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# RADIO NOISE MEASUREMENTS IN THE LONG-WAVE BAND AT THULE, GREENLAND

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)


In August 1985 we installed a Stanford University ELF/VLF radiometer at Thule, Greenland to make measurements of the natural ELF/VLF (frequencies in the range 10 Hz-32kHz) radio noise background. Thule is very nearly unique in that it lies not only at a relatively high geographic latitude (76.55°N) but it is also very close to the north geomagnetic pole, with the result that its radio noise background not only contains the normal lightning-generated noise typical of the lower latitudes (sferics, tweeks) but in addition it contains an unusual selection of magnetospherically-generated components (primarily ELF/VLF chorus and hiss) that cannot be observed on the ground, or are only rarely observed on the ground, at low and middle latitudes. The only other comparable location for such noise measurements is the Soviet station Vostok in the Antarctic. In this report we summarize many of the ELF and VLF radio noise measurements made at Thule in the three years since the radiometer was started in operation, and we compare the noise statistics with those from Sondrestromfjord, which is also located in Greenland, but at a lower latitude (66.99°N). (see reverse)


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The noise statistics covered by the measurements include the average amplitude (and thus both the power and the 'external noise factor' or $F_a$, statistic, although these latter quantities are not presented explicitly), the rms, minimum and maximum amplitudes. In addition, many measurements are given of the 'voltage deviation' statistic $V_d$, which provides a useful indication of the impulsiveness of the noise. In general, the noise quantities vary with frequency in much the same way as they do at lower latitudes, except for the influance of a magnetospheric noise component ('polar chorus') in the approximate frequency range 500-1500 Hz. There is also an exceptional level of noise at the lowest frequencies covered by the radiometer measurements (10-50Hz), which is unexpected and which may be instrumental, although we have found no indication in any of the measurements that the high noise level involves anything other than natural noise. Finally, some additional measurements made at ≈1 kHz, in the LF range, give noise amplitudes consistent with those at 32 kHz.

## ACKNOWLEDGEMENTS

This work was conducted under Air Force Contract No. F19628-84-K-0043 and through an augmentation of NASA Grant NAGW 235, with technical management being provided by the Electromagnetics Directorate of Rome Air Development Center and funding by the Defense Nuclear Agency. We very much appreciate the help of Mr. John P. Turtle, our RADC scientific officer, with the logistics involved in running an experiment at high northern latitudes. Support for the overall global survey of ELF/VLF radio noise, including, in particular, the measurements made at Sondrestromfjord, Greenland, that are also described in this report, is provided by the Office of Naval Research and the Defense Nuclear Agency through ONR Contract No. N00014-81-K-0382. We thank Dr. John D. Kelly of SRI International for the arrangements he has made for the operation of our equipment at Sondrestromfjord. None of these radio noise measurements in Greenland would be possible without the generous permission of the Danish Commission for Scientific Research in Greenland.

We are greatly indebted to Dr. Evans W. Paschal, who designed the radiometers we use for our measurements, and to Mr. Bruce R. Fortnam, who was responsible for the installation of the two radiometers in Greenland.

# Table of Contents

# 1. Introduction

## 1.1. Background Information

Rome Air Development Center contract no. F19628-84-K-0043, for which this is the final report, was first issued to the Space, Telecommunications and Radioscience Laboratory, or the STAR Laboratory, at Stanford University on 1 August 1984, and the contract expired on 31 July 1988. The contract covered two major tasks: First, measurement of the ELF/VLF radio noise at Thule, Greenland (76.52° N, 68.81° W; geomagnetic coordinates 87.5° N, 11.3° E), using the Stanford University radiometer specifically constructed for noise measurements at that location. Because of the addition of a specially designed and constructed LF filter to the Thule radiometer, these measurements could be extended up to frequencies in the lower part of the LF range, *i.e.*, to frequencies in the range 30–60 kHz. The second task covered by the RADC contract was to design and construct a compact and highly-sensitive VLF/LF receiver for balloon use, and, as it turned out, to participate in the experiments involving the receiver. This latter receiver was completed on schedule and used successfully in two major balloon experiments to measure and compare the TE and TM radio noise levels at aircraft altitudes. Since we have reported many of the results of the latter experiments at URSI meetings [*Fraser-Smith et al.*, 1987a, 1988] and a paper detailing the results of the experiments has been submitted for publication [*Turtle et al.*, 1988], we will concentrate in this report on the radio noise measurements made at Thule.

## 1.2. The Stanford University Survey of ELF/VLF Radio Noise

In addition to the ELF/VLF radiometer installed at Thule, the STAR Laboratory is operating seven other radiometers at various locations around the world, including, in particular, one located at Sondrestromfjord, Greenland (66.99° N, 50.95° W; geomagnetic coordinates 76.8° N, 37.8° E). Figure 1 shows the relative positions of the two Greenland radiometers. Although they are relatively close geographically, they differ significantly in geomagnetic latitude. Thule is purely a polar cap location, always well to the north of the northern auroral zone, whereas Sondrestromfjord is located at the transition between the polar cap and the northern auroral zone. The distinction may sound academic, but it leads to substantial differences in the properties of the magnetospheric noise observed at the two sites.

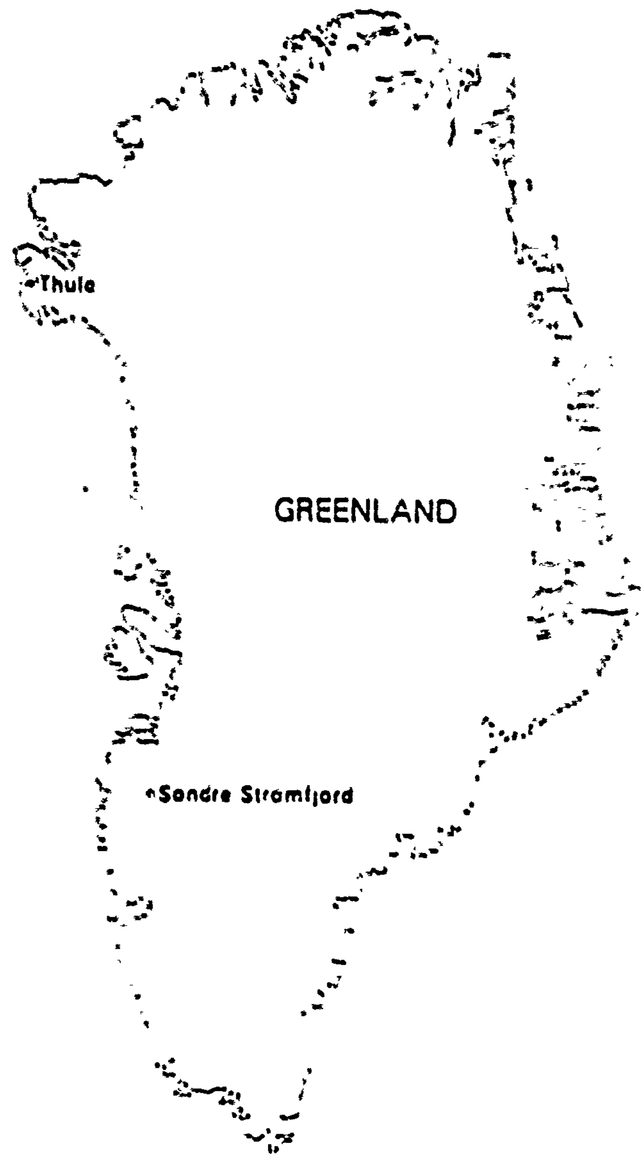


**Figure 1.** Map of Greenland, showing the two ELF/VLF radiometer sites at Thule (76.52° N, 68.81° W) and Sondrestromfjord (66.99° N, 50.95° W).

Since full details of the global survey of radio noise are given elsewhere [*Fraser-Smith and Helliwell*, 1985; *Fraser-Smith et al.*, 1987], we will only refer to a few essential details here. As described in the second reference just cited, each radiometer consists of two dual-channel receivers, each with two crossed loop antennas (East-West, North-South). One of the receivers has a response (*i.e.*, a 3dB bandwidth) covering the frequency range 1 Hz–4.7 kHz and the other covering the range 100 Hz–140 kHz. A bank of narrow-band filters (5% bandwidth) is used to monitor the noise present at 16 selected frequencies distributed approximately uniformly in a logarithmic sense through the overall frequency range of operation (Table 1). These frequencies were carefully chosen to avoid harmonics of the 60 Hz and 50 Hz power line frequencies. The output of the filters is continuously sampled and a variety of statistical quantities calculated and recorded digitally on magnetic tape, along with samples of the raw data from the filters (typically one sample per second for all 16 filters). Operation of each radiometer is under the control of a mini-computer, which not only computes the statistical data, but also monitors all essential functions of the radiometer and automatically calibrates the response of the receivers at regular intervals.

The statistical quantities computed continuously during the radiometer operation consist of the average, root-mean-square (rms), maximum, and minimum amplitudes for each of the 16 selected frequencies. They are computed at the end of every minute from 600 amplitude measurements made at a rate of 10 per second on the envelope of the noise signal emerging from each narrow-band filter. These statistical data can be read and listed directly from the digital tape with no further processing required. Later processing of the data can, with little additional computation, give (1) the 'external noise factor' $F_a$ and (2) the 'voltage deviation' or $V_d$ statistic, which is the ratio in dB of rms to average amplitude and is a measure of the impulsiveness of the noise data. Similarly, but with somewhat more computation, the sampled data can be used (3) to derive amplitude probability distributions (APD's).

Because of our use of loop antennas, our measurements are made on the magnetic field of the radio noise, and not on the electric field as was primarily the case in earlier noise surveys. Our unit of measurement is therefore the tesla (T), or, since the amplitudes are very small, either the picotesla (pT; 1 pT = $10^{-12}$ T) or the femtotesla (fT; 1 fT = $10^{-15}$ T). For comparison with two other commonly used magnetic field units, we also note that

**Table 1.** Center frequencies and bandwidths for the 16 channels of the ELF/VLF radiometer.

| Channel | Center Frequency | Bandwidth (5%) |
|---|---|---|
| ELF system 1 | 10 Hz | 0.5 Hz |
| 2 | 30 | 1.5 |
| 3 | 80 | 4.0 |
| 4 | 135 | 6.75 |
| 5 | 275 | 13.75 |
| 6 | 380 | 19 |
| VLF system 1 | 500 | 25 |
| 2 | 750 Hz | 37.5 |
| 3 | 1 kHz | 50 |
| 4 | 1.5 | 75 |
| 5 | 2 | 100 |
| 6 | 3 | 150 |
| 7 | 4 | 200 |
| 8 | 8 | 400 |
| 9 | 10.2 | 510 |
| 10 | 32 kHz | 1600 Hz |

1 gauss (G) = $10^{-4}$ T and 1 gamma ($\gamma$) = $10^{-9}$ T. It is certainly not generally true that the noise fields measured at our antennas are those associated with plane electromagnetic waves. However, the plane wave assumption is likely to be a reasonable one for frequencies in the middle and upper part of VLF range, in which case our magnetic field measurements can be used to obtain the associated electric field by use of the conversion factor 3.33 fT = 1 $\mu$V/m.

In addition to the data from the narrow band filters, broad-band ELF data, sampled at a rate of 1000 samples per second during scheduled synoptic recording intervals (currently one minute each hour), are also recorded on the digital tape. These data can be converted to spectrograms and they provide an essential check on the operation of the narrow-band filters and their associated measurements. A similar synoptic picture of activity in the VLF range is provided by analog recordings of the approximate range 200–25,000 Hz. To illustrate the form of these synoptic data, and to provide an introduction to typical lower-ELF noise at Thule, in Figure 2 we show a digital spectrogram of the lower-ELF noise recorded in the frequency range 0–400 Hz at Thule during the one minute interval starting 1939:50 UT on 4 September 1987. The spectrogram is derived by processing the digital data from one ELF synoptic interval; the data are fully calibrated and measurements of amplitude, frequency, and time can be made directly on any spectral feature. Noticeable are the two strong power line harmonic lines at 60 Hz and 180 Hz (the two horizontal lines) and typical ELF sferic activity (the many vertical lines). Although they are not clear in this particular example, measurements can also be made on the Schumann resonance lines at approximately 8, 14, 20, 26, and 33 Hz [*Polk*, 1982].

### 1.3. Low-Frequency Noise Filter

Because of the interest in the Air Force in communication at frequencies just above the VLF range, *i.e.*, in the lower part of the LF range (30–300 kHz), in 1983 we conducted a study to see if it would be possible to modify the standard ELF/VLF radiometer that was to be built and installed at Thule to provide radio noise statistics at frequencies above the standard maximum frequency of 32 kHz. We were reluctant to modify the basic radiometer design to include the higher frequency measurements, because there is an advantage to having identical instrumentation when measurements are being made at a number of different locations, some of which are particularly remote. However, we found that the extra LF measurements could be included without any hardware modifications to the basic radiometer unit by building an add-on LF filter unit that would take advantage of some uncommitted additional channels for digital recording that had been included in the original radiometer design.

The LF noise filter unit is a special, one-of-a-kind instrument designed and built at Stanford University and intended to be used in conjunction with a standard ELF/VLF radiometer

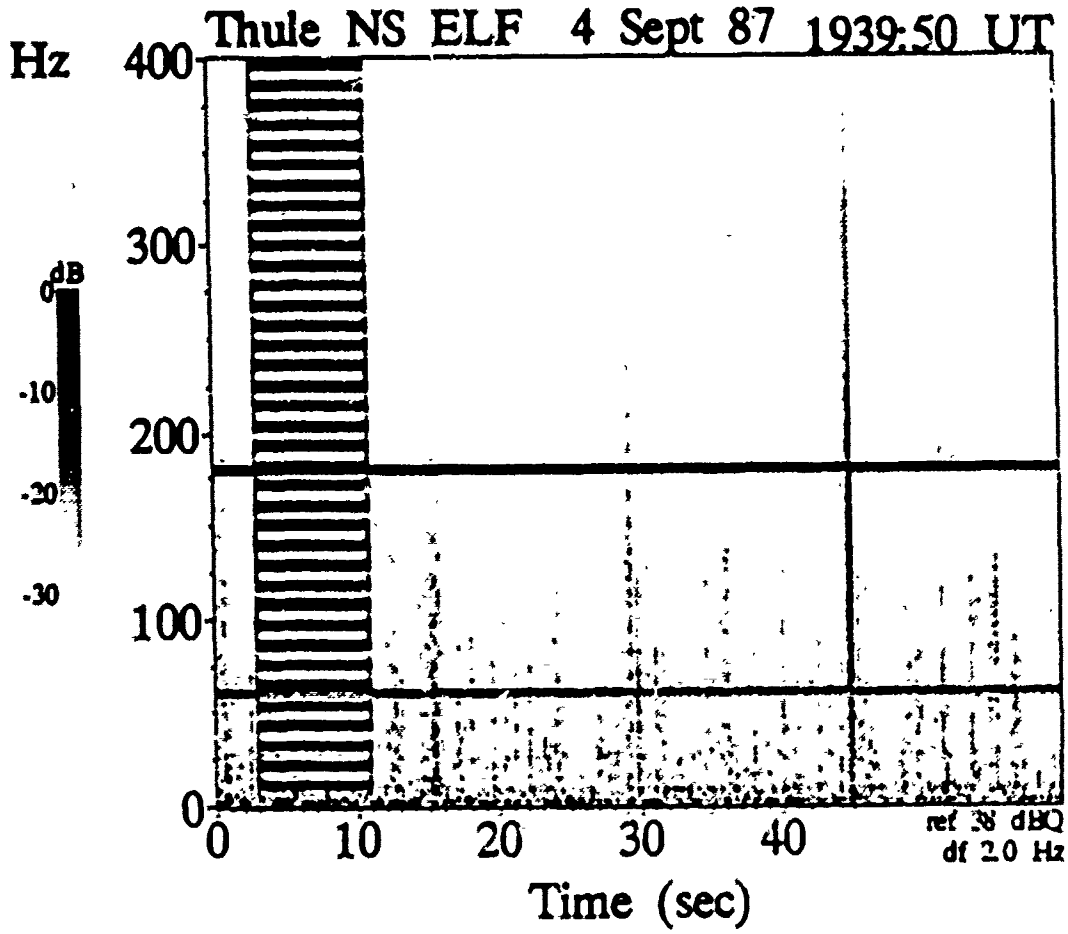


**Figure 2.** Digital spectrogram of a one-minute synoptic interval of lower-ELF noise (0–400 Hz) recorded at Thule on 4 September 1987. The spectrogram is derived from one of the ELF synoptic intervals routinely recorded at each radiometer site. The 'ladder' of horizontal lines on the left of the spectrogram is a calibration signal; the spacing between the horizontal lines is 10 Hz. The two strong horizontal lines are interference from the local power line system and a strong sferic can be seen occurring at about 45 s from the start of the record.

to make noise measurements on VLF and LF signals up to a maximum frequency of 60 kHz. The filter unit processes broadband VLF/LF signals from the VLF line receiver in the radiometer, which in its original unmodified form has a flat frequency response extending well above 60 kHz. The filter unit has a broadband translator that can move a 20 kHz (or greater) segment of the VLF spectrum lying anywhere in the range 0-60 kHz down to the range 0–20 kHz (or greater) for recording on the analog tape recorder. It also has narrowband filters, with bandwidths of 1500 Hz and 300 Hz, which can be centered on any frequency in the range 0–60 kHz to measure the amplitudes of natural and manmade noise. The narrowband filters in the LF noise filter contain two identical circuits, one for North-South and the other for East-West, thus giving the operator access to both the North-South and East-West components of the signals and providing a capability for estimating the direction of arrival of the signals.

### 1.4. Previous ELF/VLF Noise Measurements

As we have pointed out elsewhere [*Fraser-Smith et al.*, 1987b], there is an extensive literature on radio noise measurements. *Spaulding* [1982], in a particularly wide-ranging review of the noise and its implications for telecommunication systems, suggests a starting date of 1896 for this literature. However, it was many years before global measurements could be made, and, even then, the frequency ranges covered by the studies typically did not extend far down into the VLF range. Our present knowledge of the worldwide distribution of radio noise is largely based on the results of the National Bureau of Standards study that was started in 1957 [*Crichlow*, 1957]. The results of this study, which include measurements of (1) the global distribution of average noise power levels, usually as characterized by the external noise factor $F_a$, (2) the statistical quantity $V_d$, (3) APD's, and (4) the seasonal variation of some of the noise characteristics, form much of the basis for Report 322, published by the International Radio Consultative Committee (Comité Consultatif International des Radiocommunications, or CCIR) of the International Telecommunications Union [*CCIR*, 1964]. This report, together with certain updates [*CCIR*, 1982*a,b*, 1988], provides what might be termed the 'official' view of radio noise.

Unfortunately, insofar as the ELF/VLF band is concerned, the available CCIR radio noise information has three major weaknesses: First, it incorporates few measurements below

10 kHz. Second, although two high latitude stations were included in the original noise surveys, it is not clear that the contribution of magnetospheric noise to the high latitude measurements is adequately represented in the summary data. Finally, the timing of the noise data is quite coarse, since the intervals for which the data are presented are four hours long and the summary plots are organized according to the season.

More recent work has helped strengthen our knowledge of radio noise in the ELF/VLF band by partially filling some of the gaps in the CCIR data. For example, *Maxwell and Stone* [1963] and *Maxwell* [1966] provide important information concerning the electric field amplitudes of the noise below 10 kHz, as well as some indication of the variability of the fields. *Watt* [1967] discusses the *CCIR* [1964] data, but also presents additional results for some of the noise statistics [*Watt and Maxwell*, 1957a,b]. An independent series of measurements by *Dinger et al.* [1982] help provide a calibration of the VLF noise data available at that time as well as providing new information on the noise in the frequency range 1.0–4.0 kHz. APD's for the ELF/VLF range have been studied quite carefully and an analytical model developed [*Galejs*, 1966, 1967; *Field and Lewinstein*, 1978]. Inclusion of Soviet measurements in the CCIR noise models has led to a substantial improvement in their world-wide coverage [*CCIR*, 1988]. Perhaps most important from the point of view of the work reported here, syntheses have been made of all the available information on radio noise as it is observed throughout the entire radio frequency range, including the ELF/VLF range as a small subsection, which help to place the low frequency noise into a broader perspective and which provide new information about its properties, including its overall decline with increasing frequency in particular [*e.g.*, *Spaulding and Hagn*, 1978; *Smith*, 1982; *Spaulding*, 1982; *Flock and Smith*, 1984; *Fraser-Smith and Helliwell*, 1985].

Although this later work has contributed substantially to our knowledge of ELF/VLF noise, it nevertheless remains true that few measurements have been made of the APD's, $F_a$, $V_d$, or the other ELF/VLF noise statistics. Similarly, the contribution of magnetospheric and possibly even interplanetary ELF/VLF noise at high latitudes remains to be determined. Finally, with the advent of modern high-speed computers, the timing, statistical significance, and other computational features of the noise data can be greatly improved. The study discussed here was undertaken with the view of filling these gaps.

# 2. Thule Noise Statistics

## 2.1. Data Analysis

In order to provide representative ELF/VLF noise statistics for Thule, we examined our data records for the availability of simultaneous data from both Thule and Søndrestrømfjord and, as a result of this examination, we chose the two months June and December 1986 for detailed analysis. The June data should be reasonably typical for the northern hemisphere summer and the December data similarly reasonably typical for the winter. Insofar as the local ionospheric conditions are concerned, it should be noted that Thule, because of its high latitude, is in continual daylight during June and in continual darkness during December.

A first check on the quantity and quality of the recorded narrow band statistical data for the two months was made by running off plots of the daily variations of the one-minute rms amplitudes for all 16 frequency channels. Over 200 data plots were produced and examined. Although some problems were identified, including, in the December data, (1) interference from a VLF ionosonde and (2) an interval of ELF interference from an unidentified source, it was evident that there would be adequate data to provide good noise statistics for the two months. The specific data intervals finally included in the study were 0119 UT on 01 June through 0504 UT on 27 June, 1986, and 0006 UT on 2 December through 2104 UT on 30 December, 1986.

To illustrate the form of these daily data, and to provide an example of the effect of magnetospheric ELF noise on the noise statistics, in Figures 3–6 we show the daily variations during 14 June 1986 of the one-minute rms noise amplitudes at Thule for all 16 frequency channels. It can be seen that the daily variations in the lowest frequency channels are quite small, which is typical for the data we have analyzed. In the 500 Hz channel (Figure 4) there is an occurrence of polar chorus (as verified using the synoptic data) during the interval 1000–1900 UT, which converts what would more normally be a period of low lightning-related, or sferic, noise to a period of substantially increased polar chorus, or magnetospheric, noise. Before and after the interval of chorus the noise is typical of sferic activity and is quite impulsive. The polar chorus is not confined to 500 Hz: it can also be detected in the 750 Hz channel and it may also contribute to the increase observed in the 1.5 kHz channel from 1300–1700 UT [*Ungstrup and Jackeroll*, 1963]. We can now identify the intervals of polar

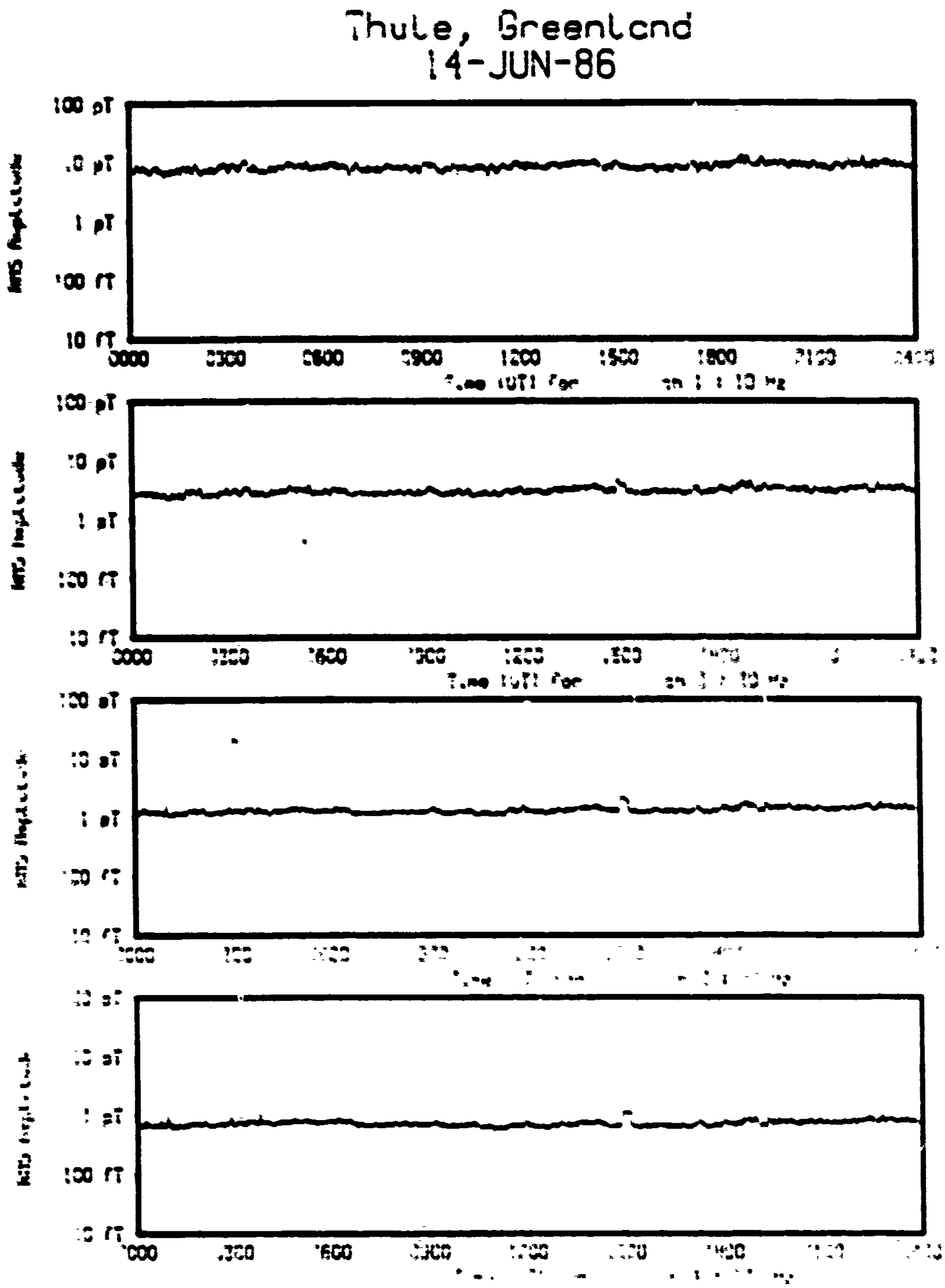


**Figure 3.** Variation of the one minute rms noise amplitudes at Thule during 14 June 1986. The data shown are for the first set of 4 narrow band channels (*i.e.*, for frequencies in the range 10–135 Hz; the frequencies are shown under each panel).

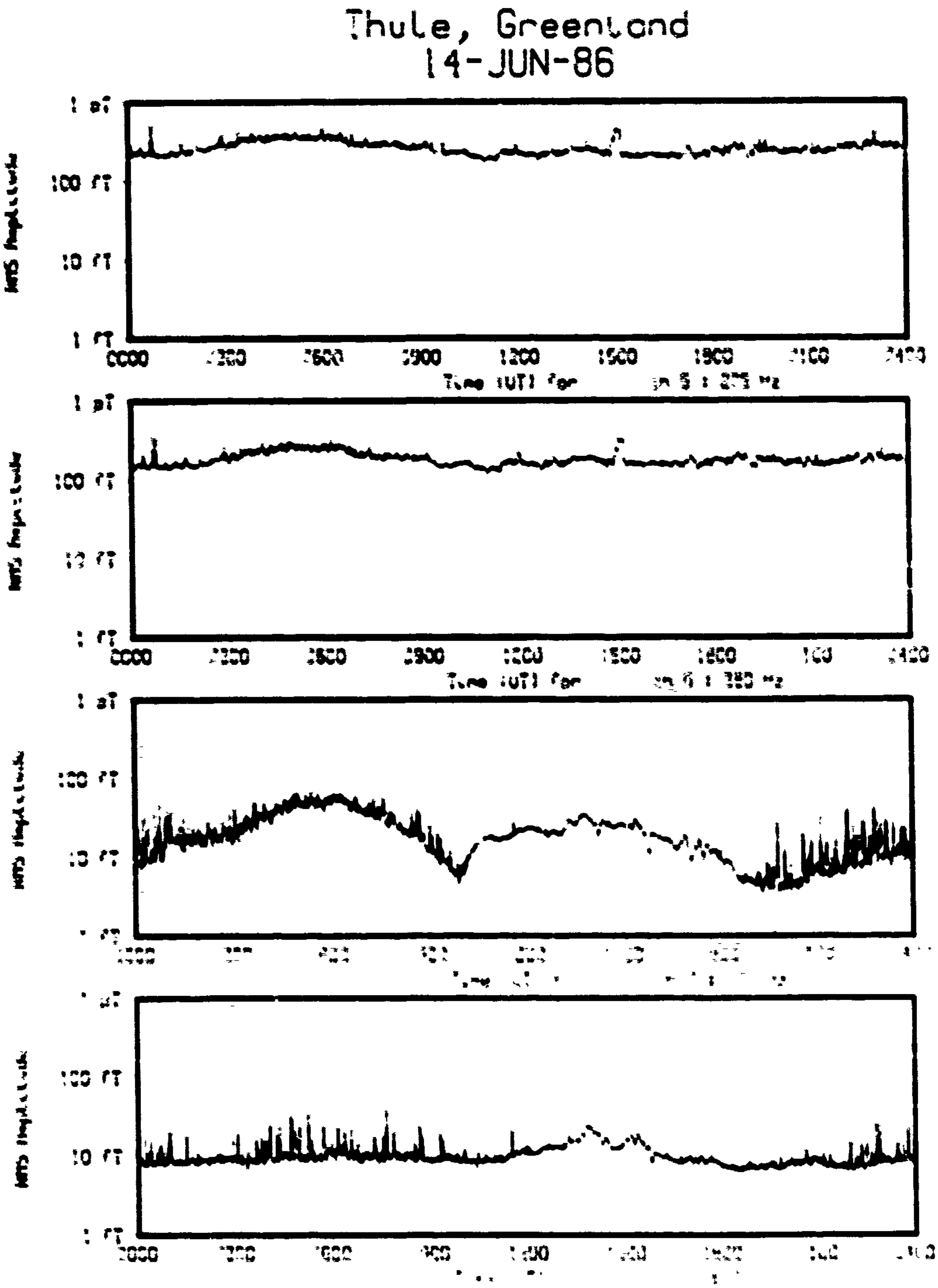


**Figure 4.** Variation of the one minute rms noise amplitudes at Thule during 14 June 1986. The data shown are for the second set of 4 narrow band channels (i.e., for frequencies in the range 275–750 Hz: the frequencies are shown under each panel).

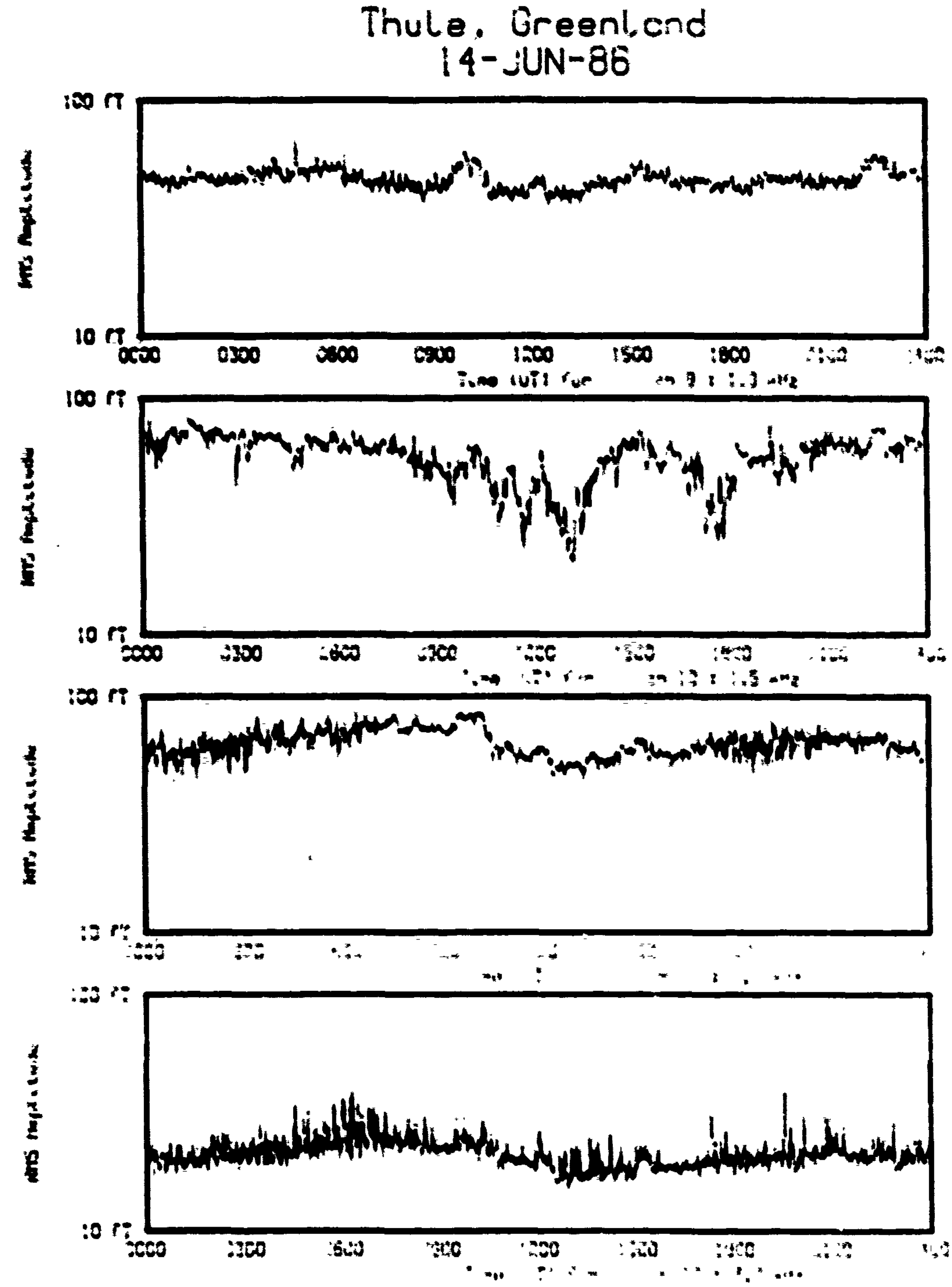


**Figure 5.** Variation of the one minute rms noise amplitudes at Thule during 14 June 1986. The data shown are for the third set of 4 narrow band channels (*i.e.*, for frequencies in the range 1.0–3.0 kHz; the frequencies are shown under each panel).

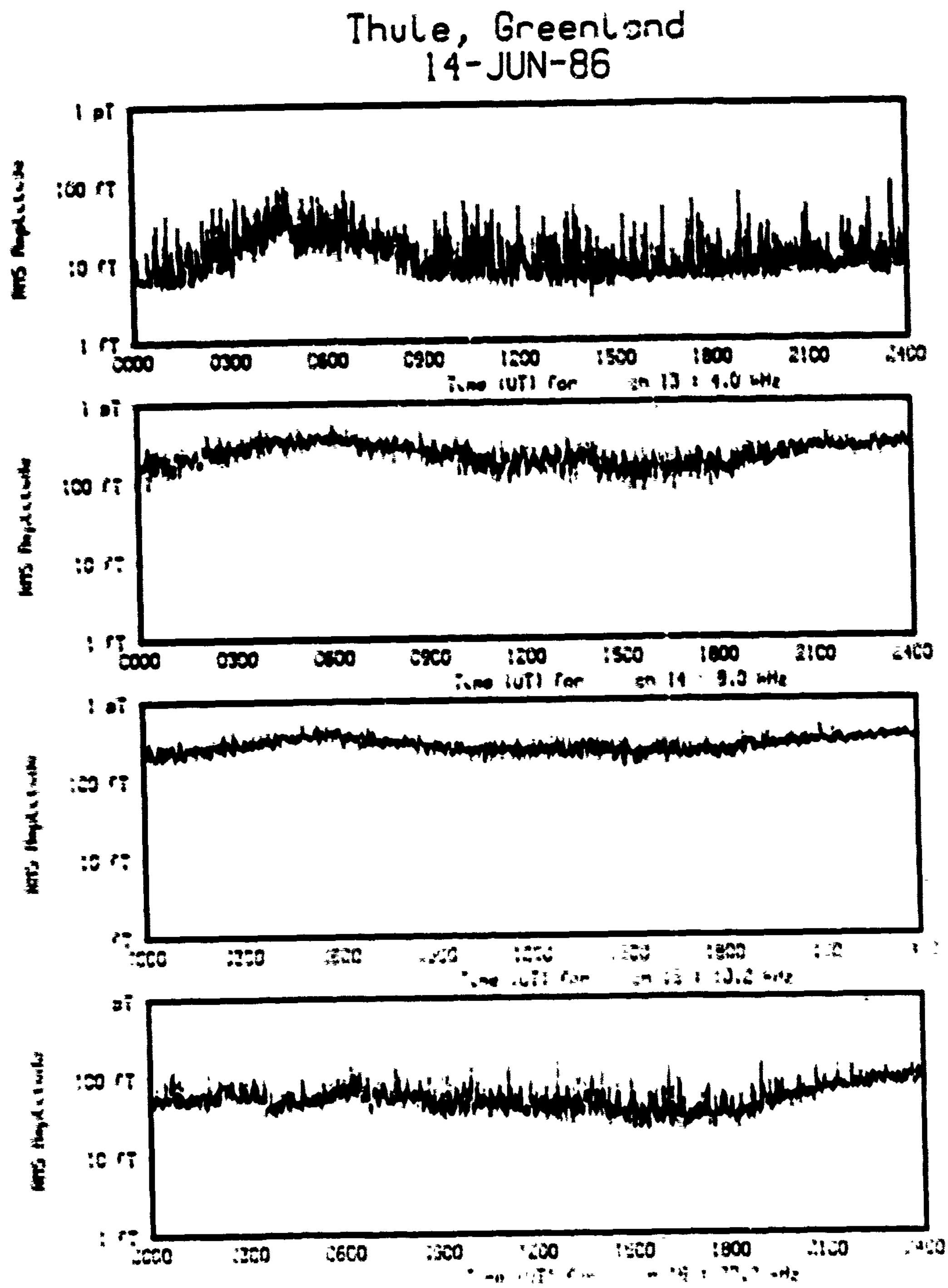


**Figure 6.** Variation of the one minute rms noise amplitudes at Thule during 14 June 1986. The data shown are for the fourth set of 4 narrow band channels (*i.e.*, for frequencies in the range 4.0–32.0 kHz; the frequencies are shown under each panel).

chorus by their effects on the impulsiveness of the noise: apart from the obvious change in the averages, as illustrated in Figure 4, $V_d$ is dramatically affected, dropping to very low values when magnetospheric noise is present.

Following the analysis of the daily data, average values of all the basic one-minute statistical measurements were computed for each of the 1440 one-minute intervals in the day, for both Thule and Sondrestromfjord for June and December 1986. The average data were then plotted to once again provide an overview of their quality and as a guide to their further processing. Some of these data, for June 1986 at Thule, are displayed in Appendix A. Finally, overall monthly averages were computed for the various quantities. Special processing was required for the December 1986 Thule data, which are contaminated by noise from a VLF ionosonde. The ionosonde operates on a schedule of two hours on followed by two hours off, starting at 0000 UT, and Figure 7 shows the effect on one of our noise statistics, in this case $V_d$. The ionosonde normally increases the noise levels in the frequency bands used for our measurements, but $V_d$, on the contrary, is suppressed, due to the smaller relative difference in amplitude between the large noise 'spikes,' which are largely unaffected by the ionosonde, and the average background noise level, which is increased by the ionosonde. In our final processing of these December Thule data we ignored all the data recorded during operation of the ionosonde, thus eliminating half of the recorded noise data from analysis.

## 2.2. Results

Our summary noise results are largely presented in graphical form. We begin by showing all the average noise amplitudes measured at Thule and Sondrestromfjord for June and December 1986 (Figures 8–11). It can be seen that there is an overall tendency for the noise amplitudes to decrease with increasing frequency, in agreement with previous measurements in the ELF/VLF frequency range [*e.g.*, *Maxwell and Stone*, 1963; *Maxwell*, 1966]. Further, many sections of the curves plotted in the figures are approximately linear, suggesting an underlying power-law variation in agreement with the generalization made by *Fraser-Smith and Helliwell* [1985] following a review of the literature on low-frequency radio noise. Specifically, these latter authors concluded that there was evidence for an overall underlying $f^{-1}$ variation of low-frequency noise amplitudes. By fitting a power-law variation of the form $A = A_0 f^{-n}$ to the curves in the figures, we find that $n$ lies in the range 0.91–1.27 for the

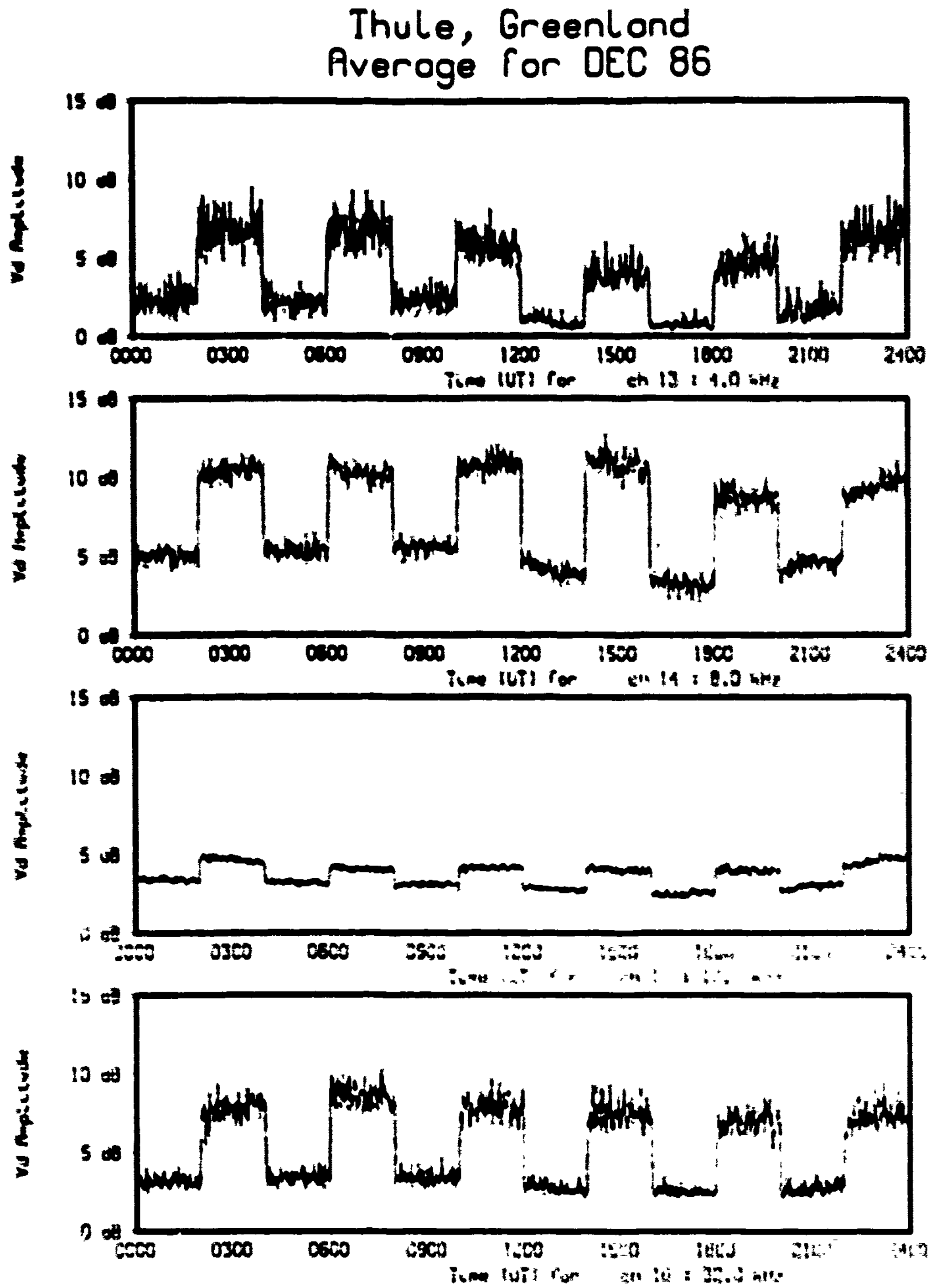


**Figure 7.** Overall average variations of $V_d$ in the four frequency ranges 4.0 kHz, 8.0 kHz, 10.2 kHz, and 32.0 kHz during the month of December 1986, showing the effects of the Thule VLF ionosonde on the data. The ionosonde operates on a two hours on, two hours off schedule, starting at 0000 UT. It tends to suppress $V_d$ when it is in operation.

Thule June data and in the range 0.77–1.26 for the December data, with the smaller values of $n$ being associated with the larger amplitude plots. The Sondrestromfjord $n$-values do not differ markedly, but there is clearly less of a drop-off of the amplitudes with frequency. For June $n$ lies in the range 0.60–1.11 and for December the range is 0.59–1.08.

Many of the amplitude variations plotted in Figures 8–11, and in later figures, show evidence of the well-known ionospheric waveguide cutoff that limits the horizontal sub-ionospheric propagation of ELF/VLF waves with frequencies roughly in the range 1–3 kHz [*e.g.*, *Watt*, 1967]. Because of this cutoff, sferics from distant lightning are comparatively more highly attenuated at frequencies at or near the waveguide cutoff frequency than at other frequencies, with the result that there is a quiet band in the noise spectrum centered on 1–3 kHz.

Figures 8–11 show two marked differences between the Thule and Sondrestromfjord amplitudes. First, it is clear that the Thule amplitudes are much higher at the lowest frequencies (10–50 Hz) than the equivalent Sondrestromfjord amplitudes. Every test we have carried out on the Thule data indicates that the noise at these low frequencies is uncontaminated by man-made noise and that the radiometer is functioning correctly as it measures the noise. We cannot eliminate the possibility of an instrumental effect or man-made noise at this time, but it appears unlikely. The second difference is the existence of a large hump in the average, rms, and minimum curves in the frequency range 750 Hz–3.0 kHz, i.e., within the waveguide cutoff range, that is missing in the Sondrestromfjord data. We initially ascribed this hump to the effects of magnetospheric noise, or, more specifically, to the occurrence of polar chorus, as was seen in Figure 4. However, further analysis showed that there were many similar occurrences of polar chorus at Sondrestromfjord, where the noise statistics display little evidence of such a hump. Further, spectrograms of the analog data recorded at Thule revealed exceptionally strong power line harmonics in the frequency range 1–2.5 kHz. This latter range is a transitional one for our measurement system in which the 5% bandwidths of our narrow-band filters necessarily begin to include some power line harmonics, whereas at lower frequencies the bandwidths are narrow enough for the harmonics to be excluded (see Table 1). We now largely attribute the hump in the Thule noise measurements to interference from power line harmonics.

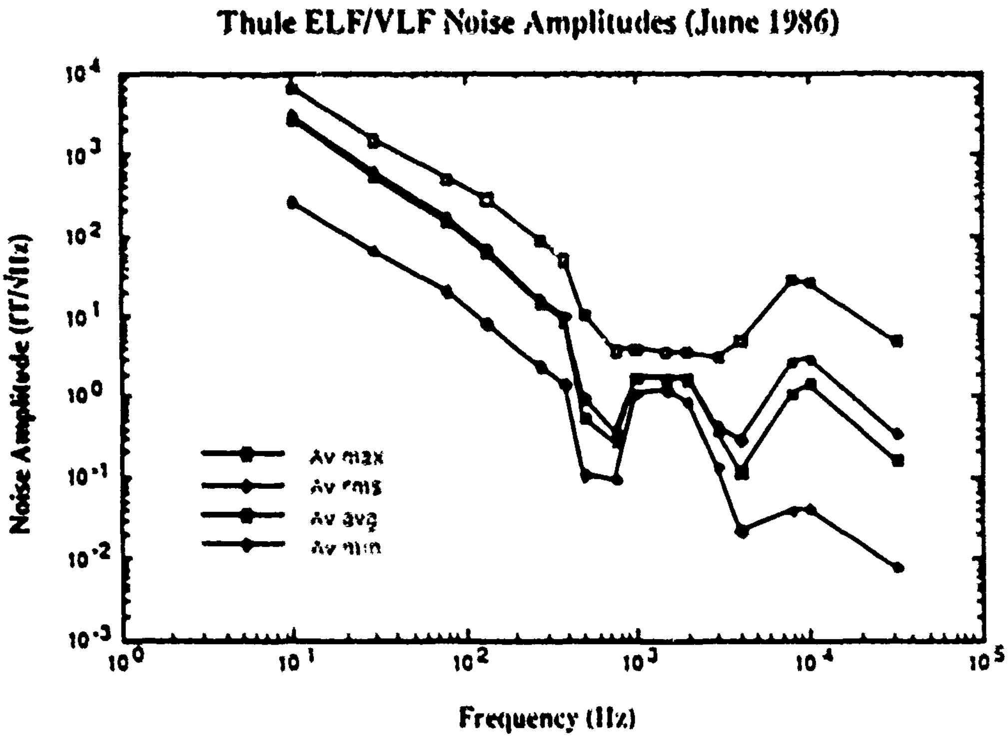


**Figure 8.** Variation of the Thule ELF/VLF noise amplitudes with frequency for the month of June 1986. Overall monthly average values for the maximum, rms, average, and minimum one-minute noise amplitudes for each of the 16 narrow-band frequency channels are shown.

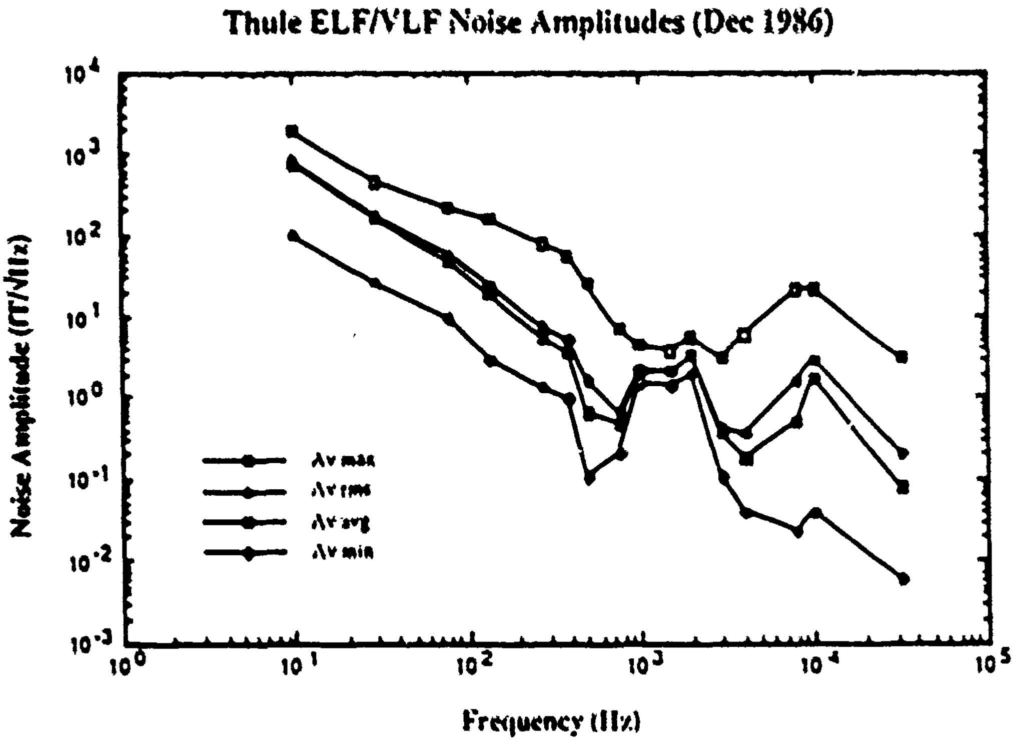


**Figure 9.** Variation of the Thule ELF/VLF noise amplitudes with frequency for the month of December 1986. Overall monthly average values for the maximum, rms, average, and minimum one-minute noise amplitudes for each of the 16 narrow-band frequency channels are shown.

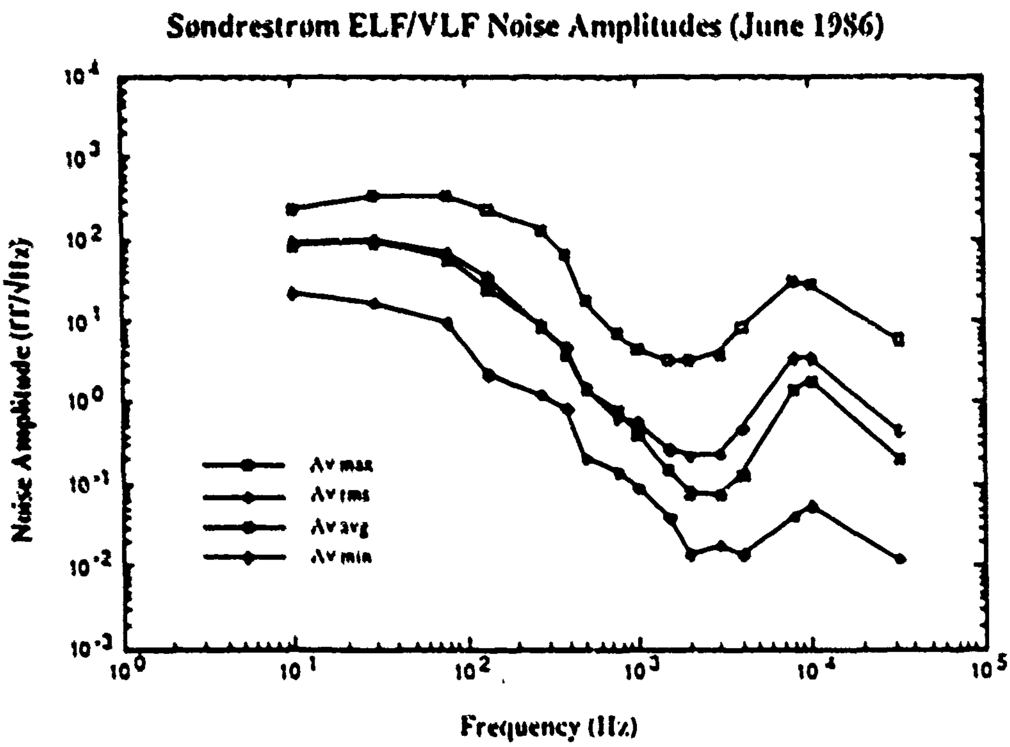


**Figure 10.** Variation of the Sondrestromfjord ELF/VLF noise amplitudes with frequency for the month of June 1986. Overall monthly average values for the maximum, rms, average, and minimum one-minute noise amplitudes for each of the 16 narrow-band frequency channels are shown.

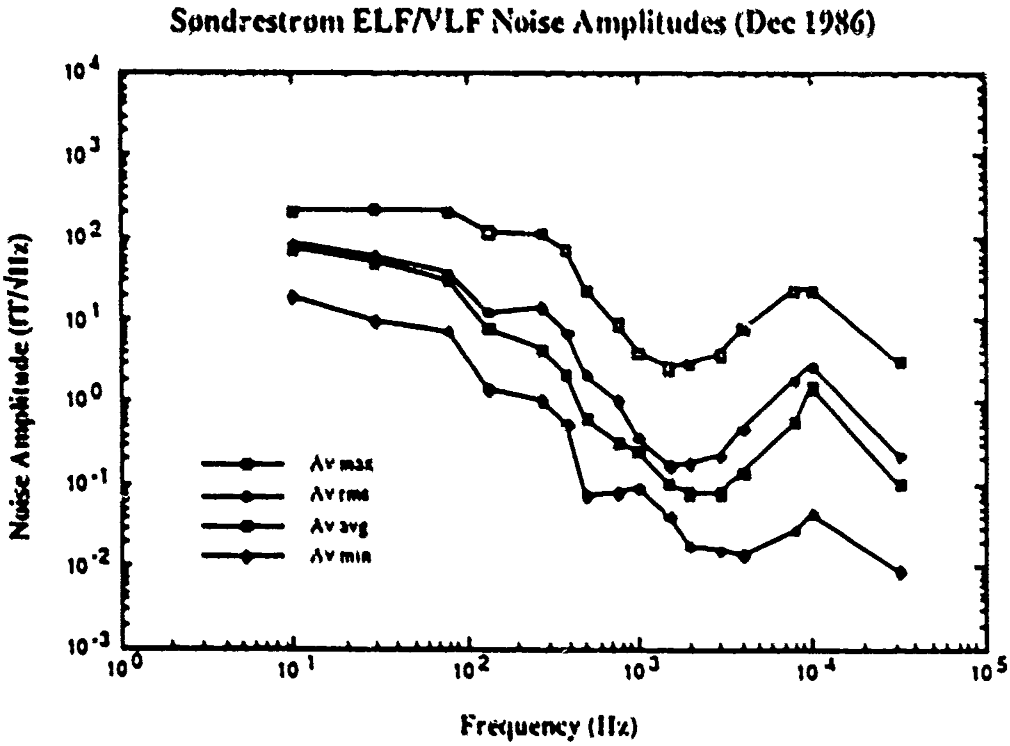


**Figure 11.** Variation of the Sondrestromfjord ELF/VLF noise amplitudes with frequency for the month of December 1986. Overall monthly average values for the maximum, rms, average, and minimum one-minute noise amplitudes for each of the 16 narrow-band frequency channels are shown.

Figures 12 and 13 provide different information about the average noise amplitudes at Thule and Sondrestromfjord. In these figures we plot, for each frequency channel, the maximum one-minute average noise amplitude measured during June 1986, the overall average one-minute amplitude, and the minimum one-minute average amplitude. In other words, we only consider the one-minute average data. The figures show that there is more of a spread in the average amplitudes measured at Sondrestromfjord, but otherwise there is little difference between the three amplitude curves plotted for each location.

Continuing with the comparison of the amplitude data, in Figures 14 and 15 we plot, for both Thule and Sondrestromfjord, and for each of the 16 frequency channels, the overall one-minute maximum amplitude, the overall average amplitude, and the overall one-minute minimum amplitude for December 1986. The curves give an indication of the overall range of the amplitude measurements at each frequency. Interestingly, the spread is greater in the Sondrestromfjord measurements, primarily because the overall maximums are larger than those at Thule. Sondrestromfjord also has a comparatively large dip in its overall minimum amplitudes in the frequency range 2–8 kHz.

It is interesting to intercompare some of the 1986 Thule average amplitude data displayed in the preceding figures. We make this comparison in Figure 16, which shows the frequency variations of the average maximum, overall average, and average minimum noise amplitudes for June and December. Although there are some deviations at certain frequencies in the VLF range, the plots in Figure 16 show that the noise amplitudes tend to be lower in December (northern hemisphere winter) than in June (summer). This result is in accord with measurements at lower latitudes [*e.g.*, *Watt*, 1967], and it is a consequence of the comparative rarity of thunderstorms in the northern hemisphere during its winter season.

As a final illustration of the 1986 Thule and Sondrestromfjord amplitude data, in Figures 17 and 18 we directly compare the frequency variation of the average one-minute noise amplitudes measured at the two locations during the two chosen months. These data show quite a remarkable correspondence between the noise amplitudes, once allowance is made (1) for the peak in the Thule data in the band 750 Hz–3.0 kHz due to magnetospheric noise and (2) for the larger noise levels in the range 10–50 Hz at Thule. There is a particularly close correspondence between the measured noise amplitudes at the highest frequencies.

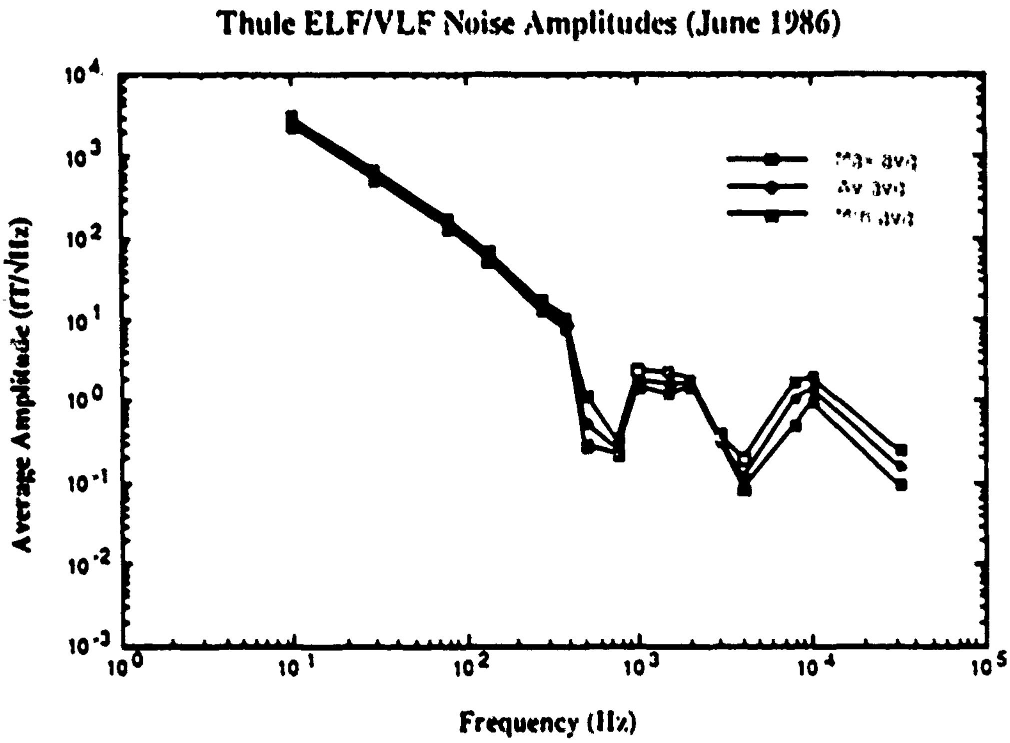


**Figure 12.** Variation of the Thule ELF/VLF one-minute average amplitudes with frequency for the month of June 1986. The maximum average amplitude, the overall average amplitude, and the minimum amplitude are plotted for each of the 16 narrow-band frequency channels.

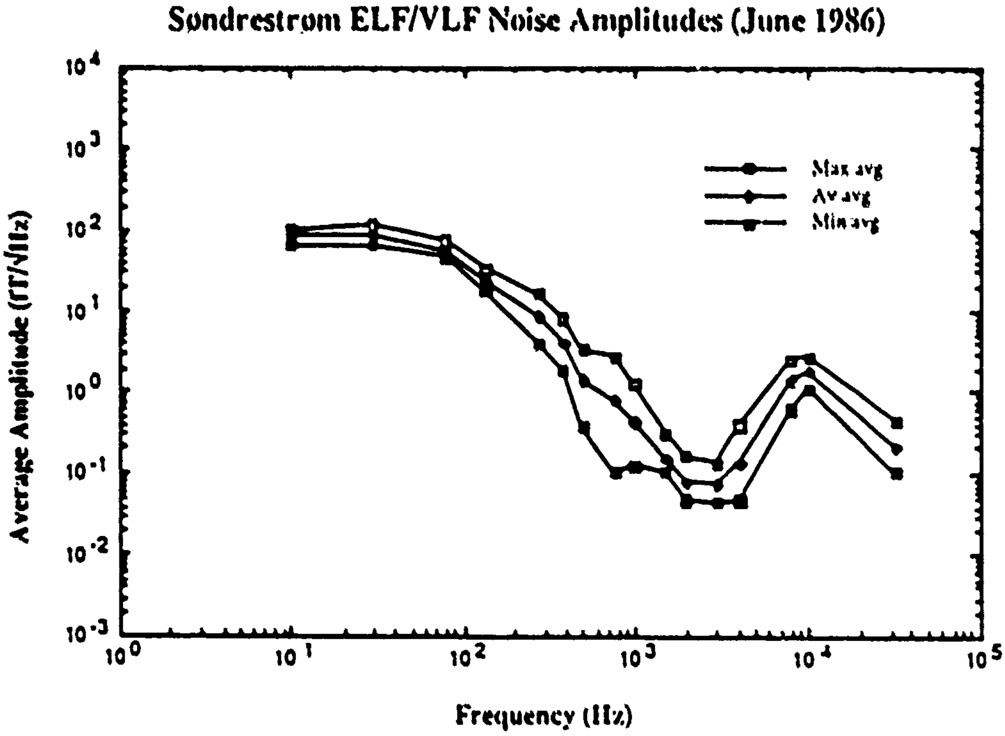


**Figure 13.** Variation of the Sondrestromfjord ELF/VLF one-minute average amplitudes with frequency for the month of June 1986. The maximum average amplitude, the overall average amplitude, and the minimum amplitude are plotted for each of the 16 narrow-band frequency channels.

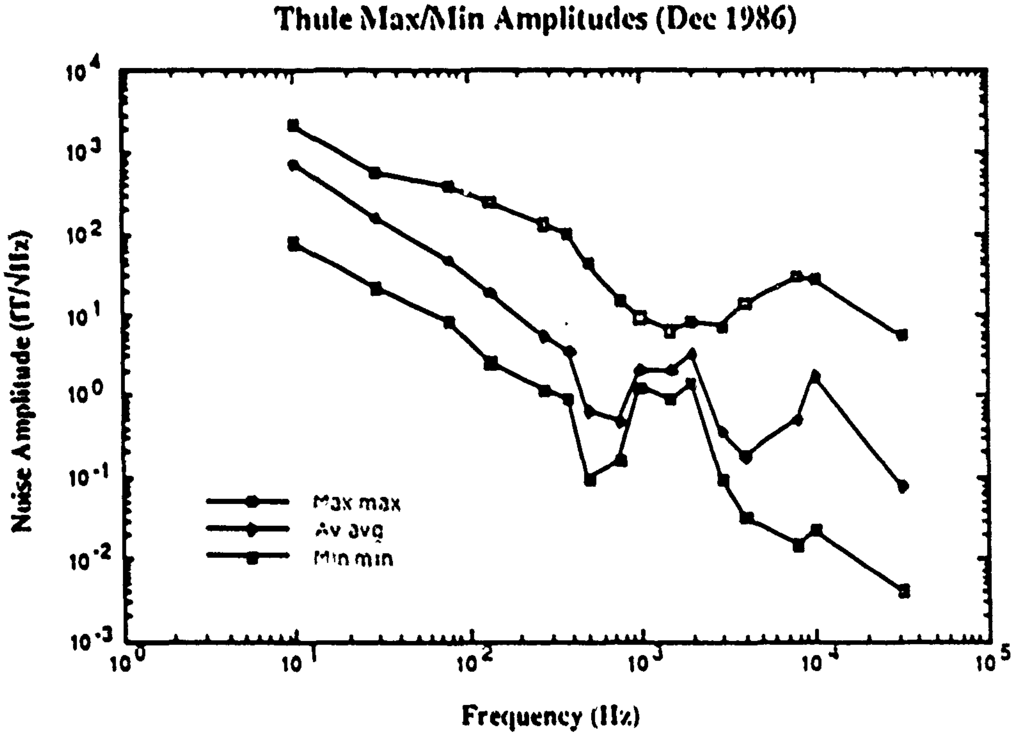


**Figure 14.** Variation of the Thule overall maximum and minimum one-minute amplitudes with frequency for the month of December 1986. The overall maximum one-minute amplitude, the overall average amplitude, and the overall minimum one-minute amplitude are plotted for each of the 16 narrow-band frequency channels.

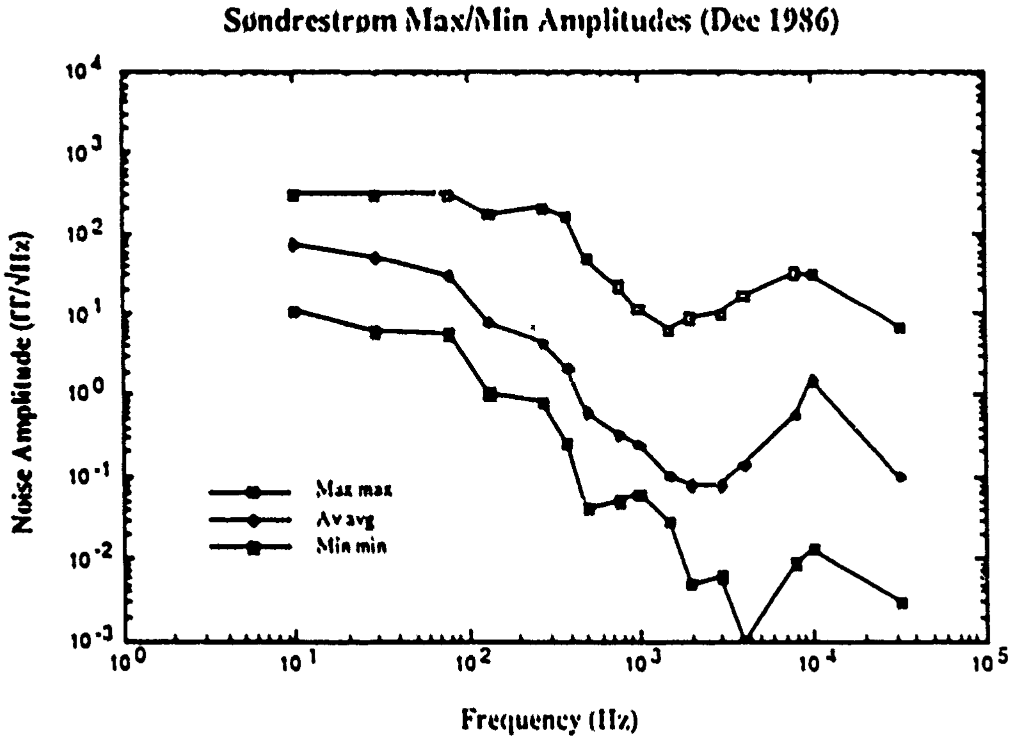


**Figure 15.** Variation of the Sondrestromfjord overall maximum and minimum one-minute amplitudes with frequency for the month of December 1986. The overall maximum one-minute amplitude, the overall average amplitude, and the overall minimum one-minute amplitude are plotted for each of the 16 narrow-band frequency channels.

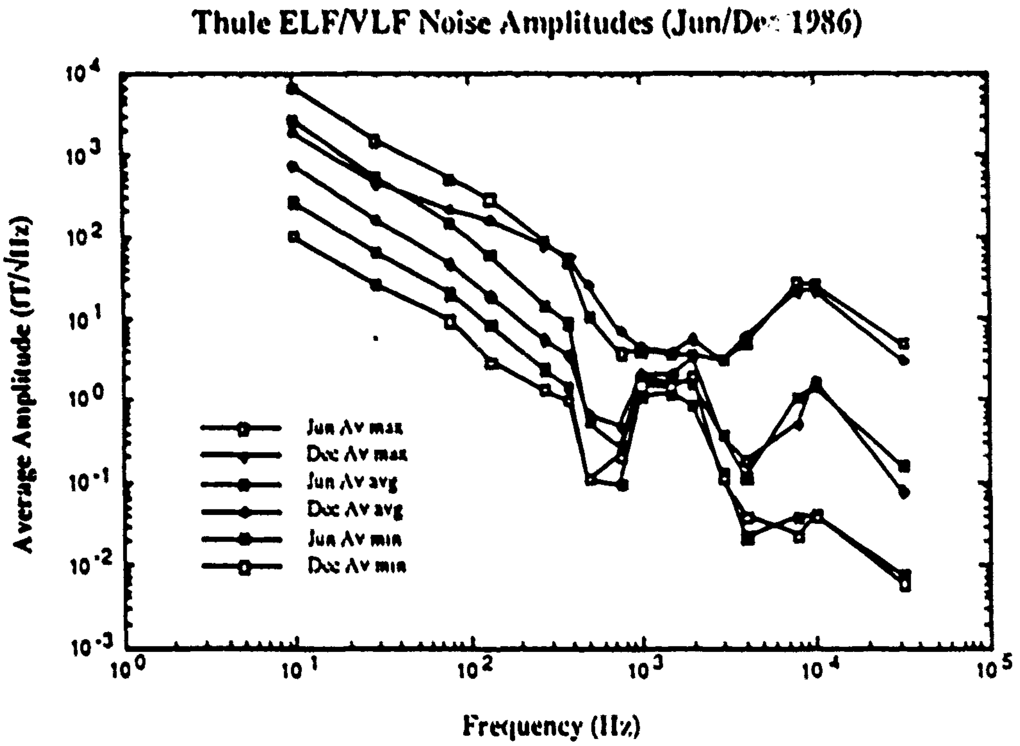


**Figure 16.** Comparison of the June and December 1986 variations of some of the Thule ELF/VLF noise amplitudes shown in the preceding figures.

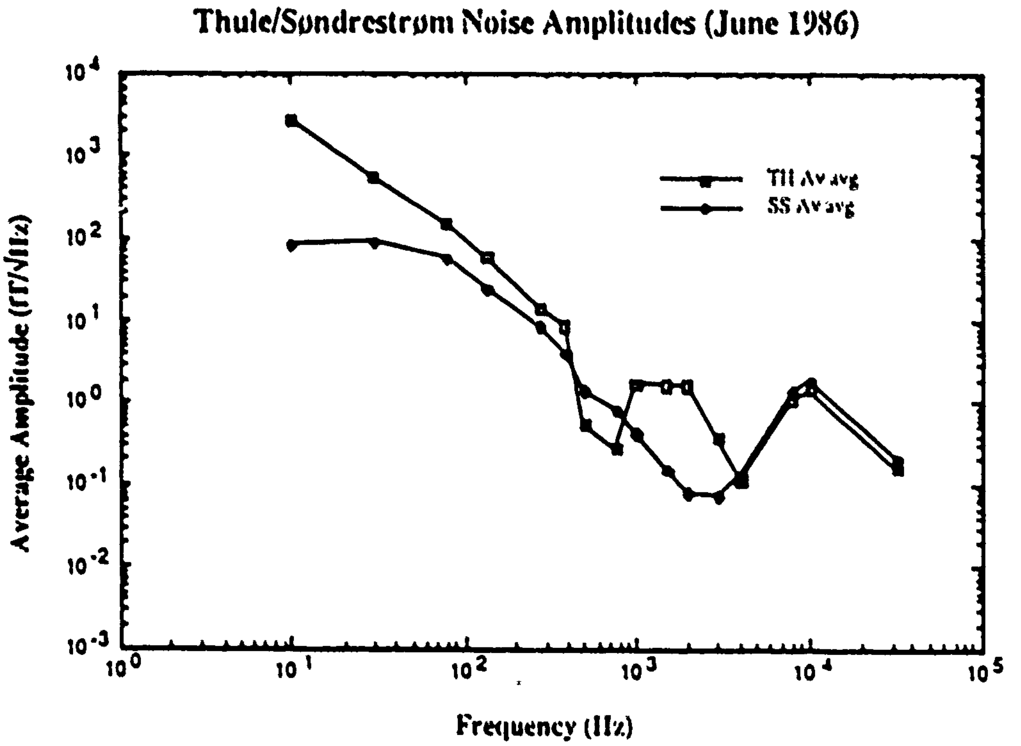


**Figure 17.** Comparison of the overall average noise amplitudes measured at Thule and Sondrestromfjord during June 1986.

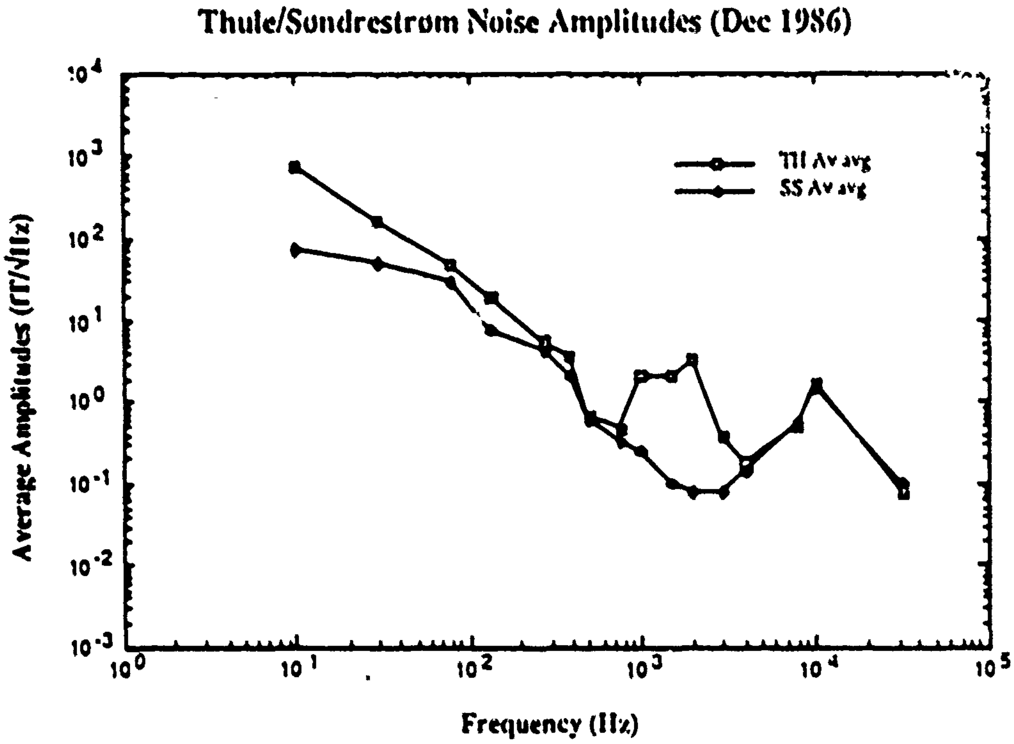


**Figure 18.** Comparison of the overall average noise amplitudes measured at Thule and Sondrestromfjord during December 1986.

We now make a brief comparison of the Thule overall noise amplitudes measured in June 1986 with those measured during June 1988. The 1988 noise data were processed in exactly the same way as the 1986 data, with the exception that it was necessary to remove the intervals contaminated with ionosonde noise in the 1988 data. One other difference is the computation of a noise amplitude at 41.0 kHz in the 1988 data. This latter amplitude is not as reliable as the others, since there was interference in the 41.0 kHz channel during the month analyzed, but we believe it is still a reasonably accurate estimate. Figure 19 shows the frequency variations of the two sets of data, and it can be seen that they are very closely similar, indicating little time variation in the noise data. It can also be seen that the noise amplitude at 41.0 kHz is in good agreement with the adjacent value for 32.0 kHz.

We now end this results section with a presentation of $V_d$ data, starting with Figures 20 and 21, showing, first, the overall average values for the maximum, average, and minimum measured values of $V_d$ at Thule for June 1986. The second of this pair of figures (Figure 21) shows the same data for Søndrestrømfjord. The effect of the inferred power line harmonic noise in the 750 Hz–3.0 kHz band is particularly evident in the Thule data, where all values of $V_d$ are greatly reduced. However, it is also interesting to see a similar dip in the Søndrestrømfjord average minimums, although it is absent in the average maximum amplitudes and is only very slightly evident in the overall average amplitudes. This latter result may well indicate a small contribution from magnetospheric noise at Søndrestrømfjord, since the generally well-defined waveguide cutoff minimum in the amplitude data suggest that the Søndrestrømfjord data are relatively free of power line harmonic interference. If we ignore the influence of the power line interference on the Thule $V_d$ amplitudes, it can be seen that there is a gradual increase with frequency, with the values at 32 kHz being roughly a factor of 10 larger than those at 10 Hz.

The next pair of figures, Figures 22 and 23, compare the Thule and Søndrestrømfjord overall average $V_d$'s for June and December 1986. The two figures are very similar and the two curves in each figure are also closely similar, except for the distinctive minimum in the Thule values due to the power line harmonics. At the highest frequencies the values of $V_d$ are nearly identical.

Finally, in Figure 24 we compare the Thule $V_d$ amplitudes measured during June 1986

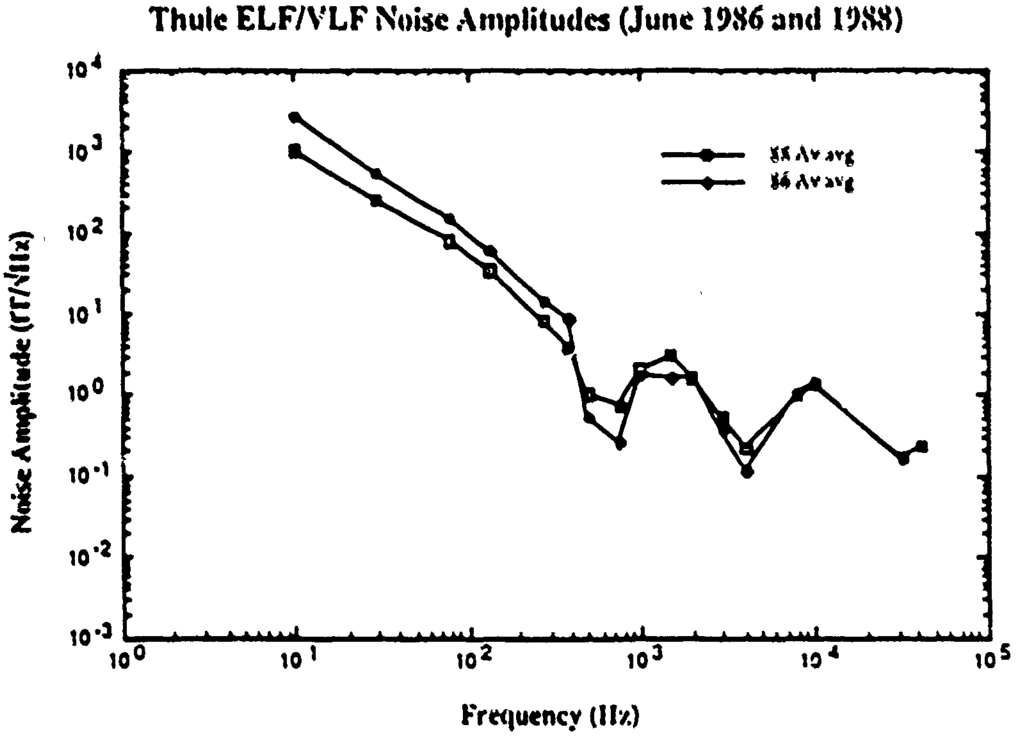


**Figure 19.** Comparison of the overall average noise amplitudes measured at Thule during June 1986 and two years later during June 1988. Included in the latter set of amplitudes is a measurement at 41.0 kHz made with the LF filter attached to the Thule radiometer.

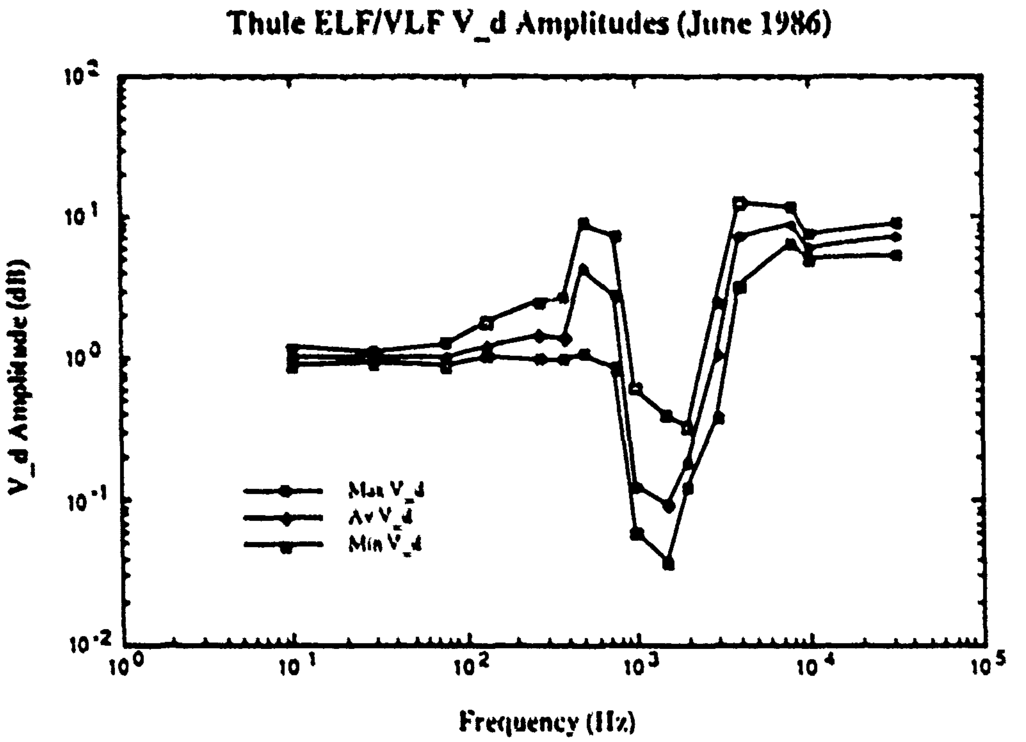


**Figure 20.** Variation of the Thule ELF/VLF $V_d$ amplitudes with frequency for the month of June 1986. Overall monthly average values for the maximum, average, and minimum one-minute $V_d$'s are shown for each of the 16 narrow-band frequency channels.

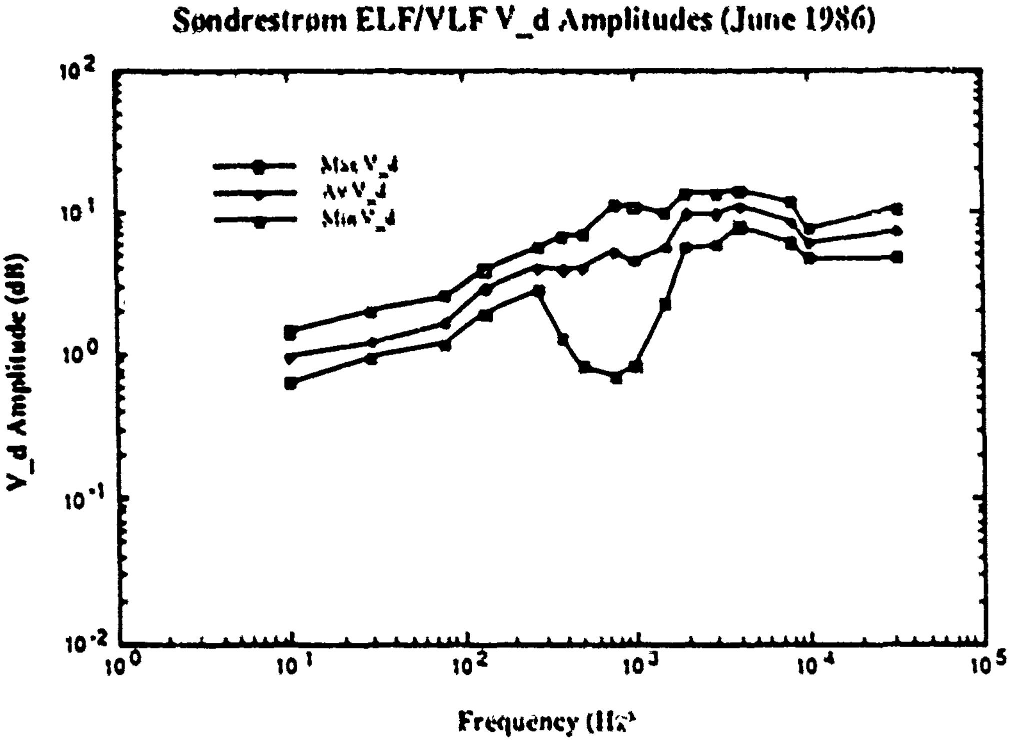


**Figure 21.** Variation with frequency of $V_d$ at Sondrestromfjord for the month of June 1986. Overall monthly average values for the maximum, average, and minimum one-minute $V_d$'s are shown for each of the 16 narrow-band frequency channels.

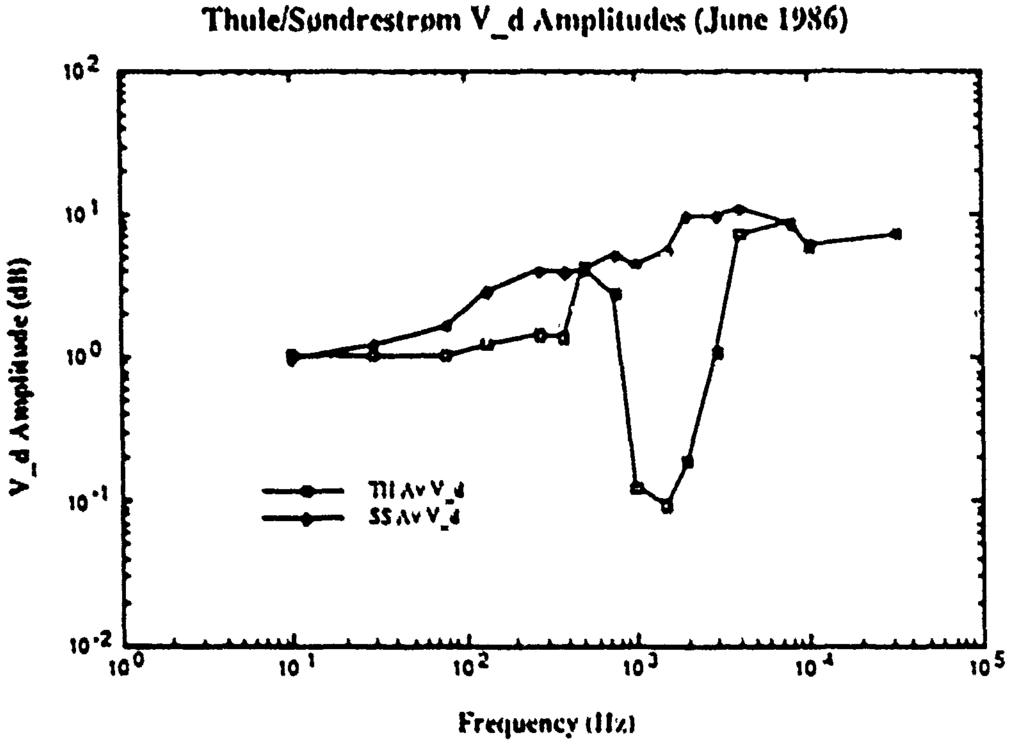


**Figure 22.** Variations with frequency of the overall average values of $V_d$ measured at Thule and at Sondrestromfjord during June 1986.

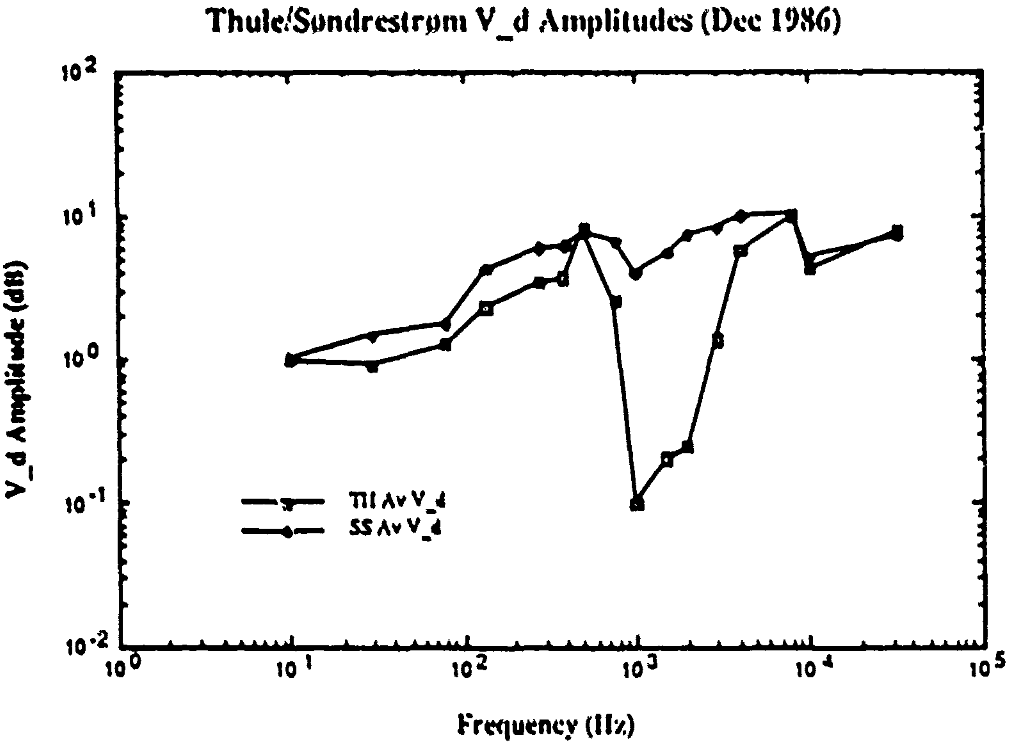


**Figure 23.** Variations with frequency of the overall average values of $V_d$ measured at Thule and at Sondrestromfjord during December 1986.

with those measured during June 1988. There is little difference between the two sets of data, just as there was little difference between the average amplitudes, indicating little variation of $V_d$ with time over the two-year interval.

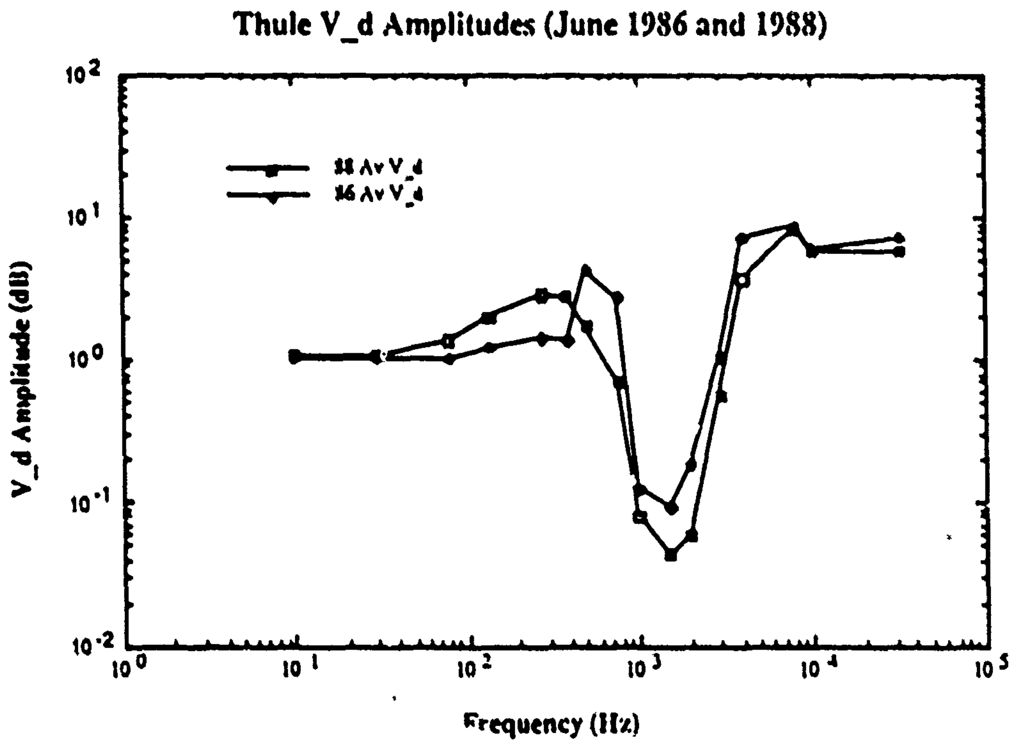


**Figure 24.** Comparison of the variations with frequency of the overall average values of $V_d$ measured at Thule during June 1986 and June 1988.

## 3. Discussion

The data we have presented give a good picture of the levels of ELF/VLF radio noise at Thule during June and December, 1986. Further, the comparison of the Thule and Søndrestromfjord data gives some indication of their geographical variation, or perhaps more relevantly here, their geomagnetic variation. We find that the ELF/VLF noise amplitudes tend to vary inversely with frequency, in accord with the results of earlier studies [*e.g.*, *Fraser-Smith and Helliwell*, 1985], whereas the $V_d$ noise statistic tends to increase with frequency, indicating that the noise becomes increasingly impulsive at higher frequencies. We have also identified an anomalous variation in the Thule noise statistics in the range 750 Hz-3.0 kHz, which we attribute to power line harmonic interference.

Magnetospheric noise (or, more specifically, polar chorus) in the frequency range 500-1500 Hz is clearly a factor in our measurements at both Thule and Søndrestromfjord, but it does not appear to have a major impact on the noise statistics we derive from the measurements. However, there are several reasons why further noise measurements are needed at Thule and Søndrestromfjord before any general conclusion about the influence of magnetospheric noise on the noise statistics is feasible. First, it is unclear how much of the contribution from polar chorus is masked at Thule by the power line harmonics. Second, our measurement intervals did not include any periods of auroral hiss, the other predominant form of magnetospheric noise observed at high latitudes [*e.g.*, Jorgensen, 1966]. Finally, studies of the solar-cycle variation of ELF/VLF magnetospheric noise are lacking, presumably due to the difficulty of making long-term measurements of radio noise at high latitudes, and thus our measurements may well have been made at a stage of the solar cycle when the occurrence of magnetospheric noise at Thule and Søndrestromfjord was atypically low. Because the electromagnetic signals and the energetic charged particles with which they interact in the magnetosphere are strongly influenced by solar activity, it is likely that the magnetospheric noise measured at high latitudes varies widely during the solar cycle. These uncertainties need to be resolved by further measurements.

Similarly, the apparently anomalous high level of noise at Thule in the range 10-50 Hz needs further investigation. As we pointed out, the noise does not appear to be either man-made or instrumental, but we have difficulty explaining the large difference between the

Thule and Søndrestromfjord amplitudes at such low frequencies.

The Thule data we have compared for June 1986 and June 1988 (Figure 19) suggest that there is little variation in the noise statistics from year to year. This is potentially an important result, but, as pointed out above, much further data analysis is needed before the time variation of the noise statistics can be established with certainty. We hope to investigate the long-term variation of the statistics further as measurements with the Stanford University radiometer array proceed.

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# Appendix: Thule Average Data

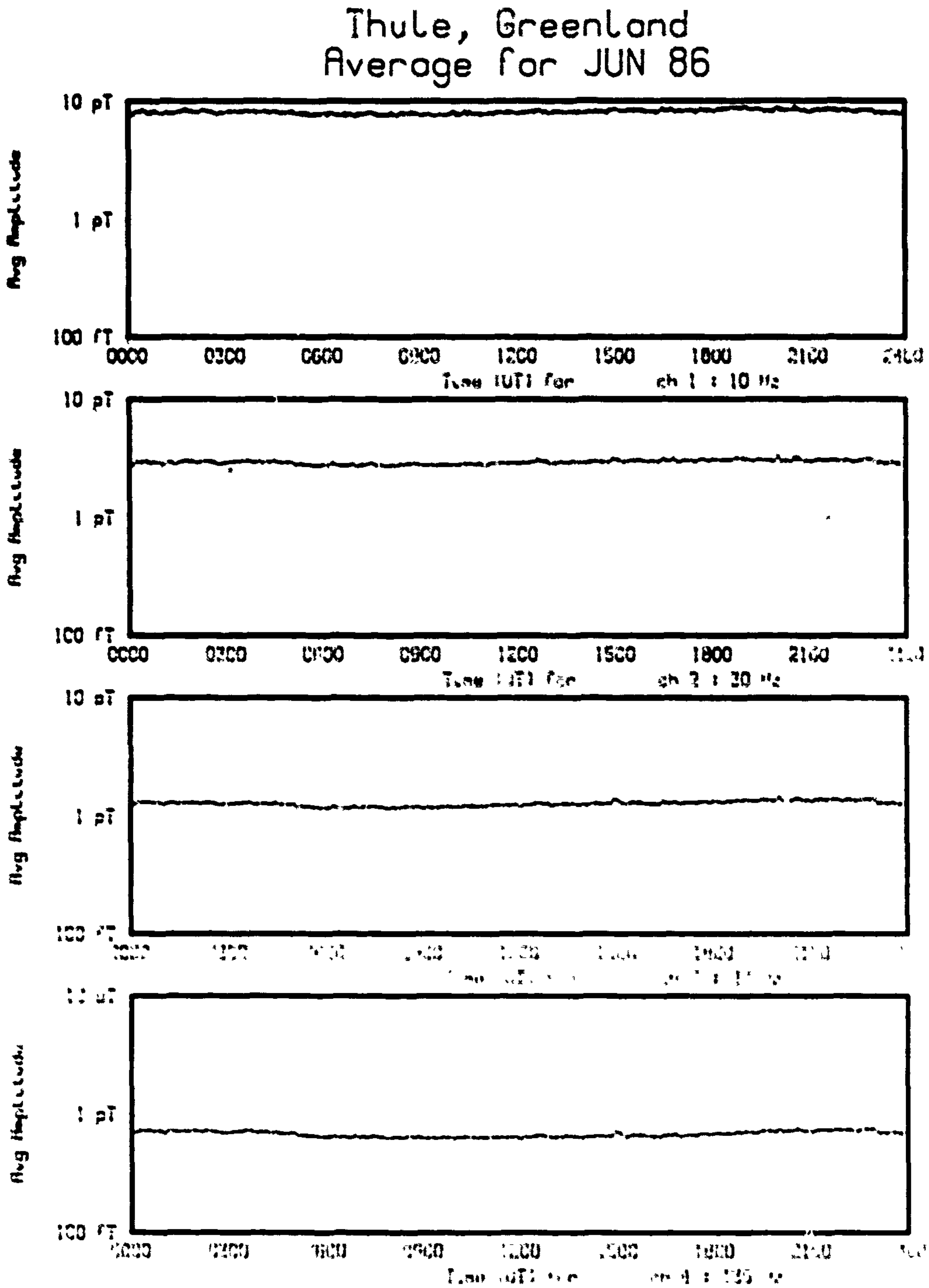


**Figure A1.** Overall average variation for the month of June 1986 of the one-minute average magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 10, 30, 80, and 135 Hz.

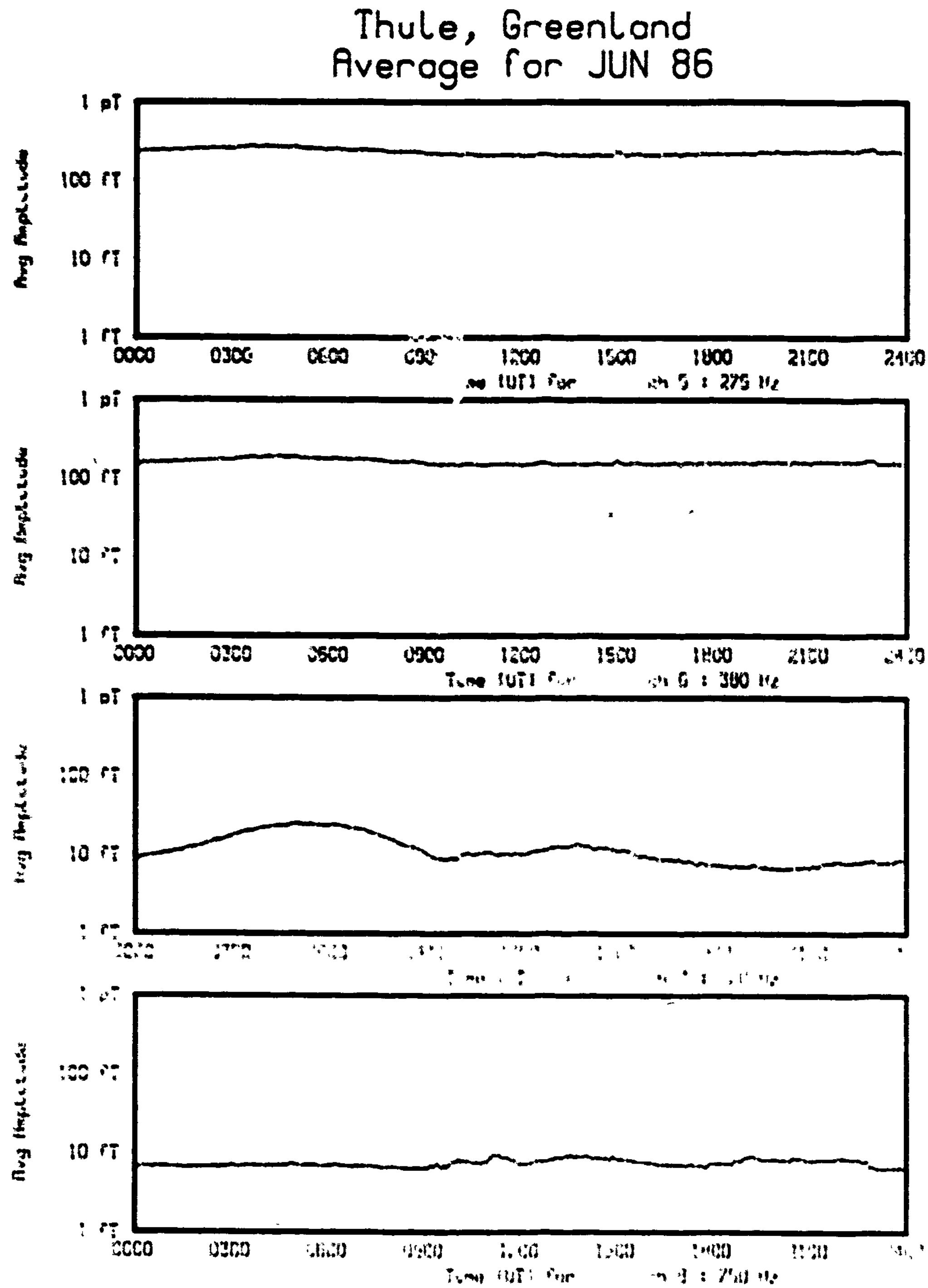


**Figure A2.** Overall average variation for the month of June 1986 of the one-minute average magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 275, 380, 500, and 750 Hz.

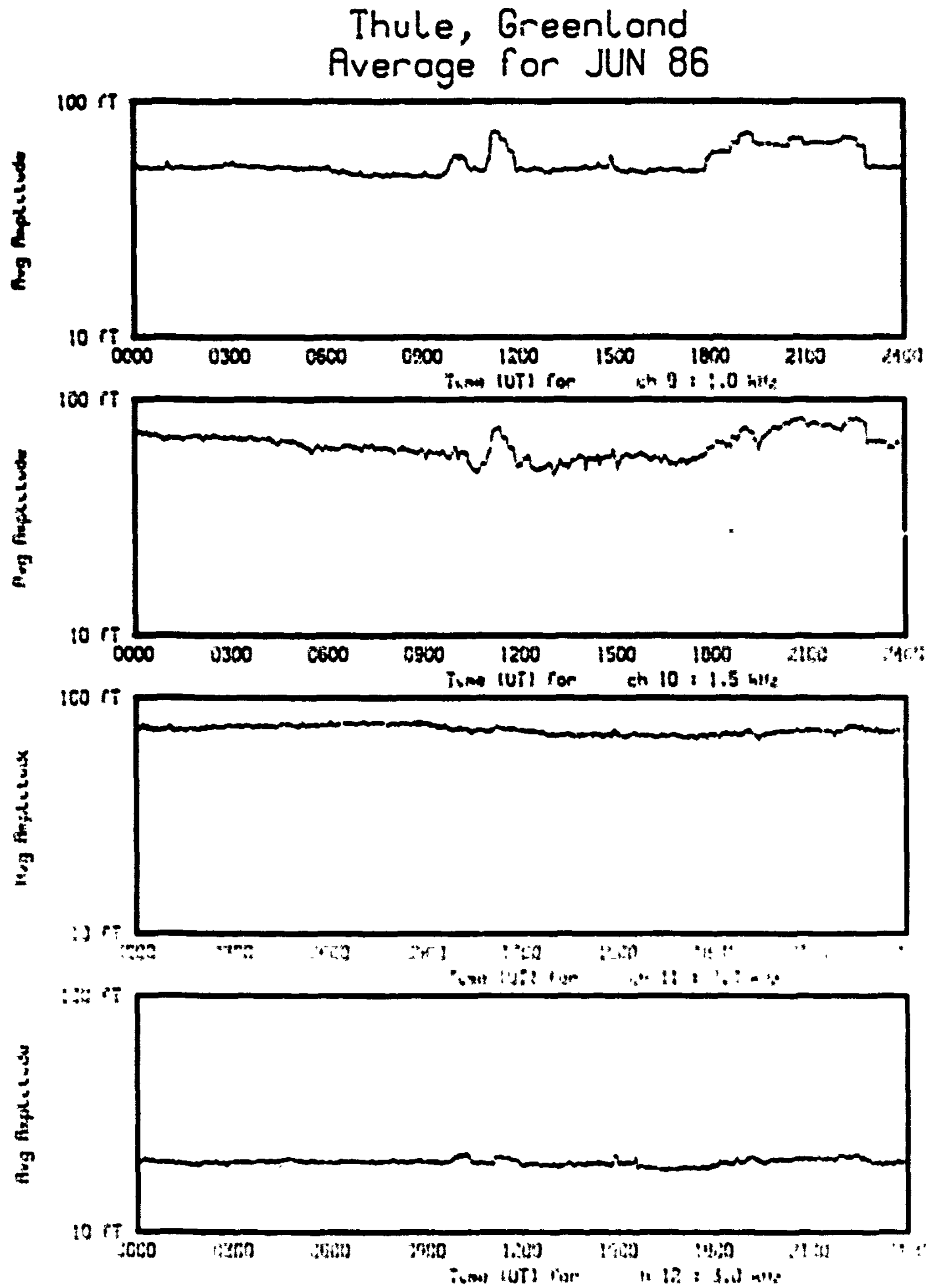


**Figure A3.** Overall average variation for the month of June 1986 of the one-minute average magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 1, 1.5, 2, and 3 kHz.

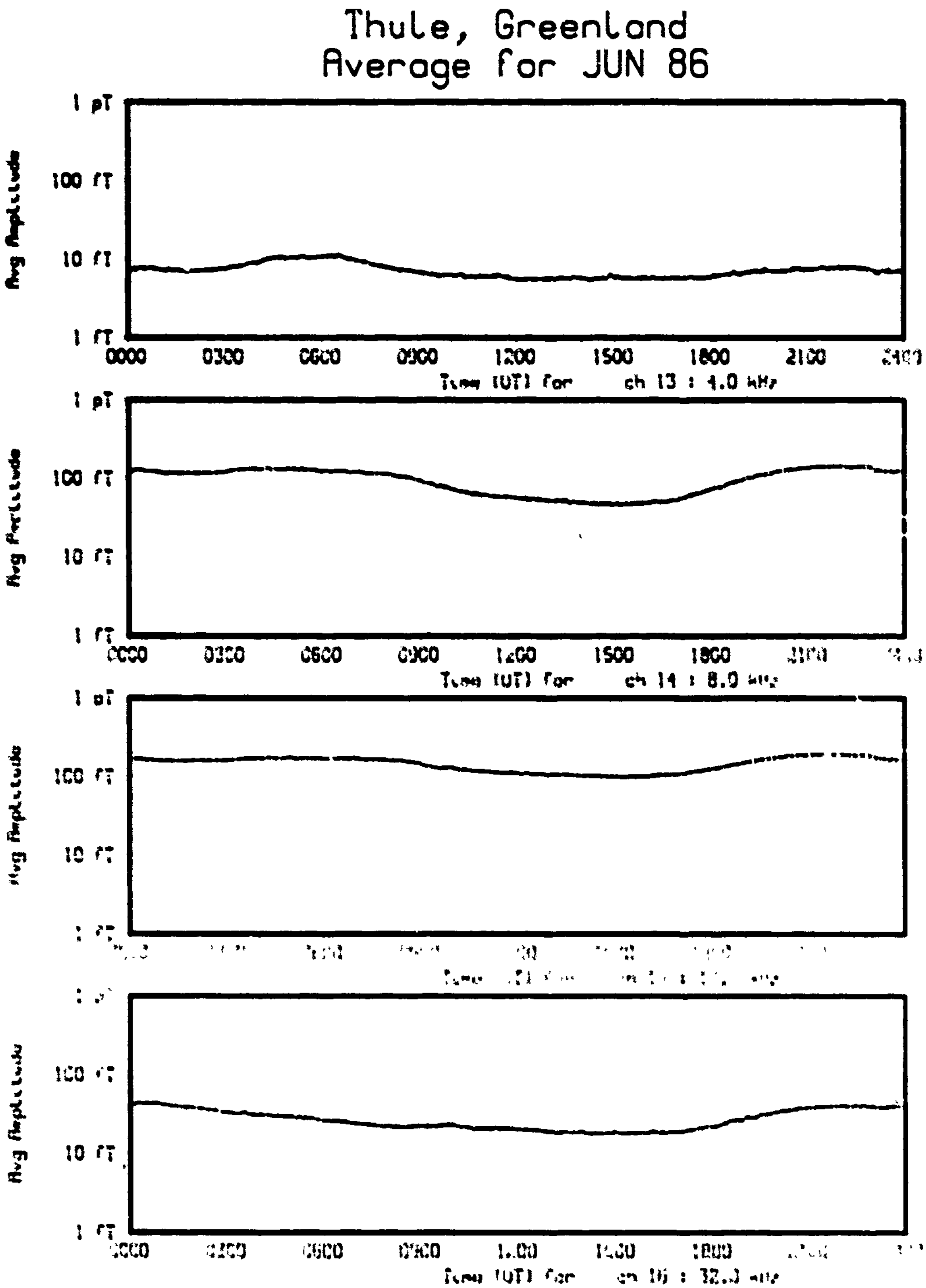


**Figure A4.** Overall average variation for the month of June 1986 of the one-minute average magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 4, 8, 10.2, and 32 kHz.

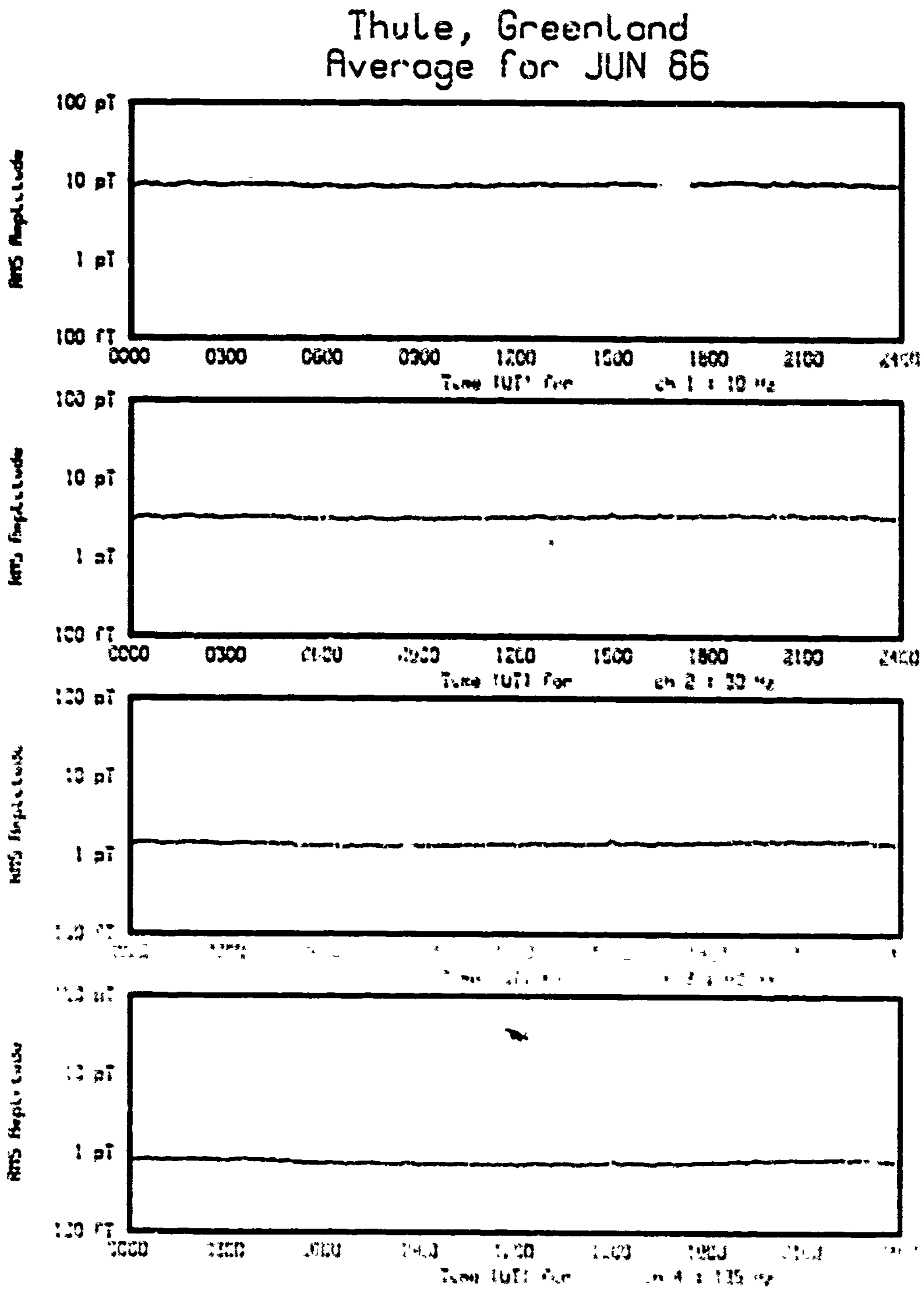


**Figure A5.** Overall average variation for the month of June 1986 of the one-minute rms magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 10, 30, 80, and 135 Hz.

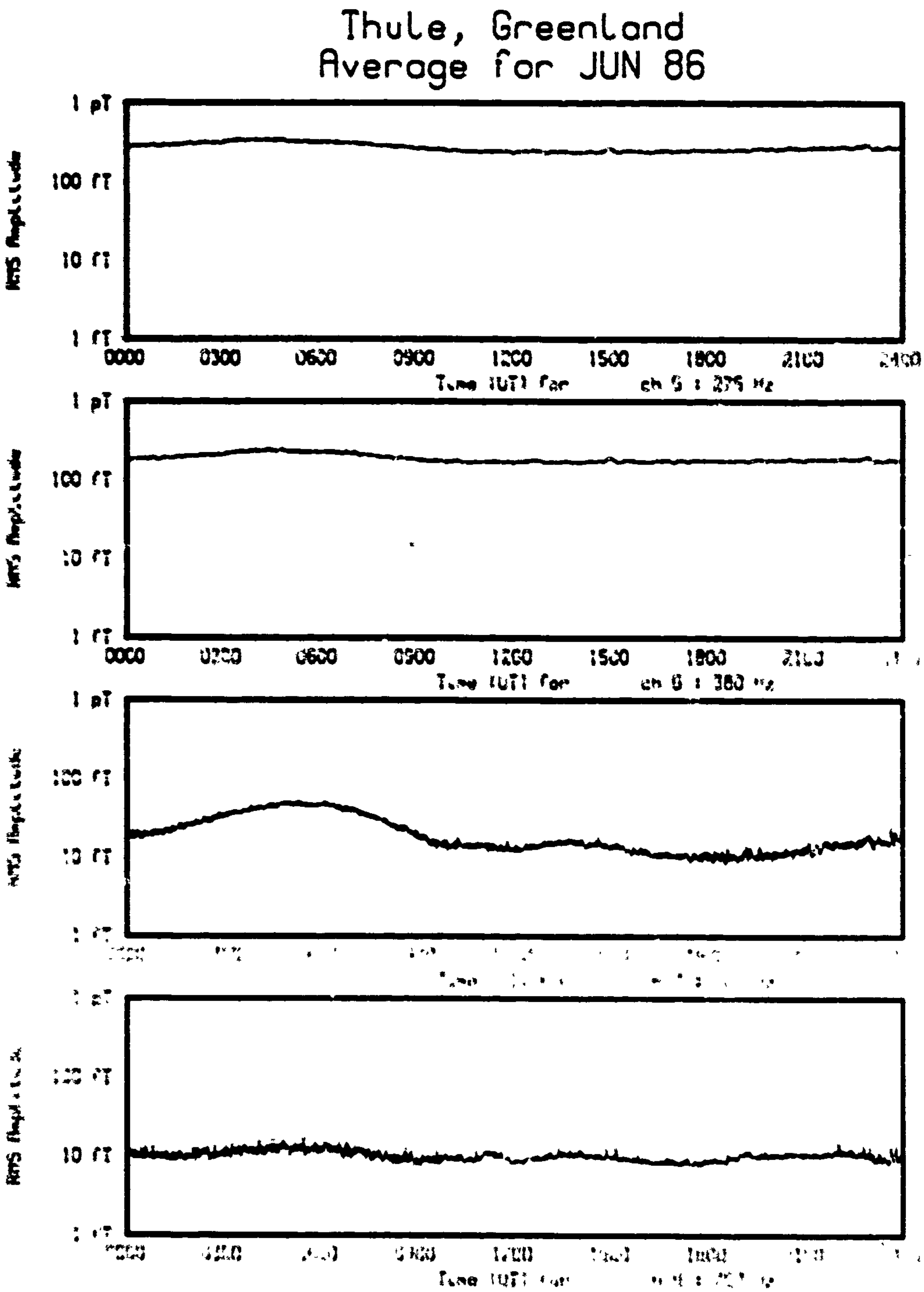


**Figure A6.** Overall average variation for the month of June 1986 of the one-minute rms magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 275, 380, 500, and 750 Hz.

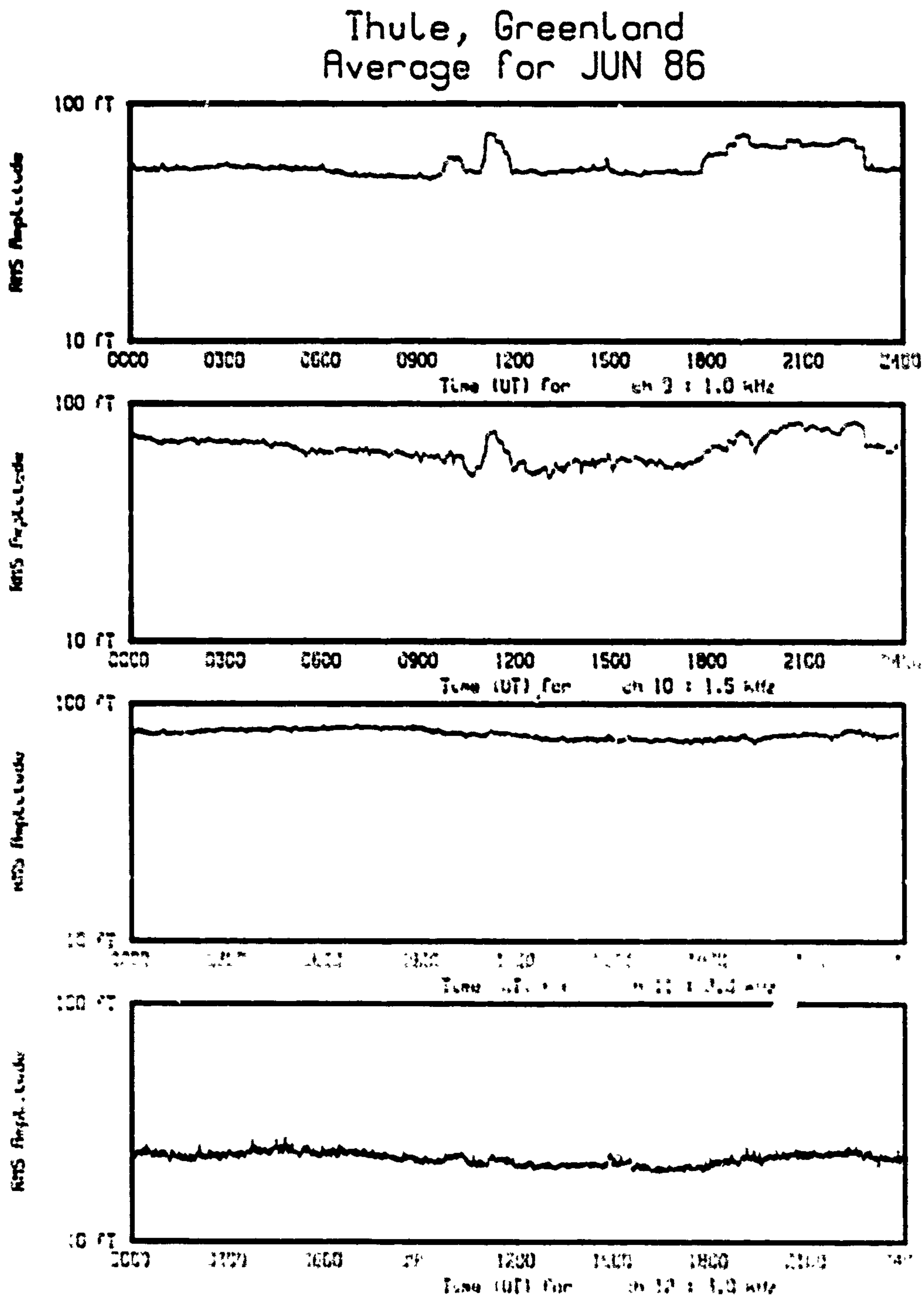


**Figure A7.** Overall average variation for the month of June 1986 of the one-minute rms magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 1, 1.5, 2, and 3 kHz.

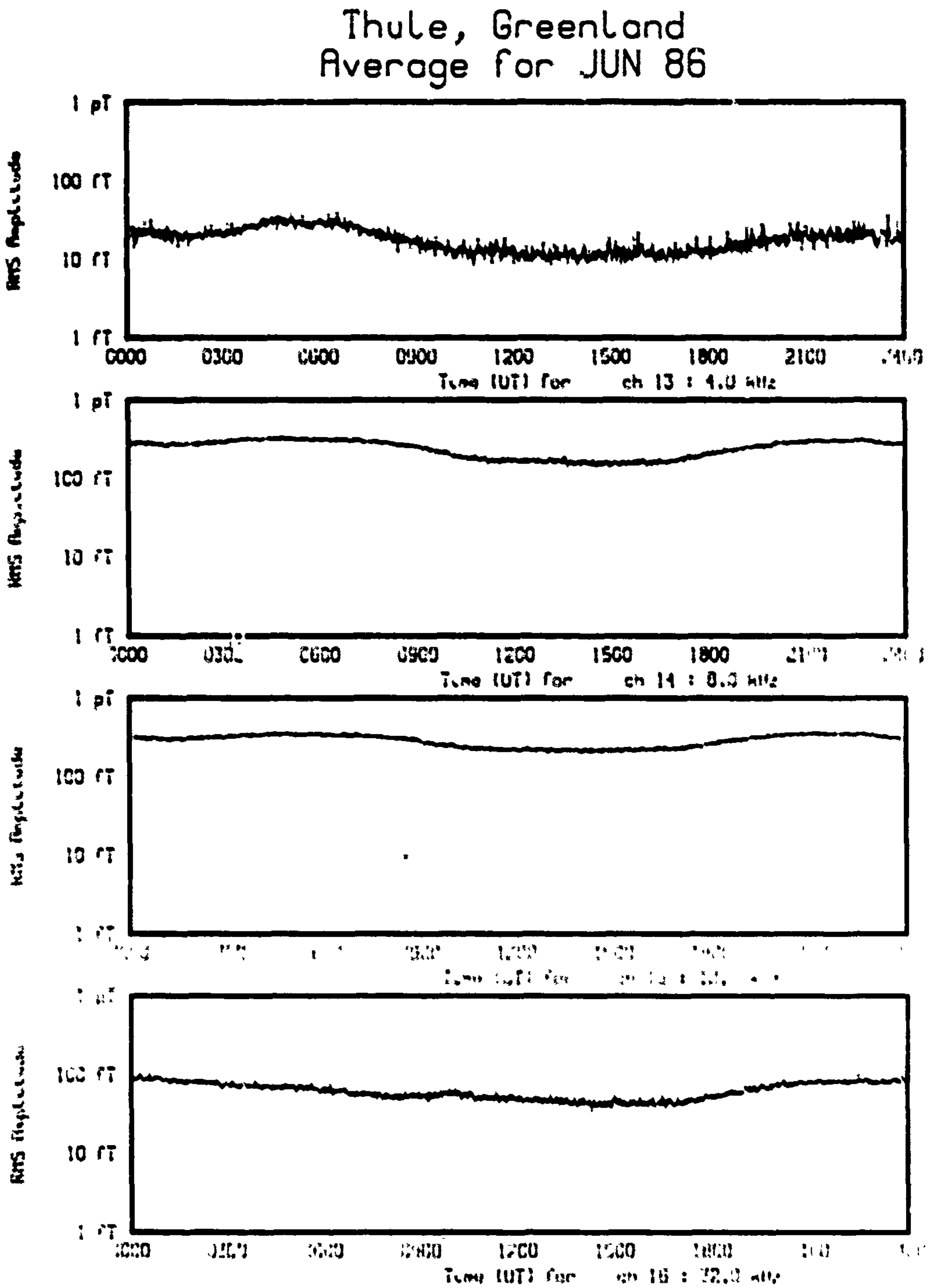


**Figure A8.** Overall average variation for the month of June 1986 of the one-minute rms magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 4, 8, 10.2, and 32 kHz.

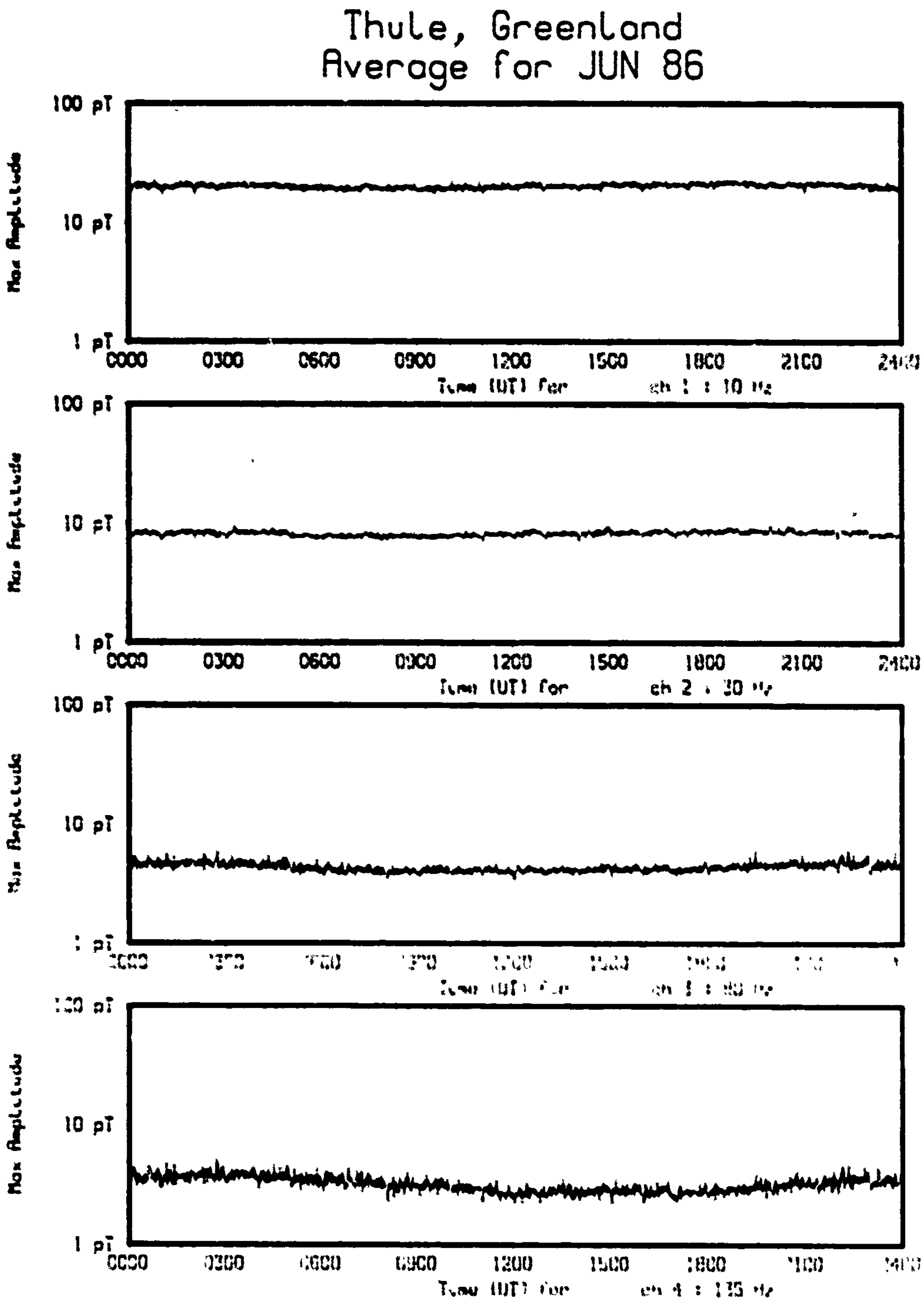


**Figure A9.** Overall average variation for the month of June 1986 of the one-minute maximum magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 10, 30, 80, and 135 Hz.

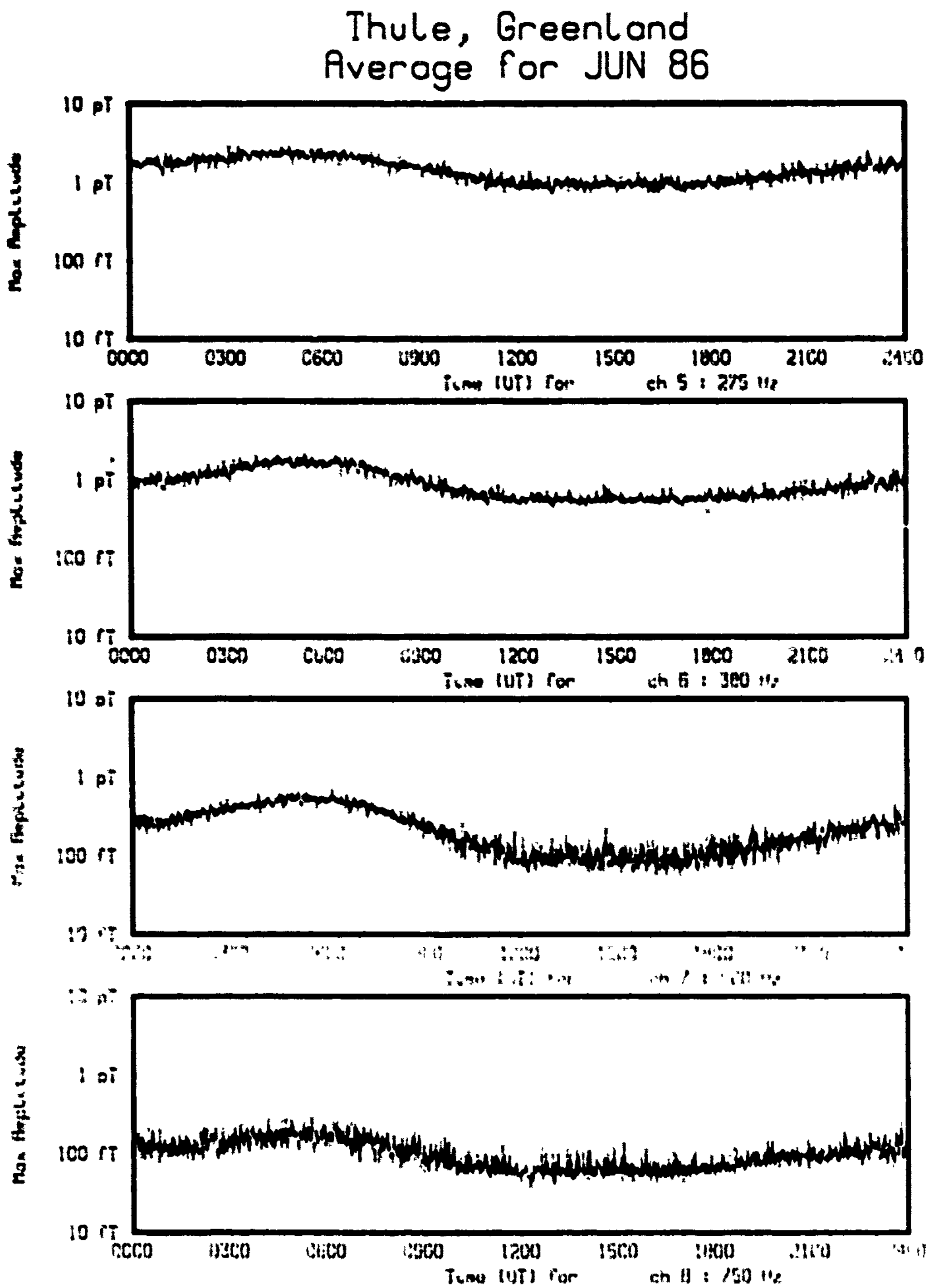


**Figure A10.** Overall average variation for the month of June 1986 of the one-minute maximum magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 275, 380, 500, and 750 Hz.

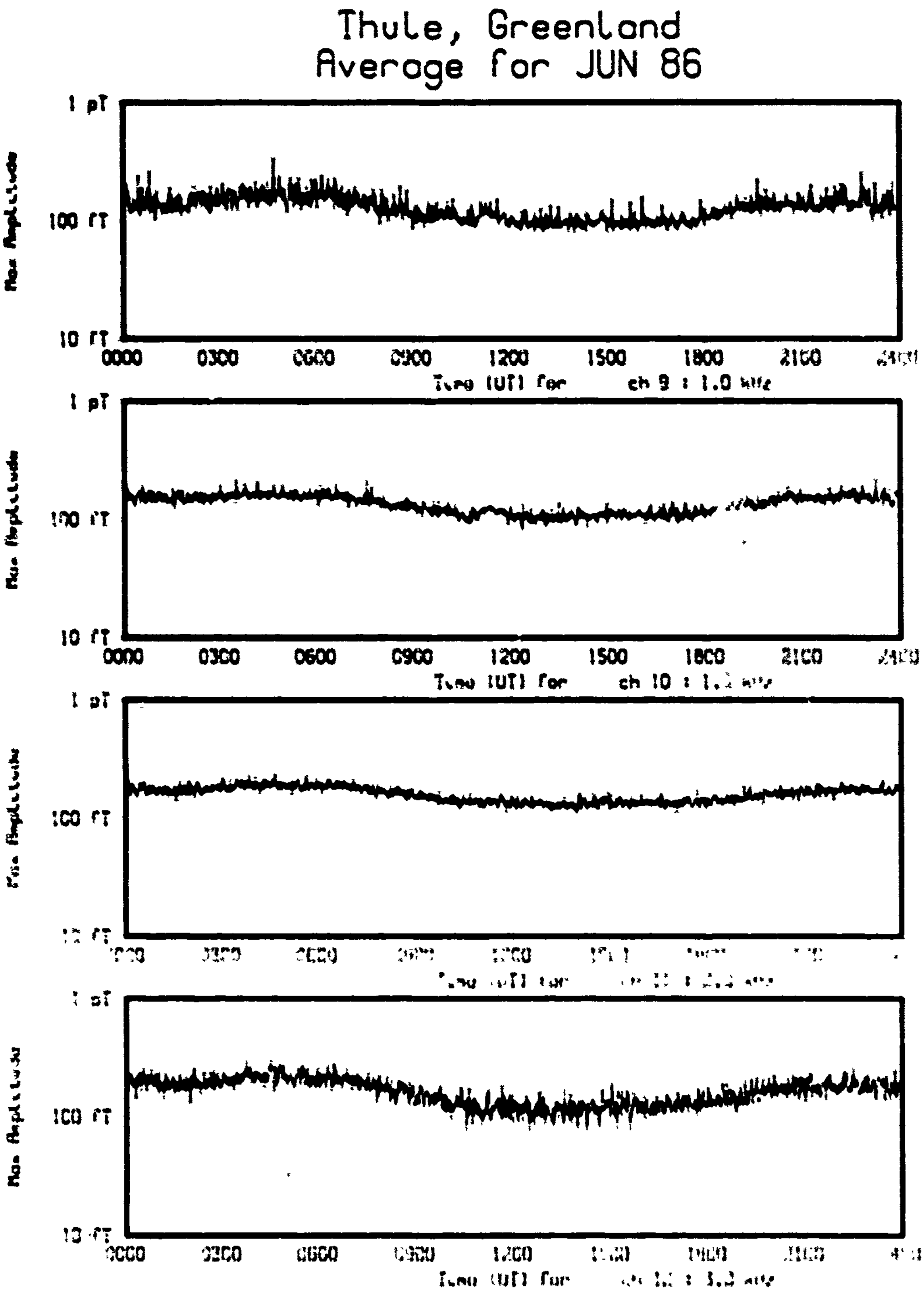


**Figure A11.** Overall average variation for the month of June 1986 of the one-minute maximum magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 1, 1.5, 2, and 3 kHz.

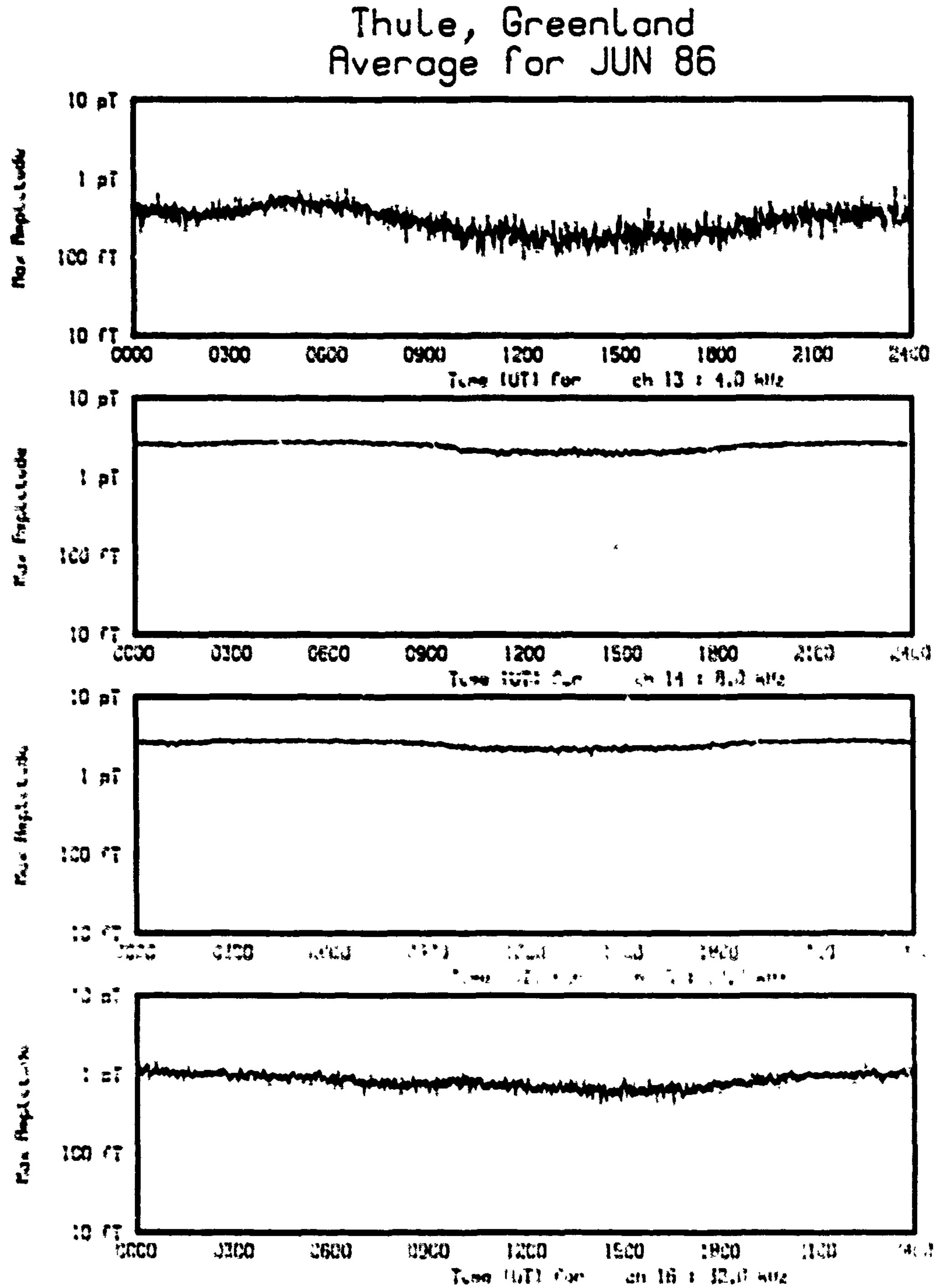


**Figure A12.** Overall average variation for the month of June 1986 of the one-minute maximum magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 4, 8, 10.2, and 32 kHz.

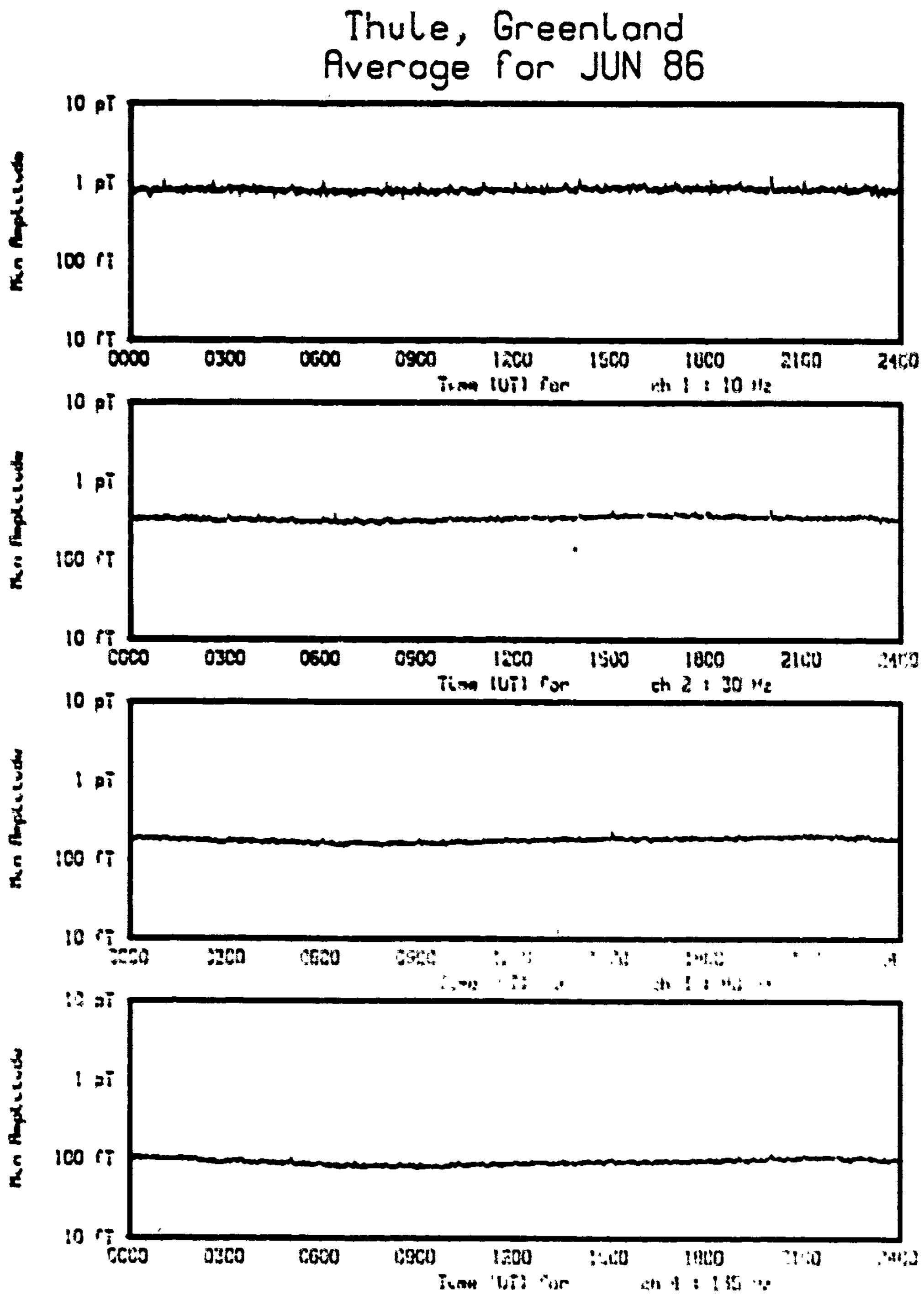


**Figure A13.** Overall average variation for the month of June 1986 of the one-minute minimum magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 10, 30, 80, and 135 Hz.

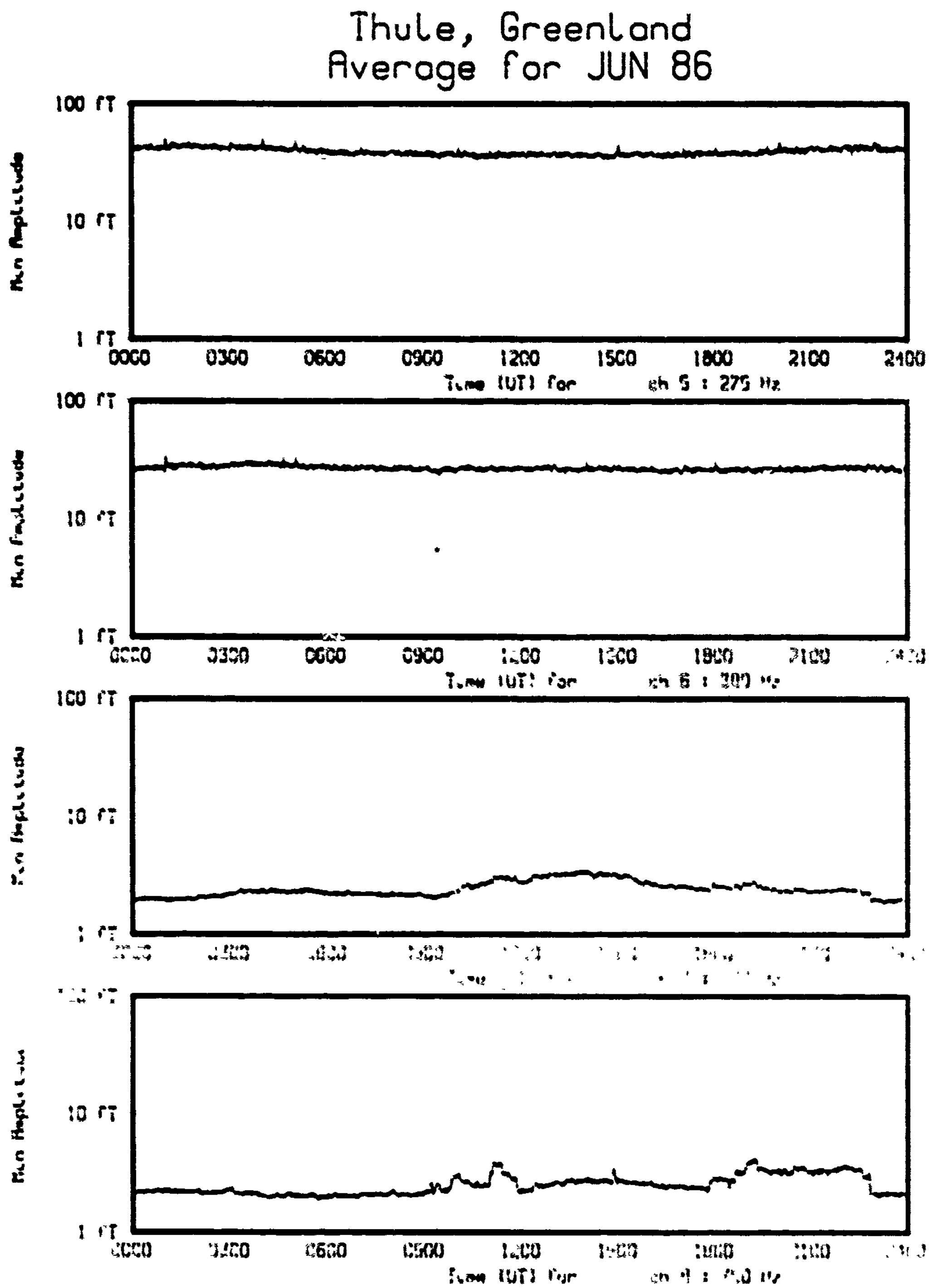


**Figure A14.** Overall average variation for the month of June 1986 of the one-minute minimum magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 275, 380, 500, and 750 Hz.

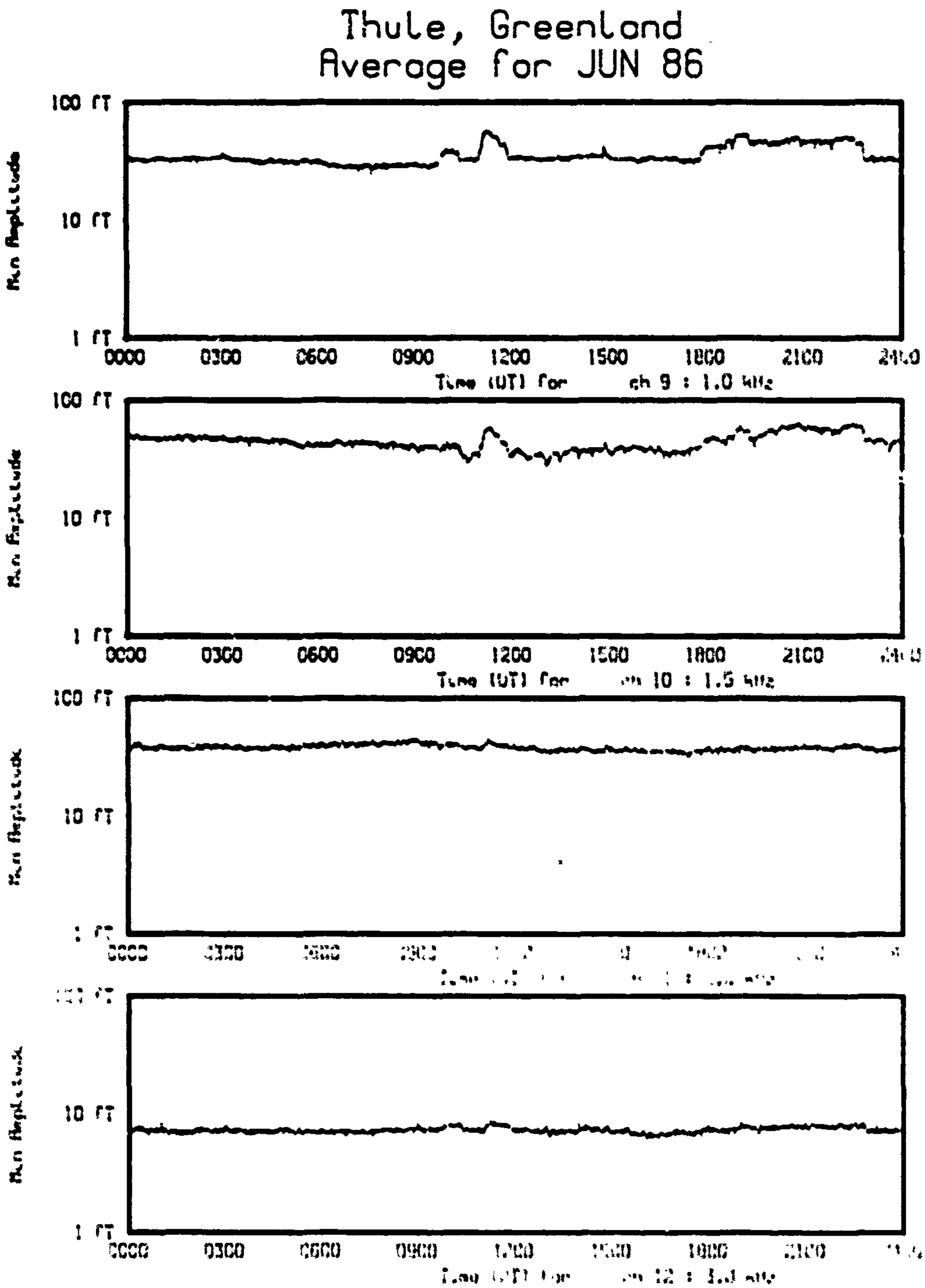


**Figure A15.** Overall average variation for the month of June 1986 of the one-minute minimum magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 1, 1.5, 2, and 3 kHz.

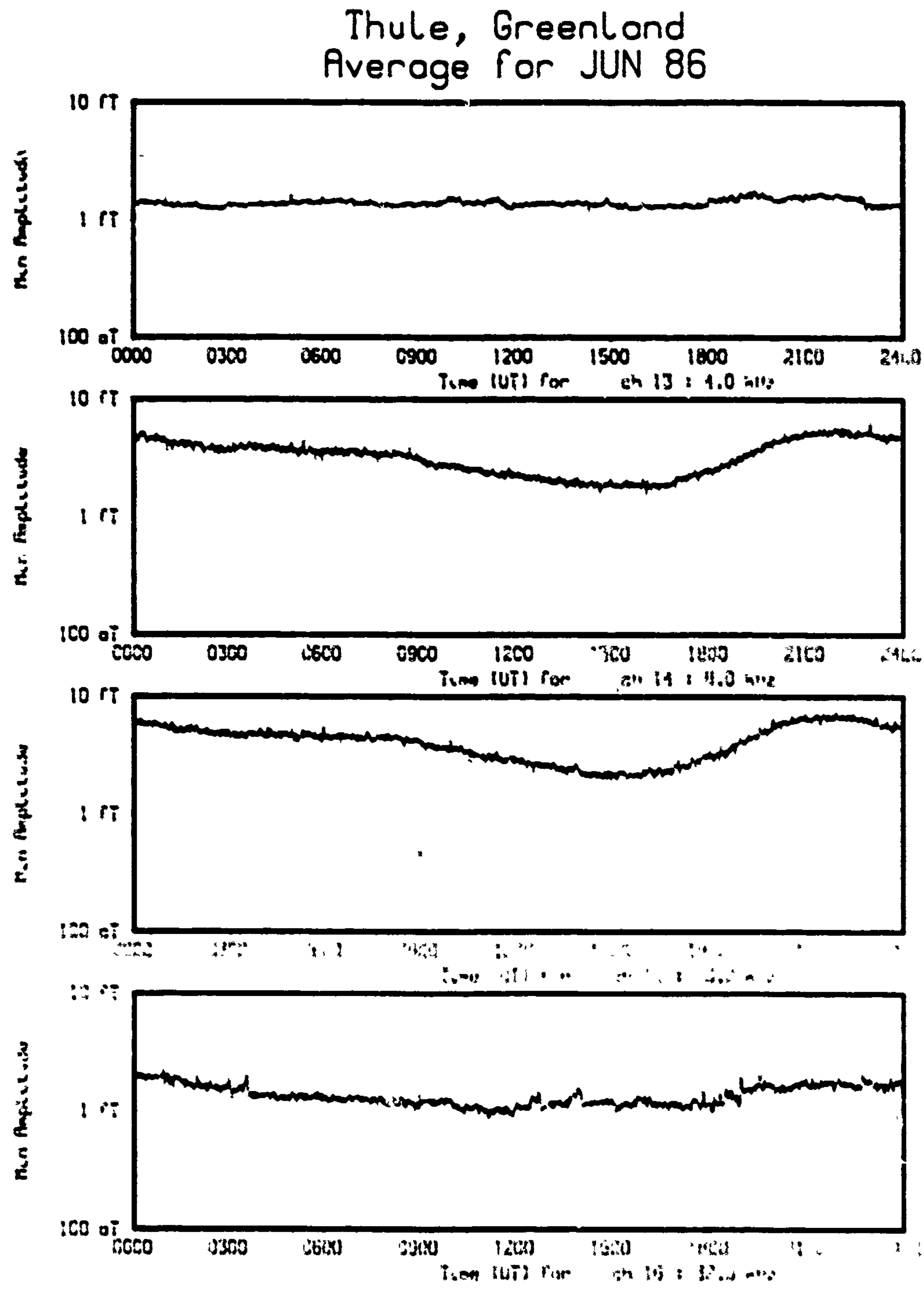


**Figure A16.** Overall average variation for the month of June 1986 of the one-minute minimum magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 4, 8, 10.2, and 32 kHz.

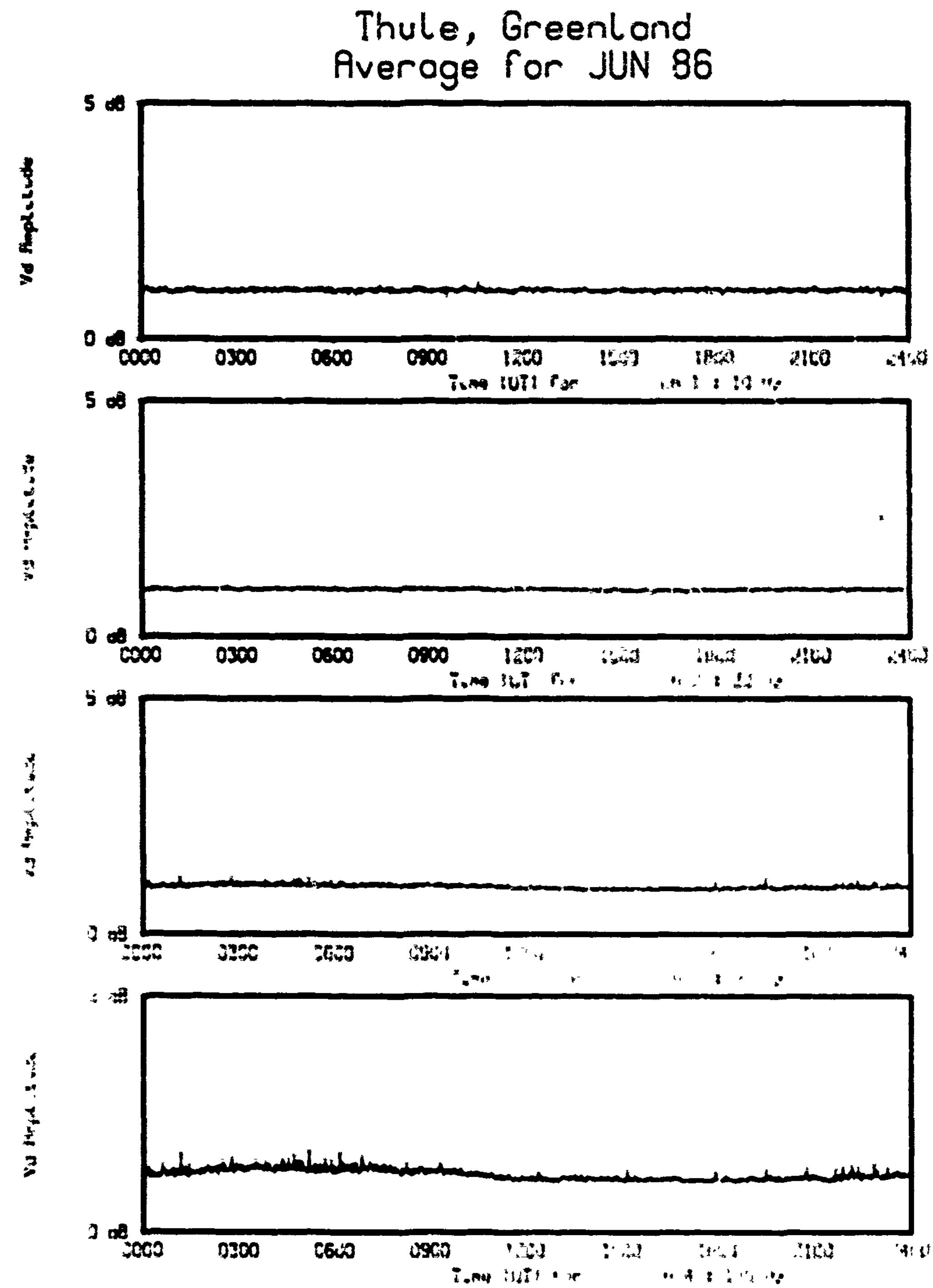


**Figure A17.** Overall average variation for the month of June 1986 of the one-minute $V_d$ statistic for the magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 10, 30, 80, and 135 Hz.

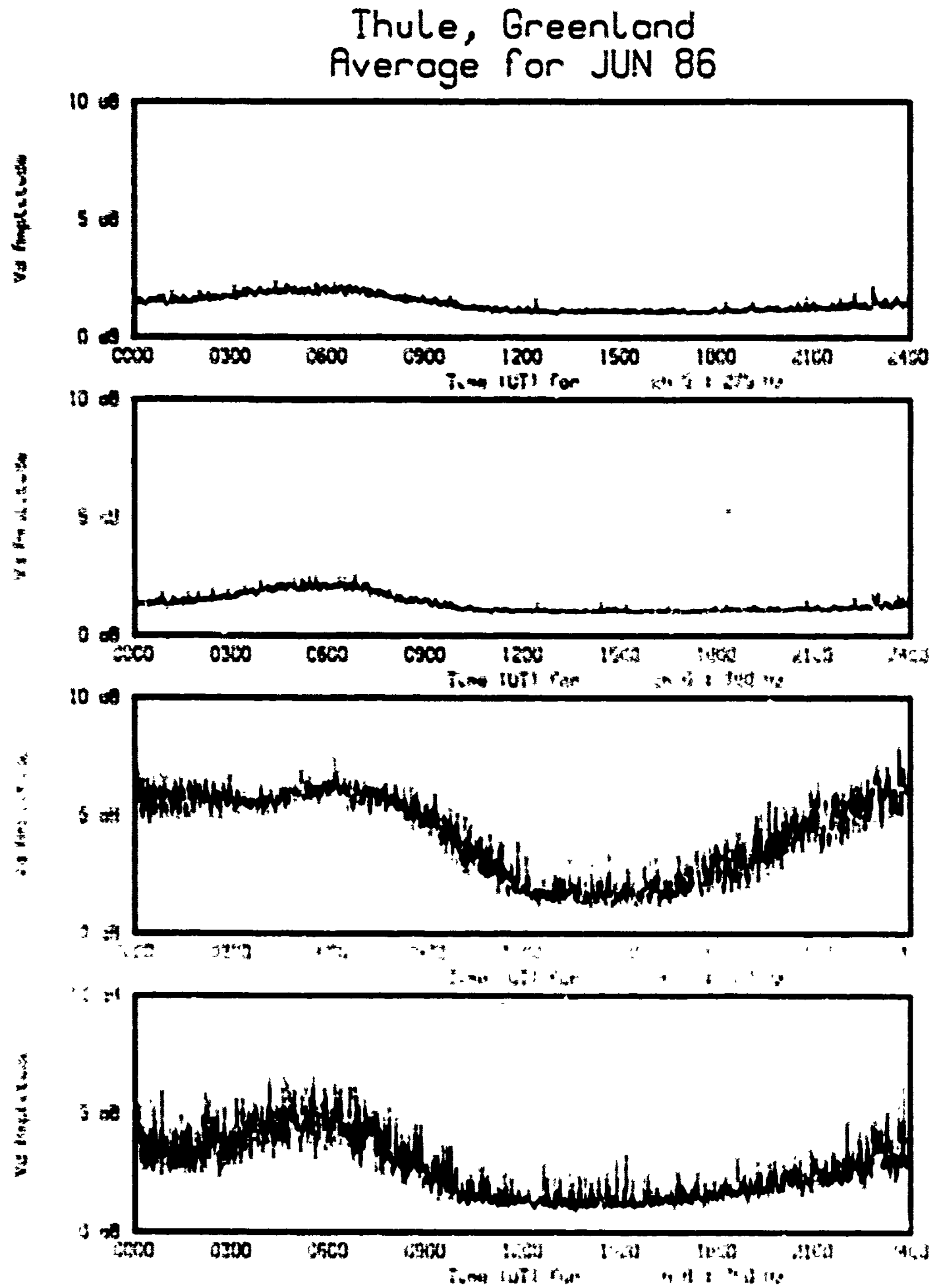


**Figure A18.** Overall average variation for the month of June 1986 of the one-minute $V_d$ statistic for the magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 275, 380, 500, and 750 Hz.

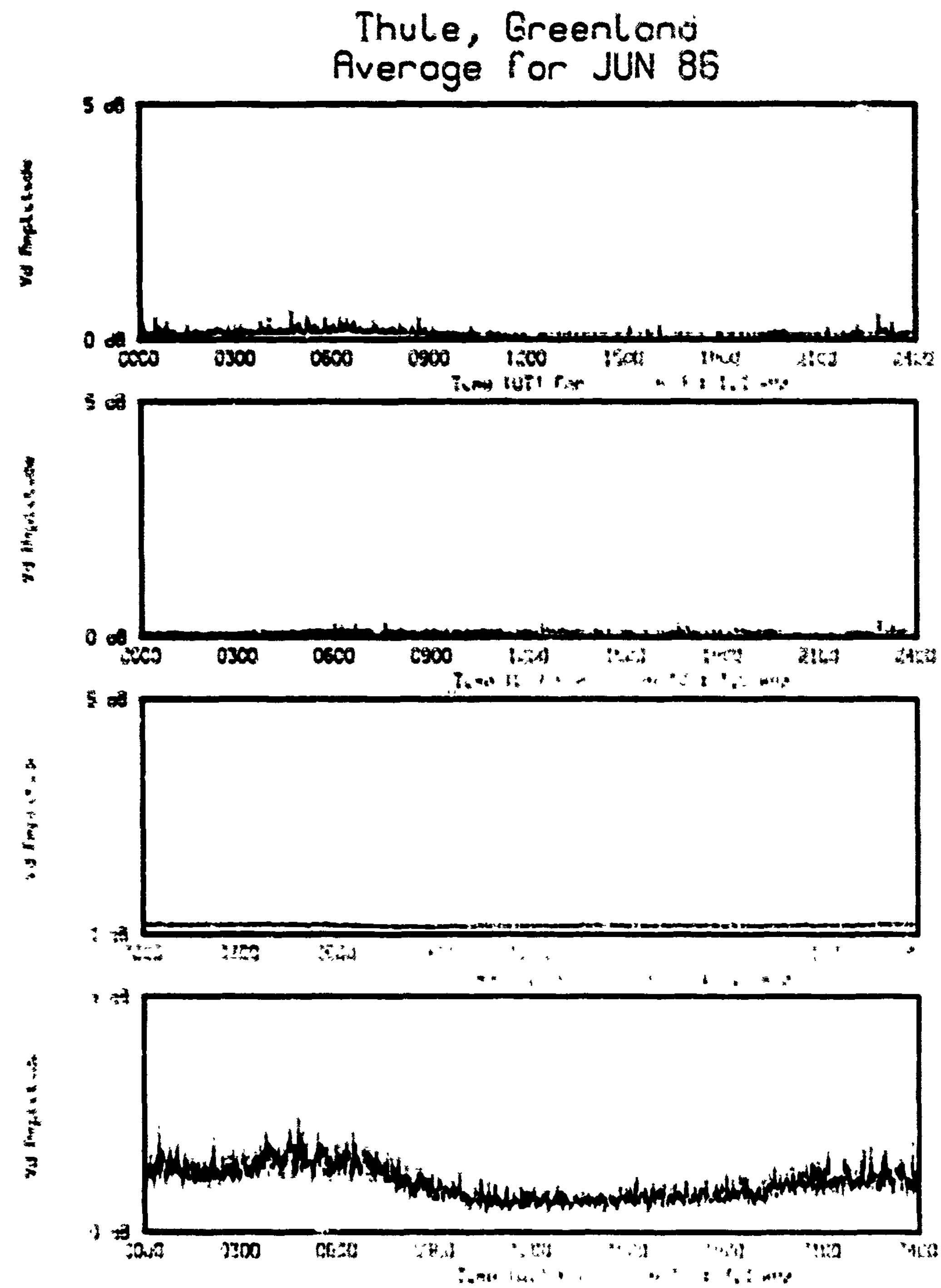


**Figure A19.** Overall average variation for the month of June 1986 of the one-minute $V_d$ statistic for the magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 1, 1.5, 2, and 3 kHz.

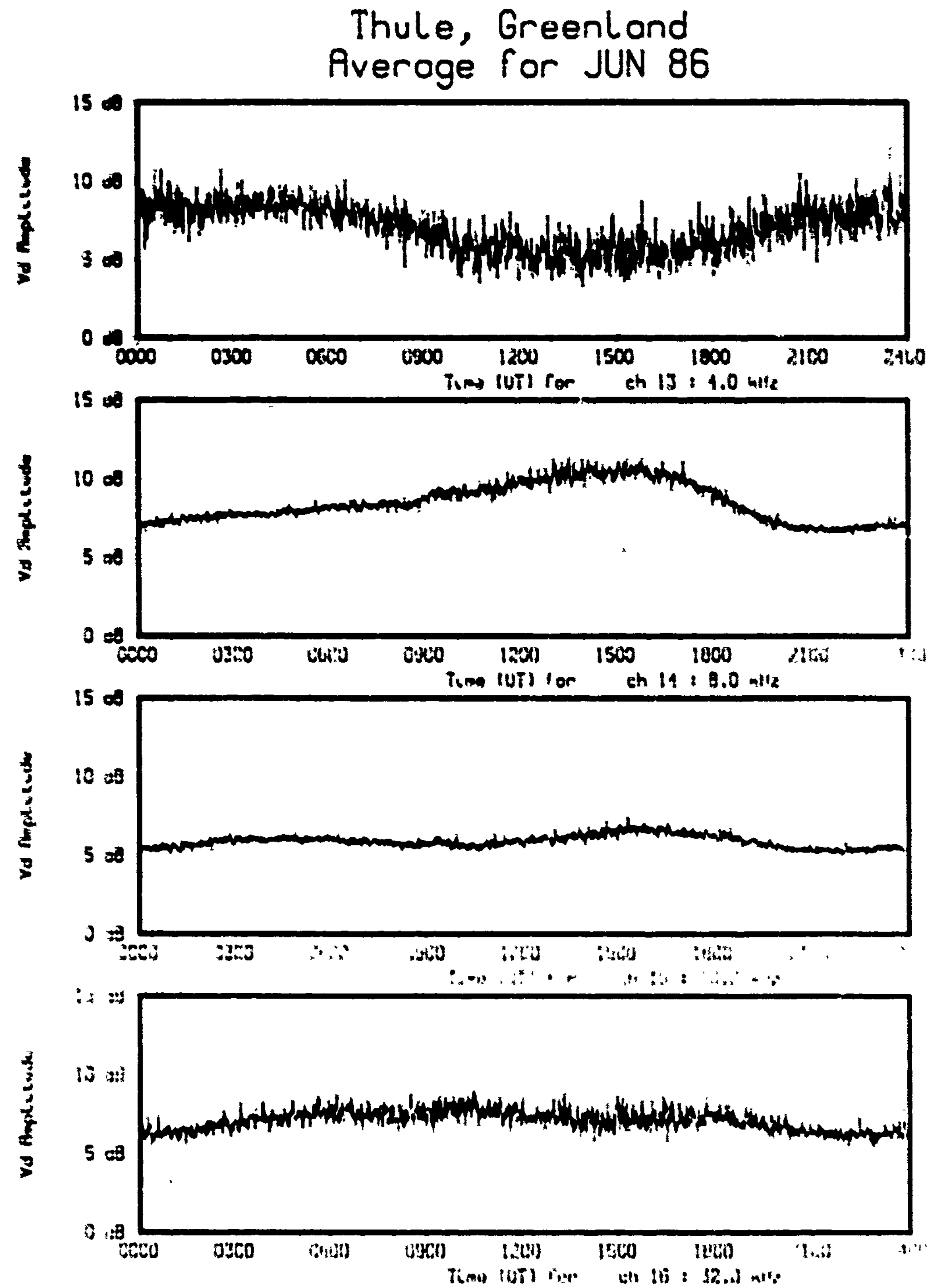


**Figure A20.** Overall average variation for the month of June 1986 of the one-minute $V_d$ statistic for the magnetic field amplitudes measured at Thule in four narrow frequency bands (5% bandwidth) centered on 4, 8, 10.2, and 32 kHz.