as unlicensed transmitting stations—and, of course, as licensed amateur radio operators. The Cradle of Radio still has much to offer the long wave enthusiast. The Long Wave Club of America would be delighted for you to visit its website, and join up. Join the CHRS VLF Special Interest Group; we'll help you see and hear radio history and today's amazing variety of signals. A wire up a tree, a small homebrew loop antenna, and a PC with a sound card is all it takes. Of course, other aspects of modern technology, such as the SDRs, can make this enthusiasm even more rewarding. Winter nights come every year, and the long wave stations flood the ether. Enjoy!

For the history-minded, Wikipedia is a goldmine of useful information and interpretive analysis. It's usually accurate. Internet searches on topics of interest will yield enormous amounts of reproduced old-time books, journals, and magazines. Many current websites will show and tell you about long wave radio, including YouTube.

Editor's note:
This is an update and expansion of articles previously published in various issues of the *California Historical Radio Society's Journal*. The author expresses his gratitude to the *CHRS Journal* editor, Richard Watts for always going the extra mile.

Endnotes

1. Jack Belrose, Introduction "ELF/VLF/LF Radio Propagation [etc.]," pp. 1–3 (NATO, 1993), http://www.dtic.mil/dtic/tr/fulltext/u2/a267991.pdf
2. Captain Linwood S. Howeth, USN (Retired), *History of Communications-Electronics in the United States Navy*, 1963, table at http://earlyradiohistory.us/1963hwm.htm
3. http://www.navy-radio.com/commsta/wailupe.htm
4. http://www.navy-radio.com/commsta/arlington/NAA-Pages%20from%20Vol3No3-2.pdf
5. L. A. Gebhard, *Evolution of Naval Radio-Electronics and Contributions of the Naval Research Laboratories* (1979), especially Ch. 3 on VLF. www.dtic.mil/dtic/tr/fulltext/u2/a084225.pdf
6. J. A. Adcock, VK3ACA, "Propagation of Long Radio Waves," *Amateur Radio* [Australia], June to Sept. 1991, as cited in *QEX*. But cosmic background radiation is very weak, although cosmic rays of high energy are constant. The Adcock article suggests nighttime low-level ionization in the D-layer promotes transmission. During the day, sunlight maximizes D-layer ionization.
7. See: http://www.navcen.uscg.gov/images/Plots/Site_Map_No_CHinch_Lg.jpg
8. http://www.angelfire.com/mb/amandx/longwave.html
9. See e.g., http://radiomap.eu/links/
10. Larry Waldbillig: http://historysdumpster.blogspot.com /2014/11/the-long-wave-radio-band.html, with a recording of its program of ID and weather.
11. http://njdtechnologies.net >> 2016 Field Day
12. UDXF – UTILITY Dxers FORUM – ELF and VLF Guide Version 1.0 - updated 15 Nov. 2001 WUN - Very Low Frequency Guide - DC to 30 kHz, http://www.udxf.nl/ELF-VLF-GUIDE-v1.0.pdf
13. https://en.wikipedia.org/wiki/TACAMO
14. https://fas.org/nuke/guide/usa/c3i/e-6.htm

15. Kyle Mizokami, "This Unarmed Plane…," *Popular Mechanics*, Apr. 26, 2017.
16. http://nato.radioscanner.ru/frequencies/article107/ (data from participant "Zesty67"). The 17.9 kHz frequency is noted as "active," so maybe that's the Atlantic frequency, and 22.7 kHz the Pacific frequency. The main TACAMO frequencies seem to nest inside the main VLF frequencies.
17. See e.g., http://x264.nl/dump/VLF-Frequencies.txt
18. Tyler Rogoway, *The War Zone*, Dec. 13, 2019: https://www.thedrive.com/the-war-zone/31477/heres-why-an-e-6b-doomsday-plane-was-flying-tight-circles-off-the-jersey-shore-today
19. Time to fly home and get a good night's sleep, PST?
20. There is similarly available bandwidth around the 17.9 kHz TACAMO frequency reported as active by the Russian website, above. See Worldwide Very Low Frequency Stations at http://www.smeter.net/stations/vlf-stations.php.
21. Source: http://www.skyandtelescope.com/astronomy-news/solar-eclipse-made-bow-waves-earths-atmosphere/

About the Author

Bart Lee, K6VK, is a longtime member and Fellow of AWA and a Fellow of the California Historical Radio Society (CHRS), for which he serves as General Counsel Emeritus and Archivist, and as one of several historians. He holds the FCC General Radio Operators License (with the RADAR endorsement) and an amateur radio extra class license. He has enjoyed radio and radio-related activities in many parts of the world and a fair amount of time on the high seas. Radio technology has fascinated him since he made his first crystal set with a razor blade and pencil lead some 65 years ago. He is especially fond of those sets of which it is said: "Real radios glow in the dark."

Bart is a published author on legal and other subjects, and extensively on the history of radio. The AWA presented its Houck Award for documentation to him in 2002, and CHRS presented its 1991 "Doc" Herrold Award to him in connection with his work for the Perham Foundation Electronics Museum, which declared him an Honorary Curator and Historian. In 2001, during disaster recovery operations in New York after the 9/11 terrorist enormity, he served as the Red Cross deputy communications lead from September 12 to September 21 (in old radio talk, the "night shift trick-chief"). Bart is a retired litigator by trade, having prosecuted and defended civil cases in federal and state courts for 40 years. He is a graduate of St. John's College (the "Great Books School") and the University of Chicago Law School (on the faculty of which he served after graduation).

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Bart Lee (Photo by Paula Carmody in Indonesia.)