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Morphology of VLF Emissions Observed with the Injun 3 Satellite

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Results of a study of very low frequency (VLF) emissions observed with the Injun 3 satellite are presented. Approximately 1200 hours of VLF magnetic field strength data and approximately 6000 frequency spectra samples are investigated in this study. These data cover invariant latitudes up to 82°, all local times, and altitudes from 237 to 2785 km. Contour plots as a function of invariant latitude and magnetic local time giving the frequency of occurrence of VLF emissions above a given intensity are presented. The most intense VLF emissions observed by Injun 3 are found to occur between about 55 and 75° invariant latitude and during the local day, with the maximum intensity occurring at about 65° invariant latitude and about 8 to 10 hours magnetic local time. The region of most intense VLF emissions was found to move to lower latitudes during geomagnetically active periods. The principal types of VLF emissions occurring in this region are ELF hiss and chorus, with the ELF hiss usually being the most intense.

INTRODUCTION

Very low frequency (VLF) radio noises are naturally occurring radio noises in the frequency range from about 1 to 30 kHz [*Gallet and Helliwell*, 1959]. Two basic types of VLF radio noises are known: whistlers and VLF emissions. *Whistlers* are VLF electromagnetic waves whose energy originates from a lightning discharge and which have propagated through the magnetosphere [*Storey*, 1953]. *VLF emissions* are naturally occurring electromagnetic waves generated by energetic charged particles in the earth's magnetosphere. Unlike whistlers, the detailed mechanism by which VLF emissions are generated is largely unknown.

VLF emissions have been extensively investigated using ground-based VLF receivers. Systematic classifications of VLF emissions according to their frequency-time spectra have been given by *Gallet* [1959] and more recently by *Helliwell* [1965]. Gallet classified VLF emissions into two categories: *hiss* and *discrete emissions*.

Hiss consists of a steady-state thermal noise spectrum with very little frequency-time structure. At least two general types of hiss are known to occur: (1) hiss above about 2 kHz, occurring predominantly near the auroral zone during local afternoon and evening, and (2) hiss in the frequency range from a few hundred Hz up to about 2 kHz usually occurring during the local daytime at middle and high latitudes. Using ground-based VLF receivers, *Watts* [1957] and *Ellis* [1959] reported VLF hiss above about 2 kHz occurring in association with solar and geomagnetic disturbances. *Martin et al.* [1960] and later *Morozumi* [1963] reported on the observation of VLF hiss above 4 kHz at Byrd Station, Antartica, and the association of this noise, which they call auroral hiss, with the occurrence of auroras. *Jørgensen* [1966] has summarized VLF hiss observations from thirteen ground stations in both hemispheres and finds that VLF hiss activity from about 4 to 9 kHz is greatest about one hour before magnetic midnight and at approximately 70° geomagnetic latitude.

Hiss in the frequency range from a few hundred Hz up to about 2 kHz, sometimes called ELF hiss, has been studied by a number of investigators. From ground-based measurements at Kiruna, Sweden (65° geomagnetic latitude), *Aarons et al.* [1960] were among the first to report the occurrence of an intense band of noise with a bandwidth of several hundred Hz and centered on approximately 700 Hz. This type of ELF hiss is primarily a high-latitude (above 50° geomagnetic latitude) phenomenon and has a pronounced diurnal variation with a maximum occurrence between 0600 and 1100 local time [*Egeland et al.*, 1965].

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Discrete emissions are noise bursts with sharply defined frequency-time structure, usually tones of rapidly varying frequency, quasi-musical sounds, etc. Many different types of discrete VLF emissions have been observed. *Gallet* [1959] and *Helliwell* [1965] have organized ground-based observations of discrete emissions into systematic classes according to their frequency-time characteristics. At middle latitudes, the most common type of discrete emission is *chorus*. Chorus consists of many randomly occurring discrete tones lasting a few tenths of a second and usually rising in frequency. Chorus was first investigated by *Storey* [1953] who found a strong diurnal variation in the occurrence of chorus with a peak around 0600 local time and a marked dependence on geomagnetic activity. At higher latitudes near the auroral zone the most common type of discrete emission is *polar chorus* [*Ungstrup and Jackerott*, 1963]. Polar chorus consists of many randomly occurring tones, rising in frequency, and generally of lower frequency than chorus found at middle latitudes. ELF hiss, of the type studied by Aarons, often occurs in the same frequency range and simultaneously with polar chorus.

Although an extensive amount of data have been obtained on the intensity and region of occurrence of VLF emissions using ground-based VLF receivers, these measurements have a number of serious disadvantages for quantitative studies which include: (1) variable and unknown absorption and transmission losses through the base of the ionosphere, (2) total internal reflection of VLF waves at the base of the ionosphere preventing some waves from being detected on the ground, and (3) difficulty in determining the latitude of a VLF emission because of long-distance propagation in the earth-ionosphere waveguide. These disadvantages are all largely overcome by satellite measurements of VLF phenomena. The purpose of this paper is to present a study of the intensity and regions of occurrence for various types of VLF emissions using data from a VLF receiver on the Injun 3 satellite.

Brief Description of the Injun 3 VLF Experiment

The University of Iowa/ONR satellite Injun 3 (1962 β_T) was a high-latitude (70.4° inclination), low-altitude (237–2785 km) satellite [*O'Brien et al.*, 1964]. A loop antenna, oriented so that the geomagnetic field is in the plane of the loop, was used to detect the magnetic component of a VLF electromagnetic wave. The frequency response of the wide-band, 0.1 to 7 kHz, receiver is shown in Figure 1. The VLF signal from the antenna was normalized to a constant amplitude by an automatic gain control (AGC) circuit. This wide-band analog signal directly modulated the telemetry transmitter so that high time resolution spectrum analysis could be performed on the ground. The wide-band signal strength was determined by telemetering the AGC feedback voltage every four seconds. The wide-band signal strength measurement was calibrated using a white noise source so that all frequency components were weighted equally. Because the frequency response of the receiver is not flat (see Figure 1), the wide-band signal strength, as determined from the AGC voltage, will be in error if the magnetic field noise spectrum is not flat. The magnitude of this error is generally small (less than 4 db) if the peak spectral contribution occurs above 1 kHz. However, as the frequency of the peak spectral contribution decreases below 1 kHz, this error increases rapidly.

In the intensity data presented in this paper, *no* frequency response corrections were made to the wide-band signal strength measurements. A rough estimate of the correction necessary for a specific noise spectrum can be obtained from Figure 1. The receiver noise level for the wide-band field strength measurement is about 1.0

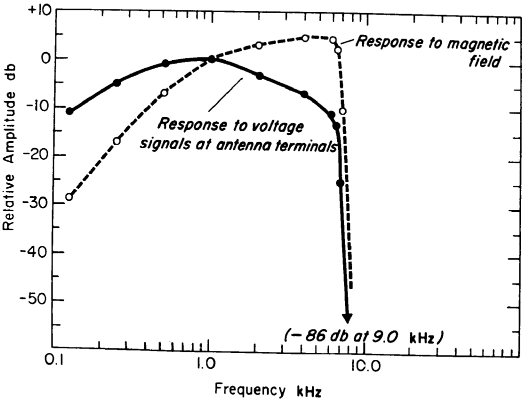


Fig. 1. Frequency response of the Injun 3 VLF receiver.

milligamma (1 gamma = 10^{-5} gauss). For a more complete description of the calibration of the Injun 3 VLF experiment, see *Gurnett and O'Brien* [1964].

THE DEPENDENCE OF VLF EMISSIONS UPON MAGNETIC LOCAL TIME, INVARIANT LATITUDE, ALTITUDE, AND *Kp*

The magnetic coordinates used in this analysis are magnetic local time (MLT), which is the hour angle between the magnetic meridian through the satellite and the magnetic meridian through the sun using the centered dipole approximation [*Chamberlain*, 1961] and invariant latitude (INV), arccos $L^{-1/2}$, where L is *McIlwain's* [1961] shell parameter.

To provide the proper normalization of the data, MLT and INV were divided into blocks, one hour by one degree. On a given revolution, the first two wide-band field strength measurements (eight seconds of data) were taken to be representative of the entire block for that revolution. During the useful lifetime of Injun 3 (December 1962 to September 1963), 1200 hours of VLF data were obtained. During these 1200 hours, the satellite passed through 58,000 MLT-INV blocks, one hour by one degree, one count per revolution. Figure 2 shows the number of wide-band field strengths above a given field strength, two measurements per MLT-INV block per revolution. This plot shows that only 24% of the field strength measurements exceeded the receiver noise level (about 1 milligamma) and that the relative occurrence of different field strengths falls off very rapidly with increasing field strength. The largest field strength found was 50 milligammas.

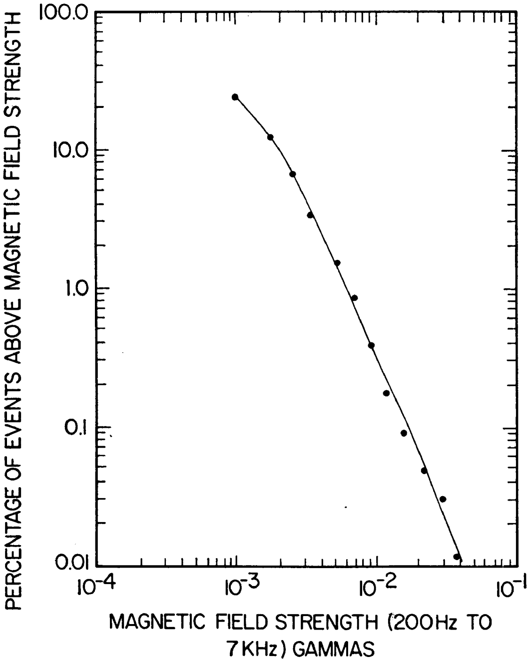


Fig. 2. The percentage of wide-band field strength above a given field strength.

To study the distribution of field strengths in magnetic local time and invariant latitude, two threshold field strengths were chosen, 1.8 and 5.3 milligammas. On a given revolution, the wide-band field strength in a specific MLT-INV block was considered to exceed the given threshold if both of the first *two* wide-band field strength measurements in that MLT-INV block exceeded the threshold value. The 1.8- and 5.3-milligamma thresholds corresponded, respectively, to power fluxes of about 7.7 × 10^{-11} and 6.7 × 10^{-10} watts m^{-2} in the 7-kHz receiver bandwidth, assuming a refractive index of 10.

Of the 58,000 MLT-INV blocks sampled during the nine-month lifetime of Injun 3, 5000 cases were observed with field strengths exceeding the 1.8-milligamma threshold, and 825 cases were observed with field strengths exceeding 5.3-milligamma threshold. The frequency of occurrence in magnetic local time and invariant latitude for field strengths greater than 5.3 milligammas was obtained by counting the number of cases having field strengths exceeding 5.3 milligammas in each MLT-INV block and dividing by the total number of times the satellite passed through that block. Figure 3 (see page 5620) shows the normalized frequency of occurrence for field strengths exceeding 5.3 milligammas. The maximum frequency of occurrence was 30% at 7 to 8 hours MLT and 58° to 64° INV. It can be seen that VLF emissions exceeding 5.3 milligammas were most common from 7 to 13 hours MLT and from 55° to 75° INV. The MLT distribution of occurrence is characterized by an abrupt increase of occurrence at 7 hours MLT followed by a slowly decreasing occurrence for later local times. The latitudinal distribution of occurrence shows a broad maximum centered on about 60° INV and virtually no occurrence below about 50° INV.

The normalized frequency of occurrence for field strengths exceeding 1.8 milligammas is given in Figure 4 (see page 5621). The maximum frequency of occurrence, 58%, at 9 hours MLT and 64° INV is approximately twice the maximum frequency of occurrence for field strengths exceeding 5.3 milligammas. The magnetic local time of the maximum for the 1.8-milligamma threshold is later than the magnetic local time of the maximum for the 5.3-milligamma threshold by about 2 hours. The region of maximum occurrence for VLF emission intensities exceeding 1.8 milligammas is bounded by approximately 6 to 18 hours MLT and 55° to 75° INV. We shall refer to this region henceforth as 'the region of most intense VLF emissions.' There were essentially no occurrences of VLF emissions exceeding 1.8 milligammas below 50° INV.

Figure 5 (see page 5622) shows the normalized frequency of occurrence of VLF emissions with field strengths greater than 1.8 milligammas in the coordinates magnetic local time (MLT) and altitude (ALT). The frequency of occurrence is computed by counting the number of occurrences of 1.8-milligamma emissions in each MLT (1 hour)-ALT (500 km) block (1 count per INV-MLT block per revolution), for which 55° ≤INV ≤ 75° and dividing by the number of times the satellite passed through that MLT-ALT block when 55° ≤ INV ≤ 75°. Events with field strengths greater than 1.8 milligammas were observed from apogee to perigee; however, more events occurred at lower altitudes, below 1500 km, than above. Table 1 gives the number of occurrences of VLF noise greater than 12.0 milligammas for 500-km altitude block (1 count per INV-MLT block per revolution) for which 55° ≤ INV ≤ 75° and 6 ≤ MLT ≤ 18 hours. This table shows that the occurrence of emissions stronger than 12.0 milligammas depends upon altitude with a maximum at altitudes less than 750 km.

TABLE 1. Altitude Dependence of the Occurrence of Most Intense VLF Emissions

Altitude, km	Number of VLF Emissions Greater than 12.0 Milligammas in the Region of Most Intense VLF Emissions
237– 736	54
737–1236	22
1237–1736	3
1737–2236	1
2237–2785	0

A possible explanation of this altitude dependence of VLF emission intensity is the dependence of the VLF refractive index on altitude. For longitudinal propagation in the whistler mode, the amplitude of the wave magnetic field can be shown to be proportional to the fourth root of the electron concentration. Since the electron concentration can vary by as much as two orders of magnitude over the altitude range of the Injun 3 orbit, decreasing with increasing altitude, variations in the intensity of VLF emissions with altitude are expected. The observed variation of VLF emissions intensity with altitude is generally consistent with this interpretation.

Figure 6 (see page 5622) shows the normalized frequency of occurrence of VLF emissions with field strengths greater than 1.8 milligammas as a function of invariant latitude (INV) and the planetary magnetic index *Kp*. The frequency of occurrenec is calculated by counting the number of occurrences of 1.8-milligamma emissions in each INV (1°) –*Kp* block (1 count per INV-MLT block per revolution) for 6 ≤ MLT ≤ 18 hours and dividing by the number of times the satellite passed through that INV-*Kp* block for 6 ≤ MLT ≤ 18 hours (1 count per INV-MLT block per revolution). It can be seen from Figure 6 that the region of most intense VLF emissions moves to lower latitudes during magnetically disturbed periods.

Carpenter [1967] studied the effect of geomagnetic activity upon the plasmapause. The relationship Carpenter found between the dawn equatorial distance to the plasmapause and *Kp* is very similar to the *Kp* dependence of the lower altitude boundary of VLF emission occurrence shown in Figure 6. Both Carpenter's and our findings reveal that there are regions (the plasmapause and the region of most intense VLF emissions) that lie at high latitudes (60° to 70° INV) during magnetically quiet periods and move to lower latitudes (40° to 50° INV) during magnetically disturbed periods.

Table 2 gives the seasonal variation of VLF emissions greater than 1.8 milligammas that occured in the region of most intense VLF emissions. The number of strong emission events was determined by counting the number of emissions in INV-MLT blocks (1 degree by 1 hour) in each season. Only one event per block per revolution was counted, using only those events in the region of most intense VLF emissions. The normalization was calculated by counting the number of times the satellite passed through any of the INV-MLT blocks in the strong emission region in a season, one count per block per revolution. The normalized frequencies of occurrence during the winter, spring, summer, and fall were 18%, 24%, 25%, and 26% respectively. These results suggest that the occurence of strong VLF emissions is not strongly dependent upon the season.

CHARACTERISTICS OF VLF EMISSIONS

Inspection of the spectrograms of the 5000 1.8-milligamma events and the 875 5.3-milligamma events showed that only three types of VLF emissions were observed more than 10% of the time with field strengths above 1.8 and 5.3 milligammas. The three types were ELF hiss, chorus, and VLF hiss. In this study ELF hiss, chorus, and VLF hiss are defined as follows: ELF hiss is hiss with frequency components from a few hundred Hz up to about 2 kHz. Chorus is a sequence of many randomly occurring discrete tones lasting a few tenths of a second and usually rising in frequency. VLF hiss is hiss with frequency components above about 2 kHz. Frequency-time spectrograms of these three phenomena are shown in Figure 7 (see page 5623). ELF hiss was present in 92% of the 5.3-milligamma events, chorus in 52%, and VLF hiss in 37%. ELF hiss was present in 59% of the 1.8-milligamma events, chorus in 50%, and VLF hiss in 31%.

To give an idea of the type and intensities of VLF emissions observed during most intense VLF emission events, we now present data from three individual satellite passes. These passes were chosen because of the presence of VLF noise and because the satellite traveled through the region of most intense VLF emissions (6 to 18 hours MLT, 55 to 75° INV) during the pass. Data from these passes are shown in Figures 8*A*, *B*, *C*. (See pages 5624–5625).

The first pass was on May 15, 1963, during a magnetically quiet period ($Kp = 1$). Figure 8*a* shows the satellite orbit, VLF spectrogram, and VLF field strength for this pass. During the pass, the satellite coordinates changed from 6 hours MLT, 40° INV, and 500-km altitude to 11 hours MLT, 75° INV, and 1350-km altitude. The field strength was high during the entire pass, reaching 5.3 milligammas during a very broad maximum centered at 12h 18m UT. The spectrogram shows two types of VLF emissions, ELF hiss in the frequency range of 200 to 1000 Hz and chorus in the frequency range of 1 to 2 kHz. The ELF hiss was observed during the entire pass and was probably the primary cause of the enhanced field strength values. Chorus was present during this pass from 12h 12m 30s UT until the end of telemetry at 12h 40m 00s UT. It appears that the chorus was not as strong as the ELF hiss and probably only accounted for the fine structure of the field strength. The probability of occurrence of emissions with field strength above 1.8 milligammas ranged from about 5% to about 40% over the orbit of the pass. The variation of the field strength corresponded well with the variations of the probability of field strengths above 1.8 and 5.3 milligammas as can be seen from Figures 3 and 4.

Figure 8*B* shows the satellite orbit, VLF spectrogram, and VLF field strength for the

TABLE 2. Seasonal Variation of Most Intense VLF Emissions

Season	VLF Emissions Greater than 12.0 Milligammas in the Region of Most Intense VLF Emissions	Normalization	Normalized Frequency of Occurrence, %
Winter (November 7 to February 6)	626	3392	18
Spring (February 7 to May 6)	551	2287	24
Summer (May 7 to August 6)	1468	5823	25
Fall (August 7 to November 6)	905	3504	26

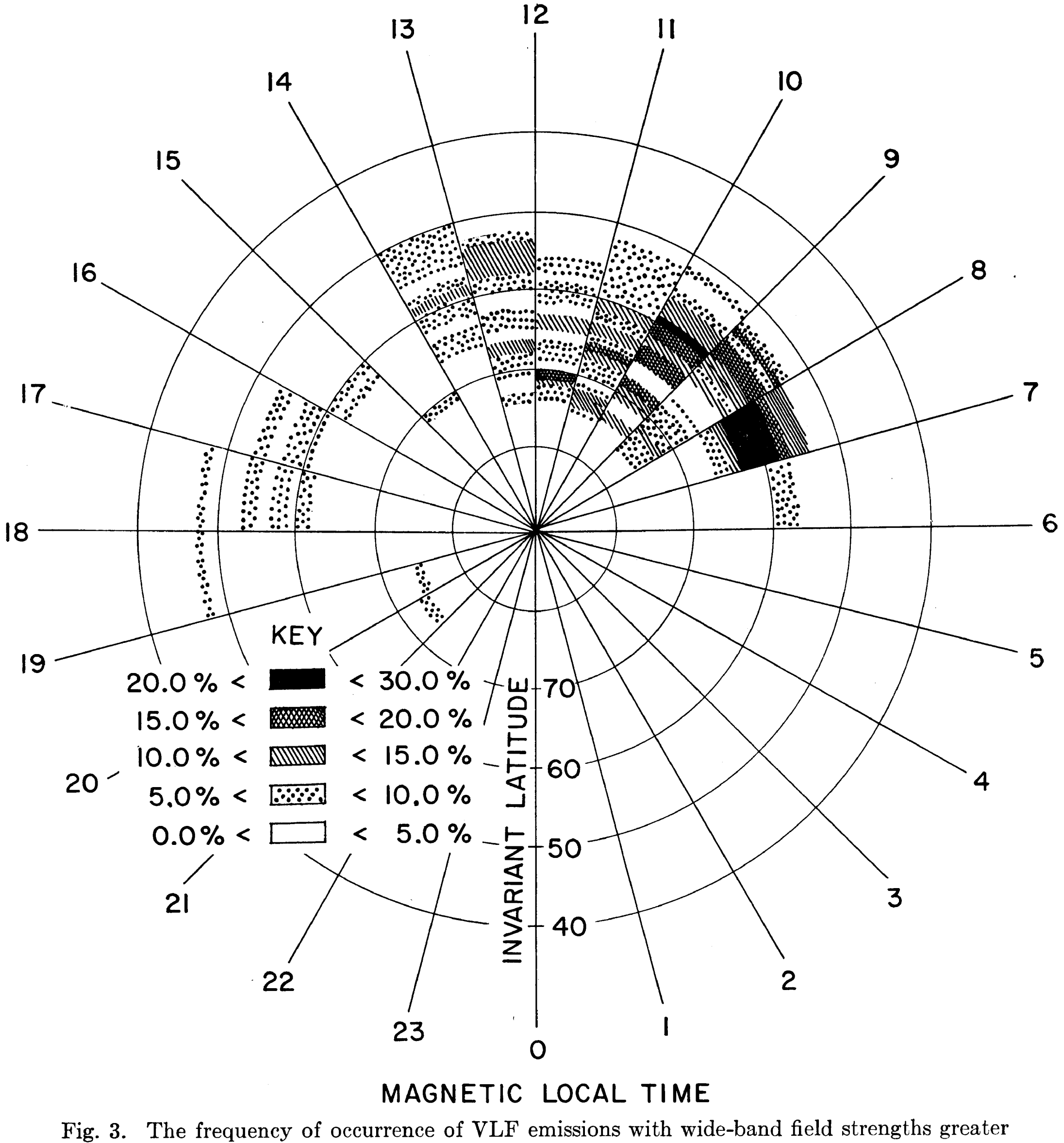


Fig. 3. The frequency of occurrence of VLF emissions with wide-band field strengths greater than 5.3 milligammas in magnetic local time and invariant latitude.

second pass to be considered. This pass was on June 10, 1963, and occurred during a magnetically quiet period ($Kp = 1$). During this pass, the satellite moved from 7 hours MLT, 81° INV, and 2200-km altitude to 12 hours MLT, 56° INV, and 2650-km altitude. The field strength was enhanced sporadically from the beginning of the pass at 10h 36m 10s UT until 10h 46m 10s UT. ELF hiss was observed during the entire pass in the frequency range of 200 Hz to 1 kHz and was most intense at about 10h 46m 00s UT. The reduced intensity of the ELF hiss before and after its maximum intensity corresponded roughly to the probability of occurrence of strong emissions shown in Figure 4. Chorus was observed from about 10h 40m 00s UT until about 10h 46m 00s UT. The spectrogram in Figure 8*b* shows a type of VLF hiss called impulsive VLF hiss by *Gurnett* [1966] from 10h 40m 00s UT until 10h 42m 00s UT.

The third pass to be considered was on

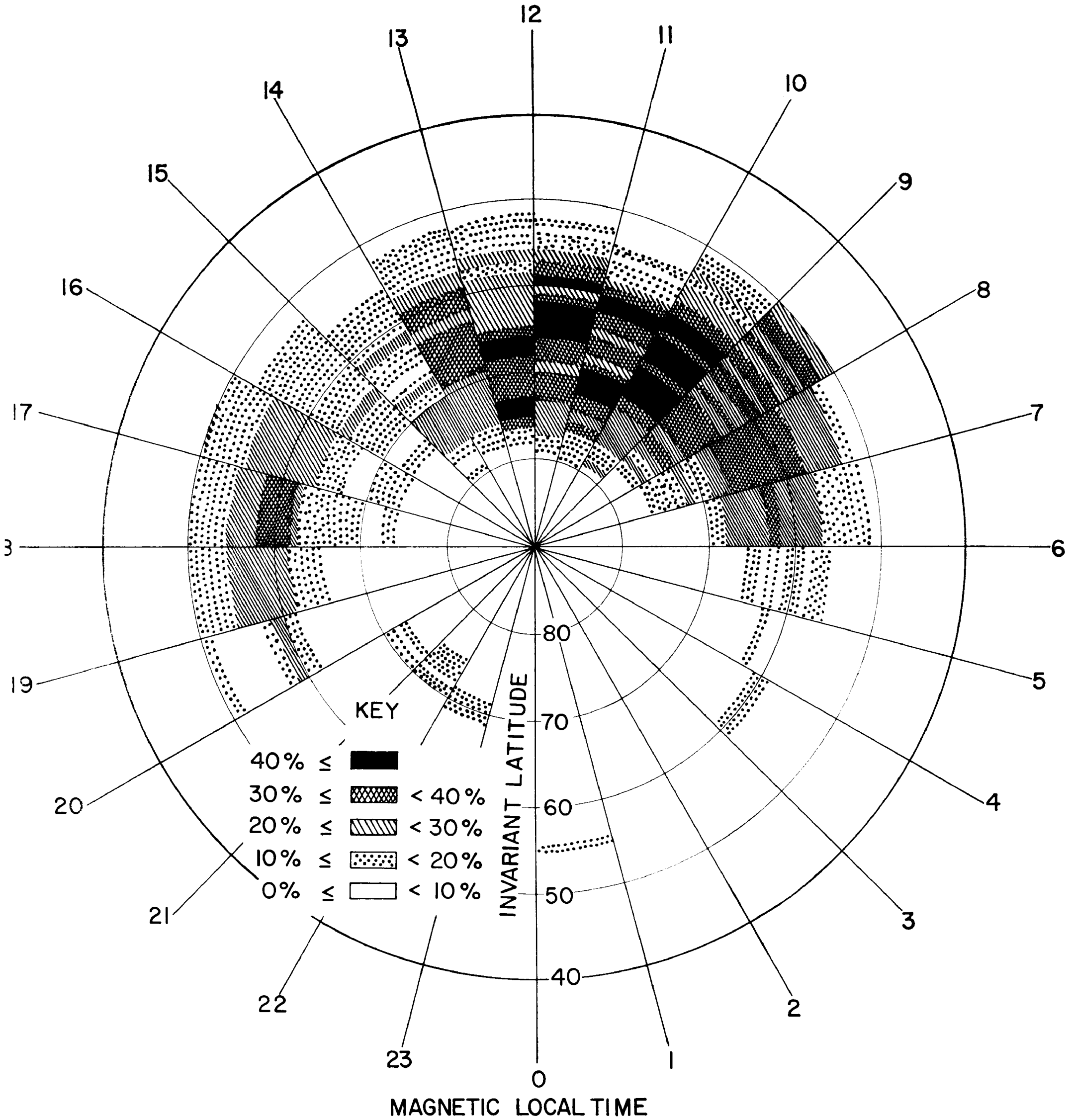


Fig. 4. The frequency of occurrence of VLF emissions with wide-band field strengths greater than 1.8 milligammas in magnetic local time and invariant latitude.

une 10, 1963, and occurred during a magietically quiet period (*KP* = 1). Figure 8*C* hows the satellite orbit, VLF spectrogram, nd VLF field strength. During the pass, the atellite moved from about 3 hours MLT, 60° NV, and 1800-km altitude to 12 hours MLT, 0° INV, and 2600-km altitude, reaching a aximum invariant latitude of 72° at 18h 24m 0s UT and the apogee altitude (2785 km) at 8h 37m 00s UT. ELF hiss was observed durng the entire pass, from 18h 15m 00s UT until 18h 40m 00s UT. The intensity of the ELF hiss on the spectrogram appears to correlate well with the field strength data. There is also good correspondence between the satellite coordinates when the field strength is 1.8 milligammas and the coordinates of the frequency of occurrence of VLF emissions equal to or greater than 1.8 milligammas shown in Figure 4.

The individual passes considered here, and others which were also examined carefully, indicate some general characteristics of VLF noise:

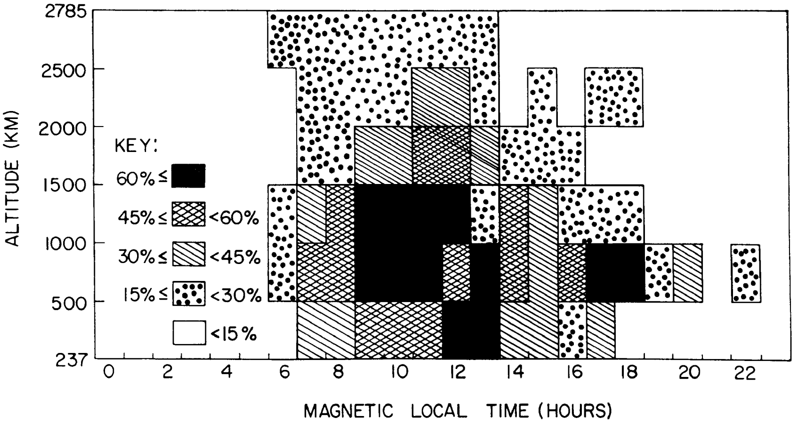


Fig. 5. The frequency of occurrence of most intense VLF emissions in altitude and magnetic local time.

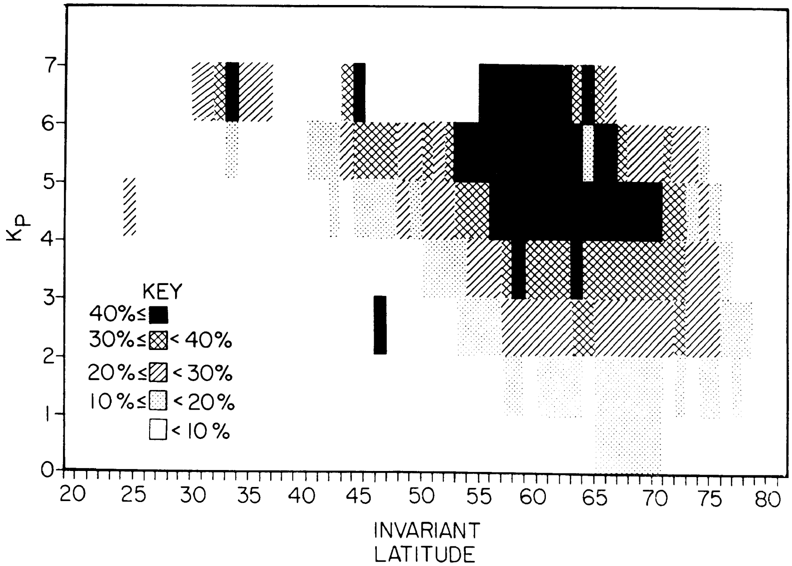


Fig. 6. The frequency of occurrence of most intense VLF emissions in *Kp* and invariant latitude.

1. The intensity of ELF hiss never changes more quickly than on a time scale of the order of tens of seconds; it increases in intensity slowly out of the receiver noise level and fades slowly into the receiver noise.

2. Chorus commonly occurs with ELF hiss.

3. The chorus associated with ELF hiss is often confined to lower latitudes than the ELF hiss. It is common to have a pass with ELF hiss and chorus both present at lower latitudes, but only ELF hiss present at higher latitudes.

4. ELF hiss usually has a constant bandwidth for a period of several minutes during a pass, commonly about 1 kHz.

5. When a bandwidth of the combination of ELF hiss and chorus changes, the upper frequency cutoff is more likely to change than the lower frequency cutoff. Lower frequency cutoff changes do occur, however [see *Gurnett and Burns*, 1968]. When upper or lower frequency cutoffs do change, they usually decrease with increasing latitude.

6. ELF hiss is the strongest VLF emission observed.

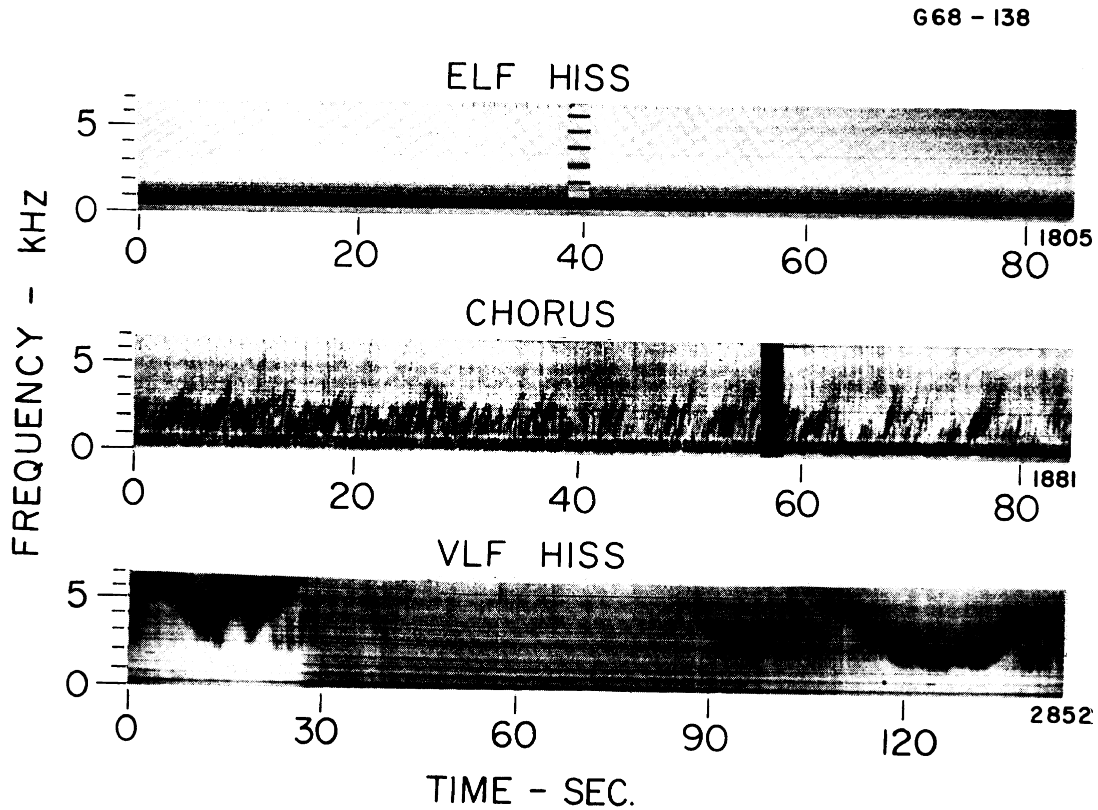


Fig. 7. Examples of ELF hiss, chorus, and VLF hiss observed with Injun 3.

7. The spectral characteristics of VLF emissions commonly remain constant over distances of several hundred kilometers (several minutes).

Comparison with Ground Station Results

VLF emissions observed with Injun 3 cannot easily be compared directly with emissions observed on the ground because no simultaneous, coordinated, ground-based VLF measurements were made. Therefore, no attempt has been made to compare individual events. Statistical comparisons are possible, but limited.

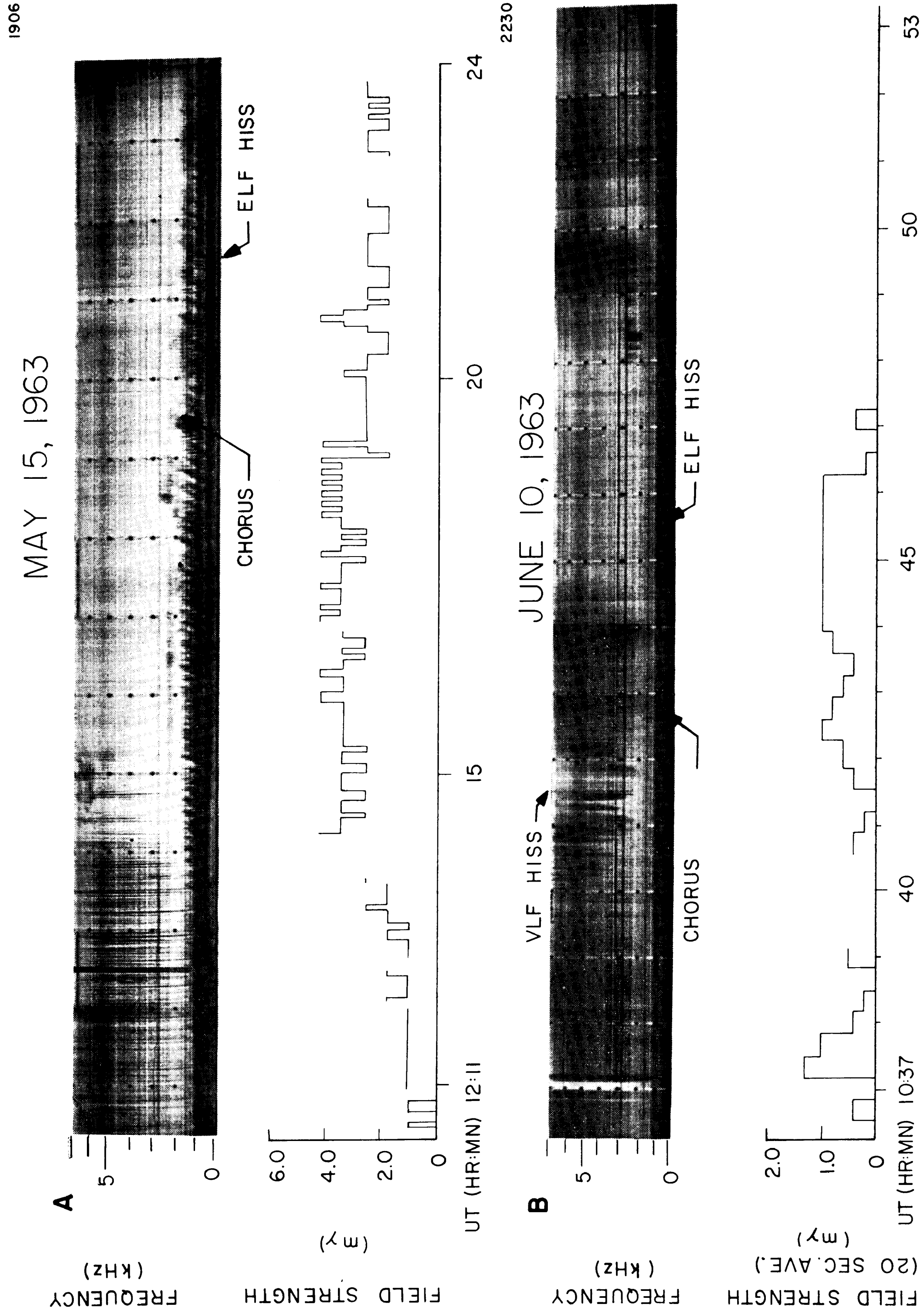
Ungstrup and Jackerott [1963] studied the occurrence of polar chorus at Godhavn, Greenland (80° INV). Polar chorus corresponds to the combination of ELF hiss and chorus mentioned above. They found its diurnal maximum to be near 10h 30m MLT, independent of latitude, season, or magnetic activity. Comparing their observations with Figures 3 and 4, we find reasonable agreement.

Egeland et al. [1965] found a pronounced morning maximum (between 6 and 14 hours MLT) in their '700-Hz noise band' observations at Kiruna, Sweden (65° INV). Again there is good agreement with our results shown in Figures 3 and 4.

Laaspere et al. [1964] determined the diurnal variation of hiss at Moisie (61.6° INV), Mont Joli (60.1° INV), and Ellsworth (66.9° INV), and they found occurrence maxima at 7 to 14 hours MLT, 6 to 16 hours MLT, and 7 to 20 hours MLT, respectively. The occurrence maxima for these invariant latitudes found in this study were 6 to 17 hours MLT, 7 to 18 hours MLT, and 7 to 13 hours MLT, respectively. Laaspere's results are consistent with those found in this study.

Discussion

We have presented a satellite study of the morphology of VLF emissions. It was found that the region of most intense VLF emissions is between 55 and 75° INV and 6 and 18 hours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MAY 15, 1963
1906
ELF HISS
CHORUS
FREQUENCY (kHz)
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0
FIELD STRENGTH (mγ)
6.0
4.0
2.0
0
UT (HR:MN) 12:11
15
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B
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2230
VLF HISS
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2.0
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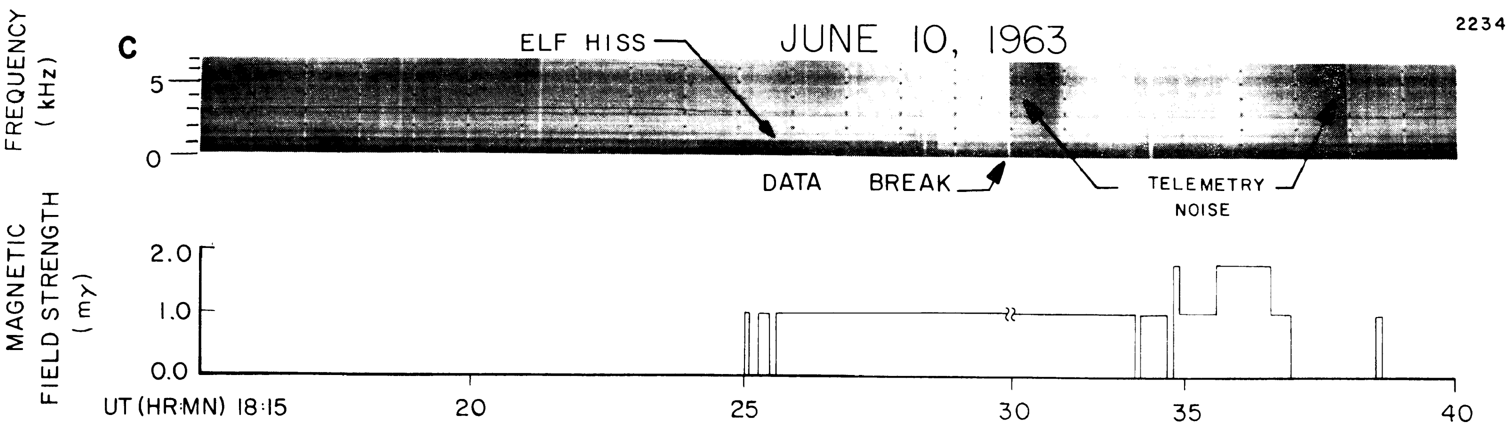

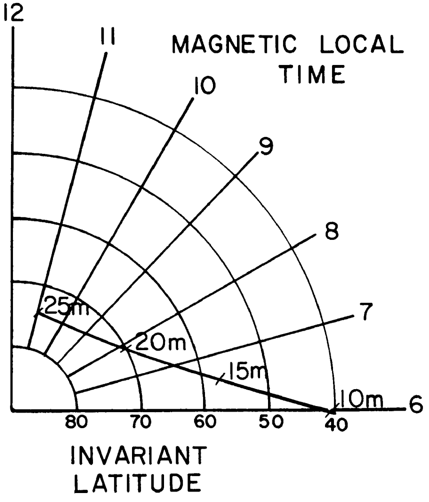

Fig. 8*A*.

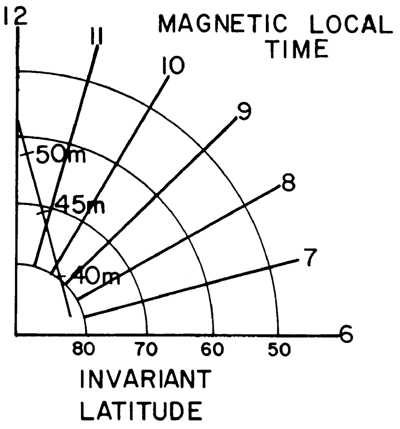

Fig. 8*B*.

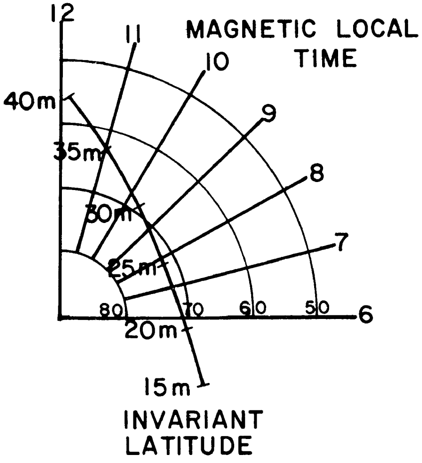

Fig. 8*C*.

Fig. 8. Injun 3 individual passes. Figures 8*A*–8*C* below correspond to passes shown above.

MLT. The maximum frequency of occurrence of most intense VLF emissions was from 60 to 70° INV and 9 to 11 hours MLT. The principal types of VLF emissions observed in the region of most intense VLF emissions were ELF hiss, chorus, and VLF hiss, with ELF hiss the most common. The occurrence of most intense VLF emissions was determined to be more likely at altitudes less than 1500 km. This altitude dependence was suggested to be due to the increase of the index of refraction at lower altitudes. The region of most intense VLF emissions was shown to move to lower latitudes during magnetically disturbed periods. The occurrence of most intense VLF emissions was found to be not strongly dependent upon season. Since ELF hiss (less than 2 kHz) was the emission most commonly observed, some correction could have been made for the nonuniform frequency response of the receiver (see Figure 1). However, in an extreme case, for ELF hiss with frequency components between 300 and 800 Hz, the measured field strength would only be a factor of 4 lower than the true field strength. In most cases, the maximum error would be less than a factor of 2.

Since this study considered only a limited frequency range, 0.1–7.0 kHz, it is possible that the field strength and regions of occurrence of some types of VLF emissions, such as VLF hiss, which often extend well outside of this frequency range may be modified by considering a larger bandwidth.

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