

A Global Survey of ELF/VLF Radio Noise

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LONG-TERM GOAL

The specific long-term goal of this project is to provide the Navy with greatly improved information about the characteristics of both natural and man-made radio noise and signals in the ELF/VLF bands (frequencies in the range 10 Hz to 32 kHz), with the object of improving the Navy's ELF/VLF radio communications.

SCIENTIFIC OBJECTIVES

The project has two related scientific objectives. The first objective is to improve knowledge of the sources of radio noise in the ELF/VLF band; the second is to improve knowledge of the propagation of ELF/VLF radio noise and man-made signals in the earth's environment, i.e., in the earth-ionosphere waveguide, in the magnetosphere, in the sea, and in the earth's crust.

APPROACH

An important feature of the project since its commencement has been its heavy emphasis on measurement, starting (in 1985) with the installation of eight ELF/VLF radio noise measurement systems around the world, including high (polar) latitudes. When in operation, each of these systems continuously computes the following radio noise statistics: the root-mean-square (rms), average, maximum, and minimum amplitude of the noise in 16 narrow frequency bands (5% bandwidth) distributed through the range 10 Hz to 32 kHz. The noise statistics are computed at the end of every minute from 600 amplitude measurements made at the rate of 10 per second on the envelope of the noise signal emerging from each narrow-band filter. Later processing of these data can, with little additional computation, give the V_d and F_a statistics, and amplitude probability distributions (APDs) are also readily derived from the sampled data. These data are recorded on digital magnetic tape and shipped back to Stanford University, where they are analyzed.

In addition to the data from the narrow-band filters described above, broad-band ELF digital data (~1 – 400 Hz), sampled at a rate of 1000 samples per second during one minute each hour, are also recorded on the digital tape. These data can be quickly processed to give spectrograms, which provide an essential check on the quality of the narrow-band digital measurements in the ELF range. A similar broad-band picture of activity in the overall ELF/VLF range is provided by simultaneous one-minute analog recordings of the radio noise in the range ~200 Hz to 32 kHz. These broad-band data can be processed to provide further noise statistics. For example, statistical analyses of the time between noise pulses can be quickly computed. The data are also an invaluable resource for further research. To illustrate, they have enabled quantitative studies to be made of the variation of APDs with the

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bandwidth of the measurements, and they have enabled us to carry out the first tests using real experimental data, of theoretically-derived probability density functions for ELF/VLF radio noise.

Because the principal source of ELF/VLF radio noise is the lightning occurring in thunderstorms around the world, our noise measurements relate closely to global weather and thus they are capable of providing independent and, as it turns out, entirely new information on two topics of great current relevance: global climate change (or global warming) and possible sun-weather relations.

The value of our measurements at Arrival Heights has been recognized by the Office of Polar Programs of the National Science Foundation, which has provided all the logistical support for the Antarctic station since it was first installed. The continued operation of the station has been subject to NSF/OPP's usual peer review process, and our measurement program has always been rated excellent.

WORK COMPLETED

We have built up an extensive database of ELF/VLF noise measurements extending back to 1985 and it is probably true to say that there is no comparable database of low-frequency radio noise measurements available elsewhere. Since most of our original data acquisition goals have been achieved, only two of the original eight ELF/VLF radio noise measurement systems installed around the world at the start of this project are currently being maintained in continuous operation (Stanford, USA, and Arrival Heights, Antarctica); four of the others (Sondrestromfjord, Greenland; Kochi, Japan; Dunedin, New Zealand; Grafton, New Hampshire) remain in place and are operated intermittently during particular short-term measurement programs. The continuously operating radiometers continue to extend what are now two uniquely lengthy collections of ELF/VLF noise data.

Over the last three years, my group has carried out several extensive analyses of the ELF/VLF data to obtain new information on subjects as diverse as (1) the diurnal and seasonal variations of the noise, (2) the locations of the principal sources of ELF noise around the world, (3) how global change might be reflected in changes in global lightning and thunderstorm activity, and (4) the best theoretical models describing ELF/VLF noise. In addition, a first experimental test of the theory of propagation of ELF radio waves at large distances from the source was carried out using measurements on signals from a Russian ELF (82 Hz) transmitter.

RESULTS

Our analysis of the times of occurrence of maximum ELF noise at Arrival Heights, Antarctica, and Sondrestromfjord, Greenland, clearly establishes North America as the strongest global source of ELF (10–130 Hz) noise [*Füllekrug and Fraser-Smith, 1997*—a surprising result, since it has long been believed that the principal sources of ELF/VLF radio noise are thunderstorms in the tropical regions of the Americas, South-East Asia, and Africa.

The same analysis by *Füllekrug and Fraser-Smith, 1997* revealed a relationship between the mean seasonal variations of continental lightning in mid- and tropical latitudes and surface temperature variations in moderate- and tropical rain forest climates, and thus they support the view that monitoring of global lightning activity may provide a thermometer-independent measure of temperature changes associated with climate variability.

Data derived from a previously cited analysis of ELF noise in the Schumann resonance range (7–50 Hz) has been incorporated into a collaborative study of global weather with NASA scientists [*Anyamba et al.*, 1997].

The above work on lightning and related phenomena generating radio signals at low-frequencies led to some interesting new observations over the last year. We quantified, for the first time, the characteristics of sprite-associated ultra-low frequency (ULF; frequencies less than 5 Hz) waveforms observed in California at a distance of about 1900 km to the west of the sprite-producing thunderstorms, and we introduced the term “ultra-slow tails” for these unusual waveforms [*Füllekrug and Fraser-Smith*, 1998]. Unfortunately, our study of the sprite-associated waveforms was made after the sprites were observed and we were not recording ELF/VLF data at the time they occurred. It is possible that there are distinctive characteristics for the ELF/VLF sferics associated with sprites and we hope to follow up on this supposition during the next sprite campaign.

While carrying out the Schumann resonance study mentioned above, we discovered a strong 82 Hz signal in the ELF data recorded at most of our measurement sites around the world. With the help of Russian scientists, we identified the source of this signal: a Russian 82 Hz transmitter in the Kola Peninsula near Murmansk. Comparison of the measured amplitudes of the 82 Hz signal with theoretical estimates made by Peter Bannister provided the first experimental test at very long distances of the ELF propagation theory used by the U.S. Navy. We are happy to report that the theory did well [*Fraser-Smith and Bannister*, 1998].

By comparing our ELF measurements with a collection of electric field measurements made at the south pole by E. A. Bering, we have been able to estimate the contribution of global lightning to the global electric circuit—the circuit that maintains a roughly 100 V/m vertical electric field in fair weather regions around the world. Our analysis suggests that lightning can only account for about 50% of the global electric field [*Füllekrug, Fraser-Smith, Bering, and Few*, 1998].

An important radio noise statistic for radio communications system designers is the so-called antenna noise factor F_a . Unfortunately, this statistic is strongly linked to the antennas used for the noise measurements, and no theoretical expressions were available for us to convert our noise amplitude measurements, made with loop antennas, to F_a values (traditionally, F_a has been derived by using vertical whip—i.e., electric—antennas, but at lower frequencies loop—i.e., magnetic—antennas have better characteristics). We therefore derived a new expression for F_a as measured with loop antennas and processed our measurements to give a comprehensive collection of F_a values [*Fraser-Smith and Liu*, 1999].

Finally, during this last year, a student of mine, D. A. Chrissan, completed his Ph.D. research on the statistical properties and modeling of ELF/VLF radio noise and on improvements in low-frequency radio communications. His dissertation was completed in August 1998 and will appear as a final technical report [*Chrissan*, 1998]. A shortened version of the abstract for this dissertation is as follows:

The objective of this work is the statistical characterization and modeling of atmospheric radio noise in the range 10 Hz – 60 kHz (denoted *low-frequency* noise), with the specific goal of improving communication systems operating in this range. The analyses are based on many thousands of hours of measurements made by the Stanford Radio Noise Survey System. The statistics analyzed include seasonal and diurnal variations, amplitude probability

distributions (APDs), impulse interarrival time distributions, background noise statistics, and power spectral densities. Noise characteristics derived from these analyses are presented, and several noise models that accurately represent low-frequency noise APDs are compared. Two of the simplest models (i.e., each with only two parameters) are found to give extremely good performance in general. These are the Hall and alpha-stable models, both of which approximate the Rayleigh distribution for low-amplitude values but decay with an inverse power law for high amplitude values. Based on the statistical characteristics of the noise data, a new clustering Poisson atmospheric noise model is developed. This model is based on several previously known statistical-physical models, but in addition takes into account the clustering of spheric impulses. It is shown that the clustering model accurately predicts the statistical features found in low-frequency radio noise data.

IMPACT/APPLICATIONS

The measurements we have made of the seasonal variations and other statistical properties of ELF/VLF noise are the first statistically robust measurements available to Navy communicators. Our most recent work specifically describes improvements to low-frequency radio communications that should result from our analyses and modeling [*Chrissan, 1998*].

Our discovery that North America is the strongest global source of ELF radio noise (10–130 Hz) has obvious implications for ELF strategic communications by the US Navy. Interestingly, the same data show that the Pacific Ocean is the quietest global location.

Our analyses of the Russian 82 Hz signals [*Fraser-Smith and Bannister, 1998*] provides the first experimental test of the ELF propagation theory used by the U.S. Navy. The fact that the theoretical predictions and experimental measurements agreed out as far as antipodal distances (as far away from the source as it is possible for a submarine to get) should have an important impact on the Navy's confidence in its ELF communications. Further, our description of the Russian transmitter, derived from Russian sources, is also likely to have to be of interest to many Navy communicators.

Our publication of Fa statistics for the ELF/VLF range [*Fraser-Smith and Liu, 1997*], as well as our more general statistical analysis and modeling of ELF/VLF noise, will have application in US Navy studies of strategic communication systems.

TRANSITIONS

As we have indicated above, our ELF/VLF measurements provide new information that is directly and importantly relevant to Navy strategic communication studies.

RELATED PROJECTS

Studies of global change are becoming increasingly important, as was recently demonstrated by Vice-President Gore's attendance at the Kyoto summit on global warming. As we have noted above, our ELF/VLF measurements relate to lightning and thunderstorm activity in the tropical regions—as well as North America. We can therefore claim that our work relates to many current projects that involve studies of global warming/global change. In fact, as demonstrated by *Füllekrug and Fraser-Smith, 1997*, our analyses can provide new information on this important topic.

PUBLICATIONS

Anyamba, E., E. Williams, J. Susskind, A. Fraser-Smith, and M. Fullekrug, “The Manifestation of the Madden-Julian Oscillation in Global Deep Convection and in Schumann Resonance Intensity,” submitted to *J. Atmosph. Sci.*, July 1997.

Chrissan, D. A, “Statistical Analysis and Modeling of Low-Frequency Radio Noise and Improvement of Low-Frequency Communications,” *Tech. Report D177-3*, Space, Telecommunications and Radioscience Laboratory, Stanford University, ONR Grants N00014-92-J-1576 and N00014-93-1-1073, October 1998.

Fraser-Smith, A. C., and P. R. Bannister, “Reception of ELF signals at Antipodal Distances,” *Radio Science*, 33, 83–88, 1998.

Fraser-Smith, A. C., and F. Y. Liu, “The Antenna Noise Factor F_a for a Vertical Loop Antenna,” to appear in *Radio Science*, 1999.

Füllekrug, M., and A. C. Fraser-Smith, “Global Lightning and Climate Variability Inferred from ELF Magnetic Field Variations,” *Geophys. Res. Letts.*, 24, 2411–2414, 1997.

Füllekrug, M., A. C. Fraser-Smith, E. A. Bering, and A. A. Few, “The Contribution of Global Lightning to the Atmospheric Electric Field,” submitted to *J. Atmos. Terr. Phys.*, 1998.

Füllekrug, M., A. C. Fraser-Smith, and S. C. Reising, “Ultra-slow Tails of Sprite-Associated Lightning Flashes,” *Geophys. Res. Letts.*, 25, 3497–3500, 1998.