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FINAL REPORT

Office of Naval Research

Contract No. N00014-81-K-0382

GLOBAL MEASUREMENTS OF LOW-FREQUENCY RADIO NOISE

March 1992

R. A. Helliwell, Principal Investigator

A. C. Fraser-Smith, Associate Investigator

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER E450-1	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Global Measurements of Low-Frequency Radio Noise		5. TYPE OF REPORT & PERIOD COVERED Final Technical 01 Mar. 1981-31 Oct. 1989
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) A.C. Fraser-Smith, P.R. McGill, A. Bernardi, R.A. Helliwell, M.E. Ladd		8. CONTRACT OR GRANT NUMBER(s) Contract No. N00014-81-K-0382
9. PERFORMING ORGANIZATION NAME AND ADDRESS Space, Telecommunications and Radioscience Lab. Stanford University, 202 Durand/4055 Stanford, CA 94305-4055		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR089-171 and R&T No. 4149171
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research, Code 1114sp 800 N. Quincy Street Arlington, VA 22217		12. REPORT DATE February 1992
		13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution unlimited, approved for public release and sale

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

ELF/VLF Noise
Global Radio Noise Measurements
Radio Noise Statistics

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

We report illustrative results obtained by Stanford University's global survey of ELF/VLF radio noise (frequencies in the range 10 Hz-32 kHz). Particular comparison is made between the noise measurements made at high (polar) latitudes with those at lower latitudes. Although most of the natural ELF/VLF noise observed everywhere in the world is lightning-generated, the high-latitude noise often contains additional components that are of magneto-spheric origin. In the data we have examined, this noise consists predominantly

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by

A. C. FRASER-SMITH, P. R. MCGILL, A. BERNARDI*,

R. A. HELLIWELL, AND M. E. LADD

Final Technical Report E450-1

February 1992

Space, Telecommunications and Radioscience Laboratory,

Stanford University, Stanford, CA 94305

Sponsored by The Office of Naval Research

Contract No. N00014-81-K-0382

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*Present Address: Teknekron Communications Systems, 2121 Allston Way, Berkeley, CA 94704

INTRODUCTION

In 1980, in response to the Office of Naval Research's *Research Opportunities Announcement (1980)*, our Laboratory proposed a three-year study of ELF/VLF (10 Hz - 32 kHz) radio noise. This proposal became the basis for ONR Contract No. N00014-81-K-0382 to Stanford University for a study of the global distribution of ELF/VLF radio noise. The starting date for the project was 1 March 1981, its Principal Investigator was Professor R. A. Helliwell, and, after the first year, its Project Director was Dr. A. C. Fraser-Smith. The project originally involved the construction of seven dual-channel computer-controlled ELF/VLF radio noise measurement systems, or 'ELF/VLF radiometers,' and their deployment at various locations around the world to characterize naturally-occurring ELF/VLF radio noise on a global basis. As it turned out, after additional support was provided (1) by Rome Air Development Center through Contract No. F19628-84-K-0043, and (2) by a DoD Instrumentation Grant, which became ONR Grant No. N00014-84-G-0202, eight radiometers were finally constructed. Deployment of these radiometers started during the winter of 1985–1985, when the first system was installed at Arrival Heights, Antarctica, and ended in November 1986 when the final system began recording at Stanford.

A full technical description of the radiometers, details of their geographical locations, and a brief description of the results obtained by some previous radio noise surveys, are given in a paper entitled "The Stanford University ELF/VLF radiometer project: Measurement of the global distribution of ELF/VLF electromagnetic noise," by A. C. Fraser-Smith and R. A. Helliwell, which appeared in *Proc. 1985 IEEE Internat. Symp. on Electromag. Compatability, IEEE Catalog No. 85CH2116–2*, pp. 305–311, August 1985.

The original ONR contract for the ELF/VLF radio noise survey was extended until 31 October 1989, when the contract finally expired. However, the noise survey has continued with support from ONR Grant No. N00014-90-J-1080. The following final technical report does not therefore describe a project that has concluded, but instead it gives a snapshot of the noise survey as of 31 October 1989. A presentation of much of the content of the report was made at the URSI Symposium on Environmental and Space Electromagnetics that was held in Tokyo, Japan, during September 4-6, 1989, and it is to be published in the Symposium proceedings, *Environmental and Space Electromagnetics*, by Springer-Verlag.

ACKNOWLEDGEMENTS

Many people and several different U.S. Government agencies have contributed to this work, which involved the construction of eight major ELF/VLF receiving systems (ELF/VLF 'radiometers'), the deployment of these systems to seven locations around the world (one was kept at Stanford), including three at high latitudes, and finally the operation of these systems for a number of years. This report covers the period up to 31 October 1989, at which time our ONR contract was converted to a grant. Thus, although this is a final report, it does not mark the end of our noise survey, which is still in progress at the date of issue of the report.

We thank R. Gracen Joiner, our Office of Naval Research Scientific Officer, for his continual help and encouragement; Robin A. Simpson, our Office of Naval Research Resident Representative during the initial phases of the project, who facilitated the deployment of our equipment around the world; Paul A. Kossey, now of the Air Force's Phillips Laboratory, and John P. Turtle of the Rome Air Development Center, for their assistance with the Thule, Greenland, receiving system; John D. Kelly of SRI International for his assistance in locating and operating a receiver at Søndrestrømfjord, Greenland; Benson T. Fogle and John T. Lynch of the Division of Polar Programs of the National Science Foundation for their help with logistics support for our receiver at Arrival Heights, Antarctica; Antonio Meloni of the Istituto Nazionale di Geofisica for assistance locating one of our receivers near L'Aquila, Italy; Toshio Ogawa of Kochi University, for assistance locating one of our receivers near Kochi, Japan; Richard L. Dowden and Neil R. Thomson of the University of Otago, for assistance locating one of our receivers near Dunedin (at Swampy Summit) in New Zealand; Evans W. Paschal, of the STAR Laboratory, for designing the receiving systems; Bruce R. Fortnam, of the STAR Laboratory, for supervising much of the construction, for installing several of our receivers, and for helping to write the initial data processing software; and Kevin G. Smith, also of the STAR Laboratory, for his help installing the receiver in Japan. We also thank the many undergraduate students who spent so much time soldering circuit boards and otherwise assembling the equipment: we have never had any difficulties with any of the receivers that can be attributed to their work.

We must also thank certain of the receiver operators for their help: Denise Rust and some of the other staff of the Incoherent Scatter Radar Facility at Søndrestrømfjord; Paolo Palangio of the Istituto Nazionale di Geofisica (for operating the L'Aquila radiometer); Michael Pot and Stephen Pearce of the University of Otago (for operating the Dunedin system).

None of the radio noise measurements in Greenland would have been possible without the generous permission of the Danish Commission for Scientific Research in Greenland; we thank Jørgen Taagholt for his excellent liason work.

This research was sponsored by the Office of Naval Research through Contract No. N00014-81-K-0382. Support for the measurements at Thule, Greenland, was provided by Rome Air Development Center through Contract No. F19628-84-K-0043. Logistic support for the measurements at Søndrestrømfjord, Greenland, and Arrival Heights, Antarctica, was provided by the National Science Foundation (NSF) through NSF cooperative agreement ATM 88-22560 and NSF Grant DPP-8720167, respectively. A Department of Defense Instrumentation Grant provided through the Office of Naval Research (ONR Grant No. N00014-84-G-0202) provided important support for additional equipment purchases.

[Paper Presented at the URSI Symposium on Environmental and Space Electromagnetics, Tokyo, Japan, September 4-6, 1989]

GLOBAL MEASUREMENTS OF LOW-FREQUENCY RADIO NOISE

A. C. Fraser-Smith, P. R. McGill, A. Bernardi, R. A. Helliwell, and M. E. Ladd

Space, Telecommunications and Radioscience Laboratory, Stanford University, Stanford, California 94305, U.S.A.

ABSTRACT

We report illustrative results obtained by Stanford University's global survey of ELF/VLF radio noise (frequencies in the range 10 Hz – 32 kHz). Particular comparison is made between the noise measurements made at high (polar) latitudes with those at lower latitudes. Although most of the natural ELF/VLF noise observed everywhere in the world is lightning-generated, the high-latitude noise often contains additional components that are of magnetospheric origin. In the data we have examined, this noise consists predominantly of polar chorus, which is concentrated in the range 300 Hz–2 kHz. It produces a characteristic signature in the noise statistics. Less frequent occurrences of broad-band (auroral) hiss can occasionally mask most or all of the lightning-generated noise in the ELF/VLF range.

1. INTRODUCTION

As we have previously reported [1, 2], our Laboratory is presently conducting a global survey of extremely-low frequency (ELF) and very-low frequency (VLF) radio noise (specifically, the survey covers frequencies in the range 10 Hz – 32 kHz). Our three high latitude stations are Thule (TH: 76.5° N, 68.8° W) and Søndrestrømfjord (SS; 67.0° N, 50.1° W) in Greenland, and Arrival Heights (AH; 77.8° S, 193.3° W) in the Antarctic, and the magnitudes of the geomagnetic latitudes for these stations range from 77° (SS) up to 87° (TH), thus ensuring that their data include representative samples of ELF/VLF radio noise of magnetospheric origin (e.g., chorus and hiss), in addition to the lightning-generated noises (predominantly sferics) that typically dominate at our five lower latitude stations (Grafton, New Hampshire (43.6° N, 72.0° W); L'Aquila, Italy (43.4° N, 13.3° E); Stanford, California (37.4° N, 122.2° W); Kochi, Japan (33.3° N, 226.5° W); and Dunedin, New Zealand (45.8° S, 189.5° W)).

The radio noise statistics computed continuously at each of the stations consist of the average, root-mean-square (rms), maximum, and minimum amplitudes in 16 narrow frequency bands (5% bandwidth) distributed through the ELF and VLF ranges (Table 1). They 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. In addition, amplitude probability distributions (APD's) can also readily be derived from the sampled data. These various statistical quantities are widely used to characterize radio noise and they are described in several reports issued by the International Radio Consultative Committee, or CCIR [e.g., 3, 4].

Comparison of the noise statistics between the high and moderate-to-low latitude locations reveals many similarities and much stability of the statistics over time; but there are also some major differences. Many of the differences consist simply of expected changes in the average levels of the statistical quantities. However, some of the changes in the statistics are caused by differences in the nature of the noise, and in particular by the occurrence of magnetospheric noise. In the data we have examined, this noise consists most frequently of polar chorus [5], which consists of a band of hiss with rising tones (as originally defined in [5]), and in our measurements it is concentrated in the range 300 Hz – 2 kHz. It produces a characteristic signature in the noise statistics, which makes its presence relatively easy to identify. Less frequently, broad-band (auroral) hiss occurs, and on occasion it can be sufficiently strong to mask some or all of the lightning-generated noise in the ELF/VLF range. The noise statistics are less effective in distinguishing between this hiss and

TABLE 1. Center frequencies and bandwidths for the 16 channels of the ELF/VLF noise measurement systems.

Channel	Center Frequency	Bandwidth (5%)
1	10 Hz	0.5 Hz
2	30	1.5
3	80	4
4	135	6.75
5	275	13.75
6	380	19
7	500	25
8	750 Hz	37.5
9	1 kHz	50
10	1.5	75
11	2	100
12	3	150
13	4	200
14	8	400
15	10.2	510
16	32 kHz	1600 Hz

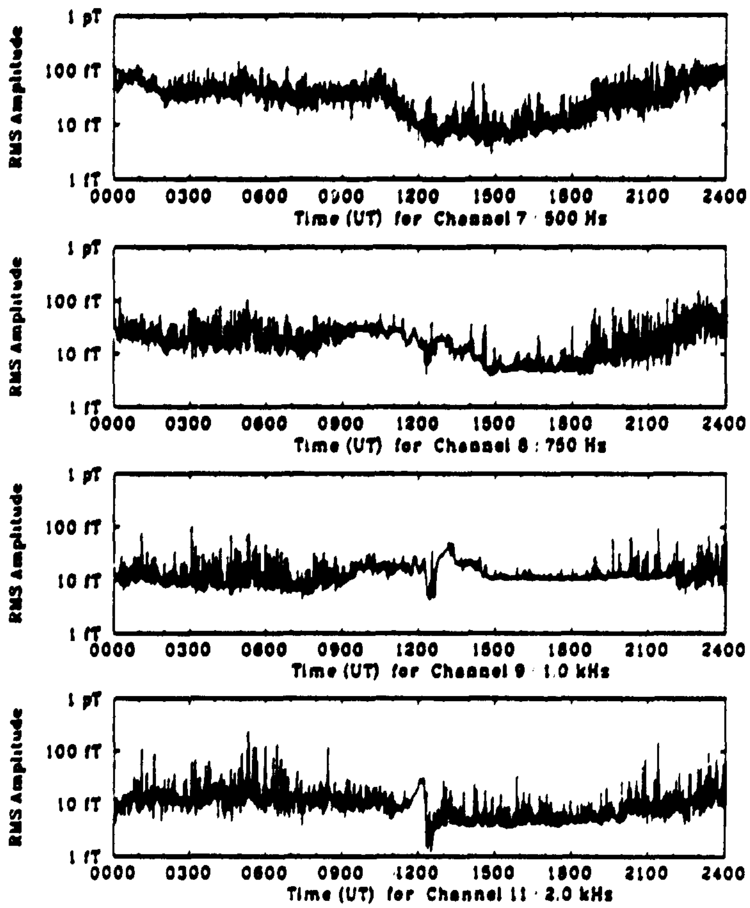

Fig. 1. Variation of the 500 Hz, 750 Hz, 1 kHz, and 2 kHz one-minute rms magnetic field amplitudes at Søndrestrømfjord, Greenland, during 13 November 1986 (UT). The applicable frequencies are shown under each panel. The amplitudes are given either in units of picoTesla (pT) or femtoTesla (fT; 1 pT = 10^3 fT = 10^{-12} T).

the lightning-generated noise, although the very strong auroral hiss events produce characteristic signatures in the statistics.

Even a partial presentation of the noise statistics being obtained by our survey would be outside the scope of this paper. We therefore concentrate on the presentation of illustrative results, with particular emphasis on the magnetospheric noise that is observed at high latitudes, sometimes quite commonly, and sometimes very strongly.

2. AMPLITUDE MEASUREMENTS

In Figure 1 we show the diurnal variation of the 500 Hz, 750 Hz, 1.0 kHz and 2.0 kHz one-minute rms amplitudes that were measured at Søndrestrømfjord on 13 November 1986. It was early winter at the measurement location; there were no local thunderstorms, and there were only a few hours of sunlight (local time at SS is 3 hours behind UT; thus 0300 UT corresponds to local noon). The data are typical in that they show considerable impulsiveness, or 'spikiness,' due to the transient and irregular nature of the sferics that are the predominant form of noise signal. Most of the time, at all frequencies covered by this study, plots of the daily variations of the one-minute average or rms amplitudes will resemble the data shown in the top panel of Figure 1, except for a general reduction in the impulsiveness for frequencies below ~ 250 Hz.

In the three lower panels of Figure 1, it will be noticed that the impulsiveness of the data tends to go through a minimum in the interval 1000–2000 UT (a 10-hour interval very roughly centered on local noon), and for some smaller sub-intervals the character of the data change entirely. For example, during the interval 1100–1230 UT the impulsiveness of the 2.0 kHz amplitude data almost completely disappears and there is an abrupt change in the average level of the amplitudes. These changes are not typical of the normal sferic noise background for the chosen frequencies, nor are they typically observed at (1) frequencies above or below the range 300 Hz – 2.0 kHz, or (2) at middle and low latitudes. We have come to recognize them as signatures for the occurrence of polar chorus in the range 300 Hz – 2 kHz. The changes are even more clearly defined in plots of the 'voltage-deviation,' or V_d, statistic, which is a specific measure of the impulsiveness of noise. We will further discuss these occurrences of magnetospheric noise in a later section.

The one-minute average data illustrated in Figure 1 can be processed in many different ways to give additional information about the morphology of ELF/VLF noise, about its modes of propagation, and about its sources [e.g., 6, 7]. One important form of processing we use is to compute average or rms amplitudes over longer time intervals, usually one- or three-month intervals. Figure 2 illustrates one form of these longer averages, using data once again from Søndrestrømfjord. Taking all the SS one-minute average amplitudes for January 1987 (the middle of the northern winter), we have computed and plotted the average noise amplitude at each of our 16 measurement frequencies for each of the eight three-hour time divisions of a 24-hour UT day. The result is a set of eight spectral distributions which provide information about the diurnal variation of the ELF/VLF noise spectrum at Søndrestrømfjord in January 1987.

Taking a general view of the amplitude data in Figure 2, there is roughly an inverse relation with frequency that is typical of all the measurements we have made in our noise survey, and which also appears to be typical of a much broader frequency range including and extending on either side of the ELF/VLF range [1]. Looking at the data in more detail, we see considerable diurnal variation, with the largest amplitudes tending to occur around 0000–0300 UT and the smallest around 1200–1500 UT. The magnitude of the diurnal variation is frequency dependent: in the frequency range 3–8 kHz the largest average amplitude is nearly ten times greater than the smallest, whereas at 80 Hz there is little difference between the amplitudes. This variability may be solely a northern high latitude phenomenon, since it is not duplicated by the data from Arrival Heights for the same month (Figure 3) or for the month of June 1986, which is an equivalent winter month in the southern hemisphere (Figure 4).

The Arrival Heights ELF/VLF measurement system was the first of our noise survey systems to be set in operation and its data base is therefore the most extensive that is available to us. In

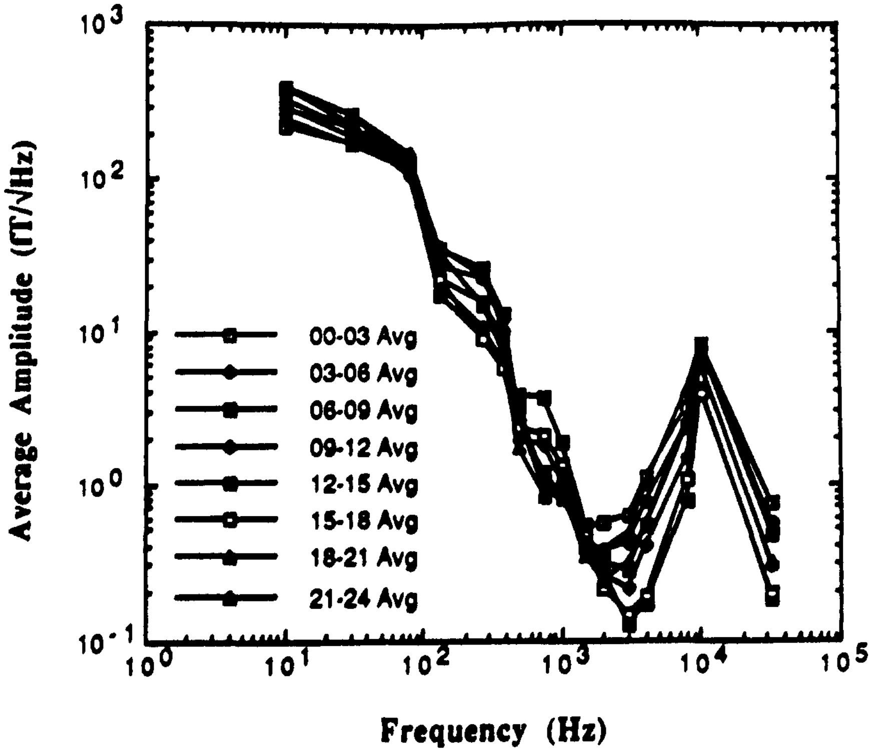

Fig. 2. Variation of the Søndrestrømfjord ELF/VLF noise amplitudes for the month of January 1987. Overall average amplitudes for each of the 16 narrow band frequencies are shown, and the data are broken down into eight 3-hour time blocks, starting with 0000–0300 UT.

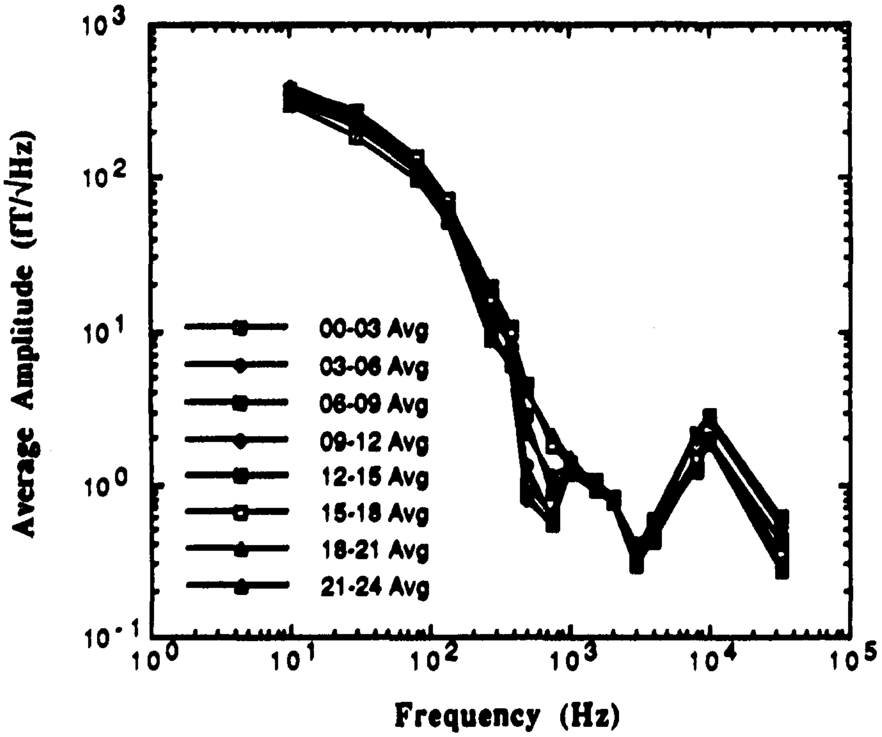

Fig. 3. Variation of the Arrival Heights ELF/VLF noise amplitudes for the month of January 1987. Overall average amplitudes for each of the 16 narrow band frequencies are shown, and the data are broken down into eight 3-hour time blocks, starting with 0000–0300 UT.

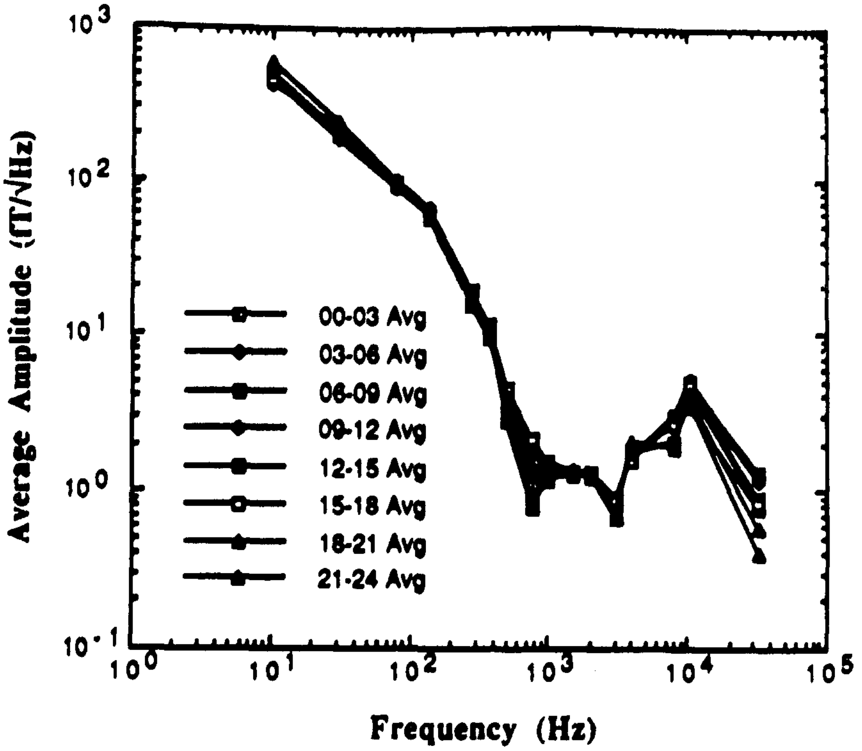

Fig. 4. Variation of the Arrival Heights ELF/VLF noise amplitudes for the month of June 1986. Overall average amplitudes for each of the 16 narrow band frequencies are shown, and the data are broken down into eight 3-hour time blocks, starting with 0000–0300 UT.

Figure 5 we illustrate the longer term variability of the ELF/VLF noise amplitudes by plotting their overall average values against frequency for each January and July in the two year interval starting January 1986. It can be seen that there is remarkably little difference between the amplitudes at frequencies below 1 kHz, but that there appear to be significant differences at the higher frequencies. However, even at the higher frequencies the year-to-year changes are not as marked as the figure suggests because the higher amplitudes are all measured during the southern winter. If we accept the evident seasonal variation, there is once again little difference in the amplitudes. This is particularly clear at 32 kHz, where the amplitudes for the three January months are nearly identical.

Finally, to illustrate some of the similarities and differences between the high and low latitude noise amplitudes, in Figure 6 we show the variation with frequency of the overall monthly average amplitudes of the June 1986 measurements at Thule, Søndrestrømfjord, and Arrival Heights, and the July 1987 measurements at Kochi. They are all summer season measurements except for those at Arrival Heights, which are taken during the southern winter. Despite the difference in season, there is close agreement between the Arrival Heights and Søndrestrømfjord monthly averages. The Thule averages also correspond reasonably well with those of the two other high latitude locations above 2 kHz, but at lower frequencies they are substantially higher. The Kochi noise amplitudes shown in the figure are roughly representative of the amplitudes that can be measured at middle and low latitudes during summer months. They are generally greater than the amplitudes measured simultaneously at high latitudes by some factor in the range 2–10, with the greatest differences occurring at the higher frequencies.

High ELF noise amplitudes have been a consistent feature of our measurements at Thule. Although Thule is particularly close to one of the geomagnetic poles, and therefore differs in that respect from our other measurement locations, there is no reason to expect higher ELF noise amplitudes near a geomagnetic pole and there is no previous record of such higher amplitudes being measured. At this time therefore we tentatively ascribe the high amplitudes to broad band ELF interference from the nearby air base.

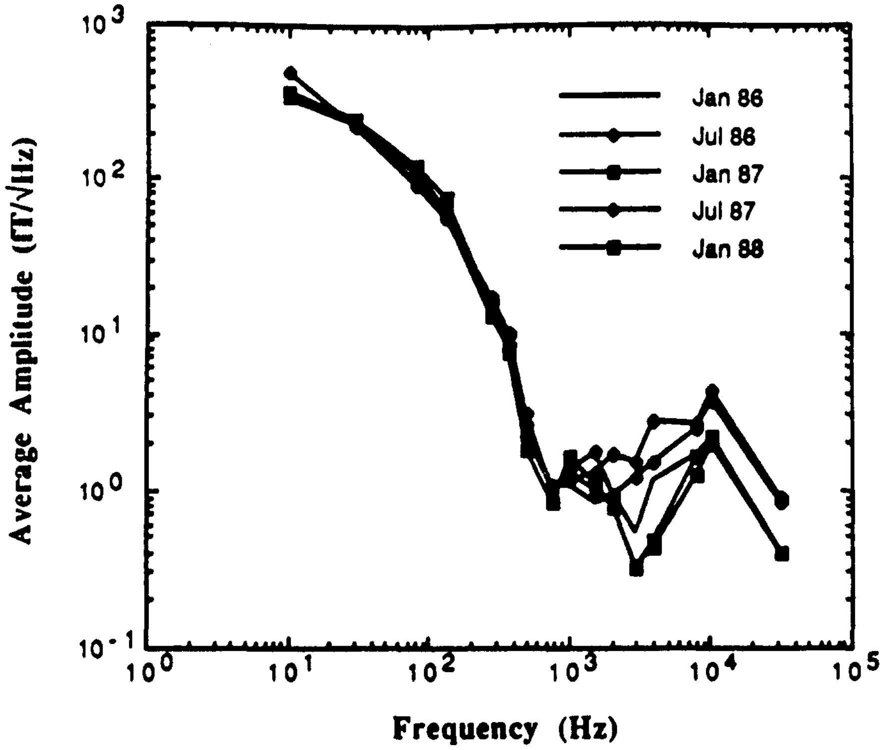

Fig. 5. Variation of the Arrival Heights overall average ELF/VLF noise amplitudes for each January and July in the two-year interval starting January 1986.

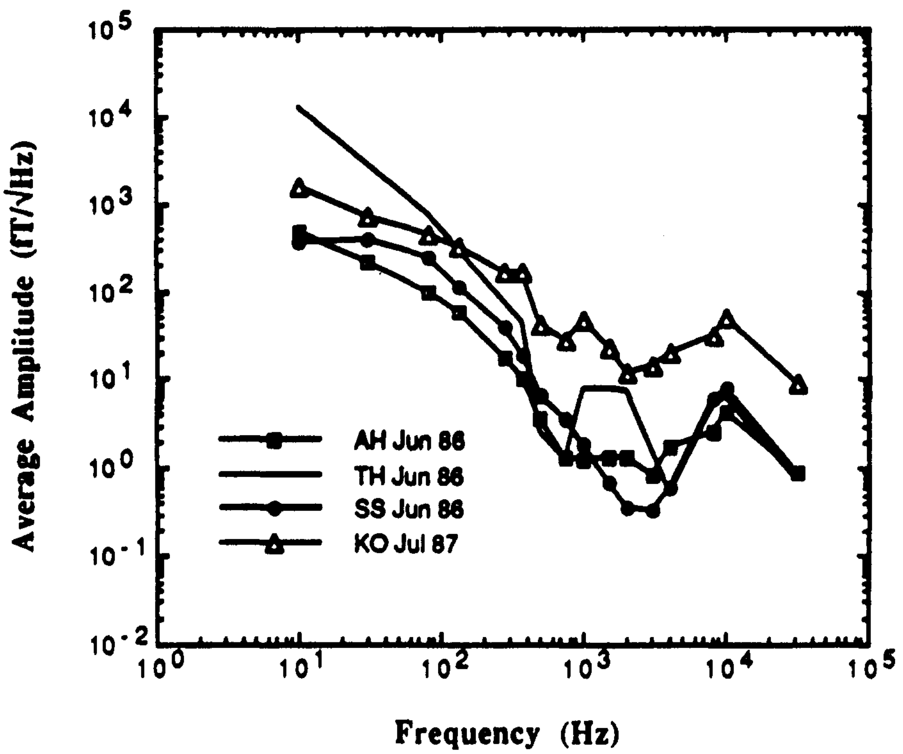

Fig. 6. Variation of the overall average ELF/VLF noise amplitudes measured at Thule, Søndre-strømfjord, and Arrival Heights during June 1986, and at Kochi during July 1987.

3. V_d MEASUREMENTS

In Figure 7 we show a representative sample of our V_d measurements. The measurements were made at Søndrestrømfjord during June 1986 and overall monthly average values of the maximum, minimum, and average one-minute V_d's are shown for each of the 16 narrow band frequencies. A tendency for the values of V_d to increase gradually from a level near 1 at the lowest frequency (10 Hz) to a level near 10 at the highest frequency (32 kHz) is a feature of the measurements shown in the figure and it is typical of the measurements we have made on purely sferic noise.

The presence of magnetospheric noise generally results in reduced values of V_d in the frequency bands in which the (non-sferic) noise occurs. Since magnetospheric noise is not always observed, whereas sferics are always present (even though they may be masked by the other noise), the first evidence for magnetospheric noise in monthly plots of V_d such as the one shown here is observed in the plots of minimum V_d values. This can be clearly seen in Figure 7, where the pronounced dip in the minimum V_d values in the range 380 Hz to 2 kHz is the result of the occurrences of polar chorus during the month. As the magnetospheric noise increases in frequency of occurrence and intensity it begins to produce changes in the monthly average values of V_d as well as in the minimum values. Presumably, if there were further increases, the maximum values of V_d would begin to be affected as well, but we have not so far observed such sustained levels of non-sferic noise.

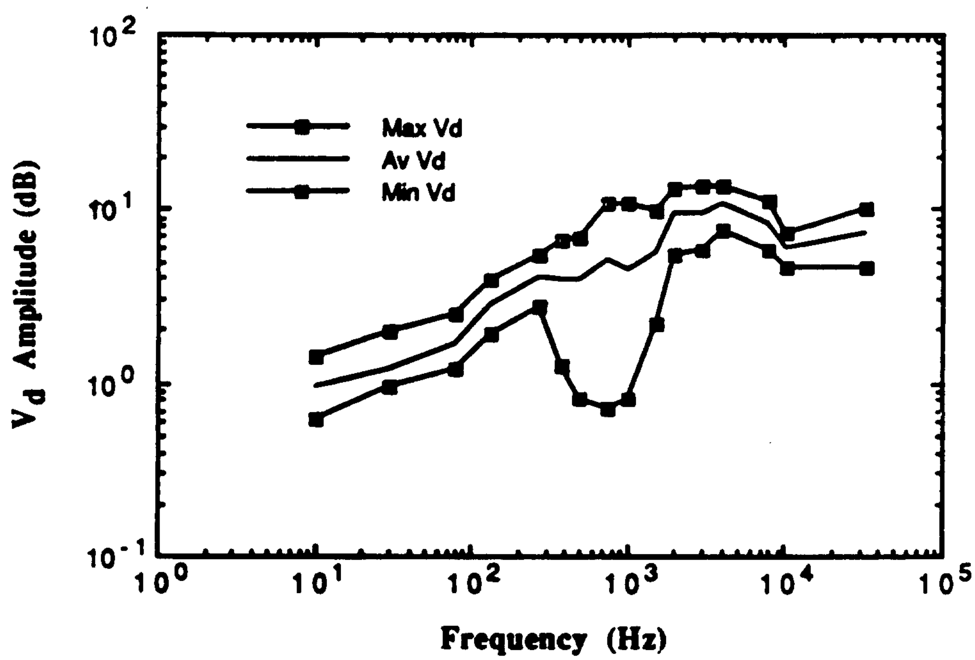

Fig. 7. Variation with frequency of V_d at Søndrestrømfjord for the month of June 1986.

4. EXAMPLES OF MAGNETOSPHERIC NOISE

We now show spectrograms of the two predominant forms of the non-sferic, or magnetospheric, noise that are observed at high latitudes. As we have mentioned, the most commonly observed form of magnetospheric noise at our high latitude stations is polar chorus, which is usually limited to the overall frequency range 300 Hz to 2 kHz. The other predominant form of magnetospheric noise is auroral hiss, which occurs over large portions of the ELF/VLF range, sometimes even extending up to frequencies of 200 kHz or more [8]. Examples of these two forms of ELF/VLF noise are shown in Figures 8 and 9.

The polar chorus shown in Figure 8 is part of an interesting, extended interval of activity at Søndrestrømfjord that started around 0900 UT on 13 November 1986 and which continued until after 1500 UT. It was not particularly strong and although its 'signature' in the plots of one-minute

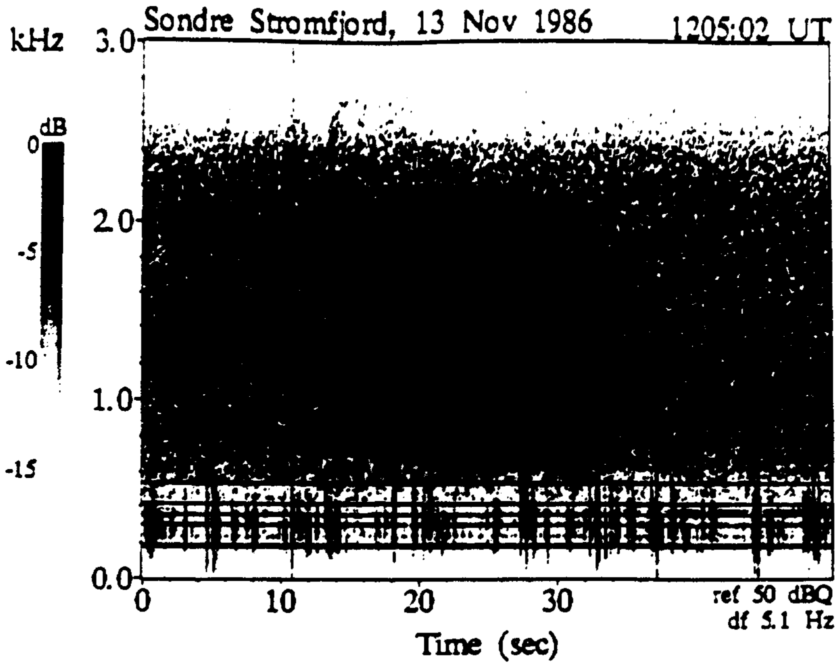

Fig. 8. A digital spectrogram of the ELF activity at Søndrestrømfjord during a roughly 50 second interval starting at 1205:02 UT on 13 November 1986. The strong horizontal lines toward the bottom of the spectrogram are harmonics of the local power supply frequency. The vertical lines are produced by sferics and the largely unstructured blackening from 500 Hz to 2.5 kHz is mostly hiss.

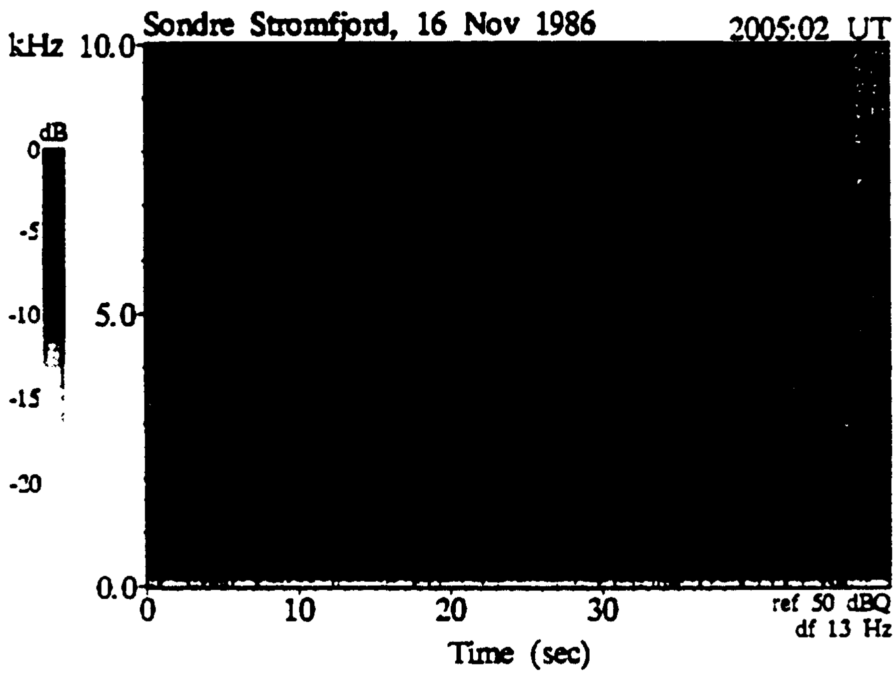

Fig. 9. A digital spectrogram of the ELF/VLF activity at Søndrestrømfjord during a roughly 50 second interval starting at 2005:02 UT on 16 November 1986. It is possible to see sferics, as well as some polar chorus around 400 Hz, but the entire display is dominated by auroral hiss, which produces the largely unstructured blackening extending over the entire 10 kHz frequency range of the display.

average amplitudes (Figure 1) is easily recognizable it is not nearly as marked as is often the case during these polar chorus events. The activity started as a series of quasi-periodic bursts of hiss, limited mostly to the frequency range 500 Hz - 1.3 kHz, and with a period of about 6 seconds between the bursts (which had a rising frequency characterisic). By 1200 UT the quasi-periodicity had essentially disappeared and the activity had increased both in intensity and in its frequency range, the upper frequency of which now approached 2.5 kHz. In addition to these characteristics, which can be seen in Figure 8, the activity developed a number of the rising elements typical of polar chorus. Since the activity only extended up to 2.0 kHz and above for about an hour, its 'signature' in the bottom panel of Figure 1 (for 2.0 kHz) is comparatively limited. The subsequent drop in the mean amplitude of the sferic activity is of great interest, since it suggests increased ionospheric absorption over a substantial region above Søndrestrømfjord.

The spectrogram shown in Figure 9 is quite extraordinary and it is shown here to make a point. The entire spectrogram, which covers a larger frequency range than Figure 8, is blackened by an occurrence of strong auroral hiss. Some sferics can be seen through the general blackening, as can a band of low-frequency polar chorus in the range 200–500 Hz. Other spectrograms of the activity show that the hiss extends up to around 16 kHz. Strong auroral hiss of this kind produces 'signatures' in our noise statistics that are similar to those of polar chorus, but with the exception that they extend to much higher frequencies. Since there are a variety of VLF navigation and communication transmissions above 10 kHz, auroral hiss has the potential to degrade these transmissions at high latitudes.

5. CONCLUSION

We have presented a number of quantitative examples of the ELF/VLF noise measurements made by our global array of ELF/VLF radio noise measurement systems and we have also presented some of the noise statistics that can be derived from the measurements. Most of the data displayed were obtained at high latitude locations. Our purpose in doing this was twofold: first, we wished to provide examples of data that are comparatively lacking, which is certainly the case for ELF/VLF radio noise data at high latitudes, and, second, we wished to emphasize the importance of magnetospheric noise, which has the potential to create difficult conditions for the reception of ELF/VLF transmissions at high latitudes.

ACKNOWLEDGEMENTS

This research was sponsored by the Office of Naval Research through Contract No. N00014-81-K-0382 and Grant No. N00014-90-J-1080. Support for the measurements at Thule, Greenland, was provided by Rome Air Development Center through Contract No. F19628-84-K-0043. Logistic support for the measurements at Søndrestrømfjord, Greenland, and Arrival Heights, Antarctica, was provided by the National Science Foundation (NSF) through NSF cooperative agreement ATM 88-22560 and NSF Grant DPP-8720167, respectively. We thank Professors T. Ogawa and M. Kusunose of Kochi University for their cooperation in the measurements in Japan; Mr. J. P. Turtle of Rome Air Development Center for his cooperation in the Thule measurements; and Dr. J. D. Kelly of SRI International for facilitating the measurements at Søndrestrømfjord.

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