The Morphology of VLF Emissions Observed with the Injun 3 Satellite

by

William W. L. Taylor

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Thesis Supervisor: Assistant Professor Donald A. Gurnett

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ABSTRACT

Results of a statistical study of very low frequency (VLF) noise observed with the Injun 3 satellite are presented. Injun 3 included a VLF experiment driven by a magnetic loop antenna capable of telemetering analog data (wide band ~ 200 Hz to 7 kHz) and digital data (wide band signal strength and outputs of six spectrum analyzer channels). To provide a fair data sample, only one eight second data point per magnetic local time, invariant latitude block (1 hour by 1 degree) per revolution was considered. This data point was classed as a 1.5 milligamma or a 4.0 milligamma event if the wide band signal strength was above 1.5 milligamma or 4.0 milligamma during the eight seconds. Using definitions which have been formulated and the analog and digital data, the type of noise present in each event was determined. By counting the total number of each type of noise in each block and normalizing, densities of occurrence of VLF noises were obtained. These data were for the period from December 1962 to October 1963.

Noise exceeding 4.0 milligamma occurred predominately from 7 to 13 hours magnetic local time and 52° to 70° invariant latitude. The noise exceeding 1.5 milligamma showed the same latitudinal dependence, but with a maximum closer to magnetic local noon. The most frequently observed VLF emission (59%) was ELF hiss with a peak occurrence for the 1.5 milligamma threshold at 75° invariant latitude and 12 hours magnetic local time. Chorus was observed in 51% of the events and VLF hiss in 31%. Other types of VLF emissions were found in less than 1% of the events. Four individual passes were examined to illustrate the statistical findings. Comparisons were made with VLF ground station statistical studies and with a satellite study of VLF hiss.

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I. INTRODUCTION

Very low frequency (VLF) radio noises are electromagnetic radio waves in the frequency range of approximately 20 Hz to 30 kHz. Two basic types of naturally occurring VLF noises are known: whistlers and emissions. The theory of whistlers was developed by Storey [1953] and extended by Helliwell et al. [1956], Ellis [1956], and Maeda and Kimura [1956]. According to these theories, whistlers are caused by lightning discharges near the Earth's surface and their spectral shape is due to propagation of this energy through the dispersive magnetosphere. Whistlers have been used to determine magnetospheric parameters such as electron and proton densities. VLF emissions are naturally occurring VLF noises whose energy does not come from lightning but from charged particles which emit electromagnetic or electrostatic waves. The three possible source regions of VLF emissions are atmospheric, extra-terrestrial, and magnetospheric. There are no atmospheric sources known other than whistler producing lightning. The magnetosphere cannot propagate VLF waves from interplanetary space because of the plasma frequency cutoff. Thus, VLF emissions must be magnetospheric in origin. The origin of VLF emissions has not been fully explained, however many mechanisms have been proposed for their origin. The suggestions include (1) Cherenkov radiation by Ellis [1957, 1959] and lately by Jørgensen [1967], (2) traveling wave tube amplification by Gallet and Helliwell [1959], Bell and Helliwell [1960], and others, (3) cyclotron radiation by MacArthur [1959], Santirocco [1960], and others, (4) transverse resonance instability by Brice [1963], and (5) proton beam amplification by Kimura [1962, 1963].

The first observation of a VLF emission was possibly made by Preece [1894]. His paper describes noises heard on telephone receivers connected to telegraph wires. From his descriptions of the phenomena, he may have observed what is now called chorus. Burton [1930] and Burton and Boardman [1933a] reported quasi-musical sounds between 500 and 1500 Hz. These sounds were probably extremely low frequency (ELF) hiss or the common combination of ELF hiss and chorus, now called polar chorus or roar. Burton and Boardman [1933b] reported hissing sounds in the upper voice range, presumably above 5 kHz. These noises were probably VLF hiss.

There have been many sets of definitions devised by various authors to classify different types of VLF emissions. Most have been qualitative and a few have been quantitative. Gallet [1959] divided VLF noises into three large groups as given in Table 1: whistlers, VLF emissions, and interactions between whistlers and VLF emissions. Two main types of VLF emissions were recognized: continuous and discrete. Continuous emissions were characterized by the fact that they were continuous in time and frequency. Hiss was given as an example of a continuous VLF emission. Discrete emissions were characterized by their transitory behavior. He recognized many types of discrete emissions including hooks, risers, quasi-vertical (typically chorus), falling tones, quasi-horizontal, pseudo-noses, and those discrete emissions too complex for the preceeding classes. Table II gives Gallet's classes of discrete VLF emissions with model spectral forms.

Helliwell [1965] gives a comprehensive classification scheme for VLF emissions. Table III shows Helliwell's model spectral forms for his classification scheme. He characterized hiss by its resemblance to thermal or fluctuation noise, dividing it into steady and impulsive hiss according to its tendency to change amplitude over periods of the order of a second. A sequence of closely spaced, discrete events, often overlapping in time, Helliwell called chorus. Rising tones, falling tones, hooks, and combinations, so named because of their characteristic shapes on a frequency time spectrogram, were grouped together with the name discrete emissions. Regularly spaced emissions were called periodic emissions and included dispersive and non-dispersive periodic emmissions. Helliwell defined quasi-periodic emissions as long period bursts of discrete events, periodic emissions or chorus. Triggered emissions were those caused by other emissions or by whistlers.

Some definitions of chorus which have also been given are those by Storey [1953], Watts [1957], Allcock [1957], Crouchley and Brice [1960], Pope [1963], Laaspere et al. [1964b], Gurnett [1964], Helms and Turtle [1964], and Jørgensen [1965]. Jørgensen divides chorus into three types depending upon its frequency. Some authors who have given definitions of hiss include Burton and Boardman [1933b], Helms and Turtle [1964], and Laaspere et al. [1964a,b]. Laaspere et al. differentiate between three types of hiss by frequency range and temporal and spacial coincidence with auroras. Additional definitions of hiss were given by Gurnett [1963], Gurnett and O'Brien [1964], Gurnett [1966], and Jørgensen [1965, 1966a,b].

Surveys of the frequency or probability of occurrence of VLF emissions have been made using both ground based and satellite VLF receivers. Some of those using ground station results were Allcock [1957], Martin et al. [1960], Crouchley and Brice [1960], Helliwell and Carpenter [1961, 1962], Yoshida and Hatanaka [1962], Pope [1963], Laaspere et al. [1964a,b], Helms and Turtle [1964], and Jørgensen [1966a,b]. Allcock [1957] reported the diurnal and seasonal variation of chorus and found that the local geomagnetic time of chorus activity increased with geomagnetic latitude at the rate of about one half hour per degree with maximum chorus appearing at 5 to 6 hours, and 50° geomagnetic latitude to 9-12 hours at 65°. Martin et al. [1958] found a maximum of both strength and occurrence at about 10 hours local magnetic time for chorus at the South Pole. Crouchley and Brice [1960] in their study of chorus found that it exhibits a maximum of occurrence at about geomagnetic latitude 60° and has a complex diurnal behavior with three distinct diurnal peaks at a low latitude (45°S) station, a large peak at about 6 hours local mean time for a mid-latitude (52°S) station and a large peak at 9-12 hours at a higher latitude (61°S) station.

Helliwell and Carpenter [1961,1962] found that chorus and hiss occurred most often between 56° and 80° geomagnetic latitude, the distribution being skewed toward the high latitude side. Yoshida and Hatanaka [1962] showed that chorus had a frequency of occurrence maximum at 59°-60° geomagnetic latitude and for hiss a maximum at 55°-62° geomagnetic latitude. In contrast to some of the earlier findings, they found that the geomagnetic local time of maximum occurrence (4 to 12 hours) decreased with increasing latitude. Pope's [1963] study of high latitude chorus found an occurrence maximum between 11 and 13 hours local time and that for 29 stations between 44° and 80° geomagnetic latitude, the local time of maximum occurrence of chorus increased with increasing geomagnetic latitude. Laaspere [1964a,b] found chorus to have a maximum from 4 to 10 hours local mean solar time, and hiss to have maxima at any time of day, depending upon the latitude of the station, the season, and the level of geomagnetic activity. High latitude station hiss was found to have approximately the same diurnal variation as chorus, shifted to later times by a few hours.

Helms and Turtle [1964] found that hiss at Byrd, Antartica had a diurnal peak at about 2100 magnetic local time. Jørgensen [1965] found that ground station polar chorus had its maximum at 7-12 hours local time and for hiss at 22-23 hours geomagnetic time. Jørgensen [1963b] used the results of thirteen ground stations and found that there was a maximum of the occurrence at about 70° magnetic latitude shortly before magnetic midnight. Figure 1 shows contour plots of the results of observations of hiss at 8 kHz averaged over 1964 for three Greenland stations taken from Jorgensen [1966a]. As can be seen from the figure, the maximum occurrence was the late evening and high latitude sector.

A satellite based study of VLF hiss in the frequency range 5.5 to 8.8 kHz has been made by Gurnett [1966] using Injun 3 data. His results are summarized in Figure 2, which shows that VLF hiss occurred in a zone about 7° wide in latitude, centered on 77° invariant latitude at 14 hours magnetic local time and centered on 70° at 22 hours. Also, the magnetic local time of maximum occurrence decreased with increasing latitude.

Because of the unique advantages of satellite based observations over ground station observations, it is more desirable to study the occurrence of VLF emissions with a satellite borne VLF receiver than from a ground based VLF receiver. Some of these advantages are:

1. The satellite observes VLF waves before they are attenuated by absorption in the D region of the ionosphere, whereas ground stations see attenuated waves.
2. The L-shell of the source in the magnetosphere is easier to determine from a satellite observation due to the existence of the earth-ionosphere waveguide.
3. The satellite is able to make rapid surveys of the spacial extent of VLF noises.
4. A satellite has wider geographical coverage than ground stations.
5. VLF waves can become trapped in the magnetosphere due to total internal reflection at the lower ionosphere boundary and thus could only be observed by VLF receivers in the magnetosphere and not by ground stations.

According to Leiphart [1962], VLF waves propagating through the ionosphere are attenuated by approximately 35 db during the local day and 10 db during the local night due to absorption at the D region. The attenuation reduces the effective sensitivity of the ground based receiver and makes power density calculations for the original wave uncertain. The attenuation also reduces the strength of man-made interference in the form of upward traveling waves at the satellite. The satellite can observe VLF waves along the propagation path in the magnetosphere, whereas ground stations observe waves propagating in the earth-ionosphere wave guide which allows VLF waves to travel considerable distances [Martin, 1958]. This makes it difficult to locate the point where the VLF wave originally entered the waveguide. The earth-ionosphere wave guide also produces a low frequency cutoff, attenuating waves below the cutoff frequency of the waveguide, approximately 1.5 kHz.

The study of the spatial and temporal occurrence of geophysical phenomena is considered to be of prime importance to the explanation of a particular phenomenon. This paper presents the results of such a morphological study for VLF emissions observed with the Injun 3 satellite. We give definitions of VLF emissions and then discuss the results of two types of studies of the Injun 3 VLF data. The first study is a statistical analysis of the occurrence of VLF emissions and the second is a study of selected individual satellite passes illustrating the statistical trends with spectra. These results indicate the frequency of occurrence of VLF emissions of various types in terms of the geomagnetic coordinates, magnetic local time and invariant latitude.

II. DEFINITIONS

Before the statistical study of VLF emissions was begun, it was determined that a set of definitions should be formulated for classifying the phenomena found in the Injun 3 VLF data. The definitions given here are semiempirical. They were based on knowledge of VLF spectra obtained both from satellite observations and from ground stations observations. The definitions depend only on the form of the emission on a frequency-time spectrogram. Although the observation point (the satellite) is moving, the reference frame for these definitions will be the observer. In other words, although the satellite is moving in space, the time duration of the event in the satellite records is important in the definitions. The definitions used in this study are listed below. The figure numbers refer to examples from Injun 3 data, which depict the type of VLF emission being defined.

I. Hiss is incoherent, band limited white noise, with a duration of minutes and with little temporal structure on a time scale less than one second.

A. VLF Hiss is hiss with components at frequencies greater than 2 kHz.

1. Steady VLF Hiss is VLF hiss with no discontinuous spectral changes on the order of seconds (see Figure 3).

2. Impulsive VLF Hiss is VLF hiss with discontinuous spectral changes on the order of seconds (see Figure 4).

B. Extremely Low Frequency (ELF) Hiss is hiss with no components greater than 2 kHz (see Figure 5).

C. Lower Hybrid Resonance Hiss (LHRH) is hiss with a lower frequency cutoff which is smoothly changing apparently due to the change of the lower hybrid resonance frequency with satellite position (see Figure 6).

II. Discrete Emissions are individual distinct emissions with durations of seconds or less.

A. Chorus is a sequence of discrete emissions. The emissions occur randomly in time, generally rising in frequency on a time scale of a few tenths of a second. The sequence lasts on the order of seconds (see Figure 7).

B. Isolated Discrete Emissions are discrete emissions which are isolated in time on the order of seconds.

1. Risers are isolated discrete emissions whose frequency rises in time (see Figure 8).

2. Falling Tones are isolated discrete emissions whose frequency falls in time (see Figure 8).

3. Steady Tones are isolated discrete emissions whose frequency remains nearly constant in time (see Figure 8).

4. Hooks are isolated discrete emissions whose frequency first falls and then rises in time (see Figure 8).

5. Combinations are isolated discrete emissions which appear to be complex combinations of risers and falling tones (see Figure 9).

C. Periodic Emissions are discrete emissions that are periodic or nearly periodic in any part of the frequency band with a period equal to the whistler mode bounce period at the frequency of the periodicity (see Figure 9).

D. Quasi-Periodic Emissions are discrete emissions that are periodic or nearly periodic in any part of the frequency band with a period not near the whistler mode bounce period at the frequency of the periodicity (see Figure 9).

E. Triggered Emissions are discrete emissions that appear to have been initiated by another emission or a whistler (see Figure 10).

Preliminary analysis of the data showed that usually the frequency components of hiss were either greater than 2 kHz or less than 2 kHz. Hiss with components both less than and greater than 2 kHz was thought to usually be the type called VLF hiss by Jørgensen [1966a] and Gurnett [1966] and was so classified. VLF hiss as defined here includes what has been called auroral hiss by other authors. The adjective auroral has been dropped because of the occurrence of this type of hiss at times when no auroras exist. In addition, VLF hiss in this paper includes VLF hiss as defined by Gurnett [1966] in his Injun 3 study of VLF hiss in the range 5.5 to 8.8 kHz. VLF hiss in this paper also includes hiss below 5.5 kHz.

The whistler mode bounce period is the time for a VLF wave propagating in the electron cyclotron (whistler) mode along a field line to travel from one hemisphere to the other and back again.

This period can be determined for a specific frequency from experimental values of whistler dispersion if we assume that the time delay is given for a particular frequency component by the Ekersley law and that no periodic or quasi-periodic emissions occur above 60° invariant latitude. Figure 11 shows whistler dispersion determined from six ground stations by Allcock [1959]. Dispersion D is defined by the Ekersley law,

$$D = T\sqrt{f}$$

where T (seconds) is the time delay at a frequency f(Hz). Thus, the whistler mode bounce period P = 2T as a function of frequency and invariant latitude can be determined and is shown for several latitudes in Figure 12.

III. DESCRIPTION OF THE INJUN 3 VLF EXPERIMENT

In December 1962 the University of Iowa/ONR satellite Injun 3 (1962 beta tau) was launched. It was a high latitude (70° inclination), low altitude (237 to 2800 km.) satellite whose principle scientific aims were to measure auroral optical emissions, the precipitated particles causing them and the VLF emissions that might have interacted with the precipitated and trapped particles. The VLF experiment included in the instrumentation was capable of detecting electromagnetic radiation in the frequency range of about 200 Hz to 8.8 kHz. The detector was a magnetic loop antenna which provided maximum coupling to the $\vec{B}$ component of an electromagnetic wave propagating in the electron cyclotron (whistler) mode. Maximum coupling was achieved by placing the antenna so that the geomagnetic $\vec{B}$ field would always lie in the plane of the loop as oriented by the satellite. There were three types of data of interest ot us in the VLF experiment.

The first type is the wide band analog VLF telemetry. The amplitude of the VLF signal from 200 Hz to 7 kHz was normalized by an automatic gain control (AGC) circuit with a time constant of 0.2 seconds. This signal directly modulated the telemetry transmitter for reception and recording by a telemetry station for later analysis in the laboratory with a frequency-time spectrum analyzer. The second part of the VLF experiment utilized in this study consisted of the satellite spectrum analyzer. It determined the absolute amplitude of the magnetic component of the wave at six frequencies, 0.7, 2.7, 4.3, 5.5, 7.0, and 8.8 kHz. The minimum amplitude of the output of each channel was sampled, digitized and telemetered every eight seconds in the most common mode of operation. The third part of the VLF experiment used was the AGC. The AGC feedback voltage was sampled by an analog to digital converter and transmitted to the ground by the digital data system. In the most common mode of operation, the AGC voltage was digitized and telemetered every four seconds. These AGC data were put into pairs corresponding to the eight seconds of spectrum analyzer data. These eight seconds of data, both analog and digital, will be called an eight second data point.

The Injun 3 VLF experiment thus provides three measurements of interest in this study: a) high resolution frequency time spectra from the wide band VLF signal which is telemetered to the ground, b) the wide band signal strength, and c) the spectrum analyzer outputs. For a more detailed description of the Injun 3 satellite, see O'Brien et al. [1964] and Gurnett and O'Brien [1964].

IV. DATA ANALYSIS

During the useful lifetime of Injun 3, approximately 1200 hours of VLF data were received as the satellite traveled through 48,000 magnetic local time, invariant latitude blocks (one hour by one degree). Magnetic local time 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]. Invariant latitude is defined to be INV = arc cos $L^{-1/2}$, where L is McIlwain's [1961] shell parameter. It was necessary to reduce the amount of data to be analyzed so that the study could be completed in a reasonable length of time. To provide equal data for each block, only the first eight second data point in each block was considered. To reduce the number of data points to a reasonable number and insure the presence of VLF data, only those data points above a set threshold magnetic field strength were examined. The data points with AGC above the threshold were called events and the types of emissions present were determined. By counting the total number of noise events of each type in a block and normalizing, the probability of occurrence of each type of noise was determined. Altitude was not considered directly

directly in this study because the VLF waves and the particles which cause them are guided along the field lines irrespective of altitude.

A computer program was designed to examine only the first eight second data point in each magnetic local time, invariant latitude block for every revolution. This guaranteed a fair statistical sampling of the data. The orbital parameters for that point were printed out if the AGC showed that the VLF signal at the satellite was above a certain threshold for both four second halves of the event. This would sample various emission equally if they were of the same strength. For this study, two threshold noise magnetic signal strength levels were chosen, 1.5 and 4.0 milligamma. Assuming a longitudinal index of refraction of 10 for VLF frequencies at the satellite altitude, good satellite alignment, and propagation in the whistler mode, these magnetic field strength thresholds correspond to power fluxes of 5.4×10^{-9} and 3.8×10^{-8} watts/m^2 over the 7 kHz bandwidth. During the 1200 hours of telemetry transmission, the satellite passed through 48,000 magnetic local time, invariant latitude blocks (one hour by one degree). Table 4 gives the total number of times the satellite passed through any given invariant latitude, magnetic local time block. Of the 48,000 data points, there were 5,300 for which the VLF noise was above 1.5 milligamma and 825 above 4.0 milligamma.

The data from every telemetry station pass for which there were AGC events was frequency-time analyzed with a Spectran spectrum analyzer. The Spectran uses 480 magnetorestrictive filters to cover the range 0-10 kHz. The filters are capacitively commutated at a frequency of 60 Hz. The resolution is thus about 20 Hz and 1/60 sec. The spectrograms were produced by a strip film 35 mm oscilloscope camera and a Tektronix intensity modulated oscilloscope. This combination of spectral analysis equipment permits real time production of spectra. A photograph was taken of the processed spectrogram including each eight second event in a picture covering 40 seconds in order to provide a permanent record of the event. Prints were made of each of the spectra of the 4.0 mγ events and the type of VLF noise was identified from the pictures of the spectrograms. The number of VLF hiss, ELF hiss, and chorus events in each magnetic local time, invariant latitude block was counted and normalized by the total number of times the satellite was in the block while it was telemetering data, see Table 4.

In addition to a normal computer output for the 1.5 mγ noise level sorting, aperature cards were punched for every 1.5 mγ event. The information punched on the aperature cards included orbit parameters, satellite and universal time, and selected energetic particle counting rates (for use in a future study). Aperature cards are computer cards with an area to insert a 35 mm negative. The negatives of the pictures of the spectrograms of the 1.5 $m\gamma$ events were attached to the aperature card, thus consolidating the analog and digital data. The type of event was then determined by a research aide who had been trained to classify emissions. It was found to be impossible to reliably identify VLF hiss from the spectrograms, so this classification was checked using the on board spectrum analyzers at 2.7, 4.3, 5.5, 7.0, and 8.8 kHz. If the output of any of these analyzers was above its noise level and the spectrograms did not show another type of emission at that frequency, the existence of VLF hiss was confirmed. Code numbers indicating the types of events were then punched on the card. Next, a computer program was used to count the number of VLF hiss, ELF hiss, and chorus events in each magnetic local time, invariant latitude block. This program also normalized the results by dividing the number of occurrences in each block by the number of times the satellite passed through that block while telemetering data.

V. STATISTICAL RESULTS

A. 4.0 mγ Statistical Results

VLF radio noise exceeding 4.0 mγ occurred in 1.7% of the 48,000 possible eight second data points. Table 5 gives the total number of 4.0 mγ events within any given magnetic local time, invariant latitude block. The normalized frequency of occurrence of these 825 events, plotted in the polar coordinates, invariant latitude and magnetic local time, is given in Figure 13. It can be seen that the most intense VLF noise is almost entirely confined to the magnetic day with a maximum in the early morning, tailing off throughout the day. The latitudinal dependence is also well defined, the noise being nearly limited to invariant latitudes between 50° and 75°. In addition, the latitude of maximum occurrence shows a very slight tendency to increase as magnetic local time increases between 8 and 12 hours.

With the 4.0 mγ noise level threshold, three types of emissions occurred with sufficient frequency to justify statistical analysis. The three types were VLF hiss, ELF hiss, and chorus. Table 6 gives the total number of ELF hiss occurrences above 4.0 mγ within any given magnetic local time, invariant latitude block, and Figure 14 shows the frequency of occurrence of ELF hiss. ELF hiss was present in 92% of the 4.0 mγ events. Because of the high incidence of ELF hiss, the distribution is essentially that of VLF noise above 4.0 mγ, Figure 13. The distribution is more localized with nearly all of the events occurring from 7 to 14 hours magnetic local time and 55° to 75° invariant latitude.

Table 7 gives the total number of chorus events above 4.0 mγ within any given magnetic local time, invariant latitude block, and Figure 15 shows the frequency of occurrence of chorus when the AGC was above 4.0 mγ. The maximum frequency of occurrence of chorus was about the same as for all noise above 4.0 mγ, although chorus occurred in only 52% of the events. Chorus is confined almost entirely to 7 to 13 hours magnetic local time and 54° to 70° invariant latitude. However, recalling that ELF hiss was present in 92% of the 4.0 mγ events, it is apparent that ELF hiss was the primary cause of the high AGC levels. It can be concluded then that Figure 15 is actually the frequency of simultaneous occurrence of ELF hiss and chorus. Chorus alone had the required flux density to cause the AGC to be above 4.0 mγ in only 3% of the 4.0 mγ events.

The total number of VLF hiss events for which the AGC was above 4.0 mγ within any given magnetic local time, invariant latitude block is given in Table 8. VLF hiss was present in 37% of the 4.0 mγ events, the frequency of occurrence of which is shown in Figure 16. The striking feature of this distribution is the fact that the maximum is some 5 or 6 hours later than for all VLF noise, Figure 13. The limits of occurrence seem to be roughly the same as for all VLF noise, however, magnetic day and 50° to 75° invariant latitude. Even though the distribution maximum appears to be somewhat different than for the ELF hiss distribution, we must conclude that Figure 16 is in reality only the distribution of the simultaneous occurrence of ELF hiss and VLF hiss. This conclusion is necessary due to the contamination by ELF hiss, that is, the fact that the sample density was controlled by ELF hiss.

B. 1.5 mγ Statistical Results

In 11% of the 48,000 possible eight second data points, the AGC was greater than 1.5 mγ. Table 9 gives the total number of 1.5 mγ events within any given magnetic local time, invariant latitude block. The normalized frequency of occurrence of these 5,300 events is given in Figure 17. The maximum frequency of occurrence of 1.5 mγ noise is approximately twice the maximum frequency of occurrence of 4.0 mγ noise. The distribution is also broader, covering magnetic local times from 5 to 19 hours and invariant latitudes from 50° to 80°. The magnetic local time of the maximum is later than the maximum in the 4.0 mγ study. Here it is 10 hours, whereas it was 7 hours in the 4.0 mγ study.

As before, only three types of emissions occurred with sufficient frequency to justify statistical analysis. The three types were VLF hiss, ELF hiss, and chorus. ELF hiss was observed in 59% of the 1.5 mγ events. Table 10 gives the total number of ELF hiss events above 1.5 mγ within any given magnetic local time, invariant latitude block. Figure 18 shows the frequency of occurrence of ELF hiss above 1.5 mγ. ELF hiss is, as before, confined to magnetic day, with a maximum occurrence of 50% at 12 hours magnetic local time and 75° invariant latitude. The range of invariant latitudes for which ELF hiss is present is 50°-80°.

Table 11 shows the total number of VLF hiss events above 1.5 mγ within any given magnetic local time, invariant latitude block. Figure 19 shows the frequency of occurrence of the 1570 VLF hiss events for which the AGC was above 1.5 mγ. These represented 31% of the 1.5 mγ events. The maximum occurrence was

32% at 7 hours magnetic local time and 59° invariant latitude. This maximum is earlier than that found for VLF hiss for which the AGC was greater than 4.0 mγ, but the distribution in magnetic local time remains significant until early magnetic evening. The distribution in invariant latitude is fairly broad extending from 50° to 78°. The invariant latitude of maximum occurrence tends to increase slightly for higher magnetic local times. Table 12 gives the total number of impulsive VLF hiss events above 1.5 mγ within any given magnetic local time, invariant latitude block. This distribution is interesting because it is concentrated at high latitudes. The lowest invariant latitude where impulsive VLF hiss was observed was 63° but 85% were above 70°. The magnetic local time of maximum occurrence tends to increase for decreasing invariant latitudes for the occurrences above 70°. Since the frequency of occurrence of ELF hiss was almost twice as great as that for VLF hiss, the same contamination of VLF hiss results with ELF hiss will be found here as was found to an extreme degree in the 4.0 mγ phase of the study. In other words, even though VLF hiss may have been present during a 1.5 mγ event, the cause of the high AGC reading in many cases was ELF hiss. Thus, Figure 19 is not a true picture of the frequency of occurrence of VLF hiss, because of the random presence of strong ELF hiss.

50% of the 1.5 mγ events contained chorus. Table 13 gives the total number of chorus events above 1.5 mγ within any given magnetic local time invariant latitude block. The frequency of occurrence of chorus above 1.5 mγ is given in Figure 20. The maximum occurrence of chorus was 40% which occurred at three points, 64° and 9 hours and 64° and 65° and 11 hours, invariant latitude and magnetic local time. The distribution of events is similar to that of all VLF noise greater than 1.5 mγ, being confined to magnetic day and invariant latitudes between 50° and 80°. This suggests that ELF hiss has again been the primary cause of the elevation of the AGC during these chorus events. Figure 20 is then not a true description of the occurrence of chorus due to the random presence of ELF hiss.

It must be emphasized that because of the high frequency of occurrence of ELF hiss which appears to be controlling the sample density of other phenomena, the frequencies of occurrence of ELF hiss above 1.5 and 4.0 mγ should be considered to be the principle result of the statistical study.

Cases of LHR hiss, risers, falling tones, steady tones, hooks, combinations, diffuse emissions and periodic, quasi-periodic, and triggered emissions were found in less than one percent of the 1.5 mγ events. Only five examples of LHR hiss were found in the Injun 3 data studied. In contrast, the Alouette satellite, which used an electric dipole antenna for its VLF receiver, observes LHR hiss with a maximum frequency of occurrence of ~ 60% [McEwen and Barrington, 1967]. The small number of cases of isolated discrete emissions is reasonable because they are isolated in time and would in general not affect the AGC. There are few cases of periodic or quasi-periodic emissions found in all Injun 3 data that were analyzed and thus few would be expected here.

VI. INDIVIDUAL PASS STUDY

In contrast to the statistical approach to the study of the morphology of VLF emissions, we will now consider a few individual passes to relate specific VLF events with the statistical findings. The passes considered were during revolutions 70, 71, 503, and 1737. The first two passes were during a disturbed period ($K_{College} = 6$ and $K_{College} = 5$), while the last two were during quiet periods ($k_{College} = 2$ and $k_{College} = 3$, respectively). The passes were all in the Northern Hemisphere and were all in the magnetic local day except for a small portion of revolution 503. These passes were chosen because of their high VLF emission activity. Figures 21-31 show the satellite trajectories in the coordinates magnetic local time and invariant latitude, spectrograms, orbital parameters and the wide band signal strengths (AGC) during the passes.

Revolution 70: As can be seen from Figures 21-23, the satellite was in the magnetic mid morning sector at middle to high latitudes during which time its altitude changed from ~ 1550 km to ~ 850 km. When good telemetry reception started, about 19:29:20 UT, chorus was being received which continued until about 19:37:10 UT. The chorus extended from ~ 0.5 to ~ 4 kHz. The satellite moved from 8.4 hours magnetic local time and 47° invariant latitude to 9.3 hours magnetic local time and 68° invariant latitude during this chorus event. Chorus in this frequency range, especially that below 1 kHz, is observed frequently with Injun 3. This observation agrees well with the statistical finding of chorus in Figures 15 and 20. The orbit passes through the area of maximum probability of occurrence of chorus. The AGC varied from 1.8 to 9.1 mγ during the chorus event but did not appear to correlate well with it.

Steady VLF hiss was observed from about 19:31:00 UT until at least 19:35:00 UT. Temporary telemetry loss at 19:35:05 UT made the determination of the end of the VLF hiss event uncertain until 19:36:36 UT. Although the band width of the steady VLF hiss appears to be only 2-3 kHz on the spectrogram due to the action of the AGC, the satellite spectrum analyzers indicate that the steady VLF hiss extends from ~ 3 kHz to beyond 8.8 kHz. During the steady VLF hiss event, the satellite moved from 8.5 hours magnetic local time and 51° invariant latitude to 9.0 hours magnetic local time and 62° invariant latitude. Steady VLF hiss typically occurs with this bandwidth and spacial extent. Comparing the spacial extent of this steady VLF hiss event with

Figures 16 and 19, we see that this event occurred in an area of relatively high probability of observing VLF hiss. The AGC appeared to correlate quite well with this VLF hiss event, reaching almost 10 mγ during peak intensity.

The identification of the beginning of the ELF hiss event during this pass was difficult, but ELF hiss was present by at least 19:32:30 UT. It continued until loss of telemetry at 19:38:40 UT. This ELF hiss is very typical, with a sharp lower cutoff and a bandwidth of about 1 kHz. The association of chorus and ELF hiss in the same frequency range or with chorus at a slightly higher frequency is also typical. The satellite moved from 8.6 hours magnetic local time and 54° invariant latitude to 9.6 hours magnetic local time and 72° invariant latitude during this ELF hiss event. These orbital parameters agree well with the statistical findings of the occurrence of ELF hiss, see Figures 14 and 18. The AGC was excited above its noise level for the entire pass (except after 19:30:35 UT) and when ELF hiss was the only VLF noise being observed, after 19:37:15 UT, the AGC was ~ 1-2 mγ. It seems apparent then that the amplitude of the ELF hiss was probably ~ 1-2 mγ during the entire pass.

Revolution 71: The orbital parameters of this pass are essentially the same as for the revolution 70 pass just considered, see Figures 24-26. The satellite was in the mid morning sector at middle to high latitudes during which time its altitude changed from ~ 1400 to ~ 750 km. No VLF emissions were observed during this pass until 21:30:00 UT when a LHRH band began to be observed. It continued until 21:31:00 UT. The LHRH was similar to other cases of LHRH in Injun 3 data with a sharp but uniformly changing lower frequency cutoff and a band width that extended above the highest satellite spectrum analyzer channel, 8.8 kHz. While the satellite was observing this LHRH, the satellite moved from ~ 8.77 to ~ 8.85 hours magnetic local time and ~ 53° to 55° invariant latitude. The AGC gives a value of between 1.5 and 3.0 mγ during the LHRH event.

At 21:30:25 UT chorus activity began and continued until 21:35:00 UT. Near the beginning of the chorus event, the chorus was primarily in a frequency range from 2 to 4 kHz with a few bursts in the 1 kHz range. In the middle of the event, there were equal amounts of chorus in each band, with some overlapping of bursts. Near the end of the chorus event the chorus was confined almost entirely to the lower frequency band. During this chorus event, the satellite moved from 8.8 hours magnetic local time and 54° invariant latitude to 9.5 hours magnetic local time and 67° invariant latitude. By comparing this path with Figures

15 and 20 showing the statistical occurrence of chorus, we can see that this chorus event occurred where the statistical probability of observing chorus is high. Digital telemetry was rather poor during this pass and AGC values are few in number. There appears to be a correlation between chorus and the AGC from 21:32:00 UT to 21:33:00 UT, with the AGC varying between 2 and 7 mγ.

The beginning of the ELF hiss event during this pass was difficult to determine but ELF hiss was present by at least 21:32:12 UT. The end of the ELF hiss event was at 21:35:15 UT. It was a typical ELF hiss event during which the satellite moved from 9.0 hours magnetic local time and 58° invariant latitude to 10.0 magnetic local time and 71° invariant latitude. The satellite path passes through the region of maximum occurrence of ELF hiss as shown in Figures 14 and 18. The poor digital telemetry made it difficult to compare ELF hiss with the AGC, but from 21:34:16 UT to 21:34:40 UT, the AGC reached a peak of 6 mγ during which time ELF hiss was the dominant emission being observed.

Revolution 503: Figures 27 and 28 show that the satellite was in the magnetic early morning sector at a high latitude and low altitude (~ 260 to 237 km) during telemetry reception. ELF hiss was observed during the entire pass from 18:12:08 UT until

18:16:48 UT. The ELF hiss was typical, with a bandwidth slightly less than 1 kHz, centered about 0.8 kHz and with a sharp lower frequency cutoff. The satellite moved from 5.6 hours magnetic local time and 69° invariant latitude to 9.4 hours magnetic local time and 71° invariant latitude, reaching a maximum invariant latitude of 72.2° while observing the ELF hiss. The statistical probability of finding ELF hiss with AGC greater than 1.5 mγ over this path varied from less than 10% at the beginning of the pass, to greater than 40% near the end of the pass, see Figure 18. ELF hiss was the only emission observed until 18:15:10 UT, during which time the AGC was never greater than 1.0 mγ.

At 18:15:10 UT until the end of the pass at 18:16:48 UT, steady VLF hiss was observed. The lower cutoff of the steady VLF hiss was about 2.5 kHz, and the upper limit was above 8.8 kHz. The satellite moved from 8.1 hours magnetic local time and 72.2° invariant latitude to 9.4 hours magnetic local time and 71° invariant latitude during this observation of steady VLF hiss. The probability of observing VLF hiss with the AGC > 1.5 mγ over this path is about 10%, see Figure 19. The AGC and the steady VLF hiss were very well correlated during this pass, for the AGC increased from 1.0 mγ to 1.8 mγ as the steady VLF hiss became stronger.

Revolution 1737: During this pass, the satellite was in the magnetic late morning and afternoon sector, at high latitudes and altitudes from 1200 to 1900 km, see Figures 29-31. ELF hiss was present from 23:35:00 UT until about 23:42:00 UT. It was difficult to tell when the ELF hiss stopped, but it was probably near the time when the AGC dropped to 0 mγ. In this seven minute interval, the satellite moved from 11.2 hours magnetic local time and 68° invariant latitude to 15.2 hours magnetic local time and 76° invariant latitude. Considering the frequency of occurrence plot of ELF hiss in Figures 14 and 18, the probability of observing ELF hiss above 1.5 mγ, for example, ranged from less than 10% to greater than 40% while ELF hiss was being observed by the satellite. The AGC generally correlated well with ELF hiss during the pass, being at a maximum of 5 mγ at the beginning of the pass and decreasing to zero when the ELF hiss appeared to disappear.

Chorus was also observed during the pass from 23:35:00 UT until 23:39:35 UT. The chorus was in the frequency range of 1 to 4 kHz with the upper frequency cutoff generally decreasing with increasing invariant latitude. During the chorus event, the satellite moved from 11.2 hours magnetic local time and 68° invariant latitude to 13.7 hours magnetic local time and 76° invariant latitude. The probability of finding chorus when the AGC was gréater than 1.5 mγ over this path varied from less than 5% to greater than 35%, see Figure 20. The AGC was well correlated with the chorus during this pass, but it seems likely that the true correlation was with the ELF hiss and the chorus appeared coincidentally.

Impulsive VLF hiss was observed from 23:38:25 UT until 23:44:00 UT with small breaks at 23:38:45 UT and 23:39:45 UT and a large break from 23:40:30 UT to 23:41:05 UT. The impulsive VLF hiss had a lower frequency cutoff of about 5 kHz and the upper frequency cutoff was above 8.8 kHz. During the observation of the impulsive VLF hiss the satellite moved from 12.8 hours magnetic local time and 74.5° invariant latitude to 16.3 hours magnetic local time and 74.7° invariant latitude, reaching a maximum invariant latitude of 76.2°. The probability of occurrence of VLF hiss with AGC > 1.5 mγ varied from 0% to greater than 15% over the portion satellite path when impulsive VLF hiss was being received, see Figure 19. Table 12 shows that this event was found where most of the impulsive VLF hiss events were found in the 1.5 mγ statistical study. The AGC was not affected by the impulsive VLF hiss observed on this pass.

Geomagnetic disturbances as measured by the local magnetic index $k_{College}$ appear to have affected the region of occurrence of large amplitude VLF emissions for these individual passes. It can be seen from Figures 22, 23, 25, and 26 that the AGC was above 3 milligamma from 52° to 68° invariant latitude during revolution 70 and from 56° to 70° on revolution 71, during a magnetically disturbed period. However, Figures 28, 30, and 31 show that the AGC was above 3 milligamma from lower than 68° to 73° on revolution 1737 and enhanced at 72° on revolution 503 during magnetically quiet periods. This change indicates that the region of maximum occurrence of strong VLF noise may shift toward lower latitudes during magnetically disturbed periods. This shift would be expected since the magnetospheric field lines along which the VLF noises propagate and the particles, which probably cause emissions move, are compressed during disturbed periods and move toward the equator. There is some indication from these passes that the region of occurrence of each type of VLF emission is also a function of $k_{College}$. This movement is not completely clear from these four passes, but further investigation would be interesting.

VII. COMPARISON WITH PREVIOUS RESULTS

In Section I, we mention studies which have been made of the frequency of occurrence of VLF emissions observed by VLF ground stations. We will compare the results found here with selected results of two of the ground station studies, Laaspere, Morgan and Johnson's [1964a] study of hiss and chorus and Pope's [1963] study of chorus. The study by Laaspere et al. used results from a number of "Whistlers-East" VLF ground stations, which were located near the magnetic meridian at low, middle, and high latitudes. For their study, all types of non-discrete emissions were called hiss. This classification includes both VLF and ELF hiss, but would not include LHR hiss, which has never been observed by a ground station [Brice and Smith, 1964].

Data from Ellsworth Station, Antarctica (invariant latitude = 67°S) and Knob Lake, Quebec, Canada (invariant latitude = 66°N) were used by Laaspere et al. [1964a]. The dependence of the probability of occurrence of hiss on magnetic local time at these two ground stations averaged over at least two years is shown in Figure 32. In addition, Figure 32 contains the corresponding dependence on magnetic local time for occurrence of 1.5 mγ VLF and

ELF hiss averaged over 66° and 67° invariant latitude as determined by the statistical study of Section V. The distribution of satellite VLF hiss used here is not strictly correct because of the influence of ELF hiss, see also Section V. The diurnal maxima for the two ground stations are 07 hours and 12 hours magnetic local time for Knob Lake and Ellsworth, respectively. The maximum for Injun 3 hiss is broad, being from 7-13 hours magnetic local time. The statistics are not as good for the Injun 3 data as for the ground station data. Nevertheless, we can see that there is general agreement between the ground station results by Laaspere et al. [1964a] and our Injun 3 data.

The results that Pope [1963] reported concerned chorus occurrence at high latitudes. He used a number of high latitude ground stations including one at Kotzebue, Alaska (invariant latitude = 67°). The dependence of the probability of occurrence of chorus on magnetic local time at Kotzebue and at Ellsworth (invariant latitude = 67°) as reported by Laaspere et al. [1964a] and the corresponding dependence of satellite chorus above 1.5 mγ at 67° invariant latitude as determined by the statistical study of Section V is shown in Figure 33. This distribution of satellite chorus is strictly not correct because of the contamination by ELF hiss, see Section V. The satellite chorus occurrence maximum is again broad, with a peak at 9 hours magnetic local time. This maximum is between the two maxima for the ground stations which were at 8 and 10 hours magnetic local time for Ellsworth and Kotzebue, respectively, showing good agreement. The ground station minima at 21 and 22 hours magnetic local time agreed with the Injun 3 minimum, 18-02 hours magnetic local time.

Jørgensen [1966a] produced contour plots of 8 kHz hiss above 68° invariant latitude, using data from three ground stations in Greenland. Figure 1 shows this contour plot for 1964. Comparing this figure with our VLF hiss findings, for example, Figure 18, we find considerable disagreement. The maximum in the ground based distribution is in the late evening, while for this satellite study, the maximum is in the late morning. The latitudinal dependence is difficult to compare since the study by Jørgensen extends to only 68° invariant latitude. This is the latitude of maximum occurrence in our study. The disagreement is probably due to the control of our sample density by the stronger phenomenon, ELF hiss.

The study of satellite VLF hiss by Gurnett [1966] was also mentioned in Section I. Comparing the summary of his results shown in Figure 2, with the results of our study for VLF hiss, shown in Figures 16 and 18, we find different areas of maximum occurrence. Gurnett's VLF hiss is confined to a narrow zone 7° wide in latitude and centered on 77° invariant latitude and 14 hours magnetic local time and centered on 70° at 22 hours. Our results show VLF hiss at lower latitudes and occurring generally earlier in the magnetic day. The disagreement in these two results is due to differences in definitions and data selection. Gurnett defined VLF hiss as VLF noise from 5.5 to 8.8 kHz that was not LHR hiss, chorus, equatorial hiss [Gurnett, 1967] or low frequency hiss usually below 3 kHz We define VLF hiss to be hiss with components greater than 2kHz. Gurnett chose data points by requiring that three satellite borne spectrum analyzers be above 3×10^{-10} gamma^2/Hz for a period of eight seconds. In this paper, the criterion for choosing data points was requiring the AGC to be above 1.5 or 4.0 mγ. The type of event was then identified by examining spectrograms and, in the case of 1.5 mγ VLF hiss, checking the output of the on board spectrum analyzers during the event. In addition, we considered only the first eight second data point per revolution in a magnetic local time, invariant latitude block, whereas Gurnett only counted one per block, but examined all points in the block for VLF hiss. The results of these differences are: 1) There was contamination of the VLF hiss results presented here due to the simultaneous occurrence of ELF hiss which would tend to shift the true VLF hiss distribution toward that of the ELF hiss distribution. This is probably the most significant cause of the discrepancy. 2) Gurnett considered some VLF hiss events that were not included here because the AGC was not above 1.5 mγ at the first data point in each of the magnetic local time, invariant latitude block. 3) Gurnett did not consider VLF hiss events below 5.5 kHz that were counted as VLF hiss here.

VIII. SUMMARY

We have presented a satellite study of the morphology of VLF emissions which are naturally occurring VLF noises not associated with lightning. The study was in two parts, a statistical study of the occurrence of VLF emissions and an individual pass study to illustrate the statistical trends with spectra. To facilitate these studies, a new set of definitions of VLF emissions was given to codify previously given definitions [Gallet, 1959; Helliwell, 1965; and others] and to make them quantitative.

For all Injun 3 data, two threshold magnetic field strengths (1.5 and 4.0 mγ), as measured and averaged every eight seconds by the satellite VLF receiver, were set. Using the definitions, the VLF emissions present in each event above the threshold were determined. To provide a uniform sample density, only one event per revolution was considered in each magnetic local time, invariant latitude block (1 hour by 1 degree). Five thousand three hundred events were examined with intensities above 1.5 mγ and 825 above 4.0 mγ.

The normalized distribution of noise above 4.0 mγ was nearly confined to the magnetic local day and 50°- 75° invariant latitude. The occurrence of VLF hiss when the AGC was greater than 4.0 mγ had a maximum near magnetic noon, and there were few events during magnetic night or at invariant latitudes less than 50° or greater than 75°. The occurrence patterns of ELF hiss and chorus when the AGC was above 4.0 mγ are quite similar to each other. Nearly all of the events occurred from 7 to 14 hours magnetic local time and 55° to 75° invariant latitude.

The normalized distribution of noise above 1.5 mγ had the same latitudinal dependence as the 4.0 mγ distribution, but the maximum was closer to magnetic noon. The occurrence patterns of VLF hiss, ELF hiss, and chorus when the AGC was above 1.5 mγ were similar to each other. The bulk of the events occurred during magnetic day and from 50° to 75° invariant latitude.

ELF hiss was found to have a greater amplitude than any other VLF emission. This strength caused misleading frequency of occurrence plots for the other VLF emissions studied statistically, VLF hiss and chorus. ELF hiss would similarly affect any study of VLF phenomena using the wide band signal strength to choose data points for its strength would prejudice the sample densities.

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TABLE 1

(After Gallet [1959], Table I, page 213)

Systematic Classification of Observed VLF Noises

---

2 Large Groups:

I. WHISTLERS -- Cause: Lightning Discharges.

All frequencies emitted at once; shape due to dispersion along the path.

II. VLF EMISSIONS -- Not caused by lightning.

Strongly associated to magnetic perturbations.

TWO PRINCIPAL TYPES:

1. Continuous in both time and frequency.

   Steady state situation. Hiss.

2. Discrete, but often with repetition tendency.

   Transient situation. Many classes recognized.

A third group more complex and rarer exists:

III. Interactions between Whistlers and VLF emissions.

The interaction involves either the continuous or the discrete VLF emissions.

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TABLE 2

(after Gallet [1959], table II, page 213)

II.2. CLASSES OF DISCRETE VLF EMISSIONS:

1. HOOKS

a b c d e

2. RISERS

2B. HOOK WITH EXTENDED RISING TAIL

3. QUASI VERTICAL (Generally FUZZY. Typical Chorus)

4. FALLING TONES

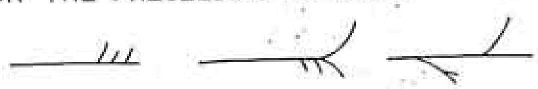
4B. PSEUDO WHISTLERS

5. QUASI HORIZONTAL

5B. COMBINATION OF 4 AND 5

6. PSEUDO NOSES (by analogy with nose whistlers)

7. TOO COMPLEX FOR THE PRECEEDING CLASSES



8. EXCEPTIONAL STRONG NOISES WITH TRAIN OF ECHOES

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TABLE 3

(after Helliwell [1965], table 7-1, page 206)

MODEL SPECTRAL FORMS OF VLF EMISSIONS

Type and Name	
I. HISS	
II. DISCRETE EMISSIONS	
A. RISING TONE	
B. FALLING TONE	
C. HOOK	
D. COMBINATIONS	
III. PERIODIC EMISSIONS	
A. DISPERSIVE	
B. NON-DISPERSIVE	
C. MULTIPHASE	
D. DRIFTING	
IV. CHORUS	
V. QUASI-PERIODIC EMISSIONS	
VI. TRIGGERED EMISSION	

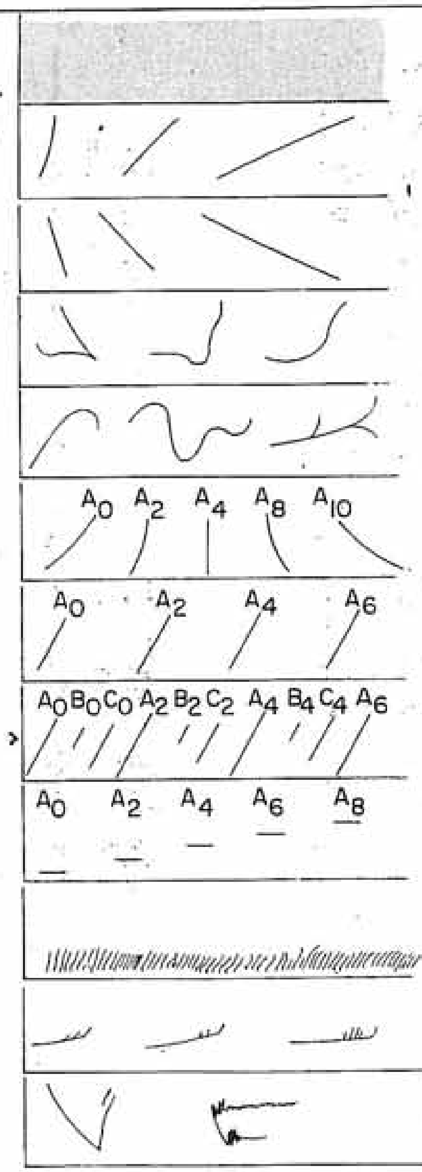

TABLE 4

The Number of Times the Injun 3 Satellite Passed Through any Invariant Latitude, Magnetic Local Time Block while Telemetering Data

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
14																						1		
15								1								2					1	1		
16	1							1					1		1	1			1		1	1		
17	3	2						1					2		2	3	1	1	3	1	4	3	2	4
18	8	2						1					2		3		1	2	3	1	3	3	2	7
19	7	7						1					3	1	4	2	1	3	4	4	4	7	9	11
20	7	6											2	2	3	3	2	3	5	4	3	7	8	7
21	8	8				1							2	4	4	4	3	5	7	6	9	11	11	10
22	5	10		2		1						1	1	5	3	3	4	6	8	7	9	8	7	7
23	7	11		1	4	1						1	1	5	4	5	6	9	11	15	11	10	10	7
24	5	8	1	1	5	3			1					6	12	10	8	12	16	16	8	10	14	7
25	6	7	1	1	6	5	2		2					7	13	12	10	17	17	21	6	15	11	6
26	11	12	1	2	4	8	4	2	3		1		1	9	13	15	14	19	17	20	7	14	14	5
27	16	12	3	2	5	8	4	6	6	3	2		2	12	21	23	14	18	13	23	10	19	10	9
28	11	8	3	2	5	5	5	5	8	3	2	1	12	16	22	17	10	13	13	19	8	15	14	8
29	16	11	9	5	4	7	7	4	12	9	9	8	13	26	37	18	12	16	14	21	13	18	17	10

TABLE 4 (CONT'D)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours) 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
30	16	10	8	5	4	6	6	3	8	9	18	13	18	24	30	12	9	12	11	17	11	16	15	10
31	19	10	13	6	5	8	10	2	8	18	30	24	26	34	31	19	17	16	15	21	11	20	20	9
32	28	11	15	6	7	11	14	6	15	23	20	26	27	38	32	27	21	23	16	22	18	19	22	12
33	23	17	25	7	11	16	25	9	18	24	21	21	26	41	35	35	30	34	29	35	28	29	27	19
34	22	21	19	13	16	19	25	12	15	16	18	20	25	37	31	27	27	29	29	28	27	31	30	24
35	29	25	25	17	17	26	27	16	15	24	22	19	27	44	30	25	23	28	28	32	23	39	29	20
36	31	23	27	23	18	28	30	19	11	20	19	16	30	40	31	29	27	31	24	30	26	33	26	20
37	26	20	31	28	26	26	30	19	15	22	18	14	24	37	34	34	29	32	28	29	36	36	26	19
38	29	24	28	26	29	31	28	16	17	20	17	19	36	43	27	35	32	27	31	34	36	33	30	23
39	33	28	27	23	33	32	29	22	19	22	19	20	34	32	29	44	27	28	30	31	37	38	27	25
40	37	33	31	22	36	33	29	24	22	19	17	19	34	39	29	41	31	28	29	34	41	35	29	27
41	38	36	31	31	33	29	28	27	20	19	21	25	35	32	31	32	29	29	31	32	36	32	28	30
42	38	40	37	31	32	34	32	29	19	18	19	22	29	40	34	35	32	32	27	35	40	32	29	29
43	39	37	36	32	33	35	34	28	19	22	20	24	41	42	34	36	31	27	33	31	38	32	29	34
44	42	33	32	35	36	36	31	29	20	26	18	24	30	42	31	30	32	31	30	28	38	29	27	35
45	41	37	42	35	35	42	39	30	23	27	22	23	34	35	34	29	36	30	33	32	35	27	29	40
46	44	36	43	45	37	41	38	30	21	27	21	27	34	48	33	35	35	36	39	39	45	30	34	42
47	48	42	45	41	33	36	36	24	28	23	25	29	30	44	35	29	38	35	33	39	38	27	36	40
48	47	44	50	47	36	40	33	27	27	25	21	27	27	41	37	36	33	35	38	44	41	31	27	37

TABLE 4 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours) 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
49	48	51	51	42	37	44	41	31	37	27	22	31	33	47	38	50	37	28	34	37	49	27	30	43
50	41	54	48	37	39	45	34	31	32	31	28	31	33	49	37	45	43	34	36	45	52	26	31	44
51	53	61	45	38	41	46	35	36	28	32	30	29	28	47	38	49	44	34	50	47	57	36	36	50
52	51	54	45	40	43	50	33	28	36	34	32	32	37	44	43	47	41	38	48	43	51	36	43	51
53	50	54	49	43	43	45	33	40	43	34	35	33	39	45	42	54	36	38	47	40	45	34	41	44
54	56	57	44	41	48	45	35	35	42	39	37	33	37	45	45	57	39	43	50	40	52	36	43	42
55	54	50	47	46	49	45	39	38	37	34	32	36	38	44	46	54	45	46	47	40	59	32	43	39
56	59	56	46	46	47	51	35	40	39	42	38	38	41	51	48	61	41	45	47	46	55	32	47	44
57	54	53	42	50	45	57	37	43	36	36	41	42	43	51	43	53	48	37	54	45	56	38	52	44
58	51	50	40	50	49	54	39	39	41	48	42	40	46	49	46	47	51	39	53	45	43	53	53	47
59	46	54	47	51	45	56	43	37	40	48	51	44	50	48	45	49	56	42	47	45	39	49	46	46
60	53	63	49	51	45	56	42	40	43	48	49	46	42	55	45	48	51	43	43	45	41	46	54	50
61	54	62	47	55	50	58	46	38	41	52	49	45	43	48	52	52	48	46	47	46	37	46	60	45
62	52	51	48	50	56	56	51	47	46	48	52	46	46	43	53	55	56	47	43	44	48	52	56	46
63	49	48	58	55	55	65	67	51	51	53	53	56	53	44	45	59	51	38	44	46	41	46	55	51
64	48	61	59	50	60	56	60	51	56	50	48	50	49	41	45	59	42	46	41	44	48	51	58	48
65	53	62	61	61	60	56	63	54	51	56	54	50	52	44	41	58	43	44	42	54	45	48	56	49
66	51	59	53	70	66	57	72	57	63	64	54	56	64	52	51	59	49	50	45	56	42	48	58	51
67	58	66	56	74	70	65	75	67	70	72	60	59	62	52	52	60	51	47	37	48	36	52	62	47

TABLE 4 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours) 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
68	56	61	55	73	68	68	73	65	70	70	58	51	56	58	46	48	48	47	45	50	56	54	64	59
69	42	55	59	63	66	63	73	62	68	67	54	43	43	44	42	52	47	50	48	45	38	47	46	57
70	52	49	56	47	60	53	65	60	64	56	54	46	35	38	33	41	34	49	32	35	34	41	42	49
71	43	48	54	49	59	49	55	58	59	42	53	50	28	30	28	32	44	38	36	36	34	42	41	38
72	42	46	42	44	57	50	53	55	49	42	45	41	31	33	27	27	38	30	29	32	35	45	42	41
73	46	50	38	40	42	44	45	58	55	40	38	35	37	29	26	26	38	28	25	29	31	33	38	37
74	36	45	41	46	40	45	35	51	38	40	33	33	29	29	32	28	30	24	24	24	23	36	36	35
75	35	37	37	39	30	35	39	43	35	39	28	25	26	26	21	22	19	15	24	21	25	34	28	35
76	36	33	32	31	31	34	33	41	41	33	27	26	29	20	22	20	20	19	18	12	23	23	24	28
77	35	38	24	25	28	26	22	24	27	29	17	25	26	17	23	20	12	16	14	15	18	19	22	22
78	26	32	23	12	26	26	21	25	24	28	19	23	21	14	17	17	10	14	12	19	15	12	18	20
79	20	25	18	18	17	22	17	17	22	22	22	18	24	18	15	15	4	10	14	18	11	16	19	21
80	17	17	15	15	9	12	8	11	13	15	15	13	11	13	12	7	6	5	13	8	10	14	16	14
81	9	6	10	9	6	9	6	7	1	3	6	12	8	6	7	4	2	3	4	6	6	8	9	11
82	3	2	2	3	5	2		1				1	1	1		1		2		2	4	4	3	4

TABLE 5

Number of AGC > 4.0 mγ Events in
Invariant Latitude and Magnetic Local Time

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
21																				1				
22																				1				
31																	1					1		
32																1	1							
33																	1							
34																	1							
35																	1							
40																			1					
43														1										
44														1										
45														1										
46																					1			
47														1				2	2					
48												1					1							
49												1		1										
50											1	1		4				1						
51											1	1		4				1						

TABLE 5 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																						
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
52									1	2	1	1	1	3	1		2	2						
53								1	4	1	2		3	4	1		2	3					1	
54								4	7		2		4	4	1	1	3	3	1					
55								5	3	3	2	1	7	3	2		3	3	2					
56				1		1		5	7	4	3	2	8	3	1	1	2	4	2					
57				1		1	2	8	7	5	4	3	8	5		1	3	2	2					
58						1	3		9	6	3	1	4	7		1	3	2	1					
59						2	2	11	5	11	5	3	3	4	1	2	3	1	1					
60						1	1	8	7	10	5	2	2	5	1	3	3	4	1				1	1
61					1			8	4	8	2	2	2	3		2	2	3	1					
62							2	8	5	6	2		3	2	2	3	2	1						
63					1		2	7	2	8	2	3	4	3		2	1						1	
64				1			1	4	3	9	4	4	4	3	1	3	2						1	
65				1		1	2	5	1	10	6	2	4	3		1	2							
66							1	5	4	3	8	3	8	2	1	1	2			1	1	1		
67					1		1	3	3	6	8	4	7	2	2					1	1	1		
68							1	1	4	11	3	4	4	1	1					1	2			
69								1	5	8	3	2	4	1				1	1	1		1		
70	1							1	3	6	5	7	2		2			1			1			1

TABLE 5 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
71								2	4	1	5	6	1	1						1	1		1	1
72	1	1						1	7	4	7	4								1	1	1		1
73								1	5	4	4	2	2							1	2			
74									2		2	3	1							2				
75									2			1	1								2			
76									1	1		1												
77										1														

TABLE 6

Number of ELF Hiss Occurrences with AGC > 4.0 mγ
in Invariant Latitude and Magnetic Local Time

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																						
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
31																						1		
43														1										
44														1										
45														1										
47																		2	1					
48												1					1							
49														1										
50												1		3				1						
51												1		2				1						
52									1	1		1		2	1		1	1						
53									3		2		2	2	1		2	2						
54								4	6		2		3	2	1	1	3	2	1					
55								5	3	2	1	1	4	2	1		3	2	2					
56				1				5	6	2	3	2	5	3	1	1	2	3	2					
57				1			1	7	7	3	3	3	5	3		1	2	1	2					
58							2	7	7	6	3	1	3	4		1	2	1	1					

TABLE 6 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
59							1	10	5	10	4	2	2	4		2	2	1	1					
60							1	7	7	7	4	1	2	5	1	2	2	3					1	1
61					1			7	4	7	2	1	1	3		1	2	2						
62							2	8	5	6	2		1	2	2	2	2	1						
63					1		1	6	1	8	2	2	2	2		1	1							
64				1			1	4	3	9	4	3	2	3	1	2	2							
65				1			2	5	1	10	6	2	4	3		1	2							
66							1	5	4	3	8	3	7	1	1	1	2			1				
67					1		1	3	3	6	8	4	7	2	1									
68							1	1	3	11	3	3	2	1	1						1			
69								1	5	8	3	2	4	1										
70								1	3	5	4	4	2		1			1						1
71								2	3		3	6	1											
72								1	6	3	5	4										1		
73								1	5	4	3	2	2											
74									2		1	3	1											
75									2			1	1								1			
76									1	1		1												
77										1														

TABLE 7

Number of Chorus Occurrences with AGC > 4.0 my in
Invariant Latitude and Magnetic Local Time

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
50												1		2										
51														2										
52									1		1			2										
53								1	2		1		2	1									1	
54								3	5		1		3	1										
55								3	1	1	1		4	1										
56				1				5	4	2	2		3	2										
57				1			2	4	6	3	3	1	3	2										
58							2	6	5	6	2		3	4										
59						7	1	9	2	10	3	1	2	2				1						
60							1	7	4	7	4	1		2				1					1	1
61					1			5	2	7	2			1		1		1						
62							2	5	2	5	2			2				1						
63					1		2	7	1	4	2			1										
64								2	2	8	4	1	1	3		1	1							

TABLE 7 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
65						1	2	4	1	9	4	1		1			1							
66								4	3	3	6	3	1	1										
67					1			2	2	6	6	3												
68									3	6	3	1	1											
69								1	5	4	2	1	1											
70								1	1	3	2	2	1		1									
71								2	1		2	1												
72									4	1	1													1
73									2	2	1													
74									1															
75												1												

TABLE 8

Number of VLF Hiss Occurrences with AGC > 4.0 mγ in Invariant Latitude and Magnetic Local Time

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
21																				1				
22																				1				
31																	1							
32																1	1							
33																	1							
34																	1							
35																	1							
46																					1			
47														1										
48																								
49														1										
50												1		4				1						
51												1		3				1						

TABLE 8 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																						
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
52									1	1		1		3	1			2						
53									3	1	2		2	4				3						
54									4		2		3	3				3	1					
55								1		1	1	1	4	2	2		1	2	2					
56				1		1				2	2	2	6	2			2	2	2					
57						1		1	1		1	2	5	4			2	2	1					
58						1	2	1	2	1	1		3	3			1	2	1					
59						2	2	1	2	3	1	1	2	1			1	1	1					
60						1		1	1	3	1		2	3				3	1					
61									1	4	1		1	2					1					
62							1	2		2	1		1	1										
63							1			2	1			1									1	
64										2	2		2	1									1	
65							1			1	2			1										
66							1			1			1							1	1	1		

TABLE 8 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
67							1			1	1				1					1	1	1		
68							1	1	1	1										1	1			
69										1								1	1	1		1		
70	1									1	1				1						1			1
71										1											1		1	1
72	1	1									2											1		1
73									1		1		1							1	1			
74											1	1	1							2	2			
75												1												
76												1												

TABLE 9

Number of AGC > 1.5 my Events in
Invariant Latitude and Magnetic Local Time

	Magnetic Local Time (Hours)																							
Invariant Latitude (Degrees)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
14																								
15																								
16													1											
17																								
18																								
19																				1				
20													1							1				
21																1				2				
22																				1	1			
23																		1		1	2			
24	1														1	1		1		1				
25															2			1		2				
26															2	1				1				
27															3	1				1				
28													1		2	1						1		
29				1											1	1								
30	1												1		1	1		1				1		

TABLE 9 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
31												1	1		1	1	1			1				
32												1	1		1	2	1	1		2				
33												1	1		1	1	1	1	1		2			
34												1	1	1	1		1		2		4			
35												1	1		1	1	1	1	1	1	3			1
36	1					1		1				1	1		1	1	1	1	1		1	1		
37	2				1							1	1		1	2	1		2	2	3	1		
38													2		1	1	1	1	4	1	2			1
39								1					1		1	1	1		3	2	2			
40	1													1	2		1		3	3	2			
41	1								1			1	1		1	1	2		4	2	3			
42	1					1	1				2		1	1	2	5	2		2	4	1		1	
43						1	1		1		1	2	1	2	1	1	2	2	5	2	2		1	
44				1	1		1	1			2	2	2	2	1	2	2	2	4	2	1		1	
45				1	2		1	1	2		1	4		1	3	1	4	3	5	3	1		1	
46		1	1		1		1	2	2		2	3		1	1	4	2	9	6	3	3		1	2
47	1		1		1		1	1	4		1	2	1	3	1	3	3	6	8	1	1		1	
48			1	1				3	5			2	2	3		2	4	4	7	1	1			
49		1			1		1	2	6	1		6	1	5	1	4	1	3	6	1	1			

TABLE 9 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
50		1			3		1		6	2	2	3	2	5	2	3	3	4	4	5	1			
51							3	1	9	3	3	3	1	4	3	5	5	6	7	4	1	2		
52					1		4	3	9	4	2	3	4	4	4	2	7	6	5			1		
53		1				1	4	6	14	6	3	3	6	4	3	4	5	6	5	2		2	1	
54	1			1		2	2	8	15	8	3	4	9	6	1	6	7	10	6	2		1	2	
55		2		3	1	2	4	11	15	8	4	5	10	6	4	5	11	11	10	3	2	1	2	
56		4	1	1		3	7	14	17	14	3	5	11	6	8	6	10	11	12	1	1	1	2	1
57		4		3	1	6	8	16	13	12	7	13	14	7	6	9	12	10	18	2			1	2
58		3		3	3	7	11	15	20	22	9	13	10	14	7	9	13	9	16	3	1	2	2	3
59	1	1	2	4	2	7	14	18	19	25	18	18	13	15	11	9	17	13	13	5		2	1	4
60		2	2	3	5	7	8	19	18	23	17	18	12	17	11	8	15	20	12	5			1	3
61		2	2	8	7	8	16	17	22	28	18	16	10	18	11	9	12	18	8	5	1		2	3
62	1	2	2	5	5	7	17	19	20	25	22	20	13	19	12	10	16	15	10	5	1			4
63	3	1	6	4	4	5	21	21	16	30	22	24	14	19	11	10	13	11	10	4			1	2
64	1	1	3	4	1	5	17	21	21	29	19	26	15	20	11	12	12	8	3	3	1	3	1	1
65	1		1	3	1	7	12	19	19	28	24	28	16	21	4	17	6	9	3	3	2	4		
66			3	6	1	6	14	25	24	32	25	23	25	24	6	12	5	6	4	2	2	2	1	
67	2		1	2	5	4	8	22	25	35	24	22	28	22	7	14	6	6	1	2	4		1	1
68		2				4	13	18	26	36	19	17	19	23	10	8	2	4	4	3	3	1	4	3

TABLE 9 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
69						2	7	17	25	33	22	16	19	15	8	8	1	4	4	3	2	4	2	2
70	2					2	6	19	22	28	27	17	15	8	5	4	1	3	3		4	3	2	2
71		1					4	12	17	18	23	21	14	9	5	3	6	2	3	2	5	2	5	3
72	2	1						11	15	14	19	18	13	12	5	2	7	1	1	3	5	4	3	4
73							2	9	25	14	18	14	14	11	7	5	4	5	1	1	4	4	2	
74						1	1	5	10	12	13	12	15	7	5	1	4	3		3	2	8	2	
75	1						1	4	8	12	8	9	15	7	6	3	2	1			3	4	2	
76	2							4	7	11	10	10	11	3	6	3	1				2	2	1	
77							1		2	7	4	10	2	1	4	1					1	1		
78									3	4	4	3	2	2	2	1						2		
79										6	4	5	1	1										
80											3	1			1									
81												1												
82																								

TABLE 10

Number of Occurrences of ELF Hiss with AGC > 1.5 mγ in Invariant Latitude and Magnetic Local Time

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
28													1											
29																								
30													1											
31												1	1							1				
32												1	1							1				
33												1	1						1		1			
34												1	1						1		2			
35												1	1						1		2			
36	1					1		1				1	1						1			1		
37	1											1	1							1	1	1		
38													1							1	1			
39								1					1		1					1				
40														1	2				1					
41	1								1			1			1				1		1			
42	1					1	1						1	1	2	1								
43						1	1					1	1	2	1						1			

TABLE 10 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
44					1		1					1	2	2	1									
45					2		1		2			1		1	1			1	2					
46		1			1			1	1			1			1	2		1	1					
47					1		1	1	3			1			1	1		3	1	1				
48								1	4			1	1	2		1		3						
49							1		6			1		3	1	1		1						
50		1			2		1		4	2	1	1	1	2	1	1	2	2						
51							1		7	3		2		2	1	2	2	3						
52					1		1		7	4		2	1	2	1	1	4	2						
53		1					3	3	9	4			3	1	1	3	3	1		1				
54						1	2	3	9	7	1		5	1		4	5	5	2	1				
55				1		1	3	5	10	6		2	5	3	2	3	7	7	2	1				
56		1		1		2	4	8	9	11		1	5	3	6	5	5	7	4	1				1
57				2	1	2	8	9	9	9	3	5	7	5	4	7	8	3	9	1				1
58				1		1	6	7	13	15	5	4	6	8	6	7	10	4	6	1			1	1
59			1	3		1	10	11	13	14	5	9	9	9	8	8	9	7	7	2				
60				2		2	5	11	14	14	5	7	5	12	7	6	7	13	5	2			1	2
61		1		4	1	4	11	10	18	19	8	11	3	13	8	6	3	11	4	3			1	3
62	1	1	1	3	3	4	12	15	14	19	10	13	4	12	10	7	6	10	6	2				4

TABLE 10 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																						
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
63	2	1	3	3	3	3	16	16	11	23	13	14	9	13	9	7	9	8	7	2				2
64	1	1	2	3		1	14	17	16	21	12	16	13	14	10	8	10	8	2		1	2		1
65	1			3	1	4	8	19	16	24	17	20	14	15	4	13	5	8	2	3		1		
66			3	4	1	4	9	24	17	26	19	18	22	15	6	11	4	4	2	1				
67	1		1	1	3	3	7	18	20	30	18	18	22	18	6	12	5	4			1			
68		1				4	9	14	20	27	17	13	12	18	8	6	2	2	1				1	1
69						2	7	12	22	29	19	13	13	11	5	5		1						
70						1	5	14	18	21	21	12	9	3	4	3								
71							3	9	14	16	20	17	9	5	2	1	3						1	
72	1							9	12	12	19	13	10	6		1	1							
73							1	5	21	14	13	12	11	8	4	2	2				1			
74							1	4	8	9	11	10	14	5	1							1		
75								3	8	10	6	8	13	3	2								1	
76								2	6	10	7	8	7	1	1									
77									2	5	3	8	1	1										
78									2	3	3	2		1	1							1		
79										3	3	5	1											
80											3				1									
81												1												

TABLE 11

Number of VLF Hiss Occurrences with AGC > 1.5 mγ in Invariant Latitude and Magnetic Local Time

	Magnetic Local Time (Hours)																							
Invariant Latitude (Degrees)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
20													1							1				
21																				2				
22																				1	1			
23																				1	1			
24																1				1				
25																				1				
26																1				1				
27																1				1				
28																1								
29																1								
30																1								
31																1	1			1				
32																1	1			2				
33																	1		1					
34													1				1		1		1			
35																	1							
36																	1							

TABLE 11 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																						
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
37	1				1												1			2	1			
38																	1		1	1				
39													1							1				
40	1																			1				
41												1					1		1	1				
42														1			1		1	1			1	
43												1					1	2	2	1			1	
44											2	1		1			1	1	2				1	
45									1			2		1			1	1	2				1	
46								1	1		1	2		1				5	3				1	
47								1	1			2	1	3			1	4	2				1	
48								1	2			2	1	2		1	1	1	3					
49									1			2	1	3		1		2	2					
50									2	1		1	1	5	1	2		3	2					
51							1		4	1	1	2		4	2	4	1	3	3					
52					1		1	3	4	1	2	1	2	2	2	2	1	4	3					
53						1	1	3	5	2	3	2	6	3	1	3		4	3					
54				1		1		3	5	4	3	2	6	4	1	4	1	5	1					
55		1		3	1	3	2	7	3	1	4	2	6	3	1	2	2	4	4	1			1	

TABLE 11 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
56		2				2	1	5	5	3	3	2	6	2	1	2	4	5	5					1
57		1		2		5	1	7	5	2	4	8	8	5	2	1	5	6	10	1				1
58		1		1	1	5	4	8	5	9	5	9	8	4	3	2	5	4	8	2	1		1	
59		1	1	3		3	2	12	5	11	8	9	6	5	5	1	4	9	5	3		1	1	
60		1	1	1	2	4	2	9	4	10	9	7	4	5	5		4	8	5	2				
61		1		2	5	2	4	10	5	11	2	4	6	7	5		7	6	5	2			1	
62		1	2	2	3	2	5	12	5	11	14	7	7	8	3		9	6	4	2	1		1	
63	2		1	2	2		7	7	3	11	11	9	5	6	2	1	4	3	2	2			1	
64				3		2	3	2	5	3	8	10	5	7	3	3	2	1	1	2		1		
65				2		3	2	8	2	3	7	7	3	4	1	5	1	1	3	2	2	3		
66		1	1	4		2	2	6	4	3	4	5	2	8		4		1	4	1	2	1	1	
67	1			1	2	1	2	3	5	6	4	4	7	5	2	2	1	1	1	1	3			1
68		1				1	3	4	4	4	2	3	1	7	2	1		2	1	2	2	1	4	1
69						1		3	2	5	5	1	1	2	1	1	1	2	3	3	2	4	1	3
70	3					2		3	2	4	4	1	1	1	2	1	1	2	1	1	4	2	1	2
71		1						3	2	6	5	4	2	1	2		2	1	3	2	4	2	4	3
72		1						3	5	1	2	4	1		1		3	1	2	2	4	4	2	2

TABLE 11 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																						
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
73							1		6	1	4	1		1	2	2	3	5		1	4	4	2	
74						1			2	2	3	3		1		1	4	3		2	2	6	2	
75	1								1	1	3	1	3	2	4	3	2	1			3	4	2	
76	2						1	1	1	1	2	2	2	2	4	3	1				2	2	1	
77							1		1	2		2		1	2							1		
78									1		3	1	2	2		1						1		
79										1	1	2	1	1										
80											1				1									

TABLE 12

Number of Impulsive VLF Hiss Occurrences with AGC > 1.5 mγ
in Invariant Latitude and Magnetic Local Time

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
63																1								
64																1								
65																								
66																				1				
67			1																1					
68																								
69																								
70																								
71																					1		2	
72																	1			1	1			
73															1			1						
74														1										
75													1	1	1	1								
76								1				1		1	1		1							
77										1					1									
78											1	1		1		1								
79										1		1	1	1										
80															1									

TABLE 13

Number of Occurrences of Chorus with AGC > 1.5 mγ in Invariant Latitude and Magnetic Local Time

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																							
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
28													1											
29																								
30																								
31																								
32													1							1				
33																					1			
34													1								1			
35													1							1	1			
36								1																
37																								
38																								
39								1					1								1			
40															2						1			
41									1			1									1			
42															2									
43															1									
44								1					1	1	1									

TABLE 13 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours) 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
45							1	1	1			1							1					
46							1	2	1		1	1		1				2						
47	1						1	1	1		1	1	1		1			1	1					
48								2	3			1	1	1				1	1					
49							1	1	4	1		3	1	3	1				1					
50					1		1		3			1	1	2	1			1	1					
51							1	1	4	2		1	1	2			1	1						
52							3	2	5	1	1	2	2	2			3	1						
53		1					3	4	9	4	1	1	3	1		1	3	1					1	
54							2	6	9	5	2	1	6	1		2	3	3	4	1			1	
55							4	8	12	6	3	2	7	2		2	3	5	2	1				
56		2		1		1	6	11	12	8	3	1	6	2	1	3	3	6	3	1				1
57		2		2		2	6	10	10	8	6	4	10	4		2	5	4	5	1				2
58		2		2	3	3	8	8	18	14	6	3	6	7	2	4	7	4	5	2			1	2
59				2	1	6	11	13	16	19	12	6	9	8	4	3	9	8	5	1		1		3
60		1	1	1	3	5	5	12	13	17	14	6	6	9	5	3	6	11	5	1			1	3
61		2	2	4	5	6	11	14	17	20	14	9	6	11	5	2	4	9	6				1	3
62		1	2	1	4	4	13	15	15	19	12	14	7	10	3	2	4	10	5	1				3
63		1	6	2	3	2	15	16	11	19	13	15	8	13	3		3	3	7					2

TABLE 13 (CONT'D.)

Invariant Latitude (Degrees)	Magnetic Local Time (Hours)																						
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
64	1	1	3	1	1	3	12	12	15	20	13	20	11	13	5	6	6	3	1					1
65			1	2	1	5	10	18	15	22	18	20	11	14	2	4		4	1	1	1	1		
66			1	2	1	5	10	19	14	25	16	18	14	16	3	6	2	3			1			
67				1	2	4	7	14	15	22	15	15	13	10	4	4	2	1						
68		1				3	9	15	15	20	12	8	6	13	6	4	2	1	1	1				1
69						1	5	13	16	17	13	10	9	7	5	2								1
70	1						2	13	18	15	16	7	6	3	3	2								1
71							3	11	11	11	13	10	7	2	2	1	2							1
72								9	13	10	14	9	7	4			2				1	2		1
73							2	4	15	9	10	10	8	7	1		1				1	3		
74							1	2	7	7	5	8	11	5	1							2	1	
75								2	7	9	3	5	6	1										
76								1	4	8	6	7.	3			1						1		
77									2	4	2	4	1											
78									1	2	2	1												
79										1	2	3	1											
80											2													
81												1												

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FIGURE CAPTIONS

Figure 1 A contour plot of 8 kHz hiss observed at three Greenland ground stations in 1964 (after Jørgensen [1966a]).

Figure 2 Frequency of occurrence of VLF hiss observed with the Injun 3 satellite (after Gurnett [1966]).

Figure 3 Examples of steady VLF hiss observed with the Injun 3 satellite.

Figure 4 Examples of impulsive VLF hiss observed with the Injun 3 satellite.

Figure 5 Examples of ELF hiss observed with the Injun 3 satellite.

Figure 6 Examples of LHRH observed with the Injun 3 satellite.

Figure 7 Examples of chorus observed with the Injun 3 satellite.

Figure 8 Examples of isolated discrete emissions observed with the Injun 3 satellite.

Figure 9 Examples of a combination, a periodic emission, and a quasi-periodic emission observed with the Injun 3 satellite.

Figure 21. Orbit in invariant latitude, magnetic local time space for the revolution 70 pass.

Figure 22. Spectrogram, orbital parameters and wide band signal strength (AGC) for the first half of the revolution 70 pass. (Note quasi-logarithmic AGC scale.)

Figure 23 Spectrogram, orbital parameters and wide band signal strength (AGC) for the last half of the revolution 70 pass. (Note quasi-logarithmic AGC scale.)

Figure 24 Orbit in invariant latitude, magnetic local time space for the revolution 71 pass.

Figure 25 Spectrogram, orbital parameters and wide band signal strength (AGC) for the first half of the revolution 71 pass. (Note quasi-logarithmic AGC scale.)

Figure 26 Spectrogram, orbital parameters and wide band signal strength (AGC) for the last half of the revolution 71 pass. (Note quasi-logarithmic AGC scale.)

Figure 27 Orbit in invariant latitude, magnetic local time space for the revolution 503 pass.

Figure 28 Spectrogram, orbital parameters and wide band signal strength (AGC) for the revolution 503 pass. (Note quasi-logarithmic AGC scale.)

Figure 33 (Cont'd.) 68°S, after Laaspere, et al. [1964a]) and the dependence of the occurrence of chorus present in Injun 3 data when the AGC was above 1.5 milligamma at 67° invariant latitude. (Note the quasi-logarithmic scale.)

G67-576

CONTOUR MAP OF THE 8KHz HISS ZONE
IN 1964 OBSERVED WITH THREE GROUND STATIONS
(AFTER JØRGENSEN, 1966a)
PERCENTAGE OCCURRENCE GREATER THAN 10^{-15} WATTS-m^{-2} H_z^{-1}

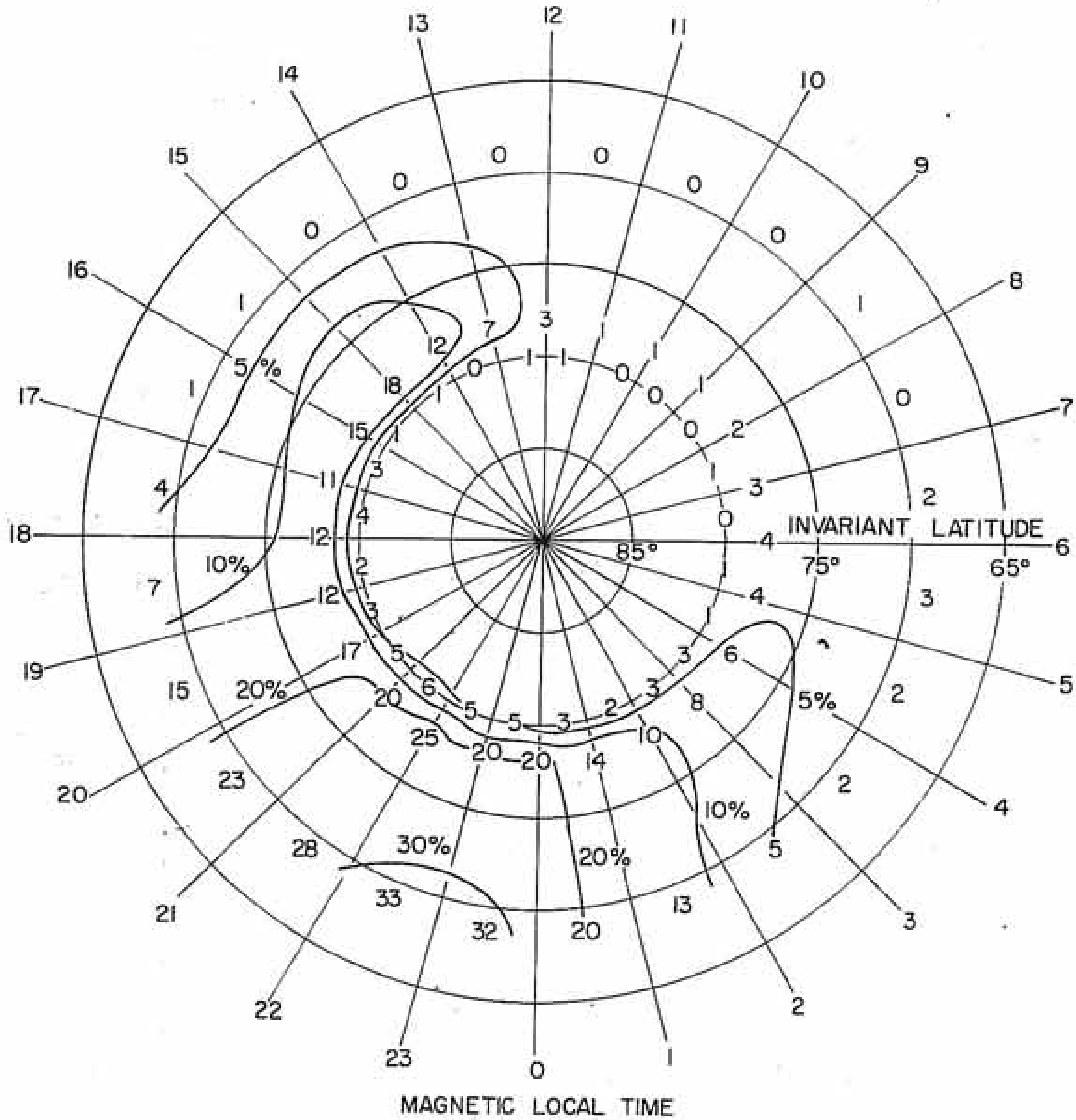


FIGURE 1

G 66-199

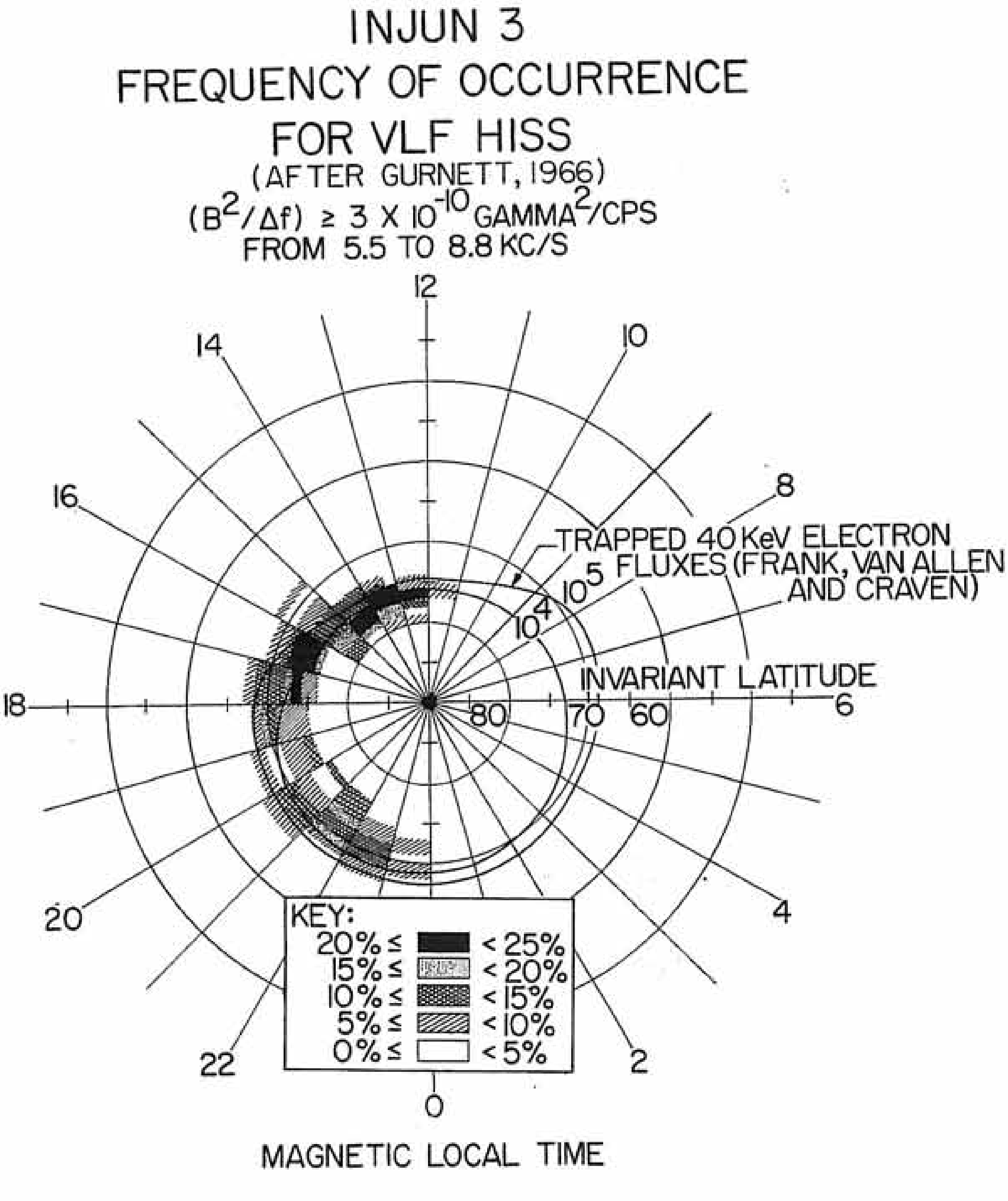


FIGURE 2

G 67-480

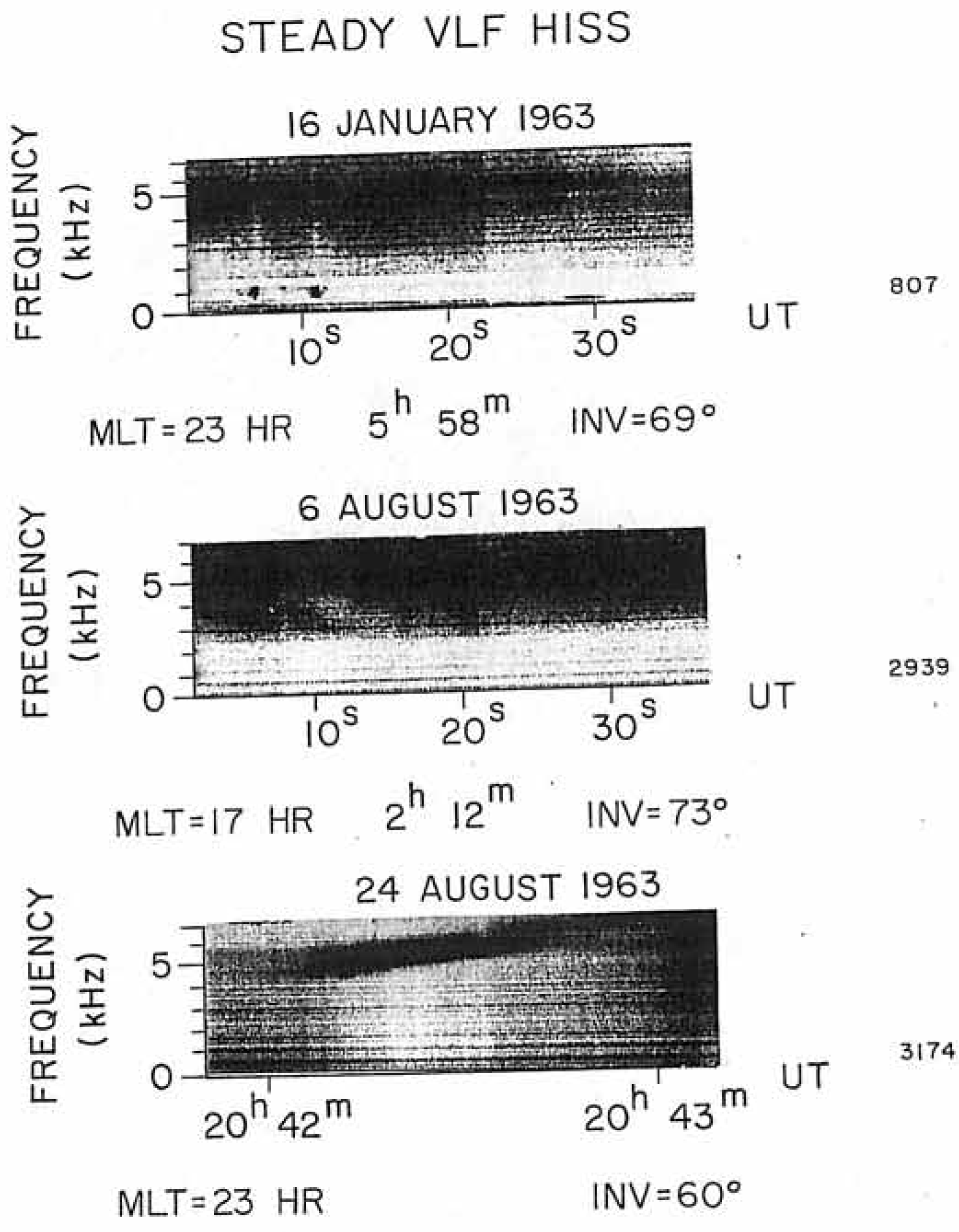


FIGURE 3

G 67-472

IMPULSIVE VLF HISS

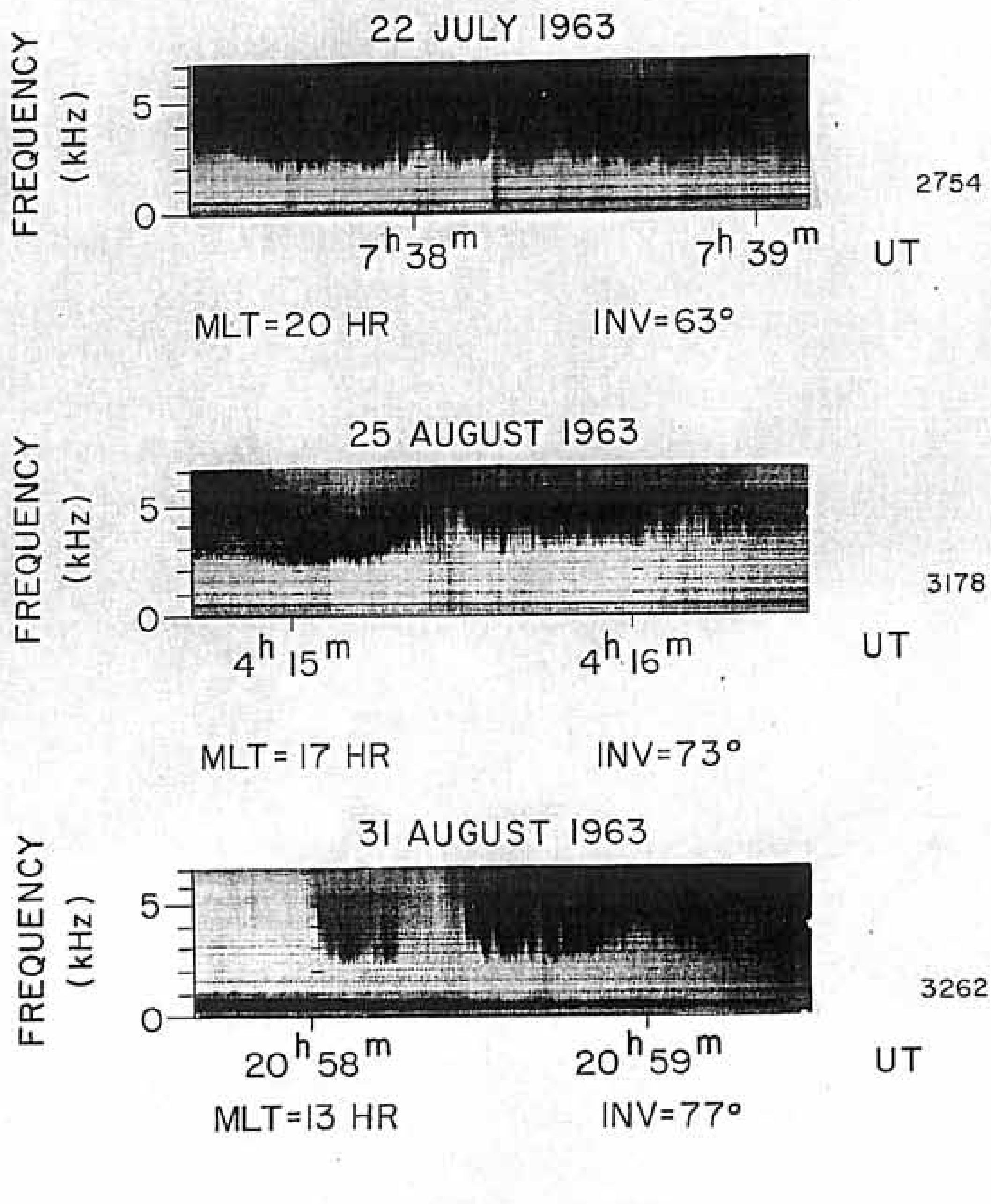


FIGURE 4

G67-459

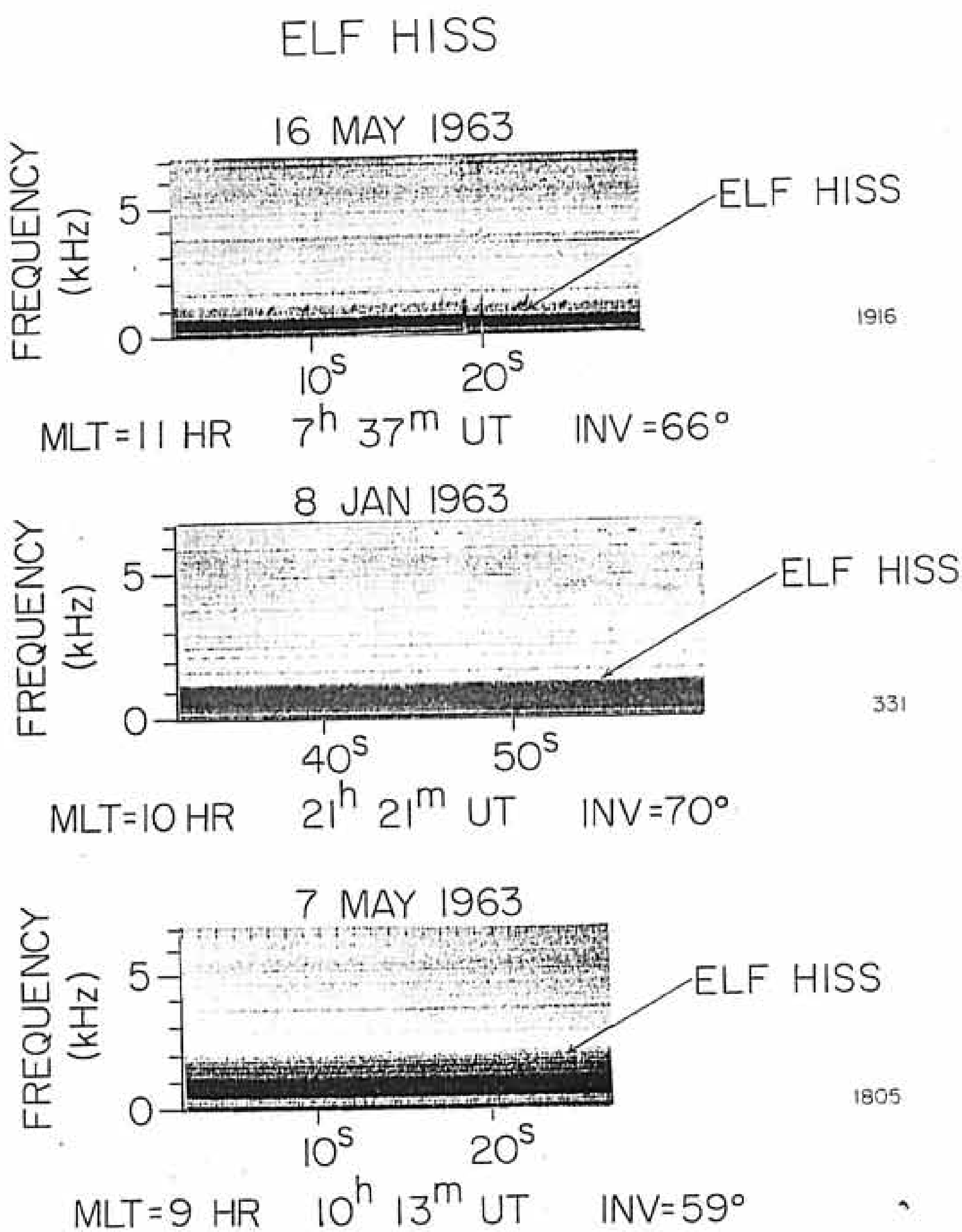


FIGURE 5

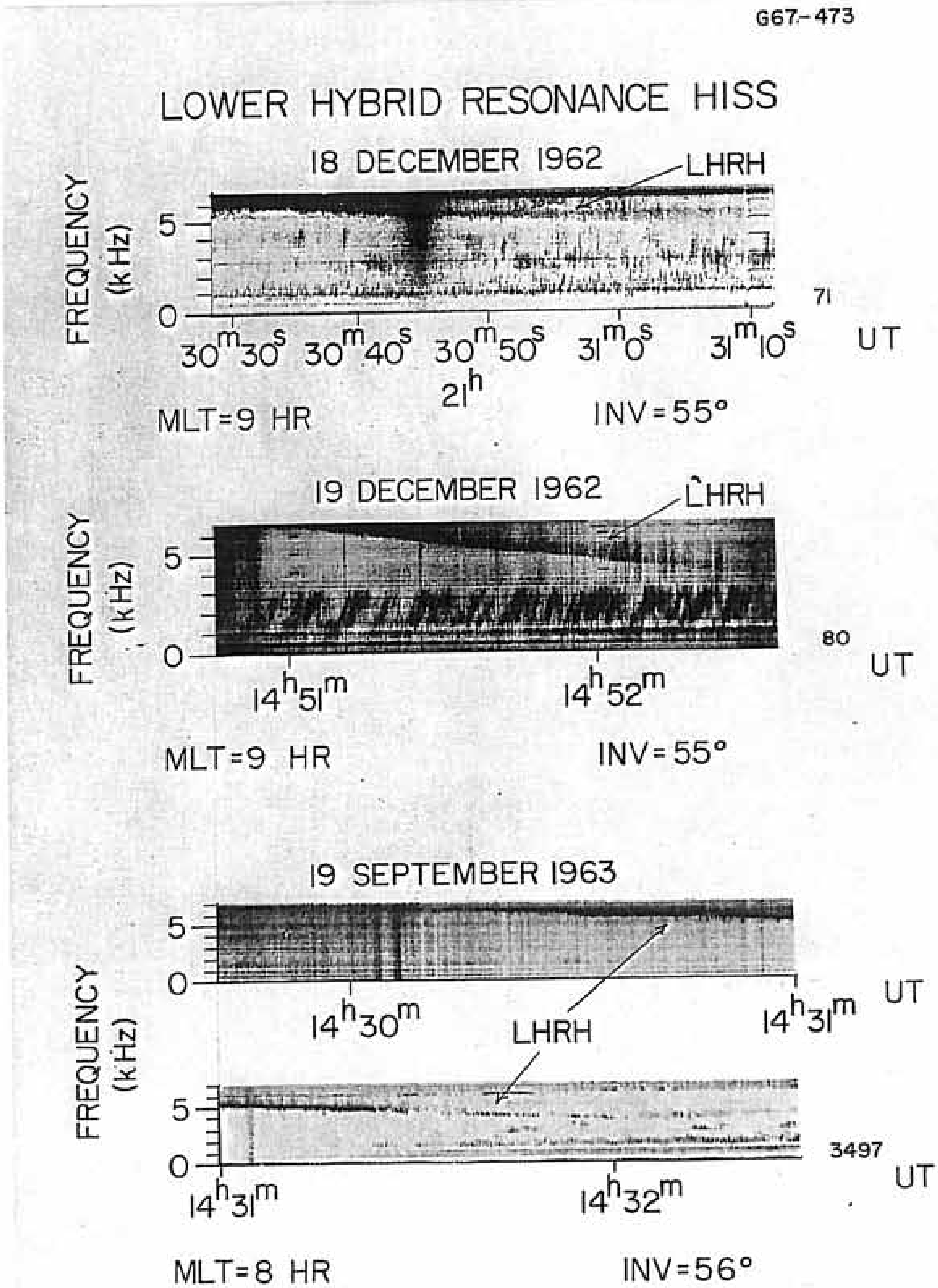

G67-473
LOWER HYBRID RESONANCE HISS
18 DECEMBER 1962
LHRH
FREQUENCY (kHz)
5
0
71
30m30s 30m40s 30m50s 31m0s 31m10s
21h
UT
MLT=9 HR
INV=55°
19 DECEMBER 1962
LHRH
FREQUENCY (kHz)
5
0
80
14h51m
14h52m
UT
MLT=9 HR
INV=55°
19 SEPTEMBER 1963
5
0
14h30m
14h31m
UT
LHRH
FREQUENCY (kHz)
5
0
3497
14h31m
14h32m
UT
MLT=8 HR
INV=56°

FIGURE 6

G67-460

CHORUS

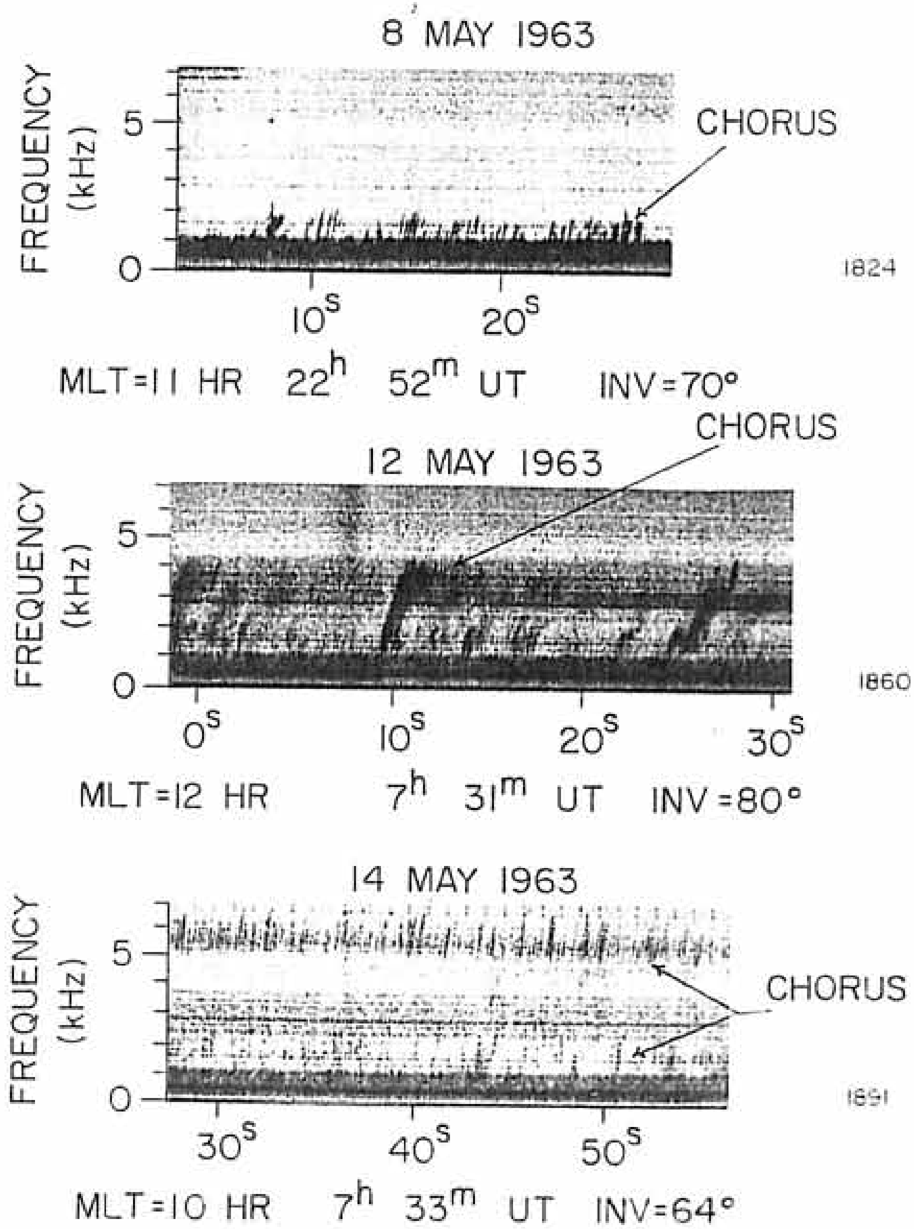


FIGURE 7

G67-471

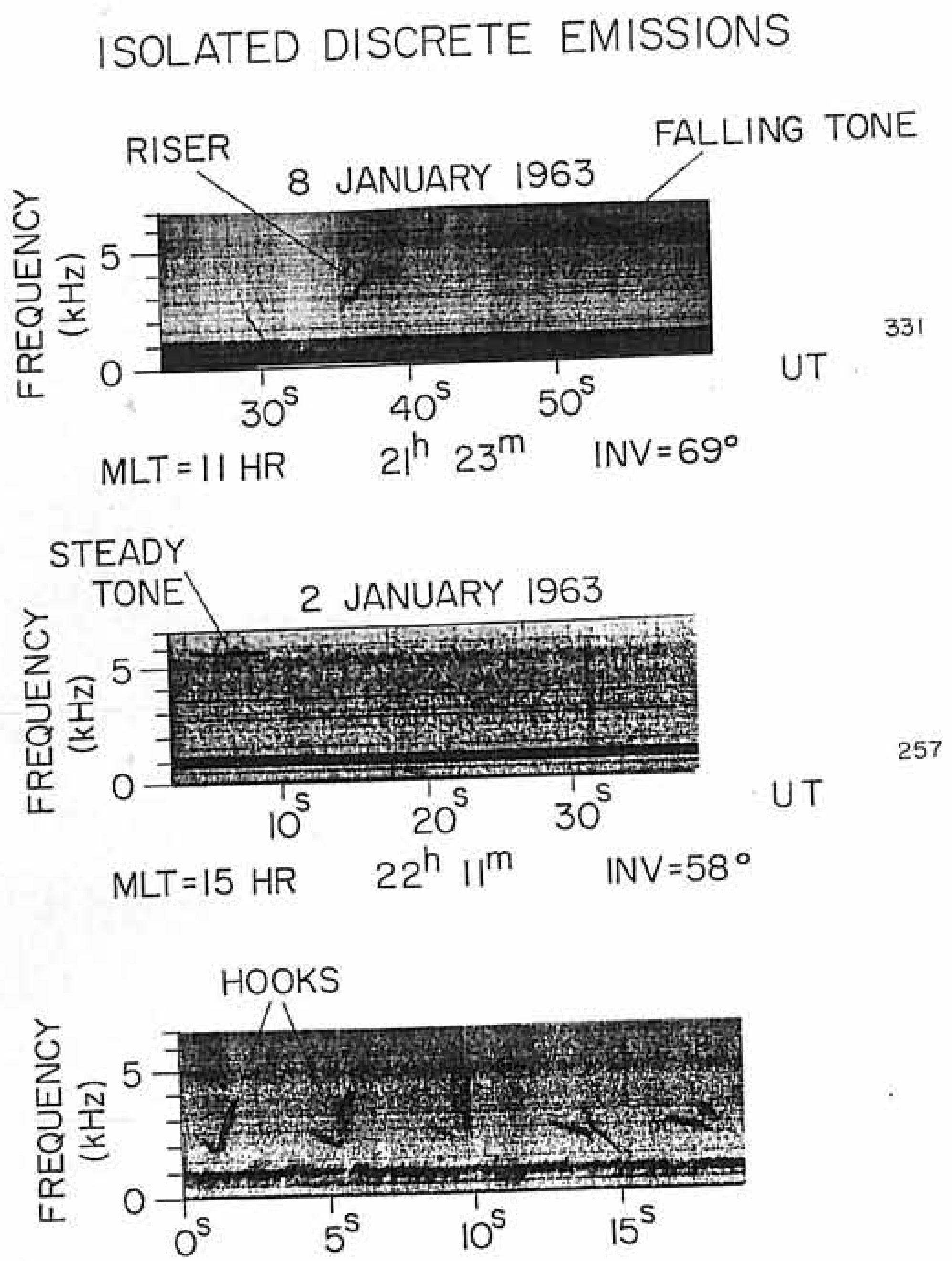


FIGURE 8

G67-469

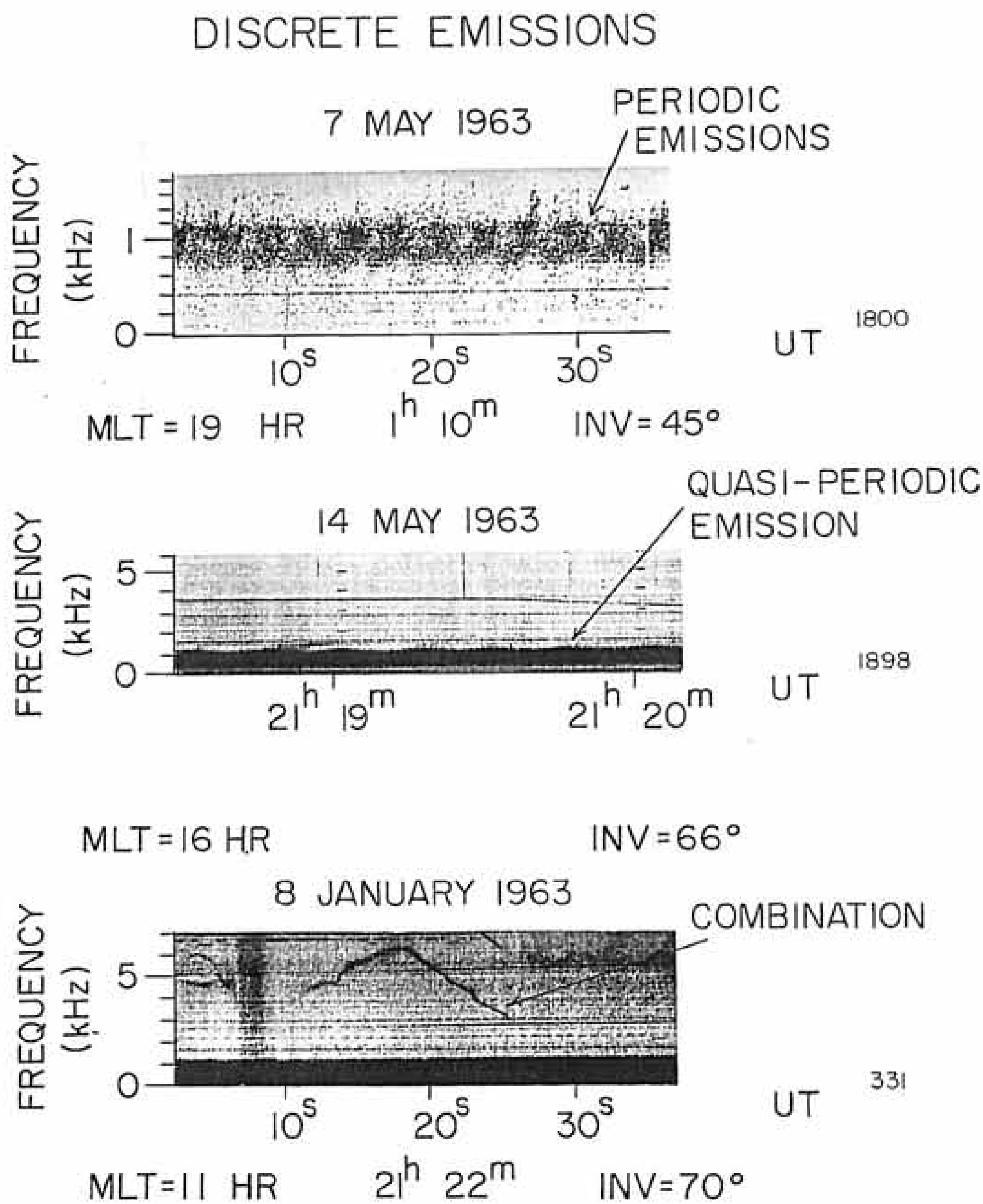


FIGURE 9

G67-470

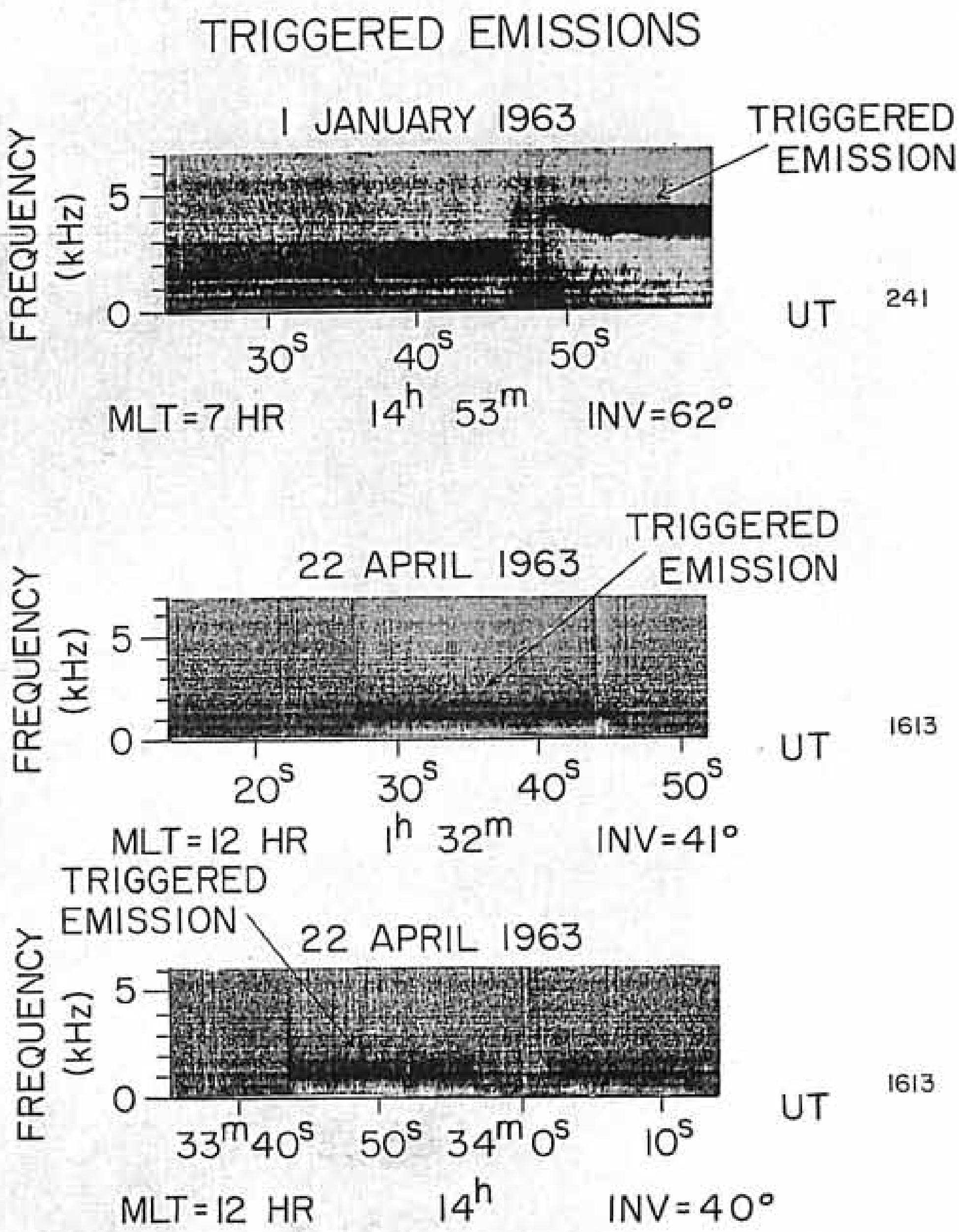


FIGURE 10

G67-462

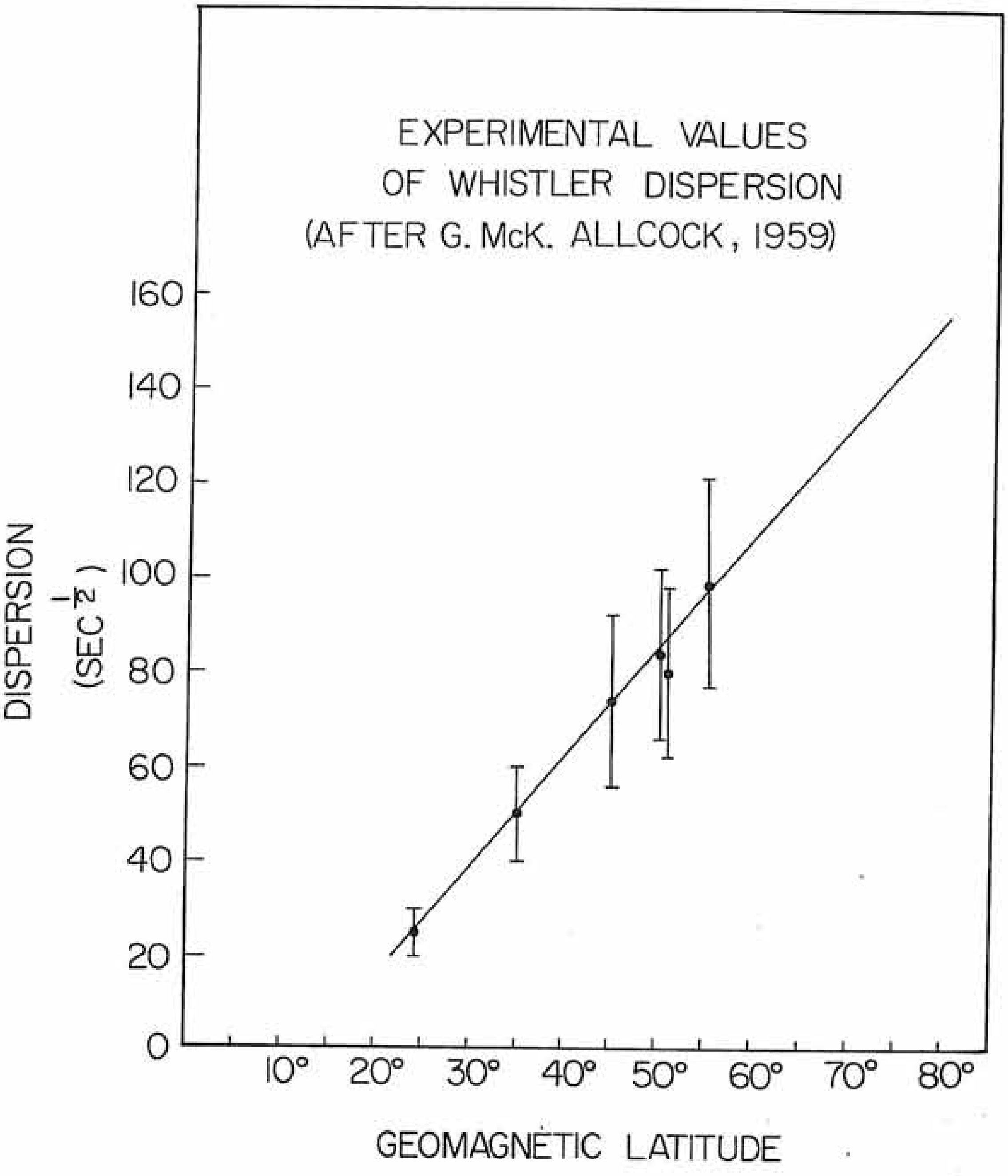


FIGURE 11

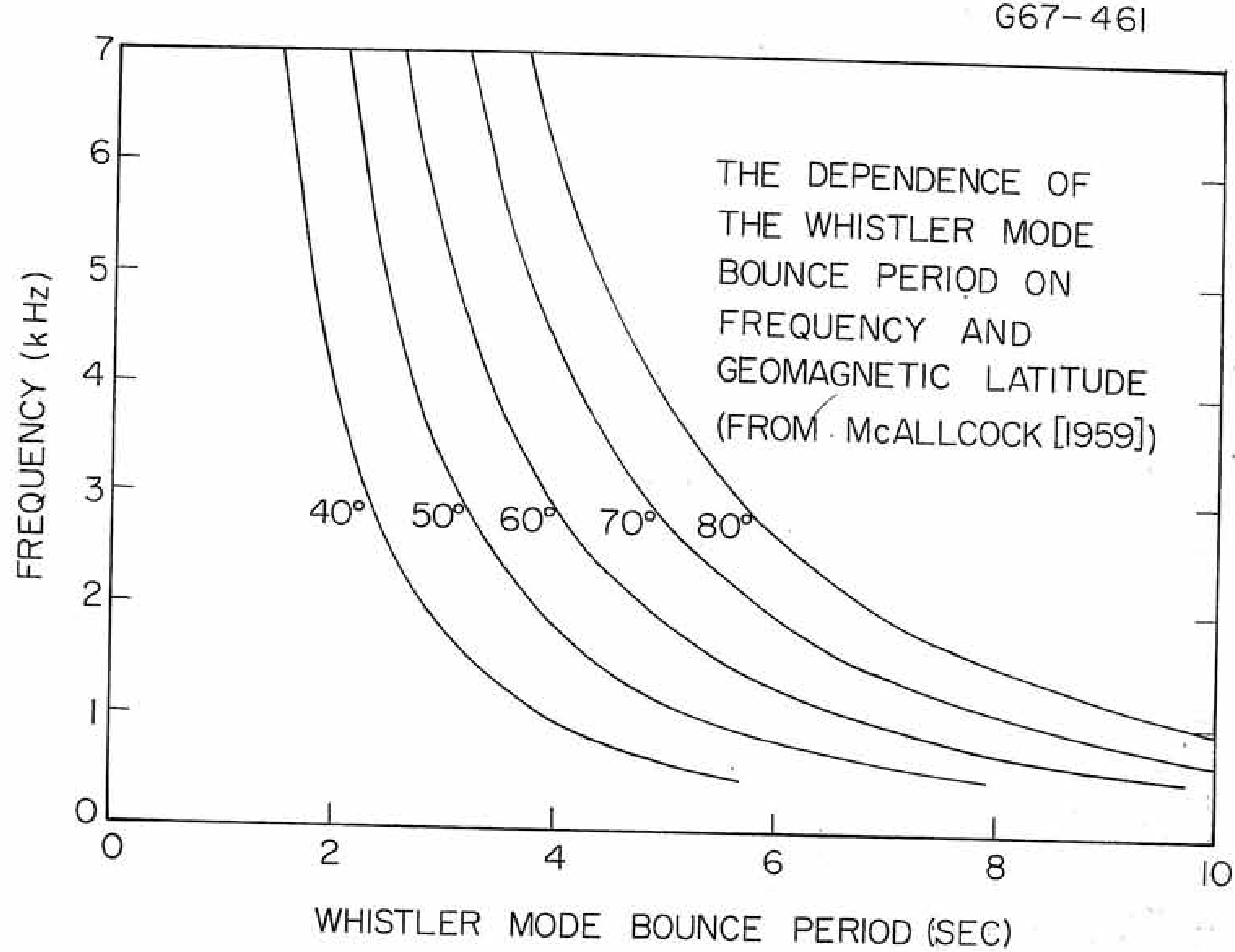

G67-461
THE DEPENDENCE OF THE WHISTLER MODE BOUNCE PERIOD ON FREQUENCY AND GEOMAGNETIC LATITUDE (FROM McALLCOCK [1959])
40°
50°
60°
70°
80°
FREQUENCY (k Hz)
WHISTLER MODE BOUNCE PERIOD (SEC)
0
1
2
3
4
5
6
7
0
2
4
6
8
10

FIGURE 12

G 67-389

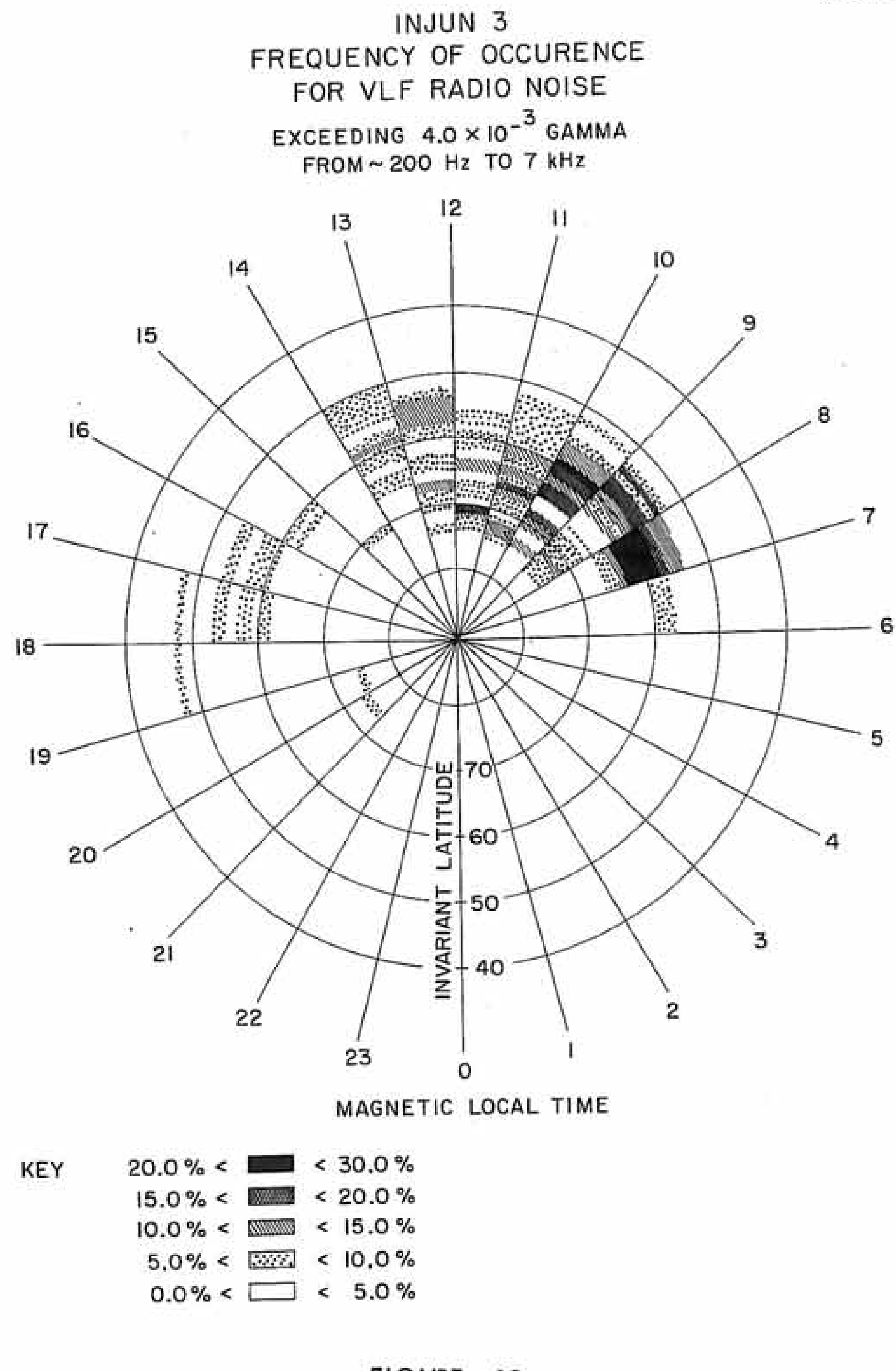


FIGURE 13

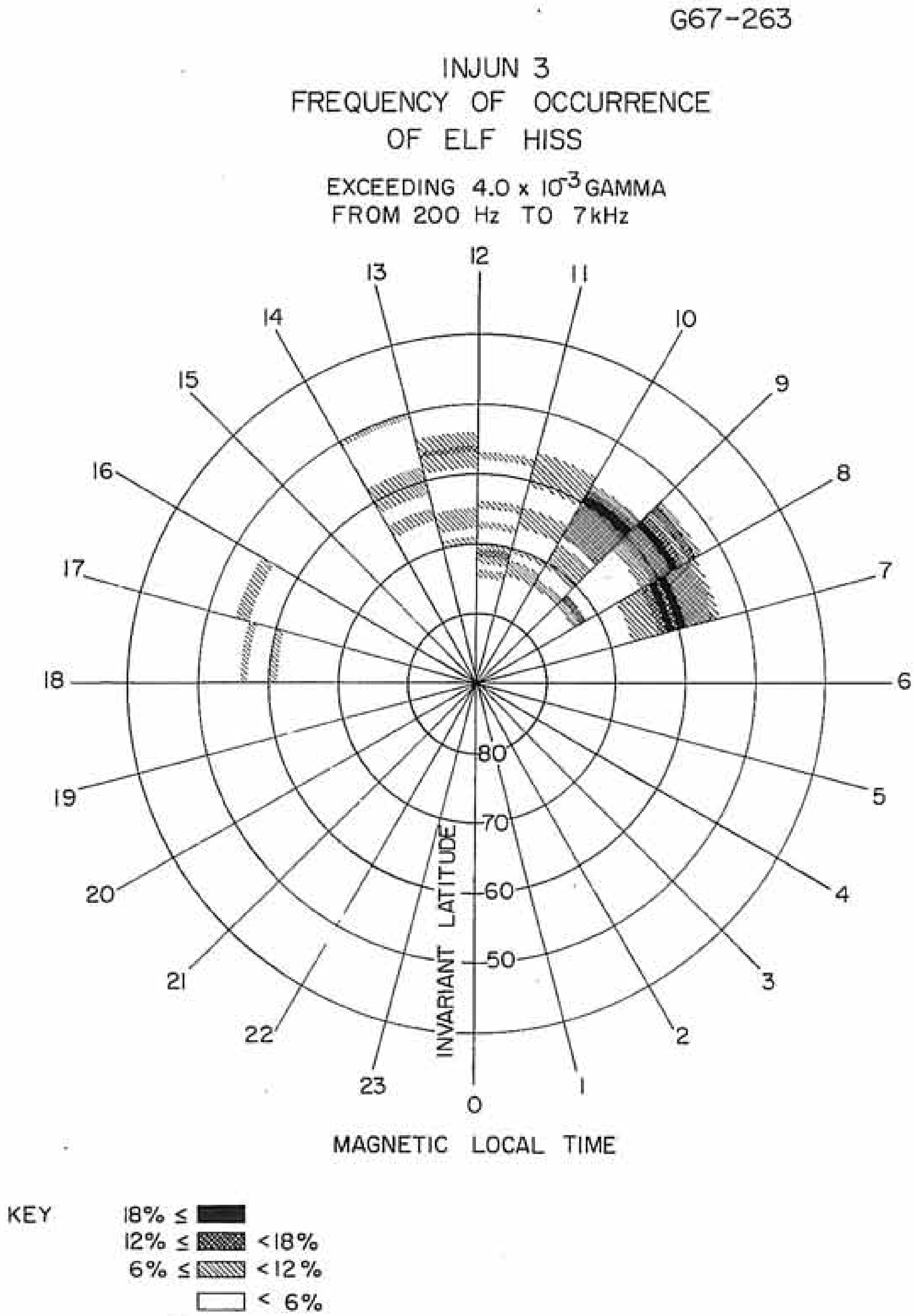

G67-263
INJUN 3
FREQUENCY OF OCCURRENCE
OF ELF HISS
EXCEEDING 4.0 x 10^{-3} GAMMA
FROM 200 Hz TO 7kHz
12
13
11
14
10
15
9
16
8
17
7
18
6
80
19
5
70
INVARIANT LATITUDE
20
60
4
50
21
3
22
2
23
1
0
MAGNETIC LOCAL TIME
KEY
18% ≤
12% ≤ <18%
6% ≤ <12%
< 6%

FIGURE 14

G67-262

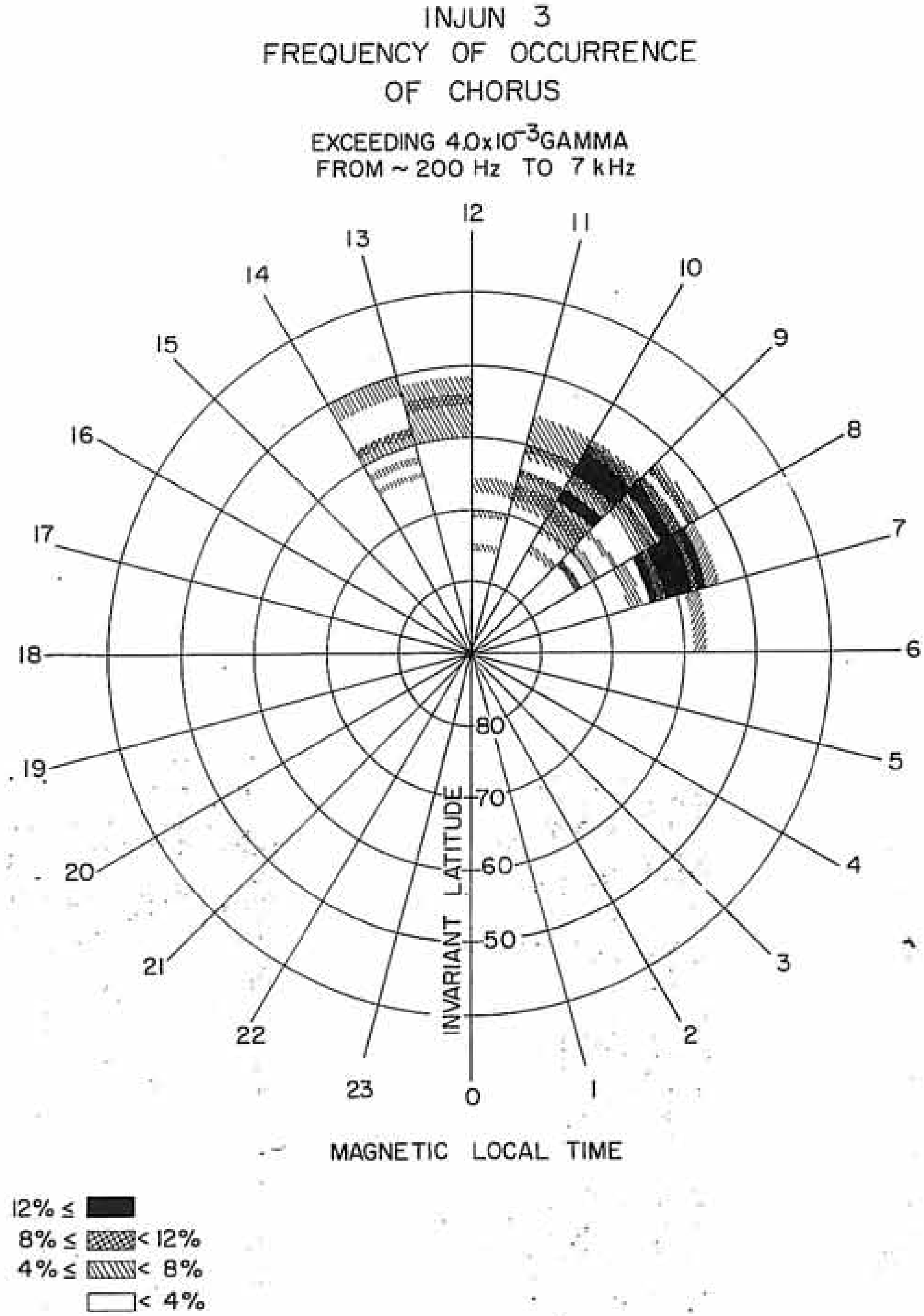


FIGURE 15

G67-264

INJUN 3
FREQUENCY OF OCCURRENCE
OF VLF HISS

EXCEEDING 4.0×10^{-3} GAMMA
FROM ~ 200 Hz TO 7 kHz

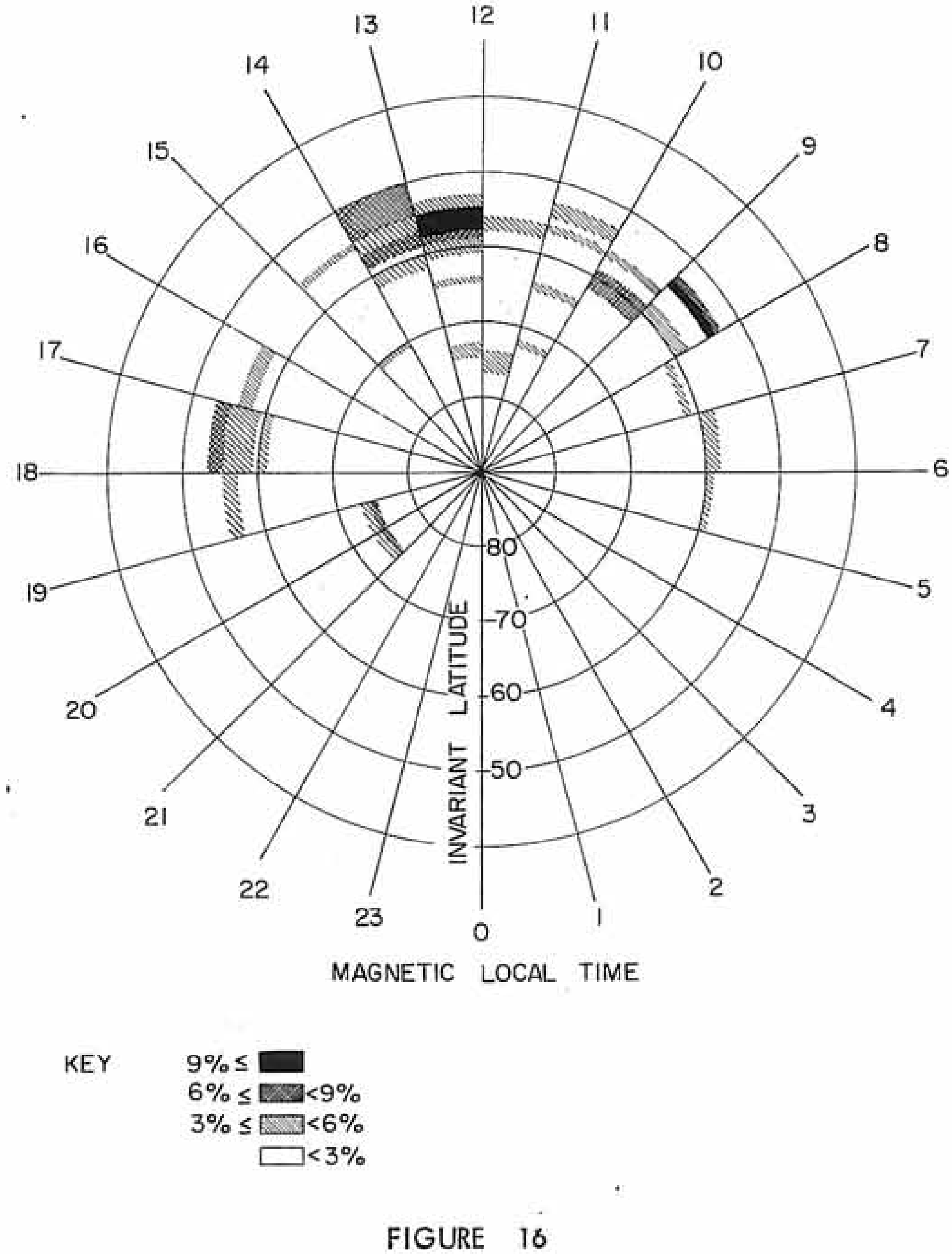


FIGURE 16

G67-388

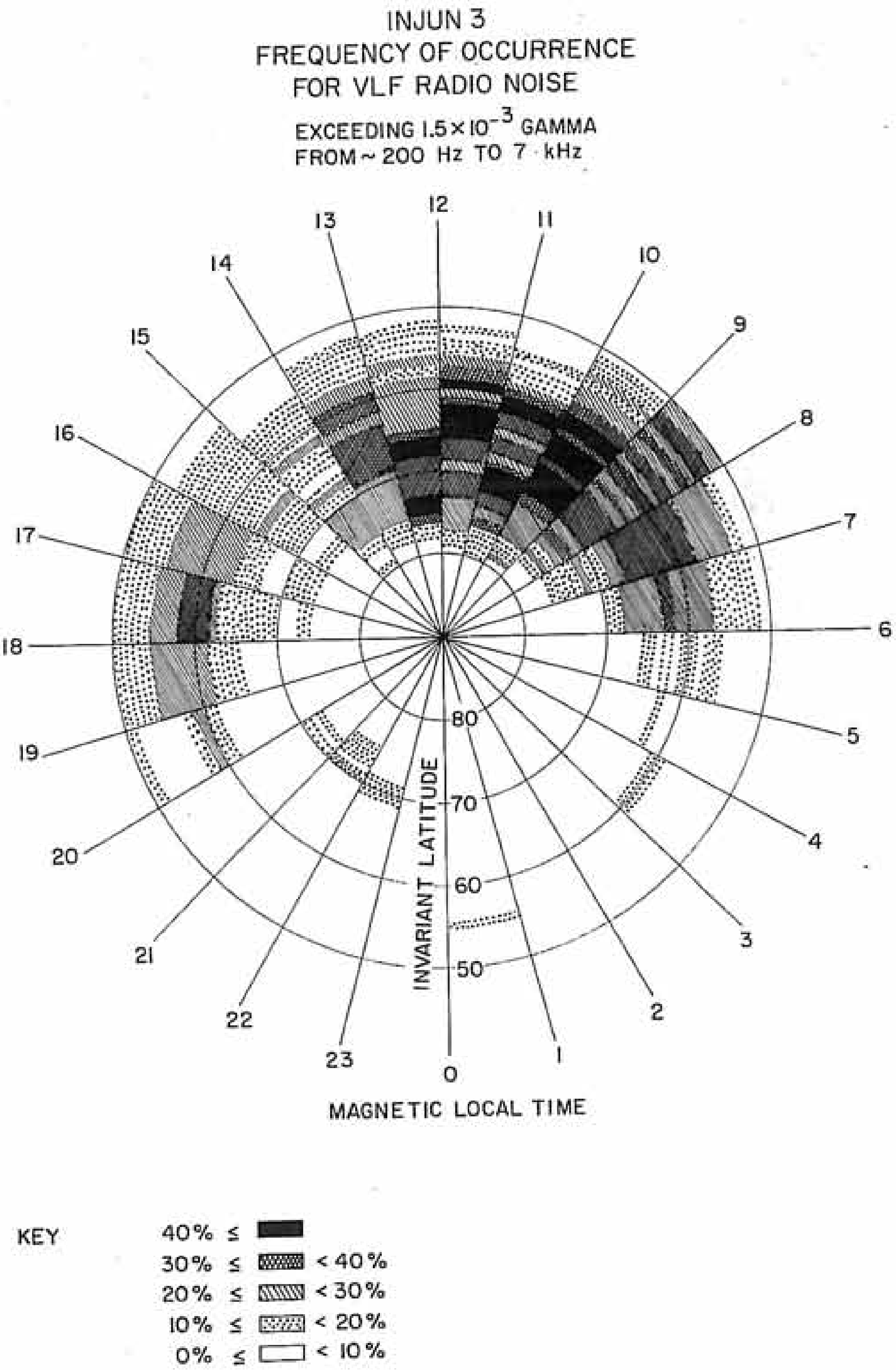


FIGURE 17

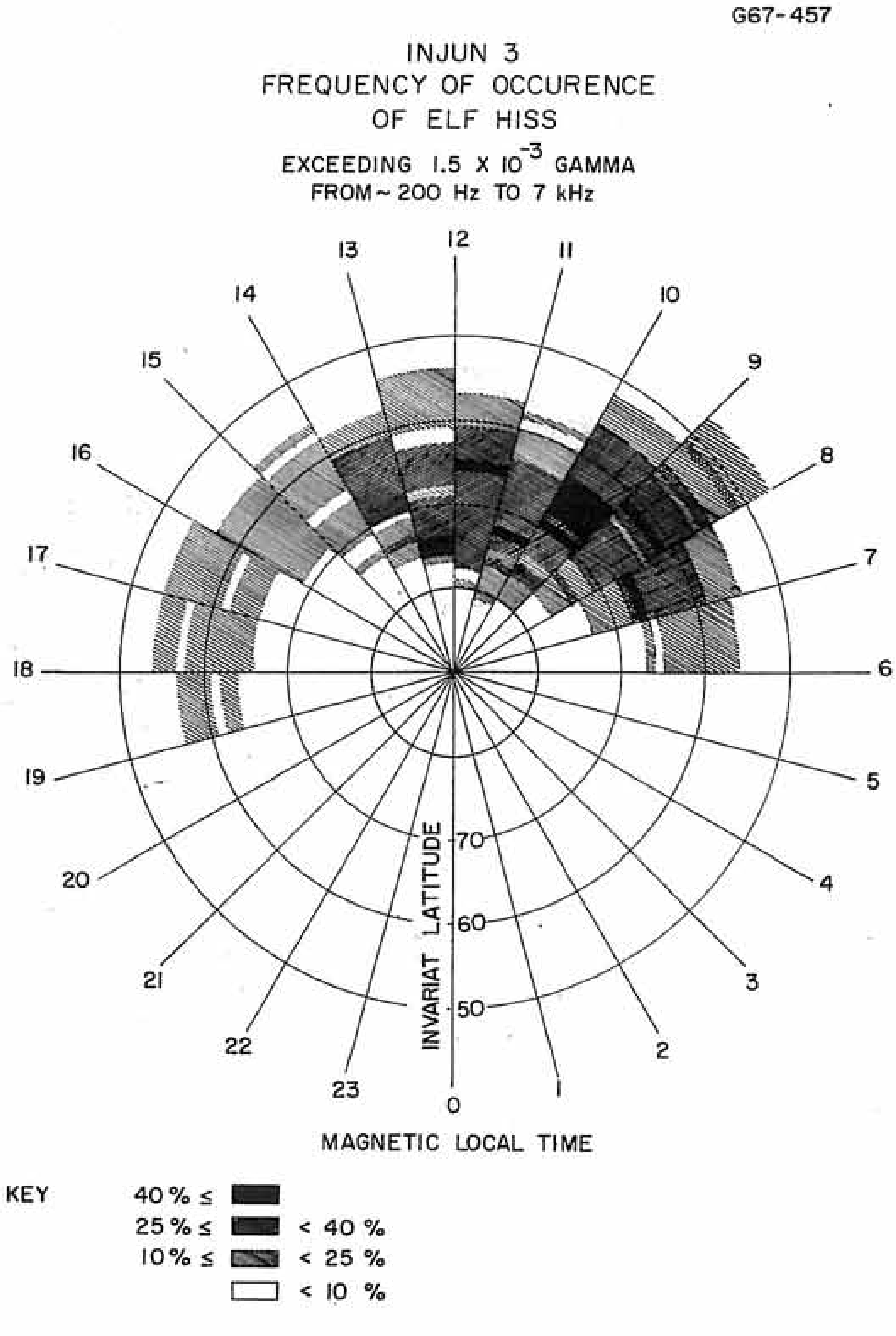

G67-457
INJUN 3
FREQUENCY OF OCCURENCE
OF ELF HISS
EXCEEDING 1.5 X 10^-3 GAMMA
FROM ~ 200 Hz TO 7 kHz
12
13
11
14
10
15
9
16
8
17
7
18
6
19
5
20
4
21
3
22
2
23
1
0
70
60
50
INVARIAT LATITUDE
MAGNETIC LOCAL TIME
KEY
40% ≤
25% ≤ < 40 %
10% ≤ < 25 %
< 10 %

FIGURE 18

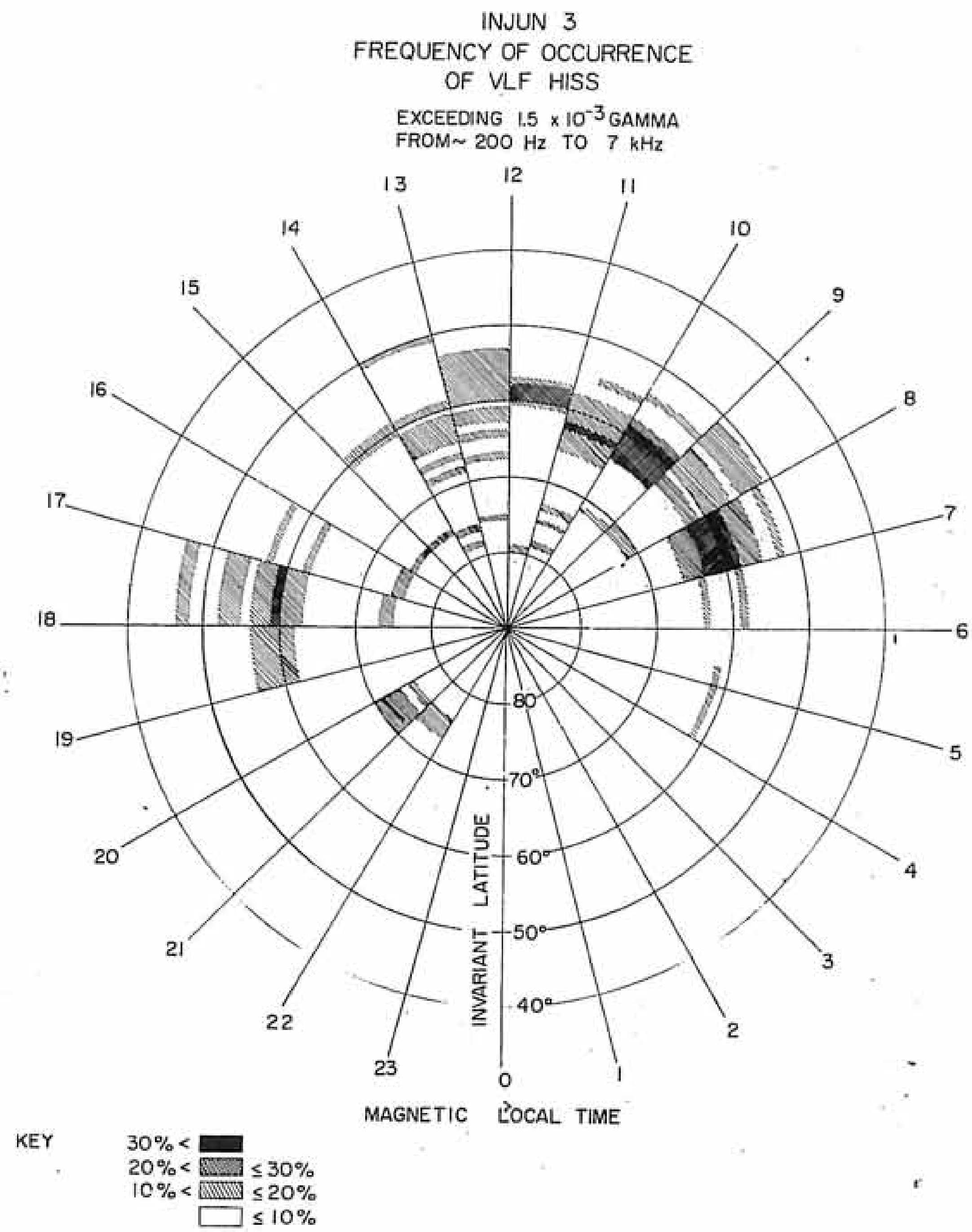

INJUN 3
FREQUENCY OF OCCURRENCE
OF VLF HISS
EXCEEDING 1.5 x 10^-3 GAMMA
FROM ~ 200 Hz TO 7 kHz
12
11
10
9
8
7
6
5
4
3
2
1
0
23
22
21
20
19
18
17
16
15
14
13
80°
70°
60°
50°
40°
INVARIANT LATITUDE
MAGNETIC LOCAL TIME
KEY
30% <
20% < ≤ 30%
10% < ≤ 20%
≤ 10%

FIGURE 19

G 67-456

INJUN 3
FREQUENCY OF OCCURRENCE
OF CHORUS

EXCEEDING 1.5×10^{-3} GAMMA
FROM ~ 200 Hz TO 7 kHz

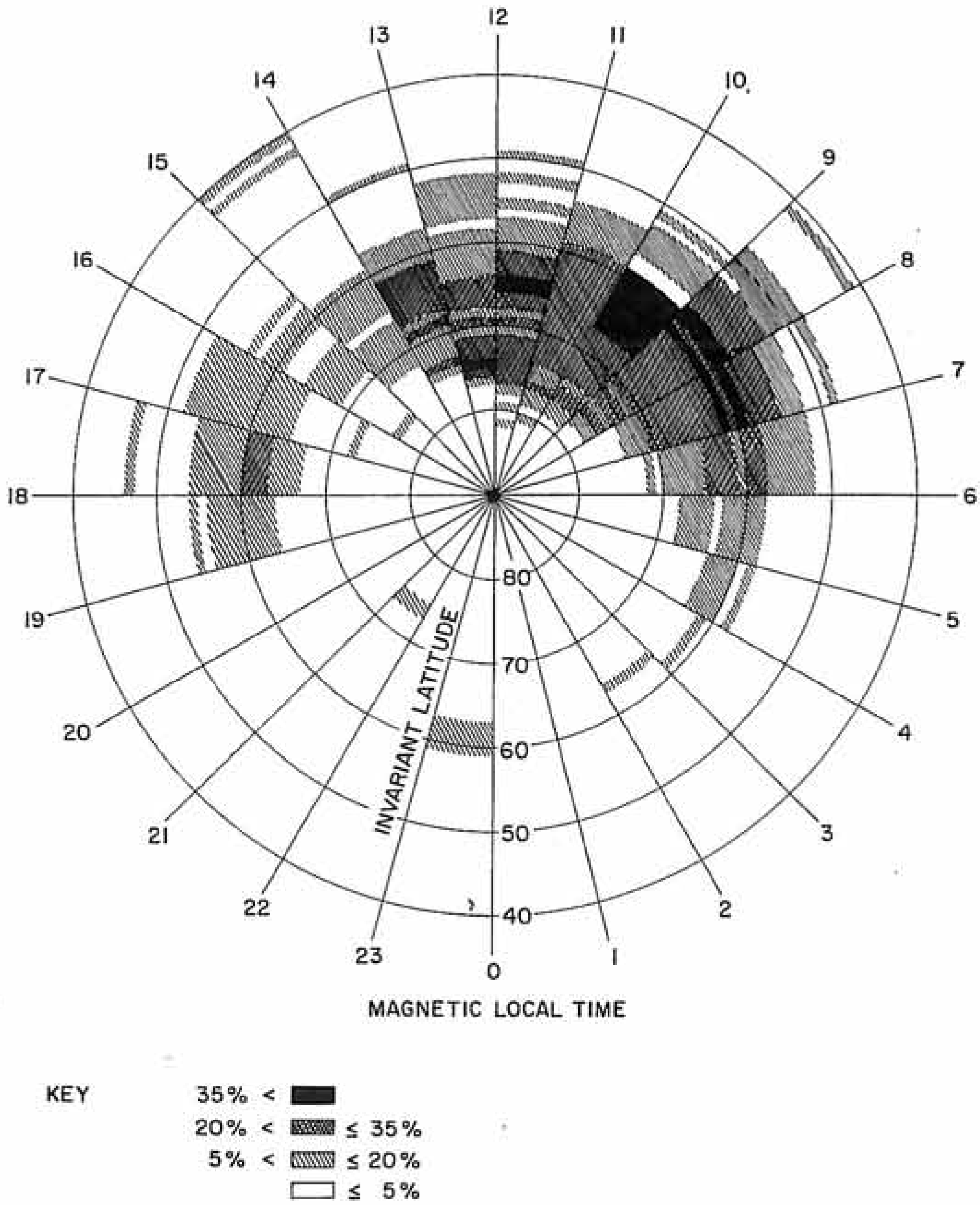


FIGURE 20

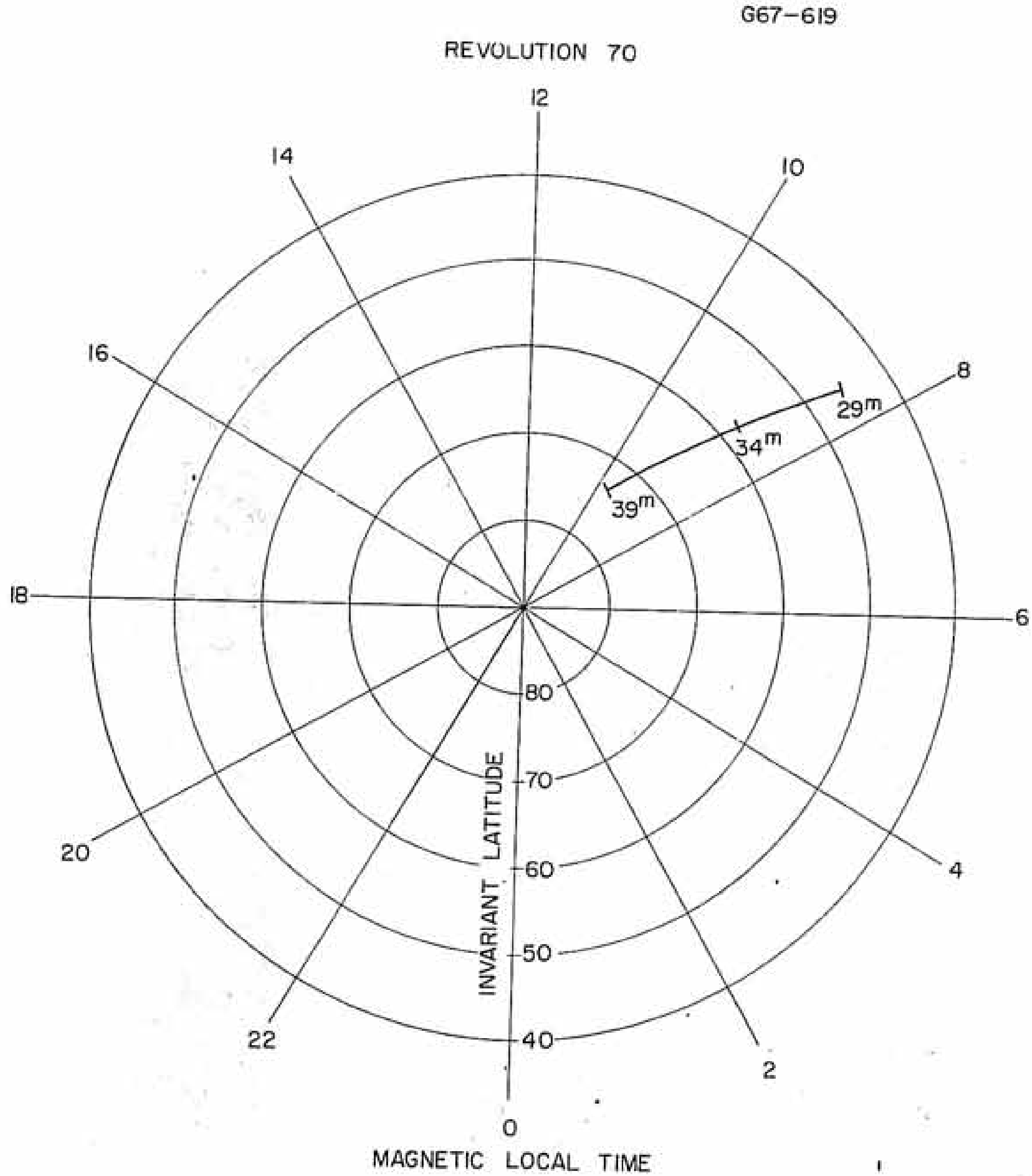

G67–619
REVOLUTION 70
12
14
10
16
8
29m
34m
39m
18
6
80
70
60
50
40
INVARIANT LATITUDE
20
4
22
2
0
MAGNETIC LOCAL TIME

FIGURE 21

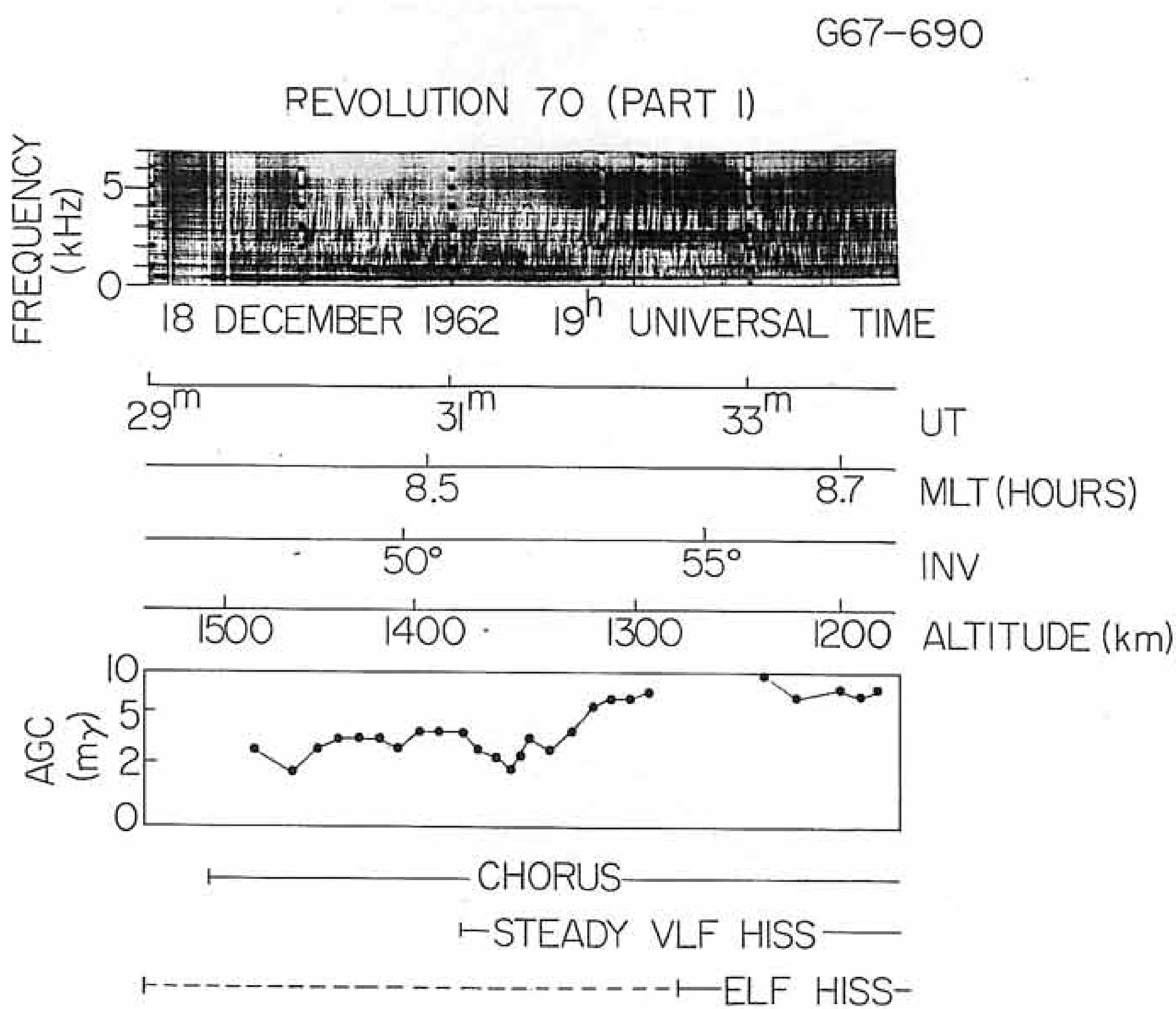
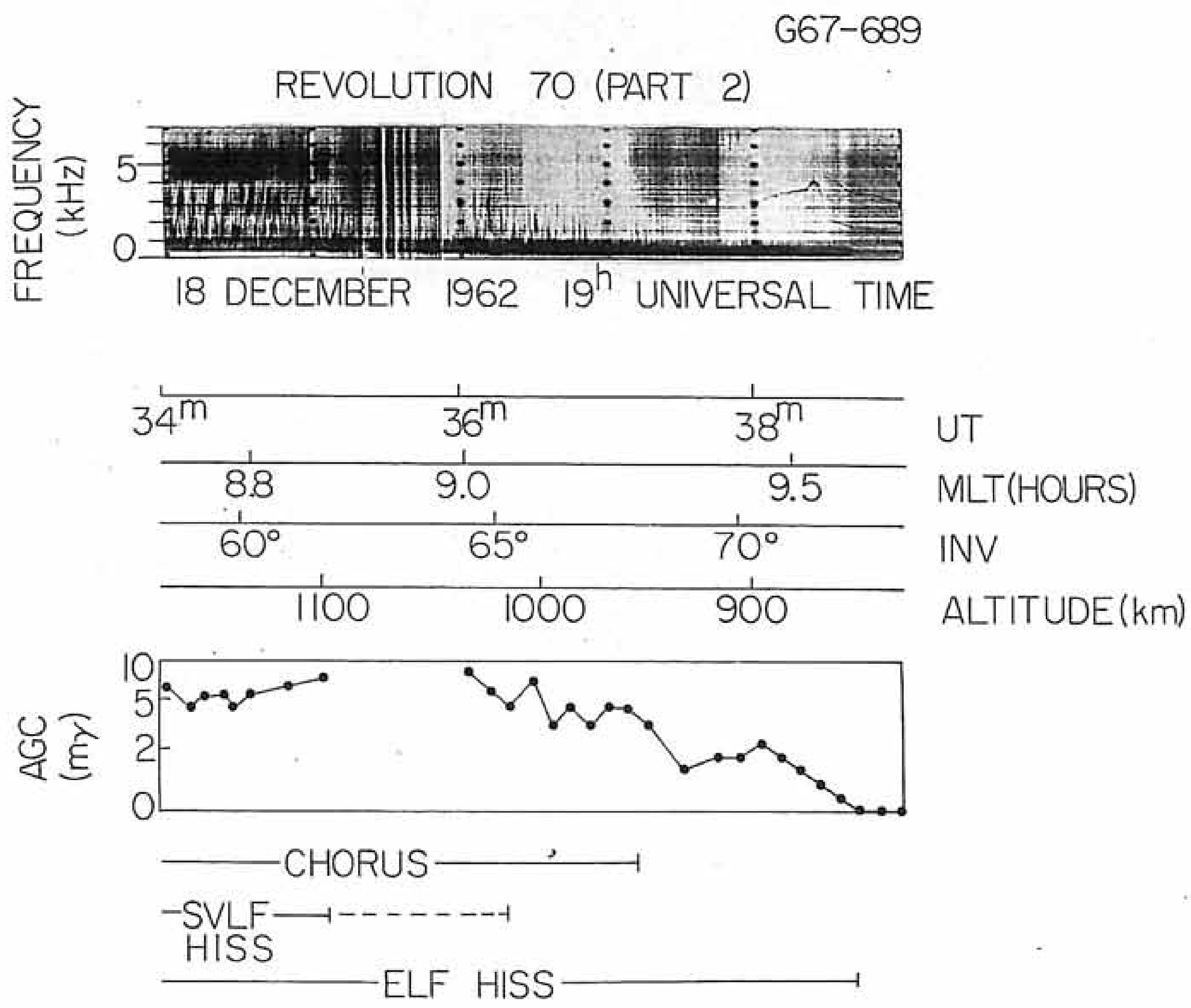

G67-690
REVOLUTION 70 (PART I)
FREQUENCY (kHz)
5
0
18 DECEMBER 1962
19h UNIVERSAL TIME
29m
31m
33m
UT
8.5
8.7
MLT (HOURS)
50°
55°
INV
1500
1400
1300
1200
ALTITUDE (km)
AGC (mγ)
10
5
2
0
CHORUS
STEADY VLF HISS
ELF HISS

FIGURE 22



G67-689
REVOLUTION 70 (PART 2)
FREQUENCY (kHz)
5
0
18 DECEMBER 1962 19h UNIVERSAL TIME
34m
36m
38m
UT
8.8
9.0
9.5
MLT (HOURS)
60°
65°
70°
INV
1100
1000
900
ALTITUDE (km)
AGC (mγ)
10
5
2
0
CHORUS
SVLF HISS
ELF HISS

FIGURE 23

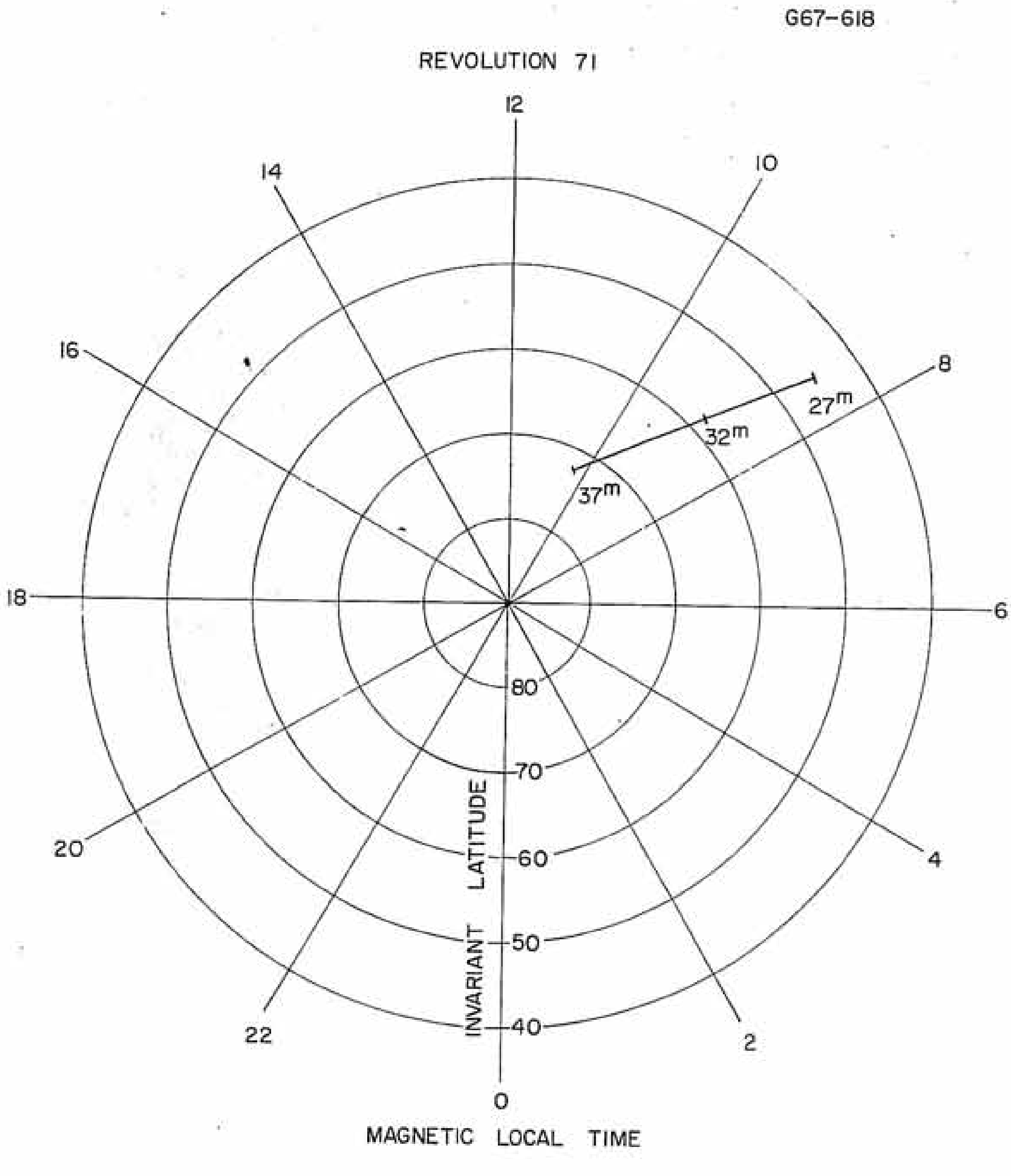

G67-618
REVOLUTION 71
12
14
10
16
8
27m
32m
37m
18
6
80
70
60
50
40
INVARIANT LATITUDE
20
4
22
2
0
MAGNETIC LOCAL TIME

FIGURE 24

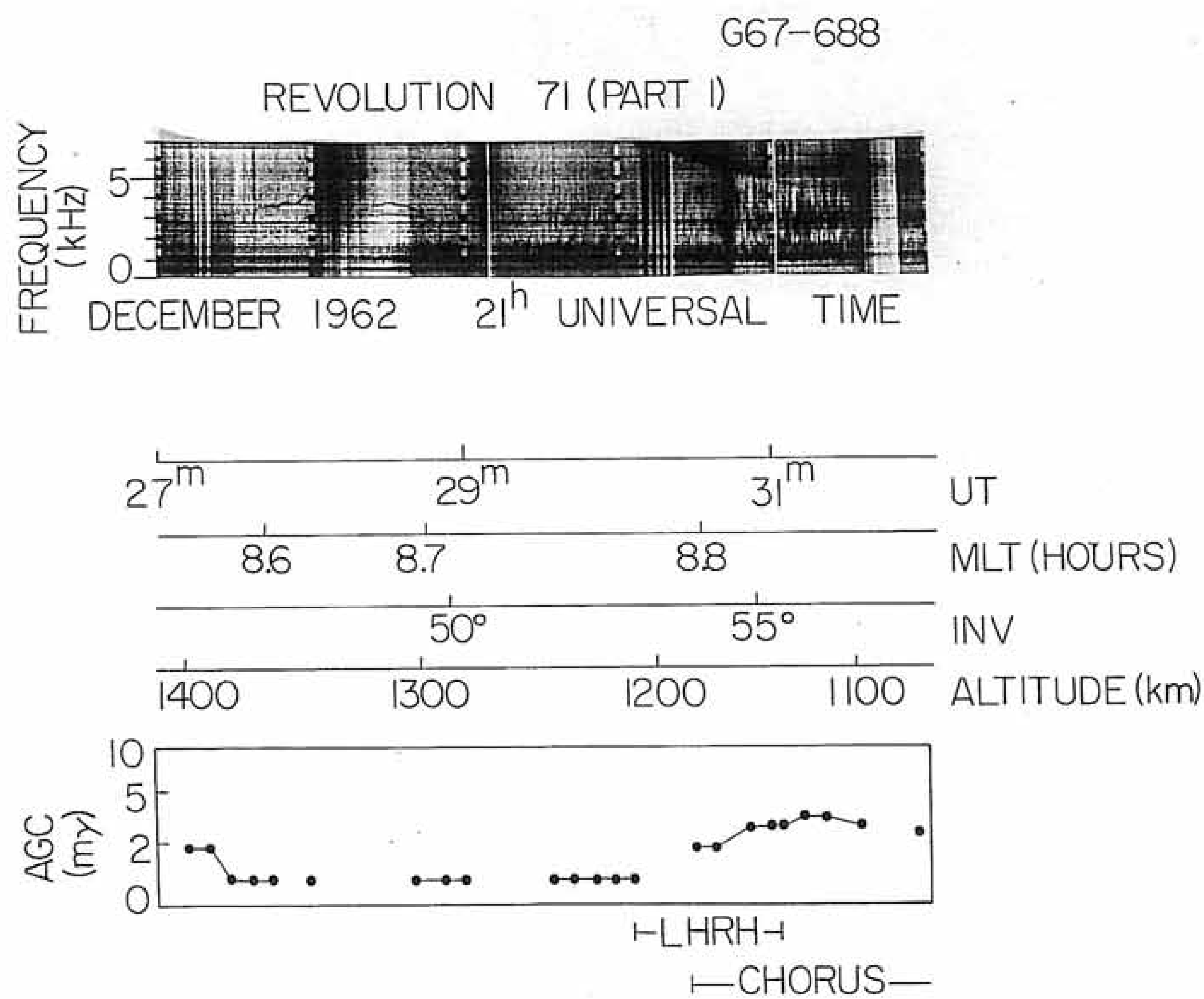
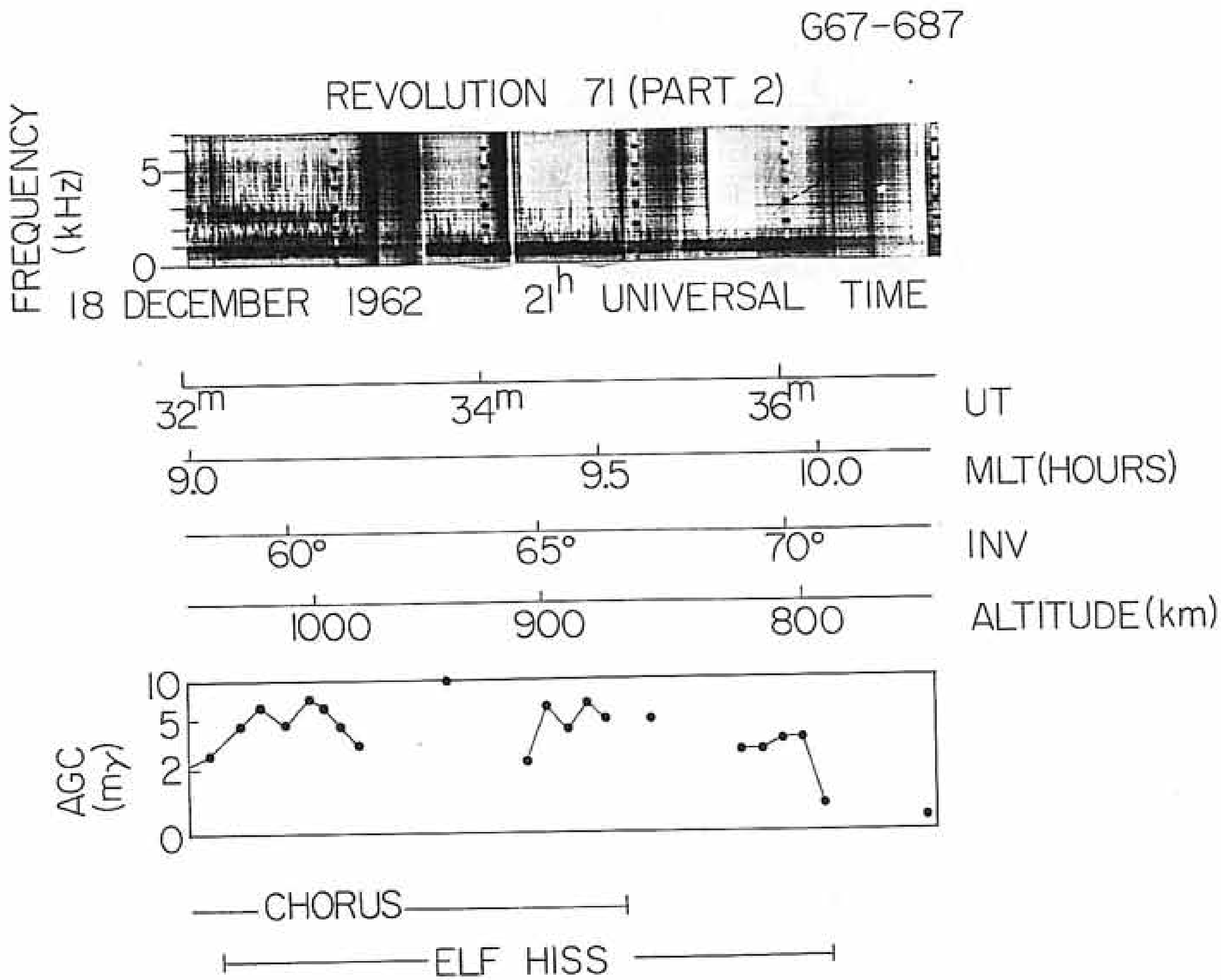

G67-688
REVOLUTION 71 (PART I)
FREQUENCY (kHz)
5
0
DECEMBER 1962 21h UNIVERSAL TIME
27m
29m
31m
UT
8.6
8.7
8.8
MLT (HOURS)
50°
55°
INV
1400
1300
1200
1100
ALTITUDE (km)
AGC (mγ)
10
5
2
0
LHRH
CHORUS

FIGURE 25



G67-687
REVOLUTION 71 (PART 2)
FREQUENCY (kHz)
5
0
18 DECEMBER 1962
21h UNIVERSAL TIME
32m
34m
36m
UT
9.0
9.5
10.0
MLT (HOURS)
60°
65°
70°
INV
1000
900
800
ALTITUDE (km)
AGC (mγ)
10
5
2
0
CHORUS
ELF HISS

FIGURE 26

G67-620

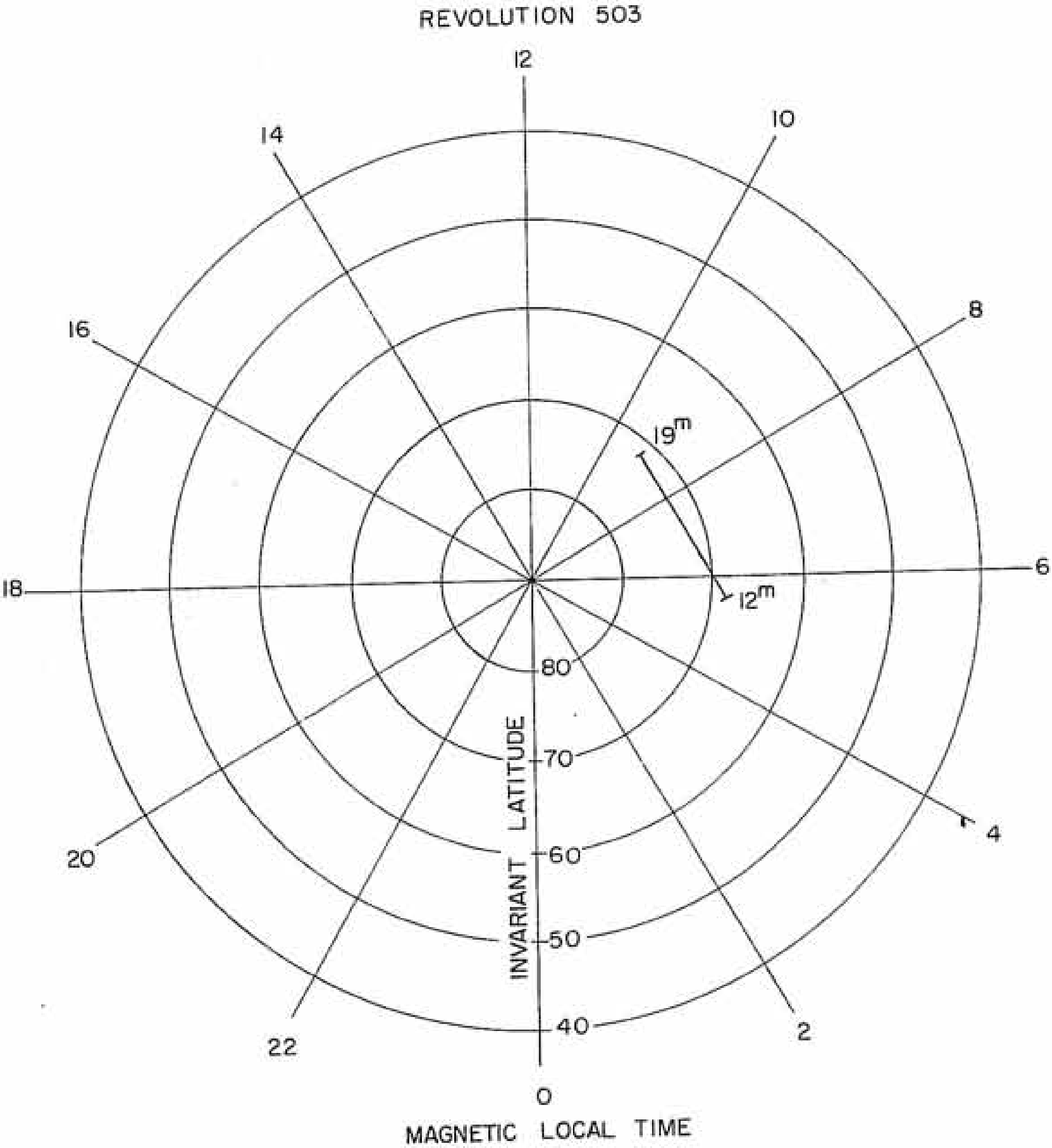
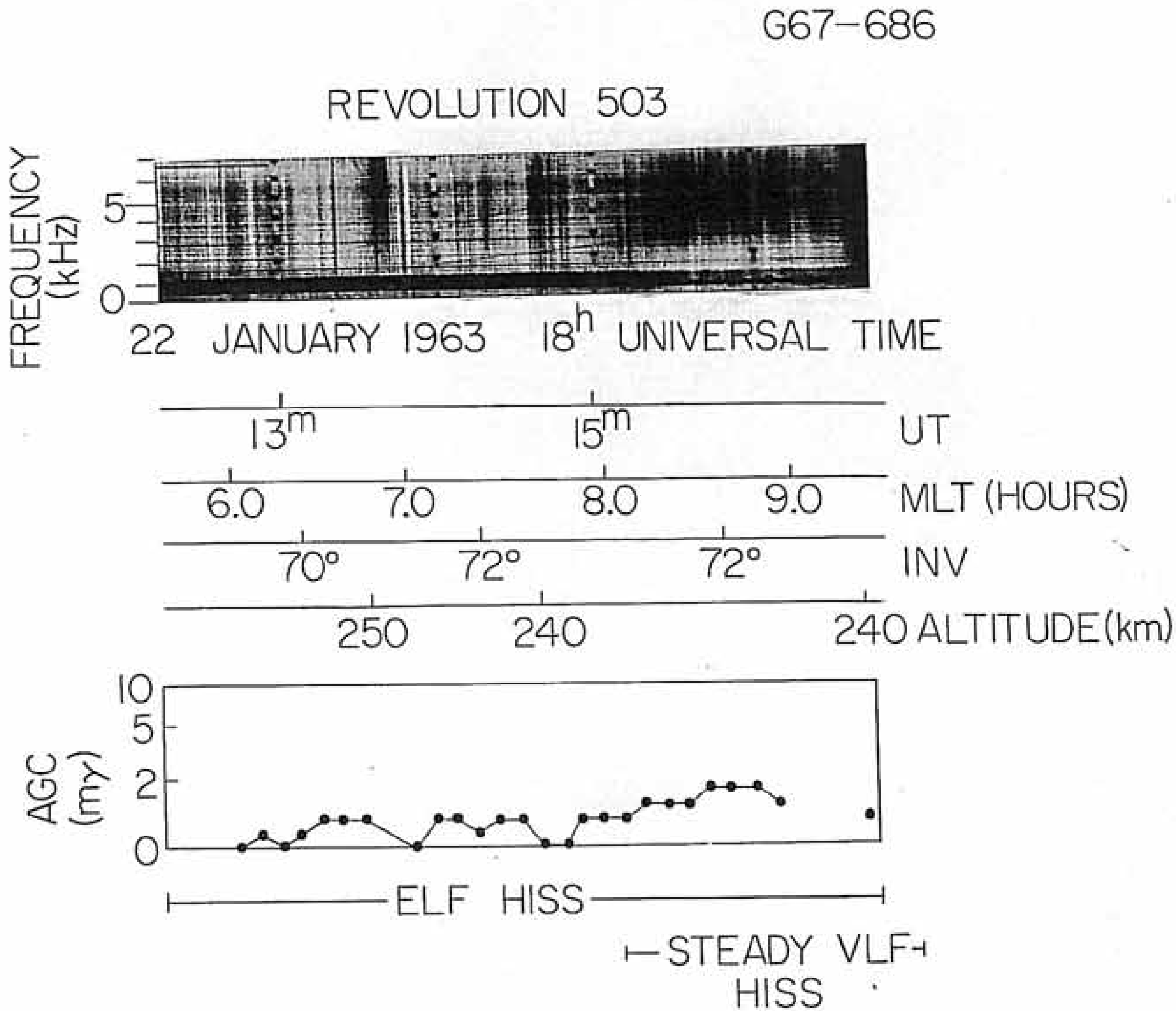


FIGURE 27



G67-686
REVOLUTION 503
FREQUENCY (kHz)
5
0
22 JANUARY 1963 18h UNIVERSAL TIME
13m
15m
UT
6.0
7.0
8.0
9.0
MLT (HOURS)
70°
72°
72°
INV
250
240
240 ALTITUDE (km)
AGC (mγ)
10
5
2
0
ELF HISS
STEADY VLF HISS

FIGURE 28

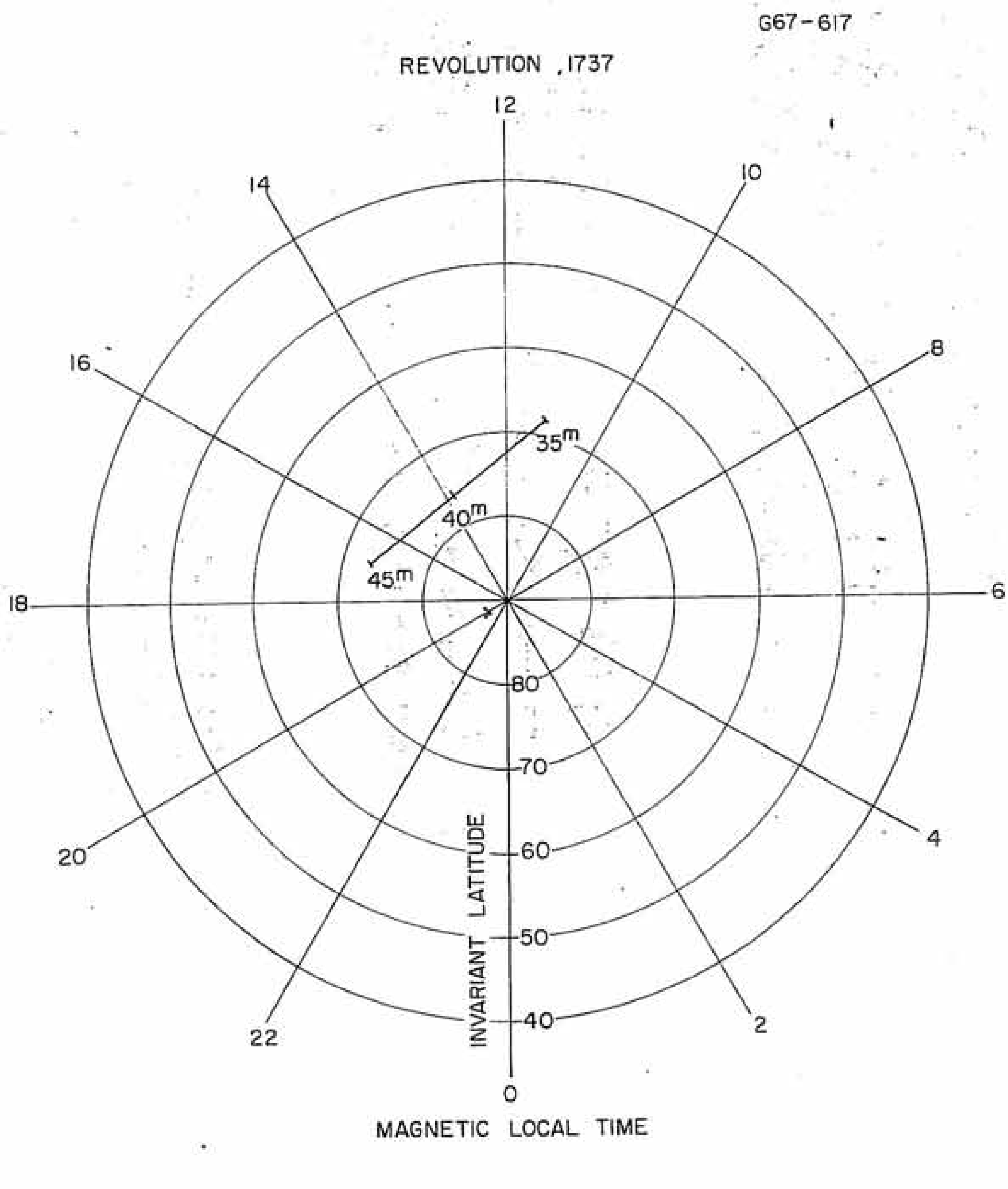

G67-617
REVOLUTION, 1737
12
14
10
16
8
18
6
20
4
22
2
0
35m
40m
45m
80
70
60
50
40
INVARIANT LATITUDE
MAGNETIC LOCAL TIME

FIGURE 29

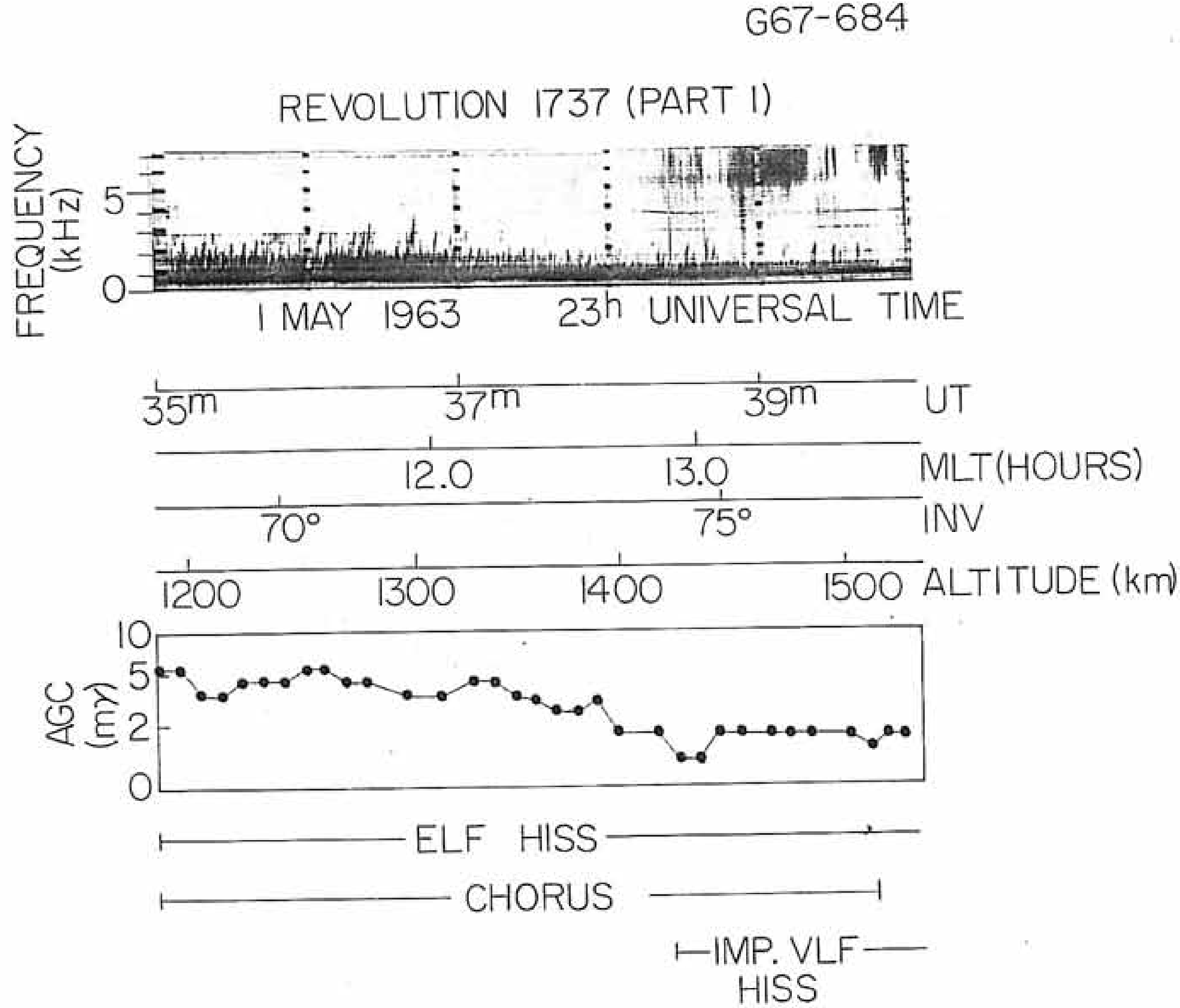
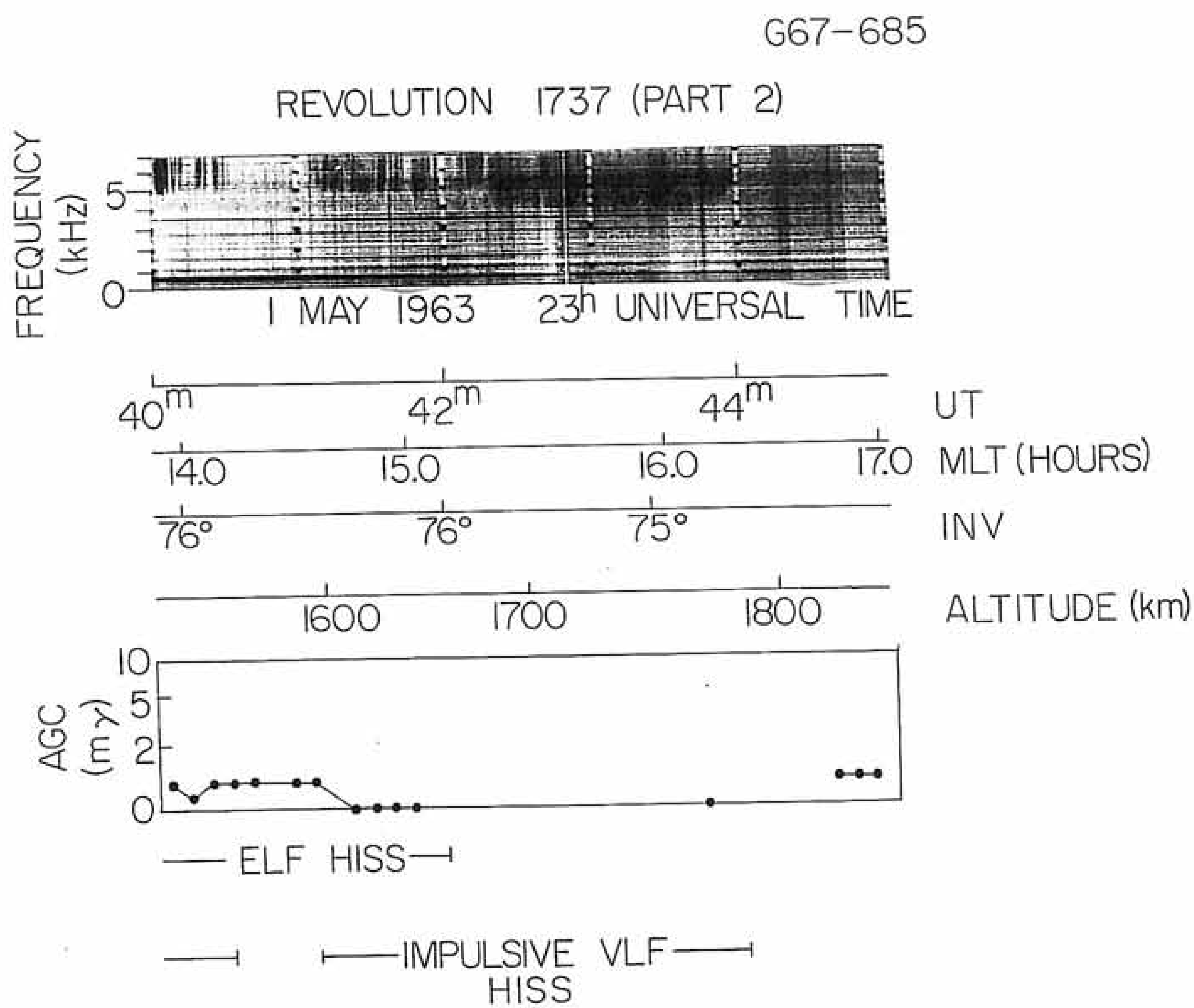

G67-684
REVOLUTION 1737 (PART I)
FREQUENCY (kHz)
5
0
1 MAY 1963
23h UNIVERSAL TIME
35m
37m
39m
UT
12.0
13.0
MLT(HOURS)
70°
75°
INV
1200
1300
1400
1500
ALTITUDE (km)
AGC (mγ)
10
5
2
0
ELF HISS
CHORUS
IMP. VLF HISS

FIGURE 30



G67-685
REVOLUTION 1737 (PART 2)
FREQUENCY (kHz)
5
0
1 MAY 1963
23h UNIVERSAL TIME
40m
42m
44m
UT
14.0
15.0
16.0
17.0
MLT (HOURS)
76°
76°
75°
INV
1600
1700
1800
ALTITUDE (km)
AGC (mγ)
10
5
2
0
ELF HISS
IMPULSIVE VLF HISS

FIGURE 31

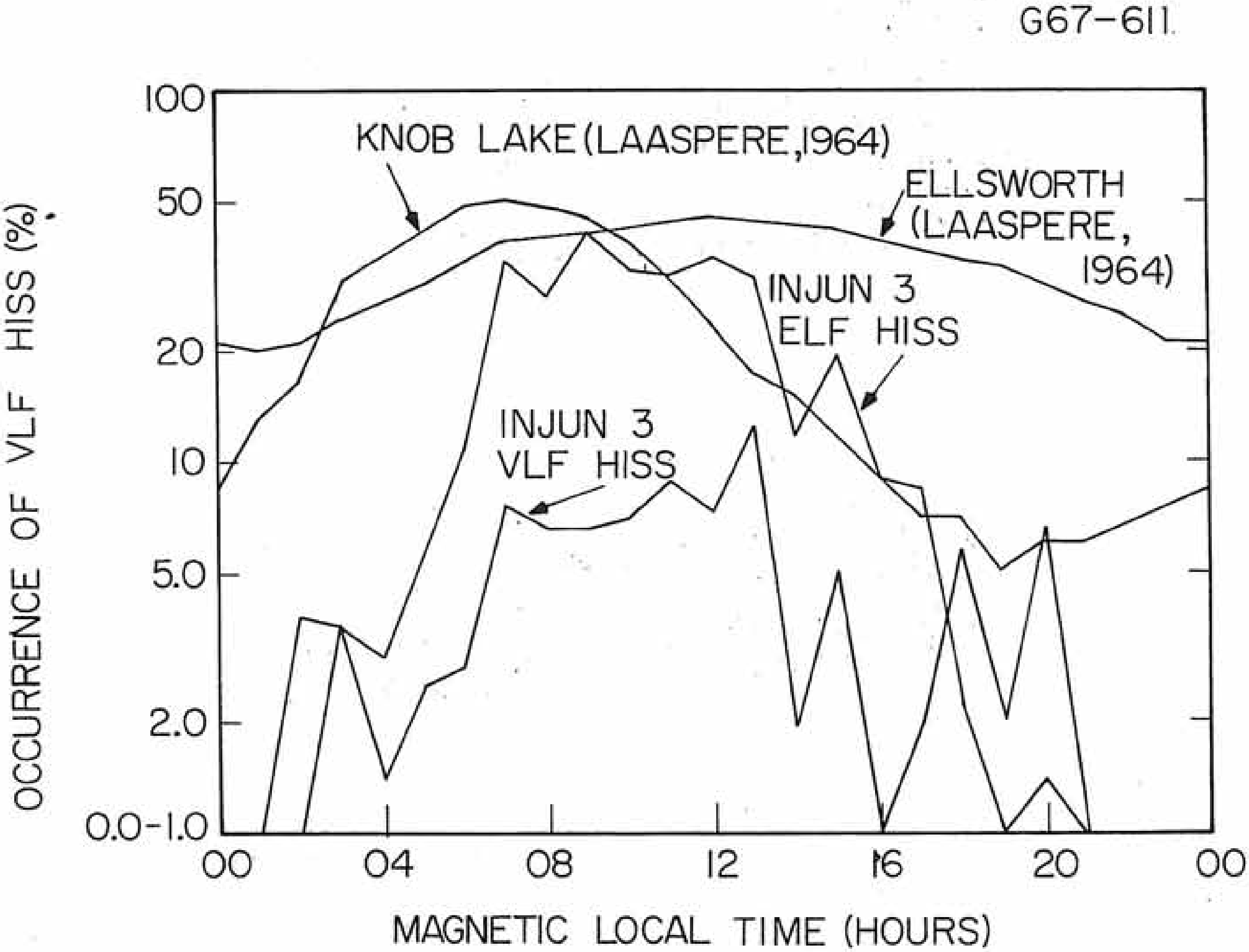

G67-611
KNOB LAKE (LAASPERE, 1964)
ELLSWORTH (LAASPERE, 1964)
INJUN 3 ELF HISS
INJUN 3 VLF HISS
OCCURRENCE OF VLF HISS (%)
100
50
20
10
5.0
2.0
0.0-1.0
00
04
08
12
16
20
00
MAGNETIC LOCAL TIME (HOURS)

FIGURE 32

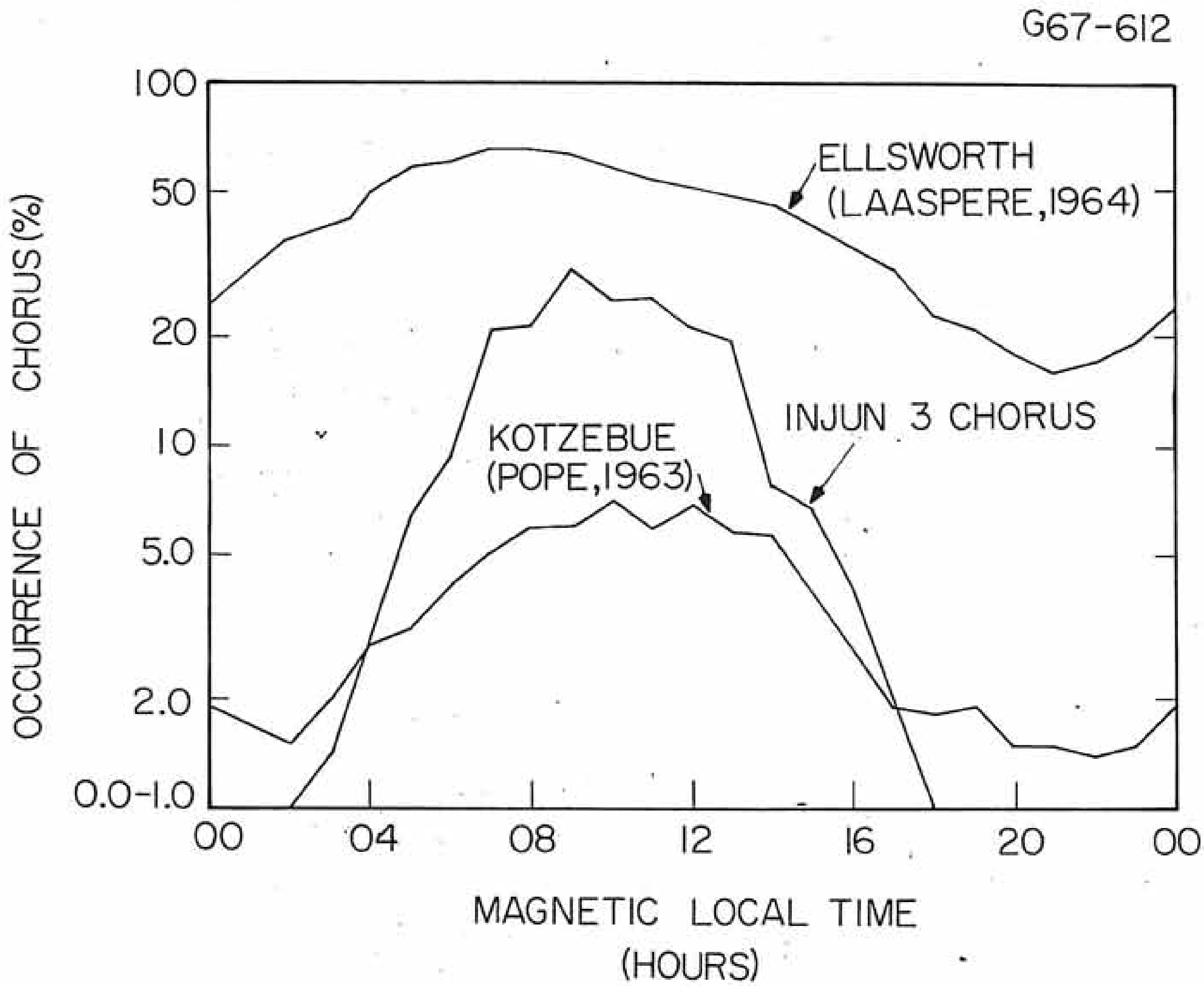

G67-612
100
50
20
10
5.0
2.0
0.0-1.0
OCCURRENCE OF CHORUS (%)
ELLSWORTH
(LAASPERE, 1964)
INJUN 3 CHORUS
KOTZEBUE
(POPE, 1963)
00
04
08
12
16
20
00
MAGNETIC LOCAL TIME
(HOURS)

FIGURE 33