

NON-ECKERSLEY LAW WHISTLERS RECEIVED
WITH SATELLITE INJUN III*

by

G. William Pfeiffer

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science
in the Department of Physics and Astronomy
in the Graduate College of the
University of Iowa

August 1966

Chairman: Assistant Professor Donald A. Gurnett

*Research supported in part by the Office of Naval Research
under contract Nonr 1509(06).

ACKNOWLEDGEMENTS

The author wishes to express sincere appreciation to Professor D. A. Gurnett for his many helpful and pertinent discussions on the theoretical and experimental aspects of this study and to Professor J. A. Van Allen for providing the necessary research facilities.

The author also wishes to express his appreciation to Mr. S. Shawhan for many hours of helpful discussion. For their assistance in producing the numerous spectrograms needed for this paper, the author wishes to thank Mrs. D. Walker, Mr. R. Shaw, Mr. R. Anderson, Miss R. Rogers, and Mr. G. Davida. Dr. R. A. Helliwell kindly supplied magnetic tape recordings of Stanford Electronic Laboratory VLF ground station data for which the author is grateful. The author also thanks Mrs. E. Robison for her careful typing of this manuscript.

Support for the Injun III project was supplied by the Office of Naval Research under contracts N9onr-93803 and Nonr 1509(06).

ABSTRACT

An experimental study of three new whistlers discovered in the Injun III satellite VLF data is presented. These whistlers are the riser, the check, and the hook whistler. They are considered unusual because they do not follow the Eckersley law for the propagation of VLF energy through the ionosphere. Reasons for believing these VLF noises to be true VLF phenomena and that they are whistlers rather than VLF emissions are presented. These whistlers are characterized by the following: (1) The riser whistler appears as a rising tone on a frequency-time spectrogram starting between 3 and 4 kc/s and extending to the upper frequency cutoff of the Injun III VLF receiver (7.2 kc/s). The total time length of the event is approximately 0.2 second. The riser whistler is found predominantly at high altitudes (≥ 1000 km) and always within 30 degrees of the magnetic equator. (2) The check whistler appears as a check on a frequency-time spectrogram; the lowest frequency component is at approximately 5.5 kc/s and the two sides of the check extend to the Injun III VLF receiver cutoff frequency at 7.2 kc/s. The total time length of the check whistler is approximately .15 second. The check whistler

is found predominantly at high altitudes (≥ 1300 km) and always within 30 degrees of the magnetic equator. (3) The hook whistler appears on a frequency-time spectrogram as two discrete electron whistlers joined at a frequency, usually less than 2 kc/s. The time interval between components of the hook whistler has varied from 0.012 sec to 0.20 sec in the cases studied. This whistler has been explained by Shawhan in a recent paper as a single lightning impulse, multiple path event. A brief outline of longitudinal and transverse propagation of VLF energy through the ionosphere is given with emphasis on a qualitative explanation of the riser whistler.

A short section on the "nose" whistler, the subprotonospheric whistler and the proton whistler, none of which obey the Eckersley law for whistlers, is presented. Other unusual whistler events observed with the satellite Injun III are also presented.

TABLE OF CONTENTS

Chapter	Page
I. Introduction	1
II. The Injun III Satellite: VLF Experiment	15
III. VLF Data Analysis	16
IV. Non-Eckersley Law Whistlers Observed with Injun III	23
V. Whistlers Received with Satellite Injun III: General	36
VI. Discussion	39
References	44
Figure Captions	47
Figures 1-24	52-75

I. INTRODUCTION

A. Electromagnetic radiation in the audio-frequency range undergoes dispersion as it travels through the ionosphere, that is, different frequency components travel at different velocities. In particular, a sharp impulse of energy, such as from a lightning impulse, that has traveled a distance through the ionosphere to an appropriate receiver will not be detected as an impulse but as a gliding tone. Early reports of such gliding tones received by ground-based very-low-frequency (VLF) radio receivers were published by Barkhausen [1919] and Eckersley [1925]. The frequencies they were working with were in the audio range between about 1 and 8 kc/s. The VLF receivers used were essentially sensitive audio amplifiers connected to long antennae. These gliding tones always started at the high frequencies and decreased continuously through the audio spectrum in a time interval of seconds or less. Although the cause of these tones, or whistlers as they are commonly called, was unknown, Eckersley [1935] was able to show that the delay time t of the frequency component f could be written as

$$t = Df^{-1/2} \quad (1)$$

where D is called the dispersion constant and is constant for any particular whistler but varies from whistler to whistler. It was also pointed out that occasionally a pair of whistlers would be found where the dispersion of one was an integer times the dispersion of the other [Eckersley, 1935]. Because of the repeated applicability of this relation, it became known as the Eckersley law for whistlers. Significant departures from this law have been observed for whistlers detected in the ionosphere by the Injun III satellite. It is these departures that we undertake to study in this paper.

B. Previous Work on Non-Eckersley
Law Whistlers Received by Ground
Stations

Storey [1953] has shown the causal relation between lightning and whistlers. He has also shown that whistlers can be divided into broad categories: whistlers where the lightning source and receiver are in the same hemisphere and whistlers that have a source in the opposite hemisphere as the receiver. In both cases the electromagnetic energy, upon entering the ionosphere, is guided approximately along the geomagnetic field lines to a conjugate point in the opposite hemisphere where part of the energy may be reflected back toward the source and the part of the energy may be transmitted to the ground. This echoing process

has produced long trains of whistlers with successive whistlers in the train showing increased dispersion according to the relations

$$D_{ns} = (2n-1) D_0$$

or

$$D_{no} = 2nD_0, n = 1, 2, 3,$$

where the first equation applies for receiver and source located in the same hemisphere and the second for receiver and source located in opposite hemispheres. D_0 is a dispersion constant for a single transit across the magnetic equator and, for a single whistler, will depend on the magnetic field line followed by the whistler energy and on the electron density along the path.

The whistlers received at mid-latitude (10° to 50° latitude) VLF ground stations obeyed the Eckersley law, however, when spectrograms from high-latitude stations became available whistlers with quite different features were noted. Some whistlers from these stations showed a tone with a frequency component increasing with increasing time as well as the more usual component decreasing with time [Helliwell et al., 1956]. The two components were joined smoothly at some frequency of minimum delay forming a "nose" appearance on a frequency-time

spectrogram; thus the name "nose whistler" (see Figure 1c). These whistlers can be easily explained within the framework of magnetoionic theory. If we assume propagation of the whistler energy nearly parallel to the geomagnetic field (it was shown by Storey [1953] that, neglecting ion effects, the VLF wave energy is required to propagate within a cone of half angle $\sim 19^\circ$ to the magnetic field) it can be shown that the phase index of refraction for a wave propagating through a plasma in a right-hand polarized longitudinal mode is given approximately by

$$n^2 \sim 1 + \frac{\pi_e^2}{\omega (\Omega_e - \omega)} \quad (2)$$

again neglecting ion effects. In the above relation

ω is the wave frequency,
 π_e is the electron plasma frequency,
 Ω_e is the electron gyro-frequency.

The group velocity is related to the refractive index by

$$v_g = c \left(n + \omega \frac{dn}{d\omega} \right)^{-1} \quad (3)$$

Performing this operation on (2) and simplifying in the limit of $\pi_e \gg \Omega_e$ we obtain

$$v_g = \frac{2c\omega^{1/2} (\Omega_e - \omega)^{3/2}}{\pi_e \Omega_e} \quad (4)$$

By taking derivatives it can be shown that the group velocity has a maximum (time delay minimum) for

$$\omega \approx 1/4 \Omega_e \quad (5)$$

From (4) it can be seen that the group velocity goes to zero for $\omega \rightarrow 0$ and $\omega \rightarrow \Omega_e$. This theory then, predicts correctly the appearance of a nose whistler.

Eckersley type whistlers received by the satellite Injun III are shown on a frequency-time spectrogram in Figure 1a. In Figure 1b the Eckersley law, $t \propto f^{-1/2}$, is plotted for the short fractional-hop and long fractional-hop whistlers in Figure 1a. A spectrogram of a nose whistler received by a high latitude (71° S geomagnetic) ground station is shown in Figure 1c (from Helliwell [1965], p. 105). In Figure 1d the time delay, proportional to the inverse of the group velocity is plotted as a function of frequency using equation (4) and an assumed Ω_e of 10 kc/s.

The low frequency limit to equation (4) is

$$v_g \approx \left(\frac{2c\Omega_e^{1/2}}{\pi_e} \right) \omega^{1/2}, \quad \omega \ll \Omega_e. \quad (6)$$

Therefore the time delay, $t(\omega)$, given by

$$t(\omega) = \int \frac{ds}{v_g} = \frac{1}{\omega^{1/2}} \int \frac{\pi_e ds}{2c\Omega_e^{1/2}} = D\omega^{-1/2} \quad (7)$$

$$\text{where } D = \frac{1}{(2\pi)^{1/2}} \int \frac{\pi_e ds}{2c\Omega_e^{1/2}},$$

is proportional to the inverse square root of frequency which is just the Eckersley result.

The effects of the zero in the group velocity at $\omega = \Omega_e$ would not be noticeable at latitudes where

$$\frac{\Omega_e^*}{4} \gg \omega_{HF}, \quad (8)$$

where Ω_e^* is the minimum electron gyro-frequency along a magnetic field line terminating at that latitude

and ω_{HF} is the high frequency cutoff of the ground VLF receiver.

The minimum gyro-frequency along a midlatitude field line (40°) is of the order of 200 kc/s while commonly used ground based VLF receivers are operated between 1.0 and 20 kc/s. At high latitudes

the minimum gyro-frequency along a field line will fall below 20 kc/s and the effects of the electron gyro-frequency will be quite evident in the form of a nose whistler.

Previously we have neglected the effects that ions may have on a wave propagating through a plasma. As will be shown below this is a good approximation for whistlers received by ground stations but must be re-evaluated for the explanation of satellite data.

Storey [1956] proposed a theory that would use deviations in the dispersion of a right-hand polarized whistler signal received by ground VLF receivers to detect the presence of ions along the path of the whistler. Specifically, it was sought to determine if ionized hydrogen was present in significant amounts in the ionosphere. After a careful analysis of the propagation equations he concluded that: Ion effects would not alter the Eckersley form significantly until the wave frequency is less than one fourth the ion gyro-frequency and that opposing effects of the ions, when integrated over the entire ray path, would tend to cancel. Therefore ion effects would be very difficult to detect at ground VLF stations.

A dispersion relation considerably different from the Eckersley form (right-hand polarized longitudinal propagation) is associated with waves propagating through a plasma in the left-hand longitudinal mode. These waves, called ion cyclotron waves [Stix, 1962] have a resonance (index of refraction goes to infinity) at each ion gyro-frequency rather than at the electron gyro-frequency. VLF energy propagating through the ionosphere in this mode would have an infinite delay time at each of these ion gyro-frequencies. The left-hand propagating wave cannot be observed by a ground-based VLF receiver, however, because as the wave follows a geomagnetic field line over the top of the path, the proton gyro-frequency will decrease to a value of the order of tens of cycles. The protons will then effectively absorb all left-hand polarized wave energy below the minimum proton gyro-frequency along the path. The remaining frequencies are far below the lower frequency cutoff of the ground-based VLF receivers.

We have demonstrated that, except for the nose whistler, longitudinal propagating waves received at VLF ground stations can be expected to follow the Eckersley law for whistlers. Transverse propagation and related dispersion effects will now be discussed.

It should first be mentioned that propagation through a plasma transverse to the static magnetic field is only possible when the effects of non-infinitely massive ions are considered

[Hines, 1957]. The dispersion relation for propagation transverse to the geomagnetic field is considerably different from the right- or left-hand longitudinal case. The principal zeros in the group velocity occur at the cutoff frequency (phase index of refraction goes to zero) and at the lower hybrid resonance frequency (Ω_{LHR}) (phase index of refraction goes to infinity). A complete discussion of transverse propagation is given by Stix [1962]. We will be concerned with the highest frequency cutoff which is at a frequency just below the proton gyro-frequency and with the lower hybrid resonance which is at a frequency generally less than 20 kc/s for propagation in the ionosphere. Since the transverse group velocity is zero at the cutoff and at the lower hybrid resonance and finite in between, there must be some frequency or maximum group velocity between these bounding frequencies. Therefore a whistler with some of the characteristics of a nose whistler might be expected for transverse propagation. One point should be mentioned, however, in connection with nearly transverse propagation. It has been shown [Shawhan, 1966c] that for wave normal directions more than a few degrees from purely transverse, the longitudinal propagation relations predominate, in particular, the resonance frequency increases from Ω_{LHR} at $\theta = 90^\circ$ to about ten times this frequency at $\theta = 80^\circ$, where θ is the angle between the wave normal and the static magnetic field vector.

Although the lower hybrid resonance frequency is within the passband of most ground based VLF receivers, effects definitely attributable to this resonance are not generally observed by ground stations. Two reasons can be cited for this. The first has just been outlined: Unless the wave has propagated exactly transverse to the geomagnetic field for a considerable distance, longitudinal dispersion results will predominate. A second explanation involves the ability of a wave to propagate out of the ionosphere. The index of refraction for VLF waves traveling in the ionosphere is large, generally greater than 10, while in the un-ionized atmosphere it is unity. Assuming these values and using Snell's law, we find that only VLF energy with wave normal angles confined to a cone of half angle of about 9 degrees with respect to the vertical will be transmitted out of the ionosphere. For ground stations located more than approximately 20 degrees from the magnetic equator the transmission cone will include waves whose dispersion is governed primarily by the longitudinal relations. Thus the total internal reflection of the VLF energy at the atmosphere-ionosphere boundary prevents ground VLF stations from receiving whistlers propagating with large wave normal angles with respect to the geomagnetic field.

With these limitations in mind, it is not surprising that the vast majority of whistlers received by VLF ground stations could be explained on the basis of longitudinal propagation alone.

C. Non-Eckersley Low Whistlers Observed
with Satellite Borne VLF Receivers

One would expect the VLF data received within the ionosphere to show evidence of transverse propagation and of the ion resonances. This has been the case. Some of the recently reported satellite-observed VLF data are summarized below.

Satellite observations of an ion gyro-frequency effect associated with the H^+ ion were reported by Smith et al. [1964] and explained by Gurnett et al. [1965] as being a left-hand polarized ion cyclotron wave excited by a lightning impulse. Another ion-cyclotron whistler, the helium whistler, has been observed with Alouette 2 by Barrington et al. [1966].

Effects of the lower hybrid resonance on VLF hiss were reported by Barrington and Belrose [1963] and by Brice and Smith [1964, 1965].

A dispersion anomaly in whistlers that has been attributed to transverse propagation was reported by Barrington and Belrose [1963]. The whistlers, received by the satellite Alouette 1, are characterized by small dispersions (4 to 5 sec^{1/2}) suggesting they have traveled directly from the source to the satellite (short fractional-hop whistlers). The dispersion of

subsequent whistlers in the train increases, but not so rapidly as to allow propagation to the normal reflection points in the lower ionosphere at the end of the field lines and back to the satellite. This whistler is interpreted by Carpenter et al. [1964] as being reflected multiply past the satellite from the lower ionospheric boundary (~ 100 km) and from a region around 1000 km in altitude. The mechanism for reflection at the lower ionospheric boundary is the same as that for reflecting ordinary whistler energy at these altitudes. A possible mechanism for the reversal of the ray direction at the 1000 km region was proposed by Smith [1964]. In explaining this whistler (termed the "subprotonospheric" whistler) it is assumed that propagation is primarily right-hand longitudinal but that near the 1000 km refraction altitude the wave normal angle must have gone through 90 degrees. Therefore the Eckersley dispersion law should be violated and the effects of the lower hybrid resonance should be evident in the form of an additional dispersion at frequencies approaching the lower hybrid resonance frequency. There has been no confirmation of the subprotonospheric whistler deviating to any extent from the Eckersley form [Carpenter et al., 1964].

Another non-Eckersley effect was reported by Carpenter and Dunkel [1965] and explained in terms of transverse propagation effects by Kimura et al. [1965]. These "transverse whistlers" have a delay time associated with them that can be written as an Eckersley term plus an added constant delay

$$t = D_0 f^{-1/2} + \Delta t . \quad (9)$$

The additional delay Δt is small and provides an effective increased dispersion at high frequencies. It was postulated that since the dispersion would increase as the lower hybrid resonance frequency was approached only if the wave normal direction were other than zero degrees with respect to the geomagnetic field, whistlers described by equation (9) must have propagated some distance nearly transverse to the geomagnetic field. The fact that the delay time can be written as a small perturbation to the Eckersley equation and not in the form required for transverse propagation is attributed to the supposition that the whistler energy traveled only quasi-transverse to the geomagnetic field and then only over a short distance. The remainder of the distance was traveled in a right-hand longitudinal mode. The majority of these satellite observed effects were observed

at dipole latitudes from 30 to 44 degrees [Kimura et al., 1965]. Another interpretation of this whistler has been given by Shawhan [1966c].

Non-Eckersley whistlers believed associated with near-transverse propagation were reported by Pfeiffer et al. [1966]. The two whistlers discovered were called the riser and the check whistler because of their appearance on frequency time spectrographs. It is intended that the initial announcement on these two whistlers will be expanded in the following sections to include accurate occurrence studies as well as information about the dispersion characteristics and other experimental features of the whistlers.

Experimental data on the "hook" whistler, another non-Eckersley law whistler found in the Injun III data [Shawhan, 1966b] are given in Section IV-C.

Spectrograms of other non-Eckersley law whistlers observed in the Injun III VLF data are presented in Section IV-D. Other interesting VLF phenomena observed in the Injun III data which arose out of this study are presented in Section V.

II. THE INJUN III SATELLITE: VLF EXPERIMENT

The University of Iowa/Office of Naval Research satellite Injun III had an active life from December 1962 until October 1963. The orbit had an initial inclination of 70.4° to the geographic equatorial plane with an initial apogee and perigee of 2785 km and 236 km, respectively. The point of apogee precessed in local time with a period of 10^4 days and therefore the satellite sampled all local times approximately three times.

A complete description of the satellite itself and of each experiment is given by O'Brien et al. [1962]. The VLF experiment is further described by Gurnett [1963] and Gurnett and O'Brien [1964]. One aspect of the VLF receiver will be reiterated here since it will be important in later discussions. The frequency response of this VLF receiver was essentially flat to within ± 5 db from .5 to 7.2 kc/s, however the response is down 86 db at 9.0 kc/s. This steep attenuation provides a very definite upper limit to the VLF signals observable with this receiver.

The receiver has a magnetic loop antenna oriented so as to detect the component of the wave magnetic field perpendicular to the geomagnetic field.

III. VLF DATA ANALYSIS

The analog VLF data received by the satellite receiver was transmitted to ground tracking stations where it was recorded on magnetic tape. On other channels of this tape were recorded a precise time signal (usually the National Bureau of Standards station WWV) as well as a precise reference tone of 10 kc/s or 4.096 kc/s. These simultaneously recorded signals have been used extensively as frequency and time standards in the processing of the VLF data. The numerous steps taken in the processing of this data will be but briefly outlined here.

The calibration tone (10 kc/s or 4.096 kc/s) is used to drive a digital clock which is an integral part of the operating console. The day, hour, minute, and second of the 5 minute mark nearest the beginning of the satellite pass are pre-set by the operator. The WWV signal from another channel of the same tape is used to start the clock at the appropriate 5 minute mark. Real time can then be read to within ± 1 second for the remainder of the pass.

A. Frequency-Time Spectrum Analyzers

The VLF data is processed by a Spectran* spectrum analyzer. This particular instrument has a set of 480 magneto-restrictive filters that scan any 10 kc/s segment of the frequency spectrum from 50 cps to 50 kc/s. The 10 kc/s segment is scanned 60 times a second. Signal amplitude information is used to intensity modulate the beam of an oscilloscope while the frequency information is applied to the vertical deflection plates of the oscilloscope. A 35 mm continuous exposure camera is mounted in front of the oscilloscope screen and provides time sweep with the moving film. Spectrograms created in this manner provide frequency-amplitude information about a VLF signal as a function of time. A frequency-time spectrogram of typical electron whistlers is shown in Figure 1a.

The National Bureau of Standards station time signal recorded on the data tape is chopped at an 8 kc/s rate and mixed with the data being fed into the spectrum analyzer. The Morse code time announcements can then be visually read at the top of the film where they do not interfere

* Model 480-25, Spectran Electronics Corp., Pompano Beach, Florida.

with the data. By this method real time can be measured from the film to within a small fraction of a second.

Another type of spectrum analyzer used in data reduction is the Missilyzer.* With this instrument a short interval of data (usually .8 to 2.4 seconds) is scanned repeatedly by a single filter and the frequency-amplitude-time spectrograph created on a type of facsimile paper. Considerably better frequency and time resolution is obtained with this system than with the Spectran instrument, however, approximately 5 minutes of laboratory time are required to scan a few seconds of real time. For the careful analysis of particular events, as in some of the spectrograms presented at the end of this paper, the Missilyzer is generally used.

B. Frequency-Time Spectrograms

Once the VLF data have been transferred from magnetic tape to film or paper, we may begin to make analytic measurements. To assist in these measurements we have available a Benson-Lehner "Oscar".† This instrument employs a projection system

* Model 675, Kay Electric Company, Pine Brook, New Jersey.

† Model F, Benson-Lehner Corporation, Van Nuys, California.

in which a 70 mm x 35 mm section of photographic film is enlarged and projected onto a 60 cm x 30 cm ground glass screen. The 15 cm x 30 cm facsimile paper may be placed directly on the viewing screen. A particular event can be followed in frequency and time with a pair of movable crossed grid-lines that generate an analog voltage proportional to their position. This information is processed by an analog to digital converter, the output of which is used to control punching on an IBM type 26 card punch. Computer programs have been written to calculate dispersions of various types of whistlers.

It is not convenient to be constantly referring back to the original 100 foot rolls of 35 mm film when making a study of a particular event. Therefore, as a further step in data reduction a 35 mm single frame, single lens reflex camera is used to photograph sections of interest on the 100 foot rolls. With this method we have photographed sections from 3.5 to 15 cm in length. Enlargements are obtained and filed according to subject. The negatives are stored on 3M Company "aperture cards". These are essentially IBM computer cards with a 35 x 38 mm aperture replacing part of columns 54 through 72. Information concerning the particular negative (e.g., revolution,

altitude, event) is punched on the remainder of the card; the card can then be machine sorted on this information.

C. VLF Data Studied and Sample Densities

High resolution spectrograms of large amounts of Injun III VLF data have not been available until recently because of the unavailability of a suitable spectrum analyzer. An aural semi-monthly sample of the ten months of VLF data was undertaken [Shawhan, 1966a] but, because the primary purpose of this study was the analysis of proton whistlers, a low pass filter set at 5 kc/s was used to eliminate some of the communication and recorder noise. Therefore, the high frequency whistler phenomenon analyzed in this paper would not have been found previously in Injun III data.

To obtain a sample of VLF data encompassing all available latitudes, altitudes, and all local times, a semi-monthly study was begun. Because of previous work on the VLF data, the 11th and 26th of the month were again chosen. When this semi-monthly study showed equatorial data to contain many new and unexplained types of whistlers, the 26th of the month data was abandoned in favor of concentrated effort on equatorial data. The 11th of the

month was continued in order to give a general average background to the study. Finally, to improve the sample density data from mid- and high-latitude tracking stations were included. The data used for this paper includes approximately 600 passes of Injun III. (A "pass" is defined here as being that portion of a satellite revolution recorded by one ground tracking station.) These passes represent about 130 hours of analog VLF data.

As the 35 mm films containing the analog VLF data were viewed, an analysis sheet was filled out. VLF events of particular interest or events in a category of study were photographed. The prints and negatives were stored as mentioned previously. From the analysis sheets computer cards were punched with the appropriate time and event information. These cards are used with a master orbit tape of Injun III to give orbital parameters of the passes and events studied. The computer output can be sorted on orbital parameters or on the events themselves.

The sample densities in altitude-magnetic latitude space, altitude-local time space and local time-magnetic latitude space are presented in Figures 2, 3, and 4, respectively. Only the absolute value of the magnetic latitude has been used because of the difficulty in assigning a sign to the value calculated by

this computer program. This is not a great hinderance in this study, however, since northern-southern asymmetries are not sought. From these figures it can be seen that data has been studied from nearly all volumes of space sampled by Injun III.

IV. NON-ECKERSLEY LAW WHISTLERS OBSERVED WITH INJUN III

The 11th of the month study and subsequent concentration on equatorial passes have yielded a number of whistlers deviating markedly from the Eckersley form. In this section we present experimental data on the riser, check, and hook whistler. The last part of this section will deal with other non-Eckersley whistlers received by Injun III.

A. The Riser

Two VLF noises that we have classified as risers are shown in Figures 5a and 5b on frequency-time spectrograms. The first appears curved over its entire length while the second appears linear over the majority of its length. We believe these signals to be true VLF phenomena for the following reasons. In a number of instances spectrograms from two tracking stations which had simultaneously tracked the satellite showed a riser event. This eliminates the possibility of local interference in the data reception. The sharp attenuation of the riser above 7.0 kc/s corresponds closely to the upper cutoff frequency of the Injun III VLF receiver; therefore, we feel certain that the signal was received by the satellite VLF receiver. We believe the signal

to be a whistler and not a type of VLF emission because, as shown below, the riser occurs in regions of the ionosphere where commonly known types of VLF emissions are virtually never observed. Whistlers are, however, regularly found in these regions. Secondly, VLF emissions tend to show repetition at short intervals [Gallet, 1959]. No such repetition is found with the riser events on which we report. In fact, often only one riser is found in a twenty-minute satellite pass; the maximum number observed was eight.

The riser deviates markedly from the Eckersley form for whistlers in that the delay time associated with a particular frequency component increases with increasing frequency.

This study has found no evidence that one of the two forms of the riser occurs in preference to the other at any altitude, latitude, or local time; when risers were occurring, generally both forms were found. Both forms of the riser were found on "active" satellite passes (i.e., passes where 100 or more electron whistlers were recorded per minute) and on relatively quiet passes.

The lower cutoff frequency (see Figure 5) has been measured for a number of risers. In the risers measured no correlation between F_{LC} and altitude, latitude, or local time has been found.

The slope of the linear portion of a number of the linear-appearing risers (Figure 5b) has been measured. Values ranged from 4.6 to $6.3 \times 10^{-5} \text{ sec}^2$ for the examples studied. Again, no correlation has been found between the slope and the position of the satellite when the riser was received.

The spatial occurrence of the riser is shown in Figures 6, 7, and 8. The various shaded blocks depict the percentage occurrence of risers in that data box. Multi-occurring risers on the same satellite pass within a box are counted only once. From Figure 6, it is evident that the riser is an equatorial and primarily a high altitude event. The lowest recorded riser occurred at 756 km (18° mag lat), however, the majority of the risers occurred above 1500 km.

Figure 7 gives some indication that risers occur at lower altitudes during local day, however this feature is not well established.

As evident from Figure 8, the riser occurs at essentially all local times within its restricted latitude region. A change to higher or lower latitudes with local time is not evident.

The total number of risers processed thus far is about 180. This may account for some of the scatter in the occurrence plots.

An altitude sequence of risers is shown in Figure 9. Very little difference can be detected in the risers with the possible exception that the 756 km event is somewhat more intense and therefore extends somewhat beyond 7.2 kc/s. This feature of only slight variance in form with altitude is common in all the spectrograms of risers studied thus far.

It has been common practice for many years to correlate spherics (VLF energy traveling from the lightning source to the ground-based VLF receiver via the earth-ionosphere waveguide) with a whistler to accurately determine the delay time and dispersion of a whistler signal. When satellite VLF data became available this technique was expanded to relate ground observed spherics to satellite observed whistlers. We have attempted to correlate in this manner risers received by Injun III and VLF ground-station data hoping to find a spheric that could be attributed to the lightning impulse causing a riser. From a total of 180 risers, six were found to fall in the two minute per hour listening time of the Stanford Electronics Laboratory ground station (the only VLF ground-station data currently available to us). In Figure 10a is presented a spectrogram of the ground VLF data for a period when two risers were detected

by Injun III (Figure 10b). Coarse time alignment was obtained from the National Bureau of Standards time station WWV that is recorded on both magnetic tapes. Next, the delay time for the whistler event at 0951:34 was calculated and the time of the initiating lightning impulse was determined. The photographic films containing the two spectra were then aligned to be coincident in time. The riser at 0951:37.5 was next analyzed. Three spherics are closely enough associated with the riser to be considered as possible initiating spherics. Since the dispersion equation for the riser is unknown we cannot be certain which spheric, if any recorded by this equipment, is responsible for the riser. The possible delay times for the three spherics indicated by arrows in Figure 10, are .32 sec, .28 sec, and .08 sec. With this same time alignment spherics immediately preceding the riser at 0951:41 indicate a delay time of .08 and .16 second. No definite spherics are seen to be associated with the electron whistler at 0951:44, however, this is not uncommon [Helliwell, 1965]. It should be mentioned that unless the dispersion characteristics of a whistler are known, it is nearly impossible to assign a particular spheric to a particular whistler. We, therefore, do not claim that any of the spherics mentioned

are associated with a riser, but merely point out that there are spherics that could be related to a riser. In the other cases studied, the inability to find an appropriate spheric-electron whistler event prevented measurements of this type from being made since accurate time alignment was therefore not possible.

B. The Check Whistler

A second whistler deviating markedly from the Eckersley form for whistlers is shown on frequency-time spectrograms in Figures 11a and 11b. We have named this whistler the "check" whistler because of its appearance on these spectrograms. We believe these events to be true VLF phenomena and to be whistlers for the same reason presented in support of the riser.

It appears that the check whistler is really the low frequency portion of a somewhat more complicated whistler event, but, because of the high frequency limit of the Injun III VLF receiver, only this low frequency portion is observed.

The lowest frequency component of the check has been measured for all of the processed check whistlers and found to vary from 5.3 to 5.8 kc/s, however, no correlation has been found between this frequency and altitude, magnetic latitude or local

time. Very little difference could be found in the appearance of any of the check whistlers on frequency-time spectrograms.

The percentage occurrence of the check whistlers is shown in Figures 12, 13, and 14 in magnetic latitude-altitude, local time-altitude and magnetic latitude-local time space, respectively. From Figure 12 it is evident that the check whistler is also a high altitude, equatorial phenomenon.

There is some evidence (Figure 13) that the check whistler occurs at lower altitudes during local day. It should be noted, however, that at this time we have processed only 15 known examples of the check whistler. When enough examples are available to form a valid statistical distribution, any of the occurrence plots may change considerably.

Figure 14 gives some indication that check whistlers occur at all local times within their restricted latitude. Again, the small number of examples does not permit a good statistical distribution.

The check whistler has always occurred on passes where there were one or more risers observed. The check whistler seems to occur with equal probability on active and quiet satellite passes. No check whistlers occurred during the two minute per hour Stanford

ground-station listening period; therefore, a search for spherics cannot be undertaken at this time.

C. The Hook Whistler

A third whistler found in Injun III VLF data that does not follow the Eckersley dispersion law is shown in Figures 15a and 15b. Because of a similarity to a type of VLF emission called hooks [Callet, 1959] it has been named the hook whistler [Shawhan, 1966b]. The physical features of this whistler will be described and then regions of occurrence will be shown.

The hook whistler is seen to be made up of two discrete components each of which appears to be an Eckersley type whistler. The two components are joined, however, at some frequency usually less than 2 kc/s.

The time difference between the two components of the hook whistler has been measured for a number of cases. The time difference Δt at 4 kc/s has been used as a reference and found to vary from .012 sec to about .20 sec for the cases studied. The minimum is near the resolving time of the processing equipment; we do not rule out the possibility of hook whistlers with shorter time intervals between components. The maximum is somewhat arbitrary; hook whistlers with time intervals between components

much greater than this are usually quite diffuse and difficult to distinguish from unrelated electron whistler events. Examples of hook whistlers with short and long time intervals Δt between components are shown in Figures 15a and 15b, respectively.

Another example of a hook whistler is shown on a frequency-time spectrogram in Figure 16a with the inverse square root of frequency plotted as a function of time for the two components in Figure 16b. The deviation from the Eckersley form is evident for the first component; the second component remains nearly Eckersley to the point where the two traces converge.

When hook whistlers are occurring, they tend to occur in rapid succession and for time intervals of minutes. This is to be contrasted to the riser and checker whistler which occur generally as single isolated cases. An example of many hook whistlers occurring in rapid sequence is shown in Figure 16c. The 30 second segment shown is representative of most of the passes which contained hook whistlers.

The two primary physical features of the hook whistler, the time interval Δt between components and dispersion evaluated at 4 kc/s, are found to vary widely among hook whistlers found in a particular region of the ionosphere.

This can again be contrasted to the riser and check whistler. As an example of the variability associated with hook whistlers from one region of space, four hook whistlers with widely varying features are shown in Figure 17a, b, c, d. The examples shown occurred above 2600 km and below satellite apogee of 2785 km. Local time and latitude are approximately the same for the four cases and are not considered to be a variable. The features of closure at low frequencies and multiple occurrence in a short length of time classifies these examples as hook whistlers.

Regions of occurrence for the hook whistler are shown in Figures 18, 19, and 20 in magnetic latitude-altitude, local time-altitude, and magnetic latitude-local time space, respectively. Shaded blocks represent percentage occurrence. From Figure 18 it can be seen that the hook whistler is found at all altitudes sampled by Injun III but is restricted to within about 40 degrees of the magnetic equator and occurs somewhat more frequently below 30 degrees magnetic latitude. There is some indication that hook whistlers occur at lower altitudes only during local day and evening as indicated by Figure 19. The hook whistler is seen to occur at essentially all local times within its latitude range of 40 degrees of the magnetic equator. This occurrence is shown in Figure 20.

Two whistlers occurring in a very short interval of time can be explained in two ways. The source lightning could be multiple flash lightning with the VLF energy from the two or more impulses following the same path to the satellite. In this case the whistlers would have the same dispersion and would not join. Many cases such as this have been seen in the Injun III VLF data. A second explanation assumes a single lightning impulse with the VLF energy entering the ionosphere at one point. Once in the ionosphere there are required two ray paths to the satellite, the dispersion associated with one being slightly greater than that associated with the other. The wave normal direction along one path may be somewhat more transverse than the wave normal direction along the other causing one whistler to deviate more from the Eckersley form and causing the increased dispersion at low frequencies. A VLF ray tracing study conducted by S. Shawhan [1966c] has shown that under certain ionospheric conditions and over a limited range of frequencies VLF energy from a single source can follow different paths through the ionosphere to reach the satellite. This range of frequencies is often between .5 kc/s and 8 kc/s. The primary physical features of the whistler derived from the ray tracing study, that is, Δt , dispersion and regions of occurrence, agree quite well with many of the hook whistlers observed in this experimental study.

D. Other Non-Eckersley Law Whistlers
Observed with Injun III

Whistlers other than the three just discussed that deviate from the Eckersley form have been observed with Injun III. Some of these are presented below. They will be but briefly mentioned since they are either relatively common in satellite data or have been exhaustively studied elsewhere. These whistlers are presented primarily for completeness.

Nose whistlers have been detected with the Injun III VLF receiver, however, the examples are relatively few and fairly poor in that only a small portion of the nose is visible. An example of a group of nose whistlers is shown in Figure 21a. The nose frequency is fairly well defined for the pair nearest the time and frequency calibration (horizontal bars superimposed over data at 1638:00). The nose frequency of these two whistlers has been determined to be 3.8 and 3.4 kc/s. The satellite was at an invariant latitude of 62 degrees at this time. The minimum gyrofrequency at the top of the field line passing through this point is of the order of 9 kc/s. The nose frequency, for VLF energy integrated along this field line is at approximately $.39 \Omega_e^*$ where Ω_e^* is the electron gyrofrequency at the top of the

path [Helliwell, 1965, p. 184]. This differs from the value of $1/4 \Omega_e^*$ quoted in the introduction because we are here integrating the dispersion relation along a field line. This places the calculated nose frequency at about 3.5 kc/s, in good agreement with the observed data.

Examples of events that we believe to be subprotonospheric whistlers were found in the Injun III VLF data. No occurrence study was made and only one example, taken to be representative, will be shown. This example is given in Figure 21b. The dispersion of the first whistler is $18 \text{ sec}^{1/2}$ indicating that it is a short fractional-hop whistler. Subsequent whistlers in the event have dispersions prohibitively short to allow propagation of the whistler energy along a field line to a reflection point in the lower ionosphere of the opposite hemisphere and back to the satellite. The satellite was below 1000 km when the event was recorded, therefore the requirements for the reception of a subprotonospheric whistler, as outlined in the introduction, are met.

Numerous proton whistler events were observed in the data analyzed. A frequency-time spectrogram of a group of these whistlers is shown in Figure 21c. The measured asymptotic frequency agrees quite well with the calculated proton gyro-frequency of 525 cps.

V. WHISTLERS RECEIVED WITH
SATELLITE INJUN III: GENERAL

In the following section we present whistlers received by the satellite Injun III that are unusual in some way other than that they violate the Eckersley dispersion law.

In Figures 22a, 22b, and 22c are three spectrograms of whistlers that have higher frequency components missing. In Figure 22a there appears to be two definite cutoff frequencies, one at about 1 kc/s, the other at about 2.9 kc/s (indicated by arrows). Thirty seconds of data are shown, the event lasted for about two minutes and was preceded and followed by short fractional-hop electron whistlers. Figure 22b shows a similar event except in this case there appears to be three separate cutoffs at approximately 1 kc/s, 2 kc/s, and 3 kc/s. Figure 22c is a similar event with a single cutoff visible at about 1.5 kc/s. A riser is also visible in the upper right hand side of the spectrogram. These whistlers have been found at all altitudes sampled by Injun III during all local times. All known events of this type occurred with the satellite within 40 degrees of the magnetic equator. No known features of the satellite receiver could cause such abrupt cutoffs in the received signal.

It should also be noted that in all examples, there are a number of ordinary electron whistlers in the background. The reason for the sharp cutoffs of the whistlers shown in Figure 22 is unknown at this time.

A somewhat opposite situation is shown in Figures 23a, 23b, and 23c in that the low frequency component of the whistlers is missing. The lower cutoff frequency ranges from 2 to 5 kc/s in the examples cited. A possible explanation for this effect mentioned by Helliwell [1965] is the following. It is known that VLF energy from a lightning impulse may travel considerable distances in the earth-ionosphere wave guide before entering the ionosphere. For propagation through such a wave guide there are cutoff frequencies corresponding to different modes of propagation. VLF energy entering the ionosphere after propagating some distance in the wave guide would not contain frequency components below the lowest wave guide cutoff frequency. Whistlers received by a satellite that were initiated by such VLF energy would also have the frequency components below the lowest wave guide cutoff frequency missing.

Another event, observed to some extent in the Injun III VLF data is shown in Figure 24. The satellite was moving in the

direction of decreasing L values at an altitude of approximately 1300 km. The VLF noise shown from 0433:30 to 0435:00 is known as chorus, a type of VLF emission commonly observed at L values between 2.5 and 6.5. At 0435:04 ($L = 3.5$) the chorus abruptly ceases and in a few seconds electron and proton whistlers are seen. The electron whistlers are short fractional-hop whistlers indicating the source is in the same hemisphere as the satellite. Electron whistlers continued for the remainder of the pass. This general feature of chorus at higher L values and whistlers at lower L values with an abrupt transition at L values from 3.0 to 4.0 has been observed on at least five other occasions in the Injun III VLF data studied thus far.

An intense VLF event can reduce the gain of the Injun III VLF receiver (because of the automatic-gain-control (agc) loop) to such an extent that a VLF event of much lesser intensity is not seen [D. A. Gurnett, private communication]. This is not the case here because the agc voltage (monitored and transmitted to the ground in digital form) indicated that the signals were only three or four times the background level during the chorus and electron whistler events. It therefore appears that the chorus-whistler event is a true VLF phenomenon and not something caused by the equipment itself.

VI. DISCUSSION

This study of the Injun III VLF data has yielded three new whistlers that we wish to consider further. The dispersion characteristics of two of these whistlers (the riser and check whistler) are so different from the Eckersley form for whistlers (right-hand longitudinal propagation) that another mode of propagation will be considered to explain these whistlers. The third whistler, the hook whistler, has two components, each of which nearly obeys the Eckersley law, yet because of small departures from this law at low frequencies the two components close at low frequencies ($\lesssim 1$ kc/s) to form a single whistler. In the following, the large and the small departures from the Eckersley law will be considered.

From the brief outline of wave propagation through a plasma given in the introduction we find there are three ways to have the delay time of a whistler increase with increasing frequency. These will be briefly reiterated.

(1) The portion of the whistler under consideration could have propagated in a right-hand longitudinal mode above the nose frequency along that field line. A whistler as shown in Figure 1c

results. This possibility does not apply here since the nose frequency for whistlers received at these altitudes and latitudes is at least ten times the frequency of the apparent "nose" of the riser.

(2) The wave could have propagated in a left-hand longitudinal mode below the proton gyrofrequency. A whistler as shown in Figure 21c is obtained. The proton gyro-frequency at these altitudes and latitudes is less than 200 cps, or at a frequency less than one-tenth the frequency at which we see the riser (3 to 7.2 kc/s); other ion gyro-frequencies are still lower, therefore, this case does not apply.

(3) The wave could have propagated in the transverse extraordinary mode. For propagation in this mode, there is an infinity in the group refractive index at the lower hybrid resonance frequency, Ω_{LHR} , and at a cutoff frequency, which can be taken to be just below the proton gyro-frequency, for the purpose of this discussion. There is, therefore, at least one minimum in the group index of refraction between these two frequencies. Such a minimum could cause the "nose" seen on the frequency-time spectrograms of the riser.

It has been shown by Shawhan [1966c] that the lower hybrid resonance frequency is generally less than 20 kc/s for

propagation in the ionosphere. Therefore, the riser is at least qualitatively explained by transverse propagation at frequencies near but below the lower hybrid resonance and above the frequency of maximum transverse group velocity.

The following points are not explained at this time:

- (1) Components of the riser below the "nose" have never been observed. Why these frequencies apparently do not propagate to the satellite has been given no theoretical basis.
- (2) It was shown by Shawhan [1966b] that the lower hybrid resonance frequency may be as low as 3 to 4 kc/s at altitudes between 200 and 600 km. Therefore, the riser could not have propagated transverse to the magnetic field over the entire path from the lower ionosphere to the satellite since frequencies above the local lower hybrid resonance frequency cannot propagate. The exact place where the wave normal direction becomes transverse to the geomagnetic field is unknown.
- (3) Although risers were recorded from 756 km to over 2700 km, at all local times and over a 30 degree latitude range, their appearance on a frequency time spectrogram remains uniquely similar, that is, the "nose" frequency has varied only from 3 to 4.1 kc/s, the slope of the linear appearing risers has

remained nearly constant and the total time interval of the riser has been nearly the same.

Few analytic statements can be made about the check whistler at this time. This is because of the small segment of the check whistler that can be detected with the Injun III VLF receiver and because of the limited number of examples available for study. A theory of the check whistler must explain the following:

- (1) Why the check whistler is limited to high altitude equatorial occurrence;
- (2) Why the check whistler occurs so seldomly (e.g., 15 check whistlers observed compared to 180 risers, and tens of thousands of electron whistlers); and
- (3) Why check whistlers appear nearly identical on frequency-time spectrograms even though the check whistler was observed at altitudes ranging from 1350 km to over 2700 km, at most local times and over a 30 degree latitude range.

The hook whistler is considerably better established since most of its features have been quantitatively derived by Shawhan [1966c] in a VLF ray tracing study. One further point can be made to support the single-source, multiple-path theory for the hook whistler. It was shown in Section IV-C that hook whistlers occur in rapid succession when they are occurring and

that they occur in a limited region of space. One would not expect to see multiple stroke lightning occur with such regularity and further, one would not expect multiple stroke lightning to be confined to any particular area on the surface of the earth. It might be expected, however, that propagation conditions required for a multiple path to the satellite would only be satisfied with the satellite in certain regions of the ionosphere.

REFERENCES

- Barkhausen, H., Zwei Mit Hilfe der Neuen Verstärker entdeckte Erscheinungen, Physic. Z., 20, 401-403, 1919.
- Barrington, R. E., and J. S. Belrose, Preliminary results from the VLF receiver aboard Canada's Alouette satellite, NASA Reprint X-615-63-36, 1963.
- Barrington, R. E., J. S. Belrose, and W. E. Mather, A helium whistler observed in Canada's satellite Alouette II, Nature, 210, 80-81, 1966.
- Brice, N. M., and R. L. Smith, Recordings from satellite Alouette I: a very low frequency plasma resonance, Nature, 203, 926, 1964.
- Brice, N. M., and R. L. Smith, Lower hybrid resonance emissions, J. Geophys. Res., 70, 71-80, 1965.
- Carpenter, D. L., and N. Dunkel, A dispersion anomaly in whistlers received on Alouette 1, J. Geophys. Res., 70, 3781-3786, 1965.
- Carpenter, D. L., N. Dunkel, and J. F. Walkup, A new very low frequency phenomenon: whistlers trapped below the protonosphere, J. Geophys. Res., 69, 5009-5017, 1964.
- Eckersley, T. L., Note on musical atmospherics, Phil. Mag., 49, 1250-1259, 1925.
- Eckersley, T. L., Musical atmospherics, Nature, 135, 104-105, 1935.
- Gallet, R. M., The very low-frequency emissions generated in the earth exosphere, Proc. IRE, 47 (2), 211-231, 1959.

- Gurnett, D. A., Very low frequency electromagnetic emissions observed with the O.N.R./S.U.I. satellite Injun III, University of Iowa Research Report 63-27, August 1963.
- Gurnett, D. A., and B. J. O'Brien, High-latitude geophysical studies with satellite Injun 3. 5. Very-low frequency electromagnetic radiation, J. Geophys. Res., 69, 65-89, 1964.
- Gurnett, D. A., S. D. Shawhan, N. M. Brice, and R. L. Smith, Ion cyclotron whistlers, J. Geophys. Res., 70, 1665-1687, 1965.
- Helliwell, R. A., Whistlers and Related Ionospheric Phenomena, Stanford University Press, Stanford, California, 1965.
- Helliwell, R. A., J. H. Crary, J. H. Pope, and R. L. Smith, The "nose" whistler--a new high-latitude phenomenon, J. Geophys. Res., 61, 139-142, 1956.
- Hines, C. O., Heavy-ion effects in audio-frequency radio propagation, J. Atmos. Terr. Phys., 11, 36-42, 1957.
- Kimura, I., and R. L. Smith, An interpretation of transverse whistlers, J. Geophys. Res., 70, 5961-5966, 1965.
- O'Brien, B. J., C. D. Laughlin, and D. A. Gurnett, The Injun III satellite, University of Iowa Research Report 62-24, 1962.
- Pfeiffer, G. W., D. A. Gurnett, S. D. Shawhan, and R. R. Shaw, Non-Eckersley law whistlers observed at equatorial latitudes with satellite Injun 3, Nature, 210, 827, 1966.

- Shawhan, S. D., Experimental observation of proton whistlers from Injun 3 VLF data, J. Geophys. Res., 71, 29-45, 1966a.
- Shawhan, S. D., Ray tracing in the ionosphere at VLF frequencies; An explanation of Non-Eckersley law whistlers, Paper 4-4-2, 1966 Spring URSI Meeting, Washington, D. C., 1966b.
- Shawhan, S. D., VLF ray tracing in a model ionosphere, Ph.D. dissertation, Department of Physics and Astronomy, University of Iowa, August 1966, to be published, 1966c.
- Smith, R. L., An explanation of subprotonospheric whistlers, J. Geophys. Res., 69, 5019-5021, 1964.
- Smith, R. L., et al., An ion gyrofrequency phenomenon observed in satellites, Nature, 204, 274, 1964.
- Stix, T. H., The Theory of Plasma Waves, McGraw Hill Book Company, Inc., New York, 1962.
- Storey, L. R. O., An investigation of whistling atmospherics, Phil. Trans. Roy. Soc. (London), A, 246, 113-141, 1953.
- Storey, L. R. O., A method to detect the presence of ionized hydrogen in the outer atmosphere, Can. J. Phys., 34, 1153-1163, 1956.

FIGURE CAPTIONS

Figure 1. Spectrograms and sketches of whistlers explained by considering only right-hand longitudinal propagation of VLF energy through the ionosphere: (A) Short and long fractional-hop whistlers received by Injun III, (B) Dispersion measurements of these whistlers showing that they obey the Eckersley law for whistlers, (C) Nose whistlers received at a ground VLF station, (D) Sketch of nose whistler using equation (2).

Figure 2. Magnetic Latitude vs Altitude: Sample density of Injun III VLF data studied. Data box represents 10° magnetic latitude x 10 km altitude. The number of satellite passes through each box is denoted by shading.

Figure 3. Geographic Local Time vs Altitude: Sample density of Injun III VLF data studied. Data box represents 2 hours x 100 km altitude. The number of satellite passes through each box is denoted by shading.

Figure 4. Magnetic Latitude vs Local Time: Sample density of Injun III VLF data studied. Data box represents 10° magnetic latitude x 2 hours. The number of satellite passes through each box is denoted by shading.

Figure 5. Spectrograms of Riser Whistlers Received by Injun III: (A) Non-Linear Riser, (B) Linear Appearing Riser. Low frequency cutoff F_{LC} shown for both risers.

Figure 6. Magnetic Latitude vs Altitude: Percentage occurrence of riser. Data Box = $10^\circ \times 100$ km. Percentages denoted by various shaded boxes.

Figure 7. Geographic Local Time vs Altitude: Percentage occurrence of riser. Data box = $10^\circ \times 100$ km. Percentages denoted by various shaded boxes.

Figure 8. Magnetic Latitude vs Local Time: Percentage occurrence of riser. Data box = 10×2 hours. Percentage denoted by various shaded boxes.

Figure 9. Altitude sequence of riser. The appearance of the riser on a frequency-time spectrogram remains nearly the same over the altitude range in which they are found.

Figure 10. Injun III--Ground Station Comparison.

- (A) Spectrogram of spherics received by Stanford Electronics Laboratory ground station (44° N lat, geomagnetic).
- (B) Spectrogram of Injun III VLF data for same time interval. Risers are visible in center of spectrogram. Arrows at top of spectrograms denote, from left to right, spheric associated with electron whistler at 0951:34.5, three spherics that could be associated with the riser at 0951:38, two spherics that could be associated with riser at 0951:41.

Figure 11. Spectrograms of check whistlers received by Injun III.

(A) Highest altitude check whistler.

(B) Lowest altitude check whistler.

The extreme similarity of the two whistlers is to be noted.

Figure 12. Magnetic Latitude vs Altitude: Percentage occurrence of check whistler. Data box = $10^\circ \times 100$ km. Various shaded boxes denote percentages.

Figure 13. Geographic Local Time vs Altitude: Percentage occurrence of check whistler. Data box = 2 hours $\times 100$ km. Various shaded boxes denote percentages.

Figure 14. Magnetic Latitude vs Geographic Local Time: Percentage occurrence of check whistler. Data box = $10^\circ \times 2$ hours. Various shaded boxes denote percentages.

Figure 15. Spectrograms of hook whistlers received by Injun III.

(A) Hook whistler with short time interval between components.

(B) Hook whistler with greater time interval between components.

Both whistlers close at low frequencies and both whistlers have one component that does not obey the Eckersley law for whistlers. Note that the time scale in Figure 15a has been expanded by a factor of 4.

Figure 16. Spectrogram of hook whistlers received with the Injun III VLF receiver.

- (A) Frequency-time spectrogram of hook whistlers.
- (B) Plot of $f^{-1/2}$ as a function of time for the two components of the hook whistler in (16A).
- (C) Spectrogram showing many hook whistlers occurring in a short time interval.

Figure 17. Spectrograms of hook whistlers received by the Injun III satellite between 2600 and 2785 km. Although these whistlers were received in approximately the same region of the ionosphere, they differ considerably in time difference Δt between components and in dispersion.

Figure 18. Magnetic Latitude vs Altitude: Percentage occurrence of the hook whistler. Data box = $10^\circ \times 100$ km. Various shaded boxes denote percentages.

Figure 19. Local Time vs Altitude: Percentage occurrence of the hook whistler. Data box = 2 hours \times 100 km. Various shaded boxes denote percentages.

Figure 20. Magnetic Latitude vs Local Time: Percentage occurrence of the hook whistler. Data box = $10^\circ \times 2$ hours. Various shaded boxes denote percentages.

Figure 21. Whistlers received by Injun III that do not obey the Eckersley law for whistlers:

- (A) Nose whistler.
- (B) Subprotonospheric whistler.
- (C) Proton whistler.

Figure 22. Whistlers received by Injun III that apparently have high frequency components missing. The definite cut-off frequencies are indicated by arrows in the left-hand margin.

Figure 23. Whistlers received by Injun III that apparently have low frequency components missing.

Figure 24. Chorus-whistler event received by Injun III. Chorus abruptly ceases at 0435:00 and electron whistlers start at 0435:04 (shown by arrow).

G66-533

TYPICAL WHISTLERS AND DISPERSION PLOT

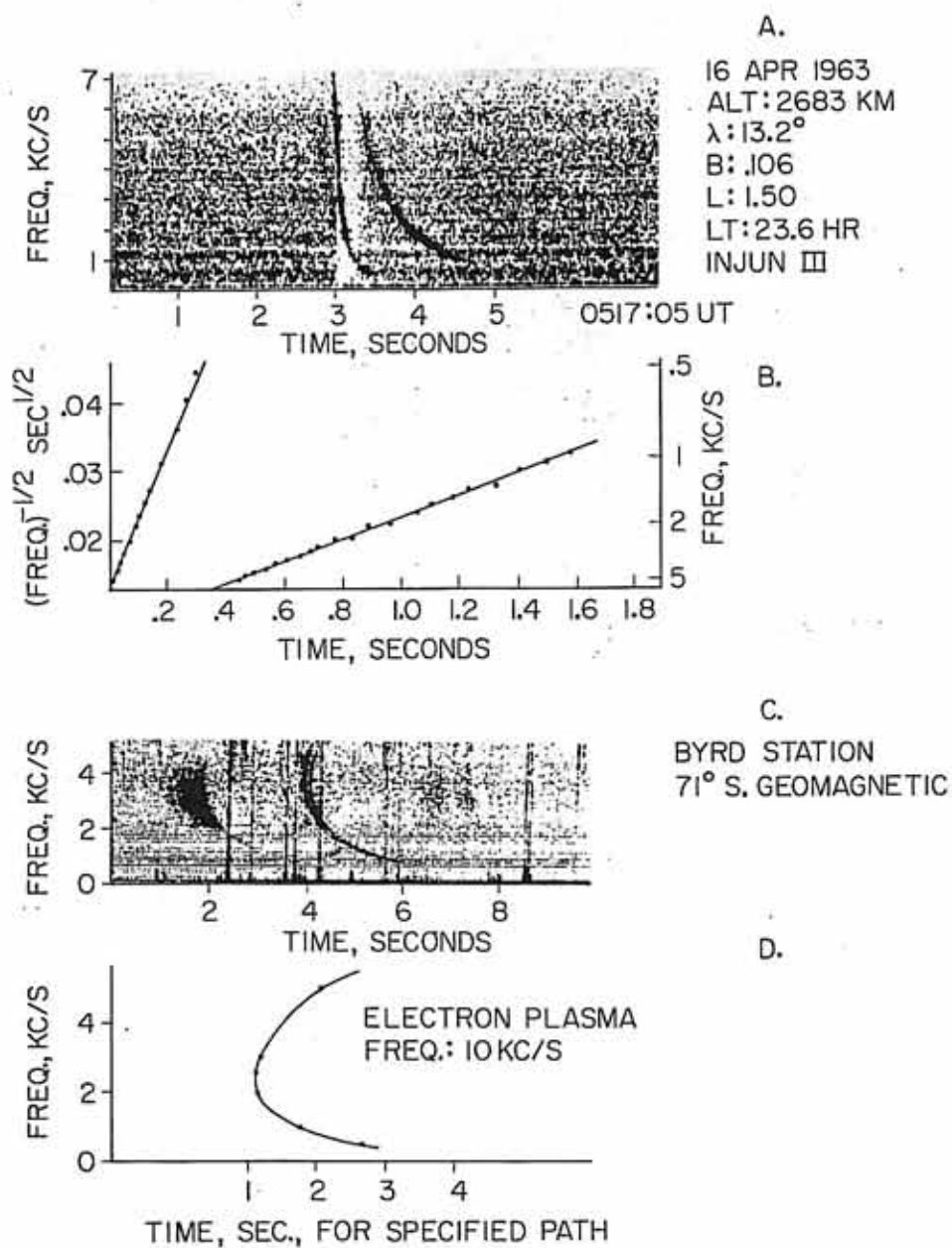


Figure 1

G 66-434

MAG. LATITUDE VS ALTITUDE: SAMPLE DENSITY
OF INJUN III VLF DATA STUDIED

DATA BOX = 10° LAT. X 100 KM P = NUMBER OF PASSES

\square $P=0$, \square $0 < P < 5$, \square $5 \leq P < 10$, \square $10 \leq P < 20$, \blacksquare $20 \leq P$

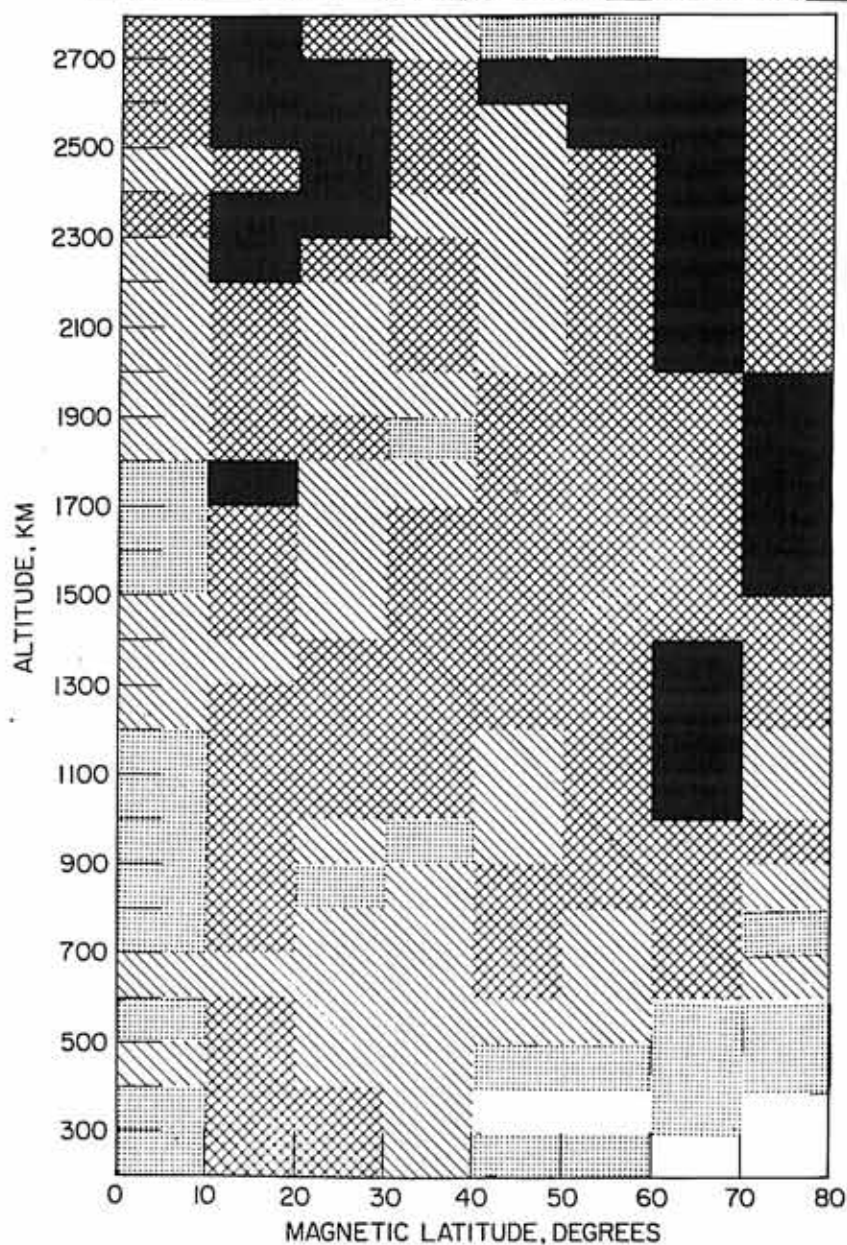


Figure 2

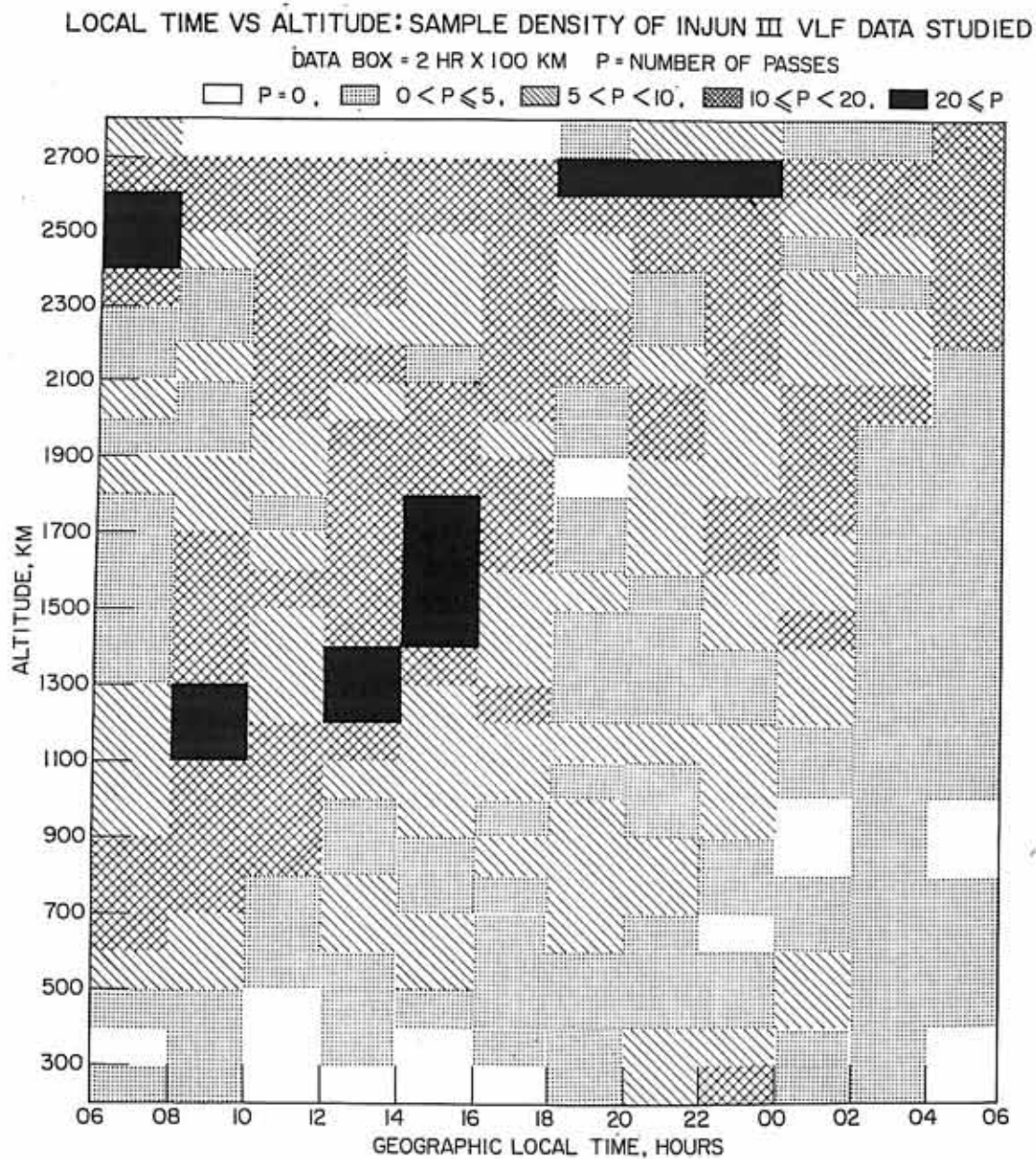


Figure 3

666-450

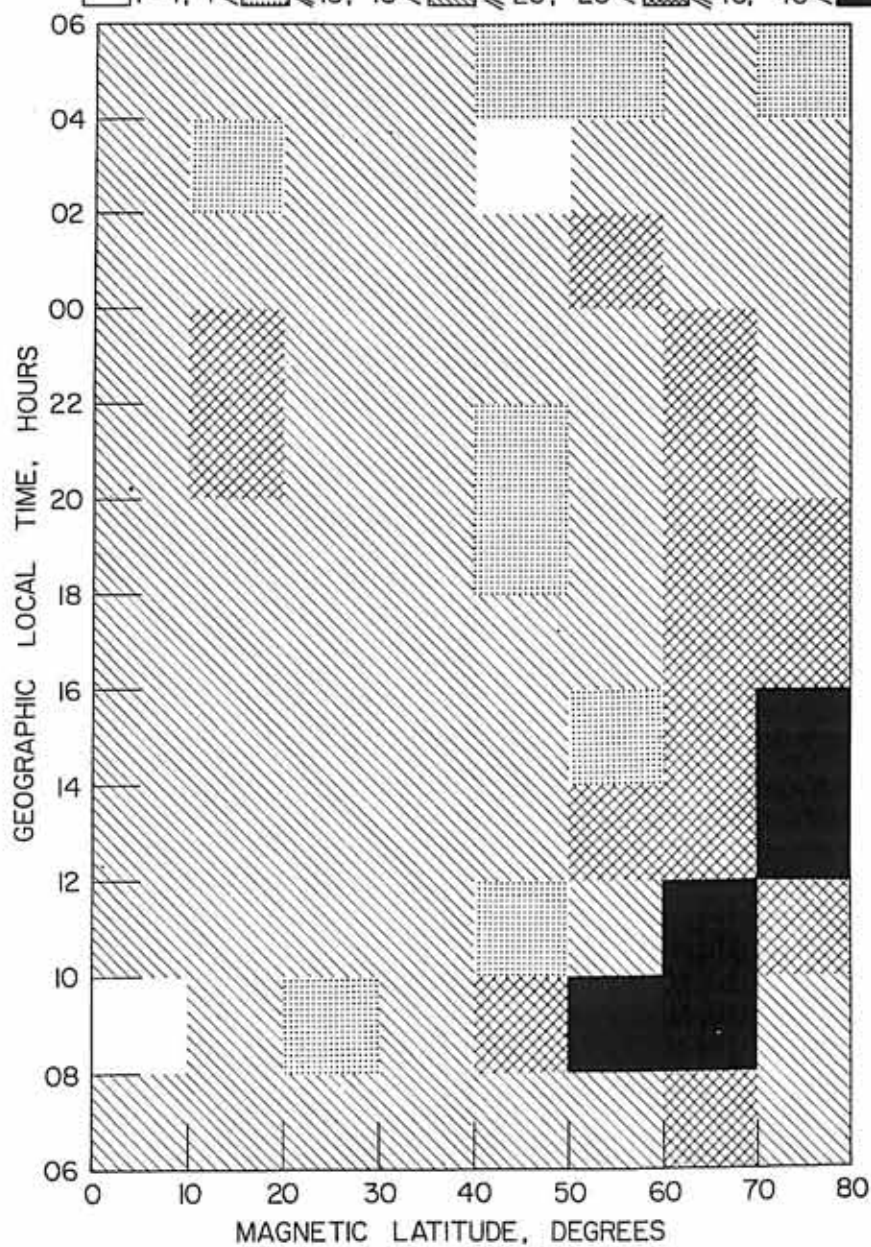
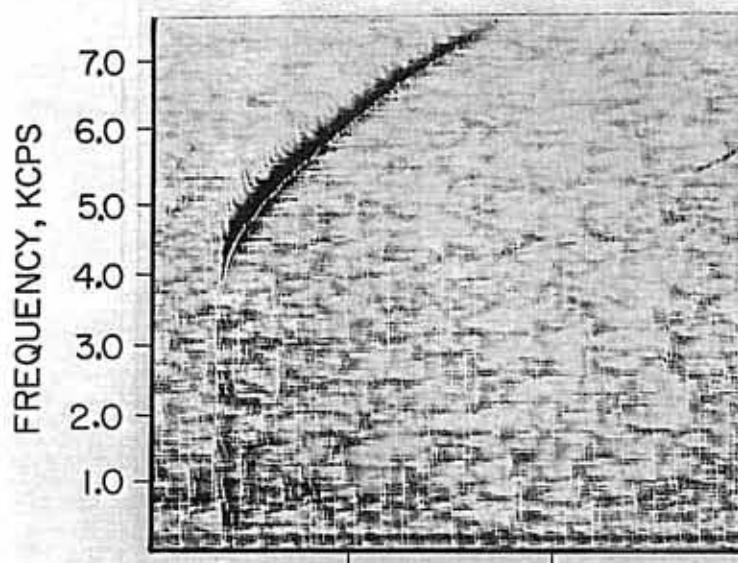
MAGNETIC LATITUDE VS LOCAL TIME; SAMPLE DENSITY
OF INJUN III VLF DATADATA BOX = 10° LAT X 2 HR P = NUMBER OF PASSESP=1, $1 < P \leq 10$, $10 < P \leq 20$, $20 < P \leq 40$, $40 < P$ 

Figure 4

G66-505

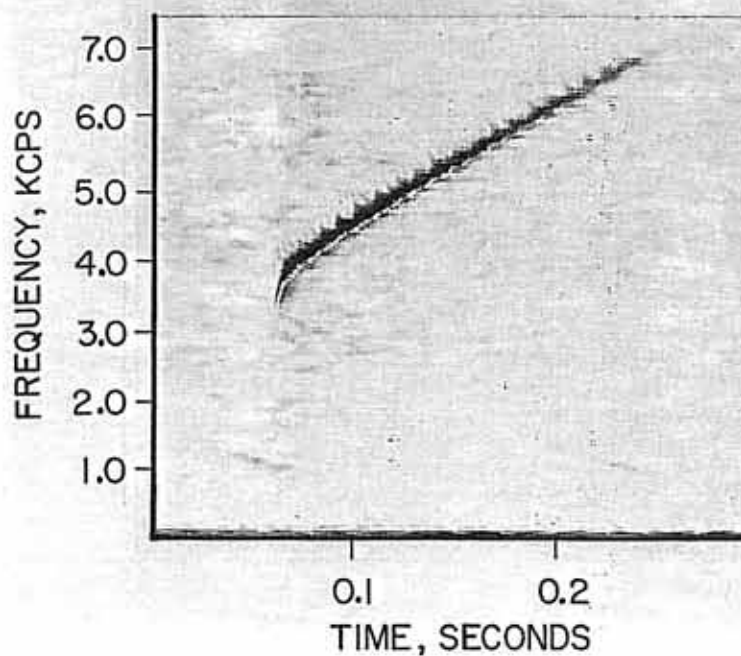
RISERS RECEIVED WITH
SATELLITE INJUN III

A.



4 JAN 1963
1010:52 UT
ALT: 2607 KM
 $\lambda: 11^\circ$
B: .112
L: 1.54
LT: 16.7 HR

B.



30 APR 1963
1730:30 UT
ALT: 2665 KM
 $\lambda: 15^\circ$
B: .119
L: 1.56
LT: 17.5 HR

Figure 5

G 66-433

MAG. LATITUDE VS ALTITUDE: PERCENTAGE OCCURRENCE OF RISER

DATA BOX = 10° LAT. X 100 KM

□ 0%, 0 < ▤ < 25%, 25 ≤ ▨ < 50%, 50 ≤ ▩ ≤ 75%, 75 < ■ ≤ 85%

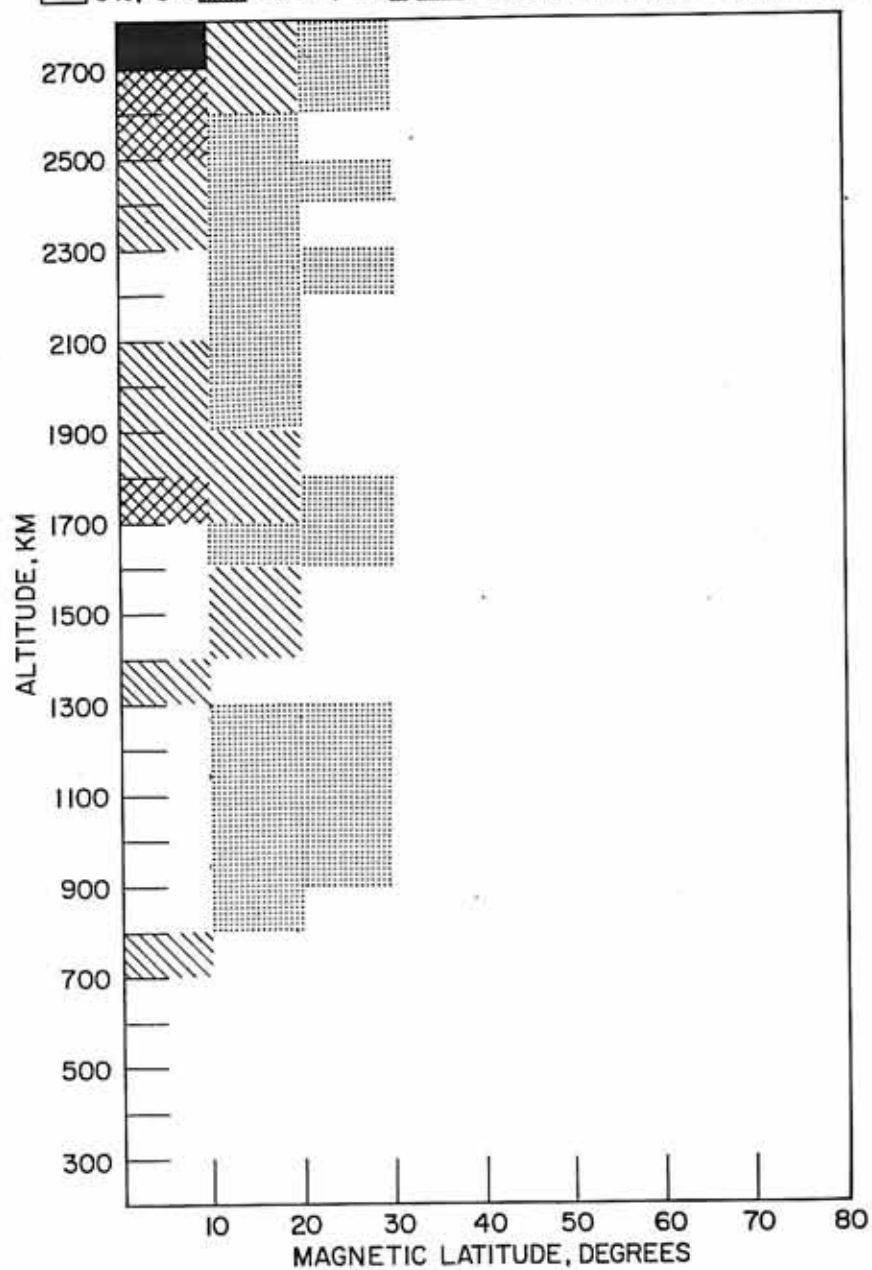


Figure 6

G 66-449

LOCAL TIME VS ALTITUDE: PERCENTAGE OF OCCURRENCE
OF RISER

DATA BOX = 2 HR X 100 KM

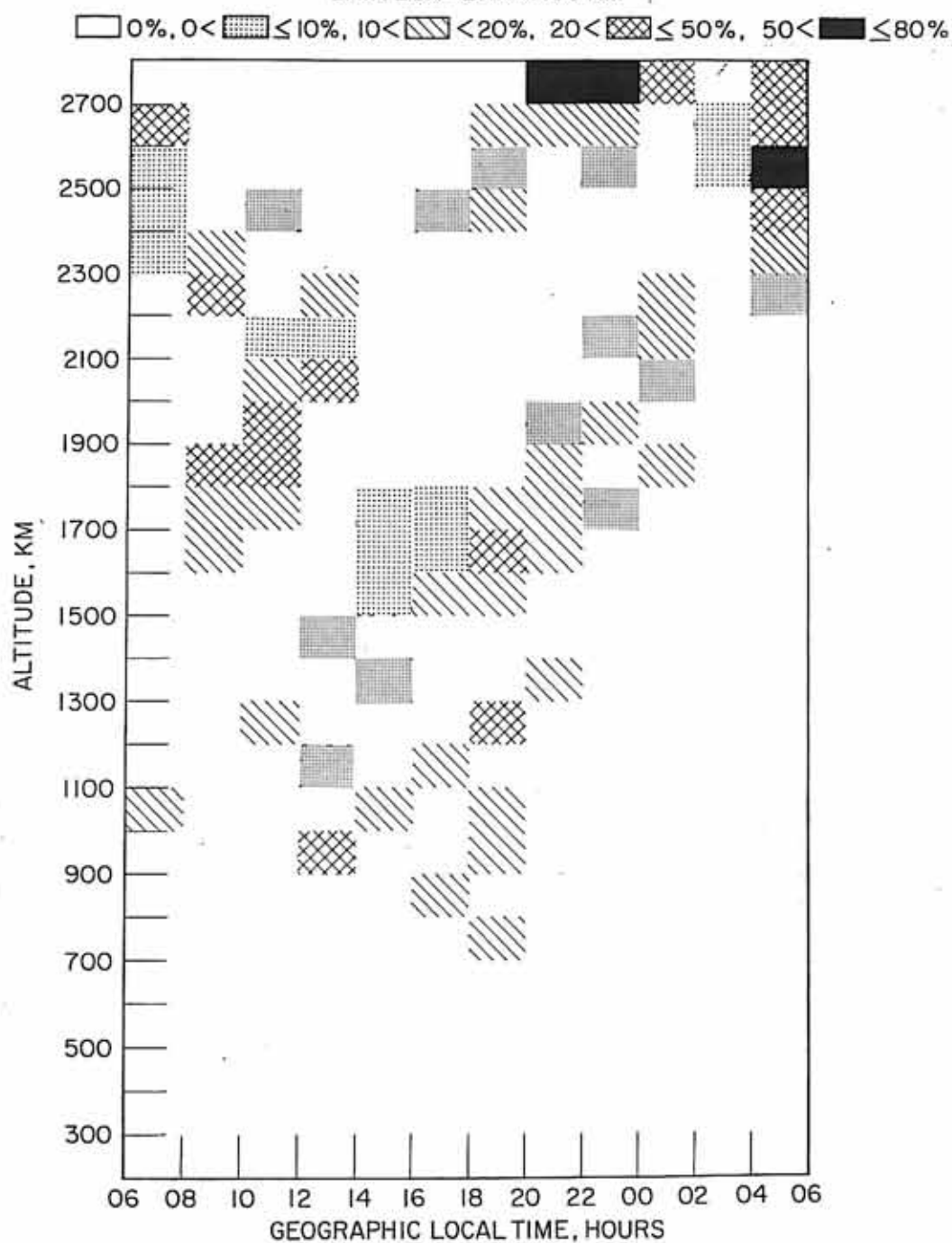


Figure 7

MAGNETIC LATITUDE VS LOCAL TIME : PERCENTAGE OCCURRENCE
OF RISER

DATA BOX = 10° X 2 HR

0% , 0 < ≤ 10% , 10 < ≤ 25% , 25 < ≤ 50% , 50 < ≤ 80%

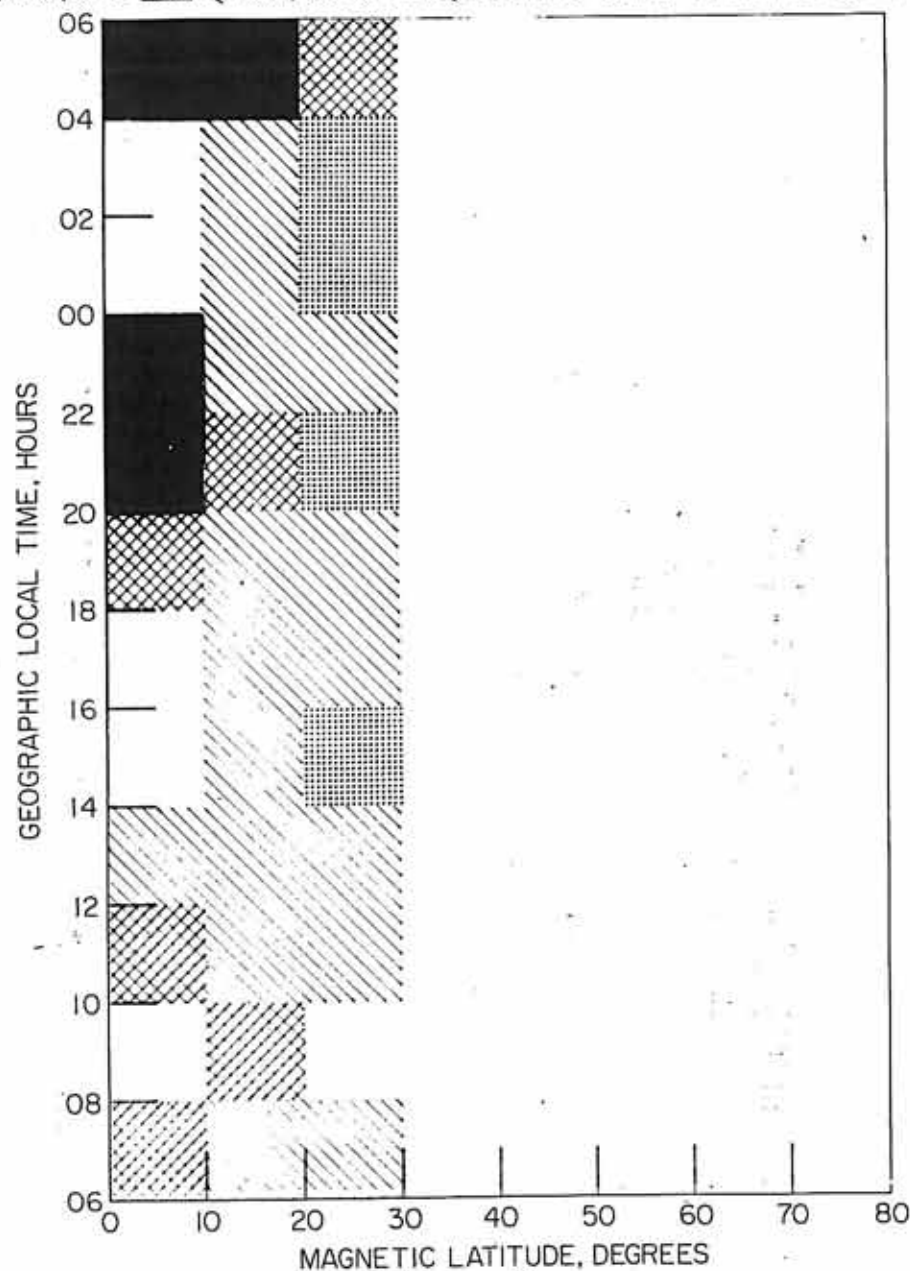


Figure 8

G 66-415

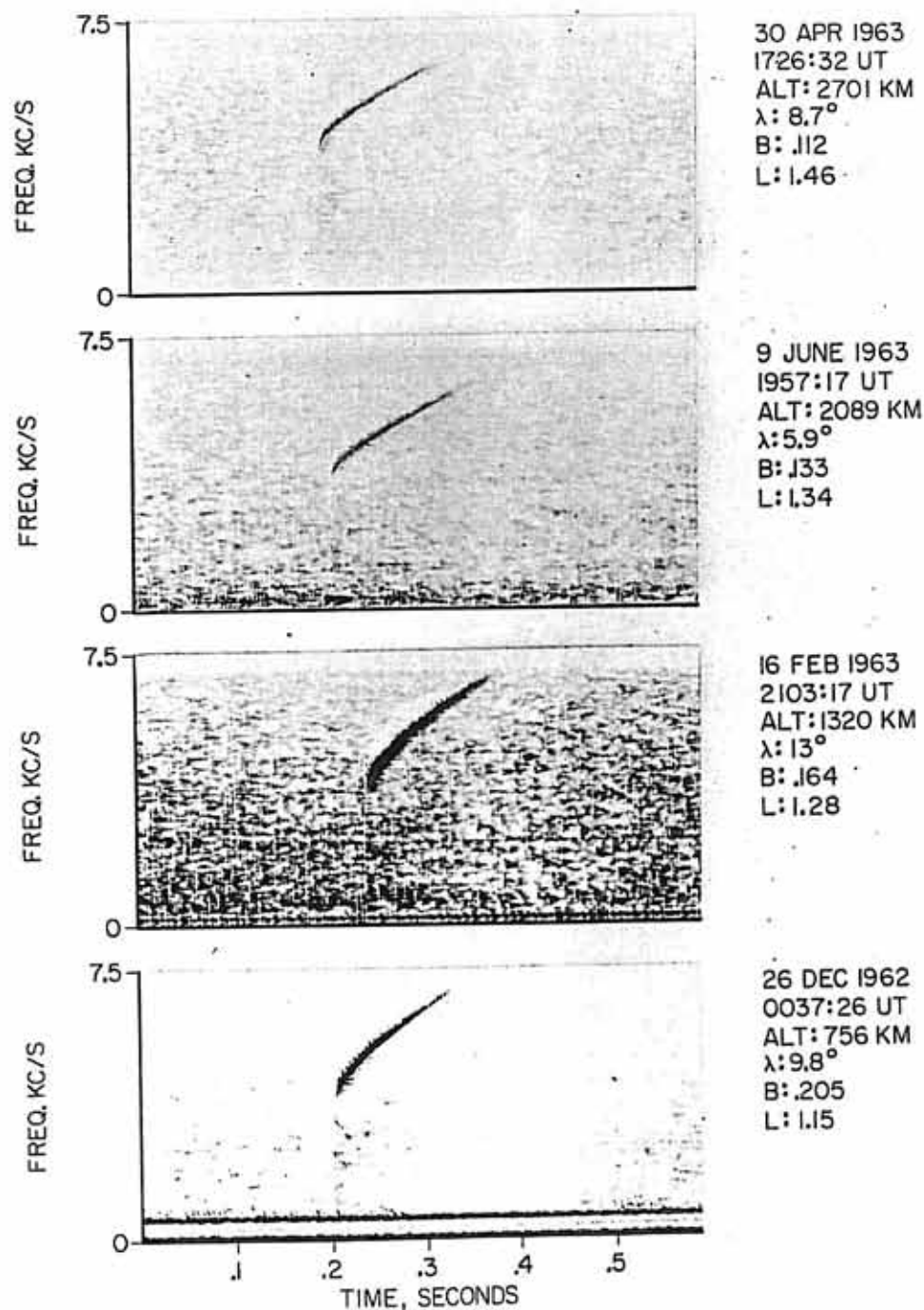
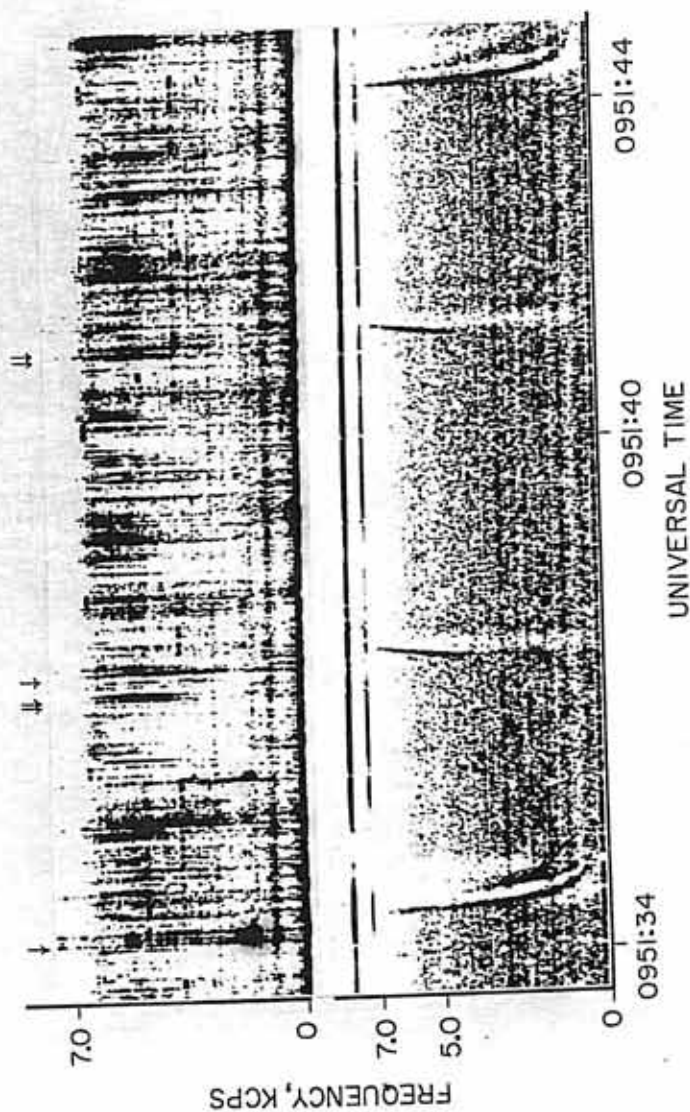
ALTITUDE SEQUENCE OF RISER WHISTLERS
RECEIVED WITH SATELLITE INJUN III

Figure 9

G66-475

INJUN III - GROUND STATION COMPARISON



STANFORD
44° N. LAT. GEOMAG.
122° W. LONG.

7 JAN 1963
ALT: 2521 KM
 λ : 14.3°
B: 113
L: 1.41
LONG: 90° W.

Figure 10

G66-474

CHECK WHISTLERS RECEIVED WITH SATELLITE INJUN III

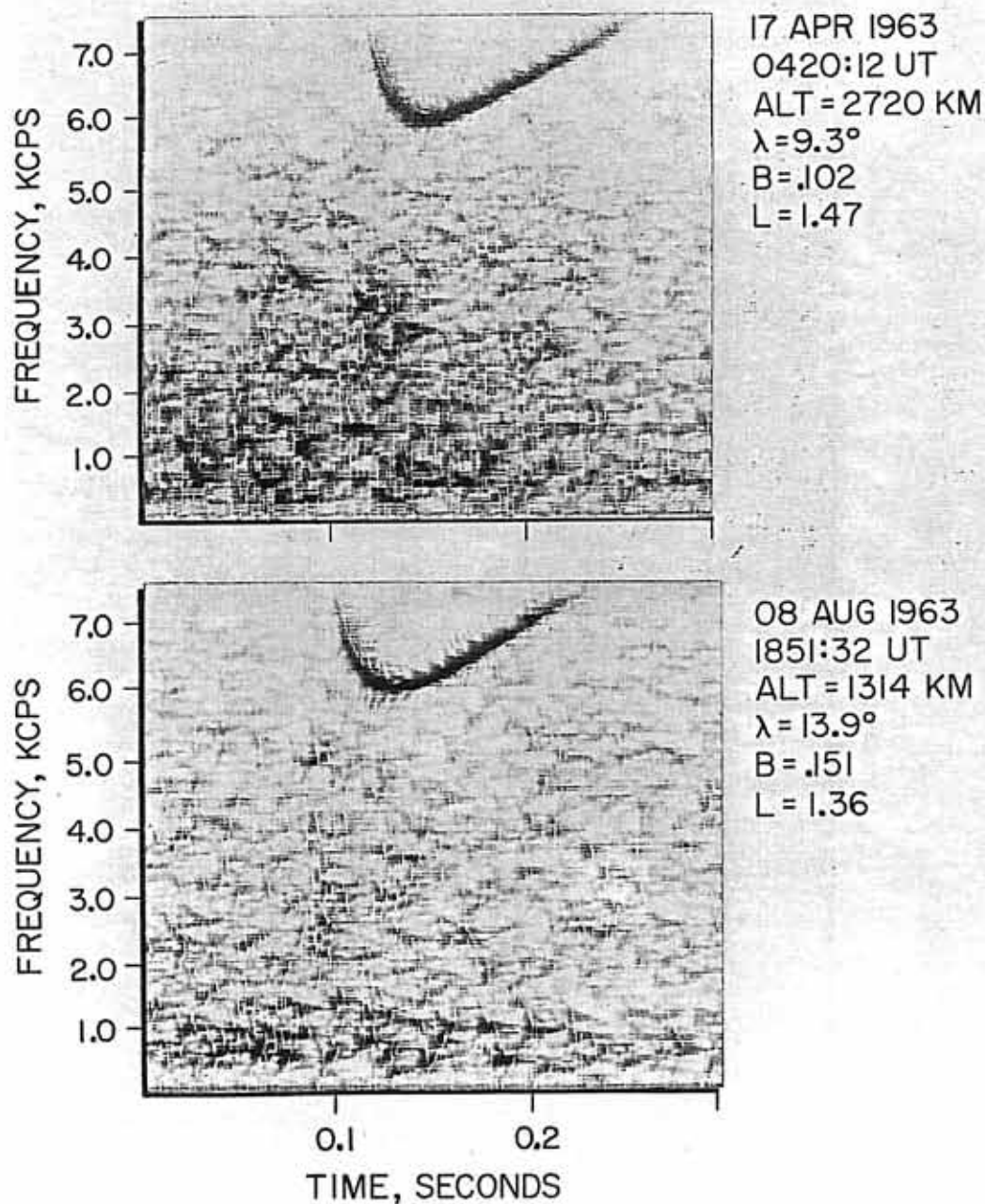


Figure 11

G 66-432

MAG. LATITUDE VS ALTITUDE: PERCENTAGE OCCURRENCE
OF CHECK WHISTLER
DATA BOX=10° LAT. X 100 KM

0%, 0 < [diagonal lines] ≤ 5%, 5 < [cross-hatch] ≤ 10%, 10 < [dotted] ≤ 20%, 20 < [solid black] ≤ 25%

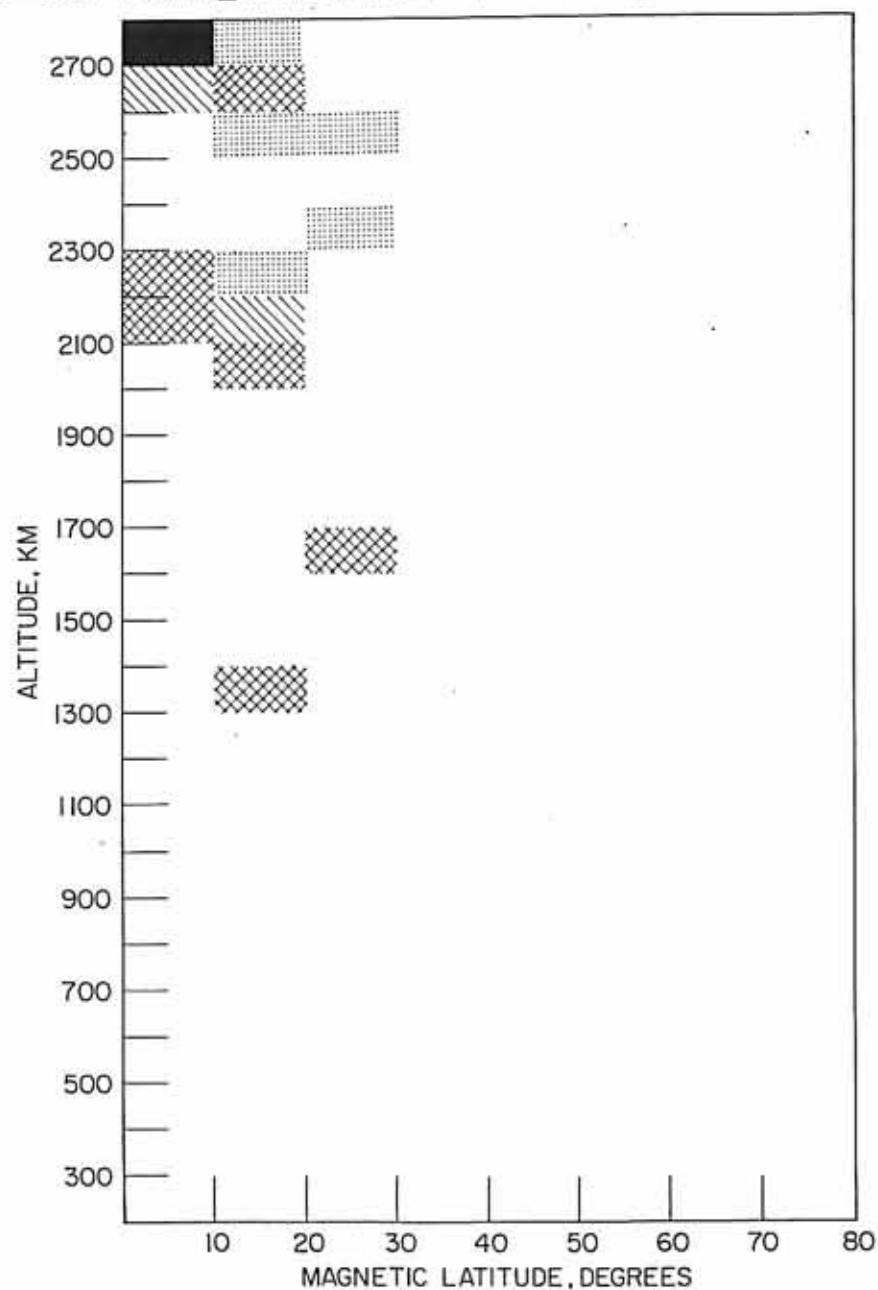


Figure 12

G66-451

LOCAL TIME VS ALTITUDE: PERCENTAGE OCCURRENCE
OF CHECK WHISTLER

- DATA BOX = 2 HR X 100 KM

□ 0%, 0 < ■ ≤ 5%, 5 < ▨ ≤ 10%, 10 < ▩ ≤ 20%, 20 < ■ ≤ 35%

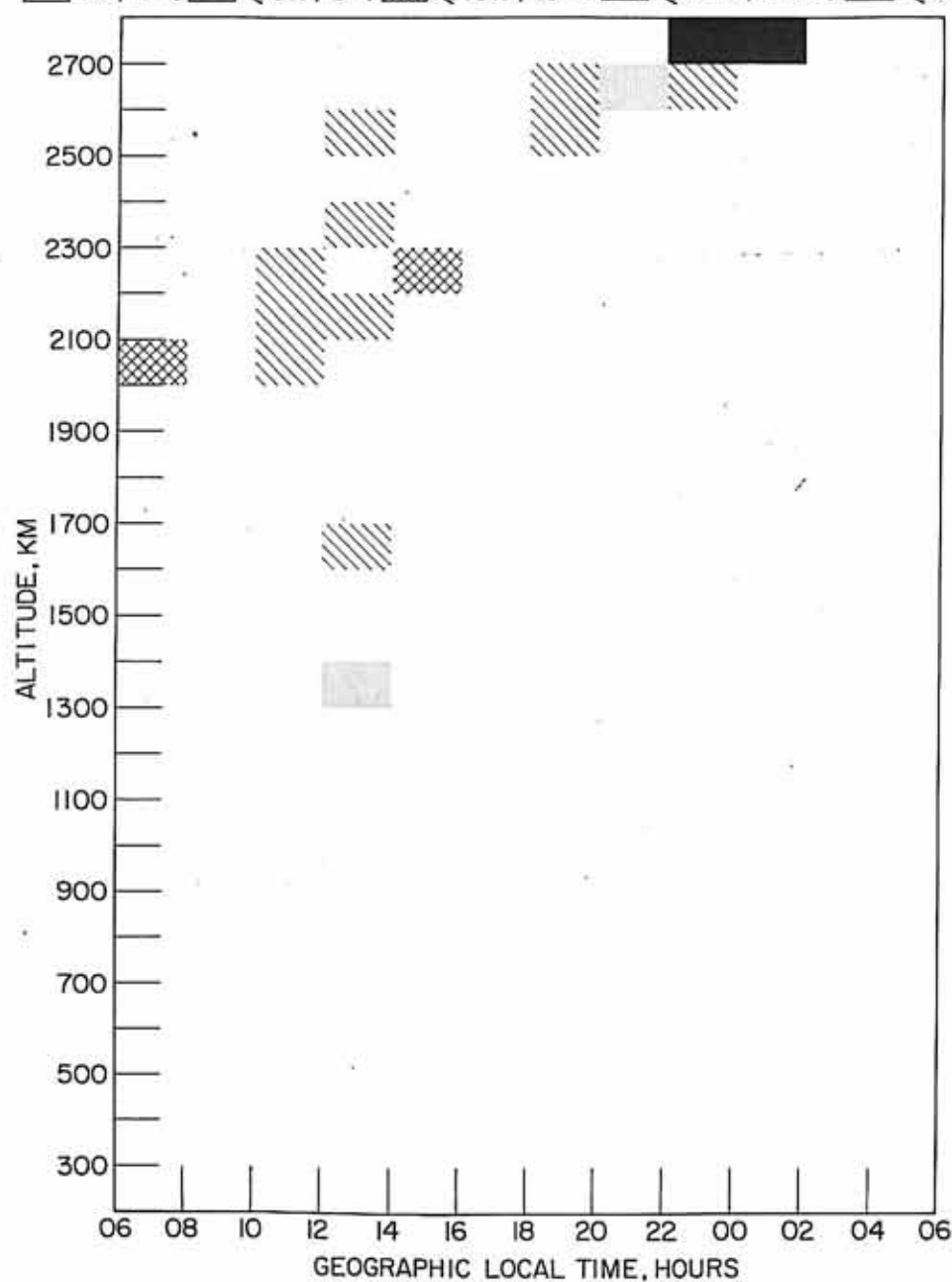


Figure 13

G 66-467

MAGNETIC LATITUDE VS LOCAL TIME: PERCENTAGE OCCURRENCE
OF CHECK WHISTLER
DATA BOX = $10^{\circ} \times 2$ HRS

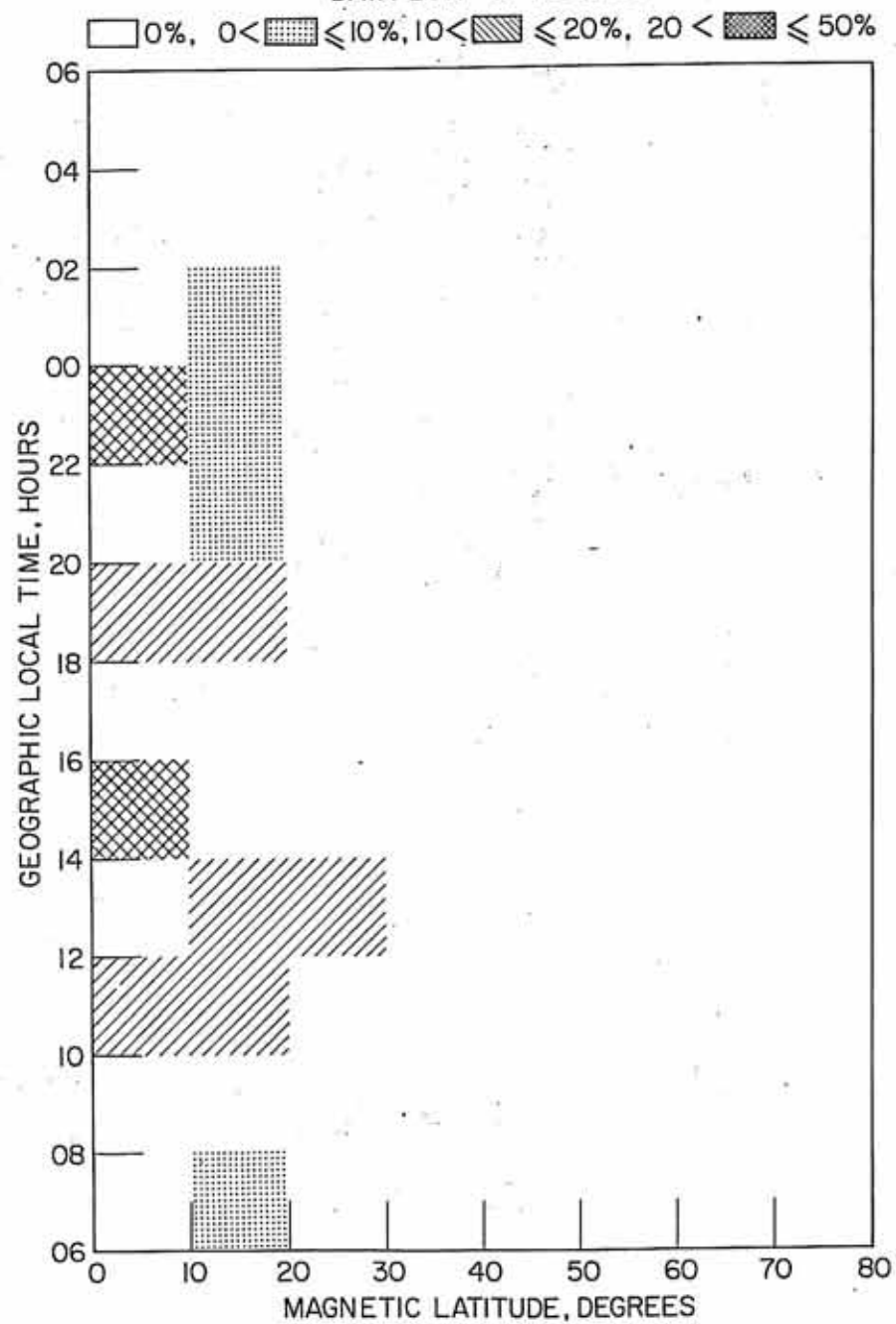
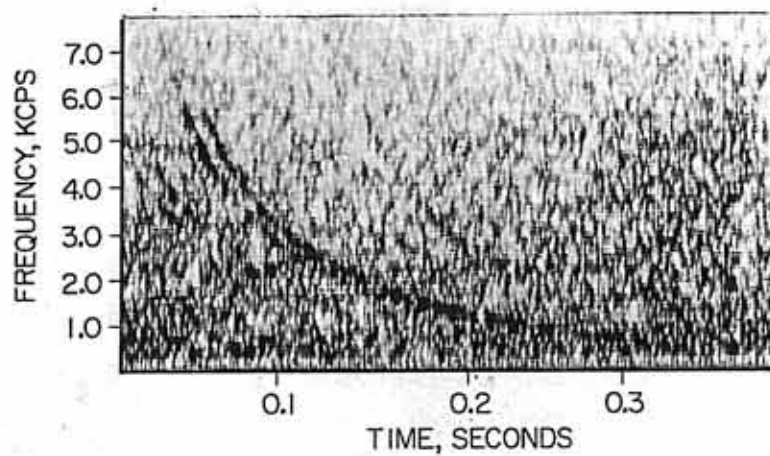


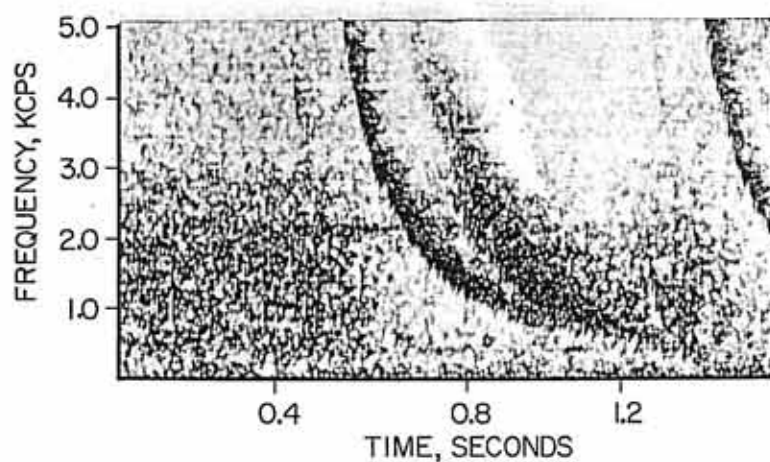
Figure 14

G 66-481

HOOK WHISTLERS RECEIVED WITH SATELLITE
INJUN III

A.

12 APR. 1963
0453:19 UT
ALT: 2704 KM
 λ : 10.1°
B: J0J
L: 1.47
LT: 23.9 HR



B.

7 JAN. 1963
0948:10 UT
ALT: 2633 KM
 λ : 21.0°
B: J19
L: 1.62
LT: 3.73 HR

Figure 15

046-506

HOOK WHISTLERS RECEIVED WITH SATELLITE INJUN III

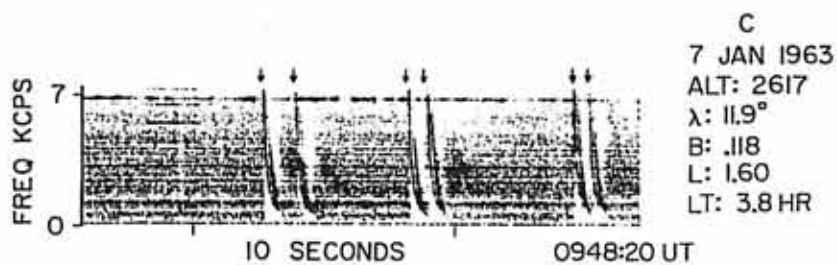
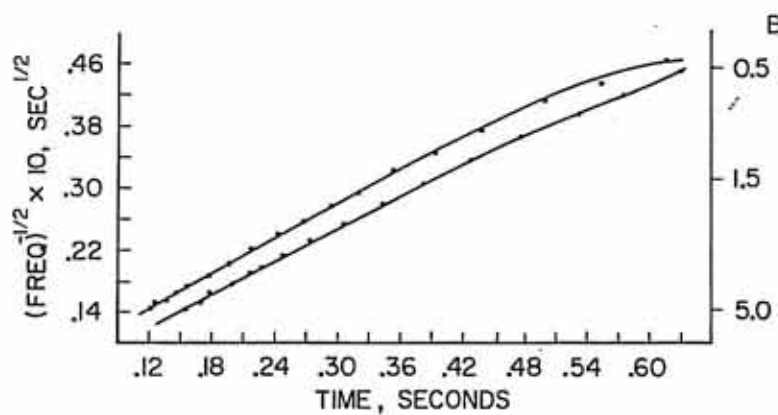
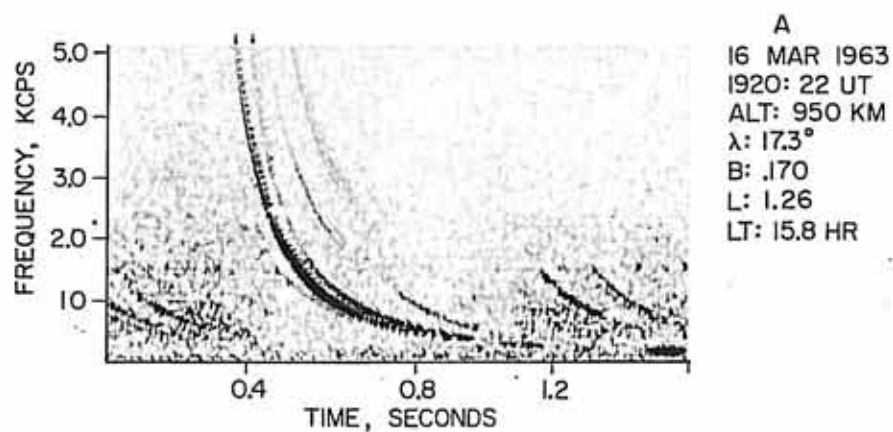


Figure 16

G66-483

HOOK WHISTLERS RECEIVED WITH SATELLITE INJUN III

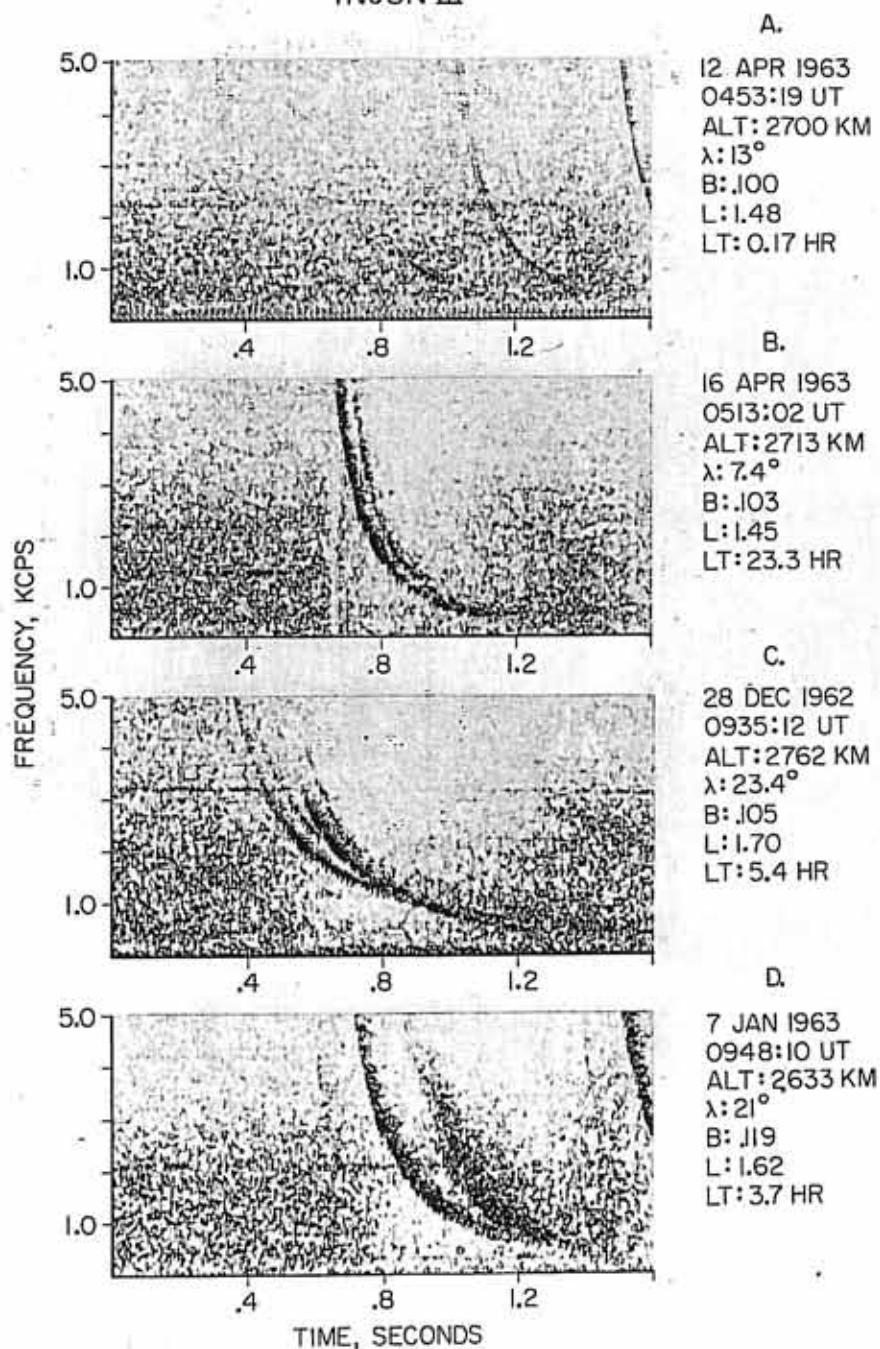


Figure 17

G66-431

MAG. LATITUDE VS ALTITUDE: PERCENTAGE OCCURRENCE
OF HOOK WHISTLER

DATA BOX = 10° LAT. X 100 KM

0%, 0 < 5%, 5 < 15%, 15 < 25%, 25 < 40%

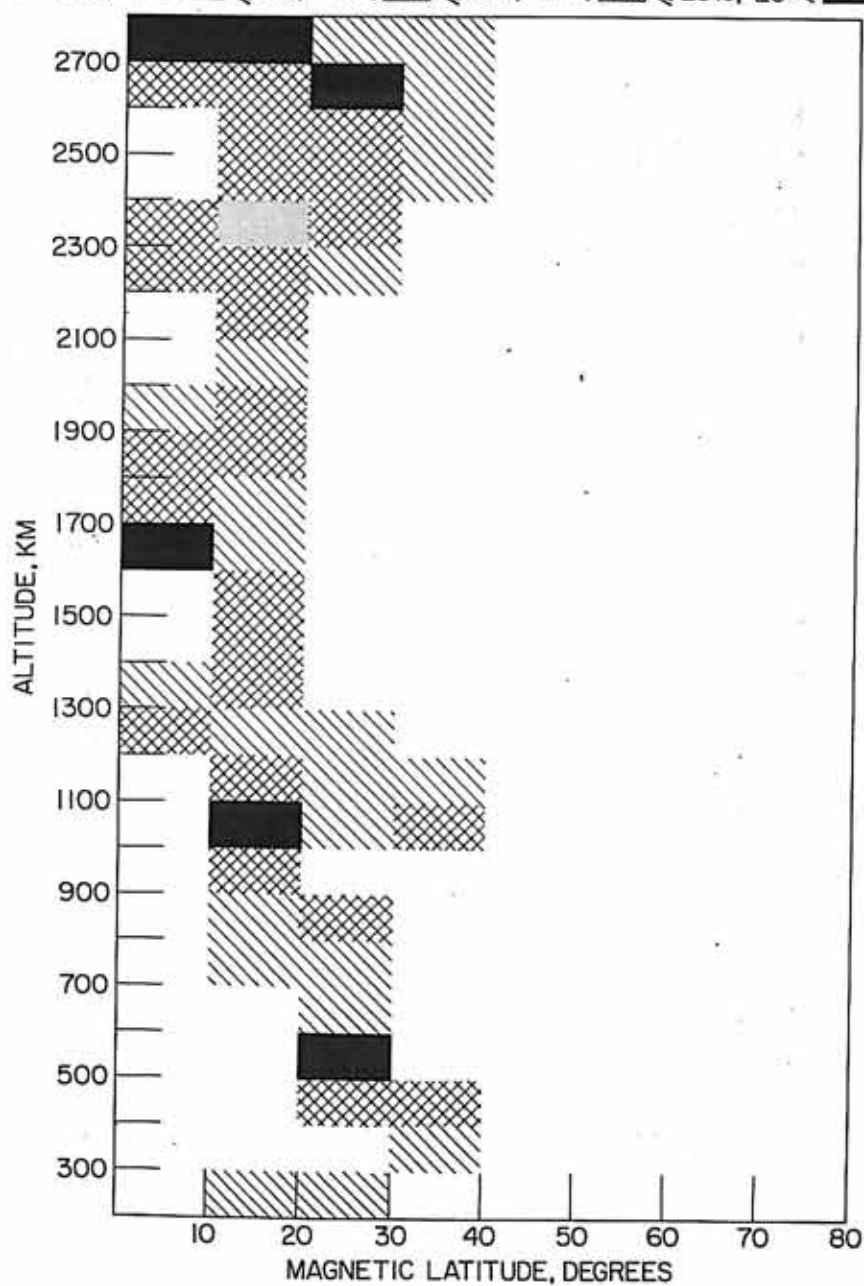


Figure 18

LOCAL TIME VS ALTITUDE - PERCENTAGE OCCURENCE OF HOOK WHISTLER

DATA BOX = 2 HR X 100 KM

0%, 0 < 10%, 10 < 20%, 20 < 30%, 30 < 50%

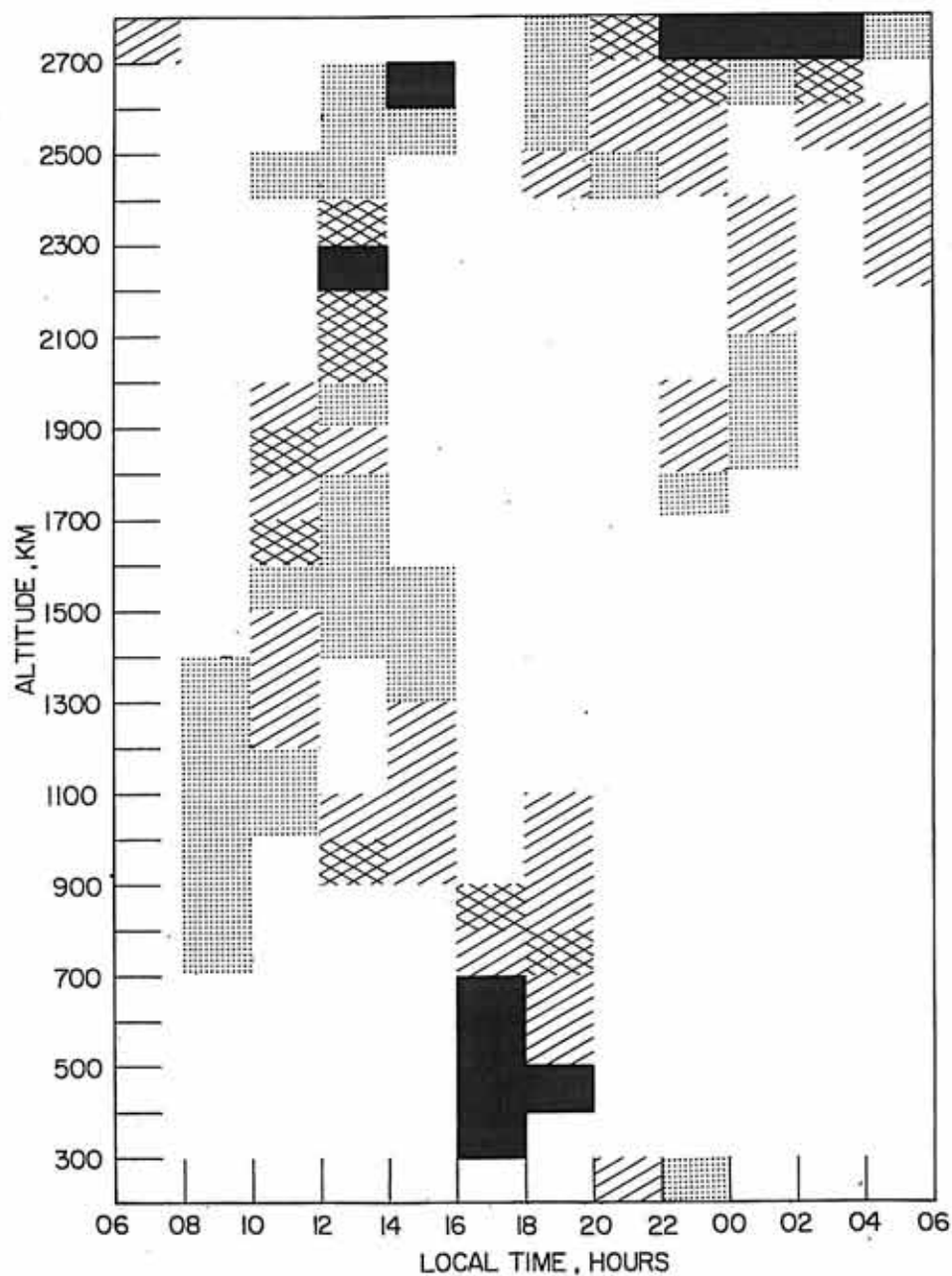






Figure 19

G66-468

MAGNETIC LATITUDE VS LOCAL TIME: PERCENTAGE OCCURRENCE OF HOOK WHISTLER

DATA BOX = $10^{\circ} \times 2$ HR.

0%, 0 <  ≤ 10%, 10 <  ≤ 20%, 20 <  ≤ 50%, 50 <  ≤ 75%

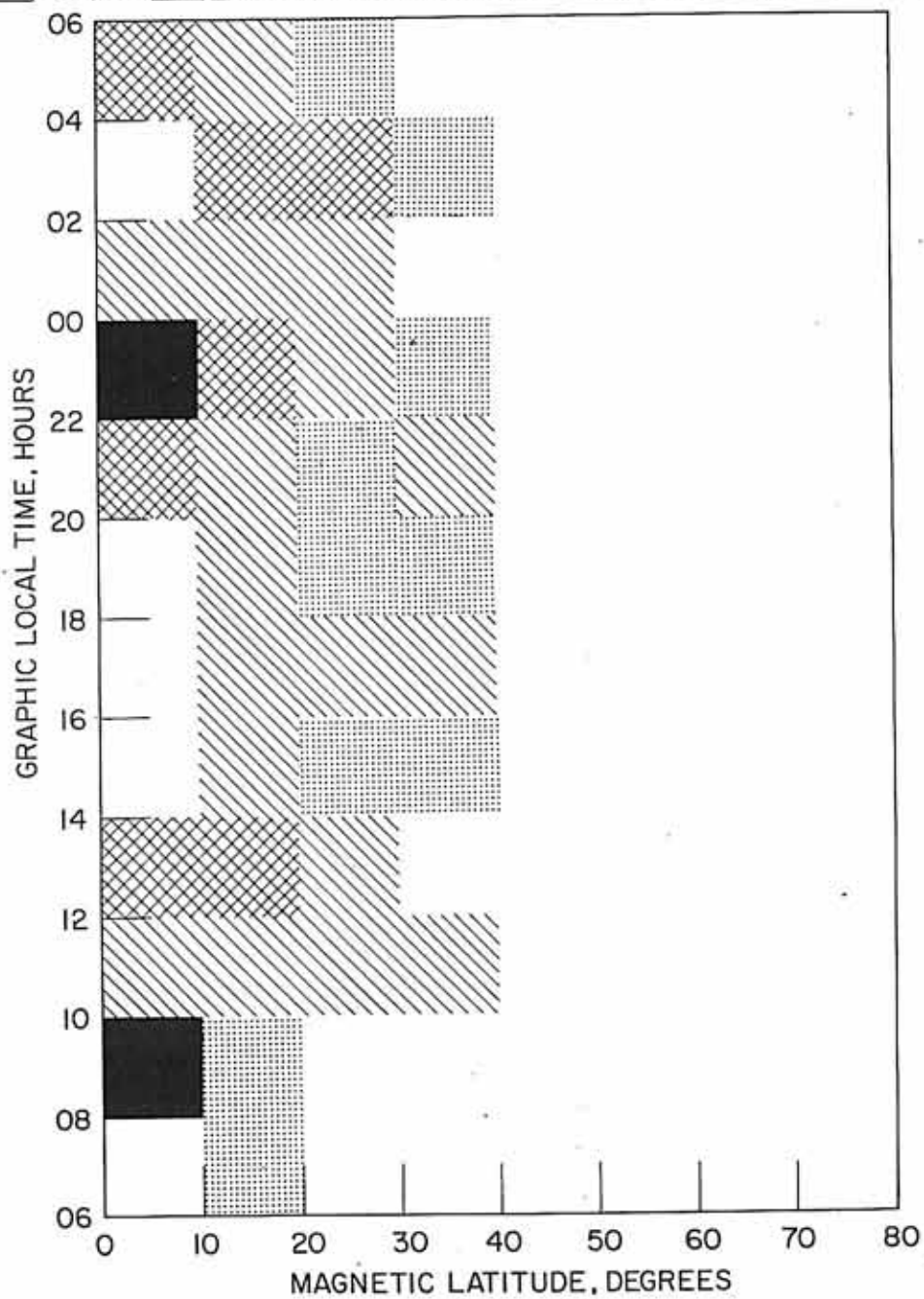


Figure 20

G66-511

NON-ECKERSLEY LAW WHISTLERS RECEIVED
WITH SATELLITE INJUN III

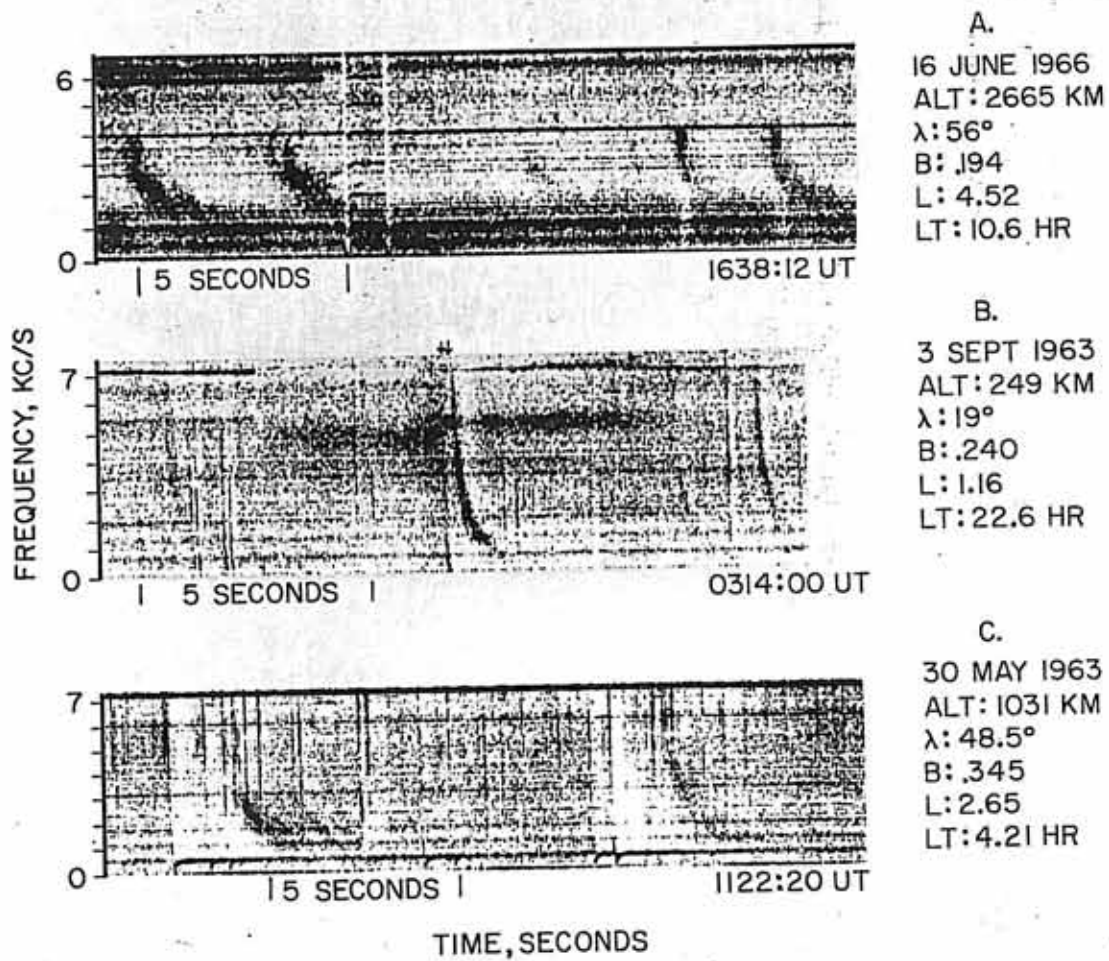


Figure 21

WHISTLERS WITH HIGH-FREQUENCY COMPONENTS MISSING RECEIVED BY SATELLITE INJUN III

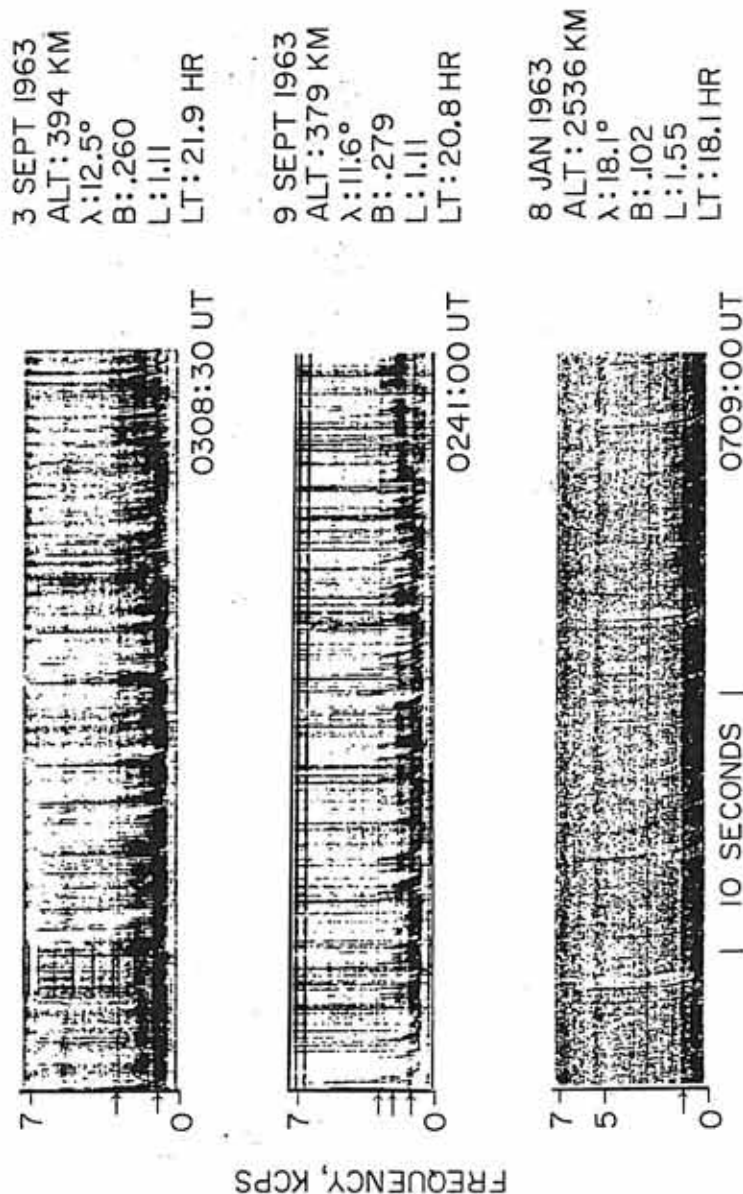


Figure 22

G66-480

WHISTLERS WITH LOW-FREQUENCY COMPONENTS
MISSING RECEIVED BY SATELLITE INJUN III.

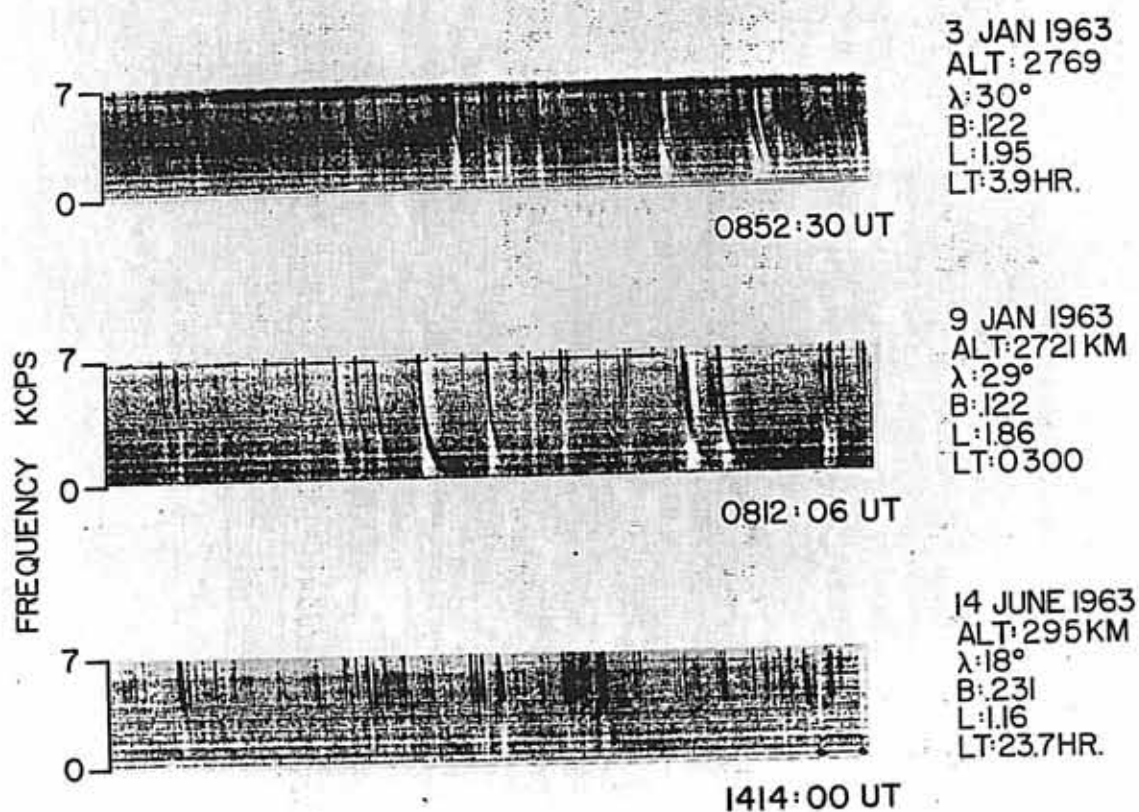


Figure 23

G66-448

CHORUS-WHISTLER EVENT OBSERVED
WITH INJUN III
23 AUG. 1963

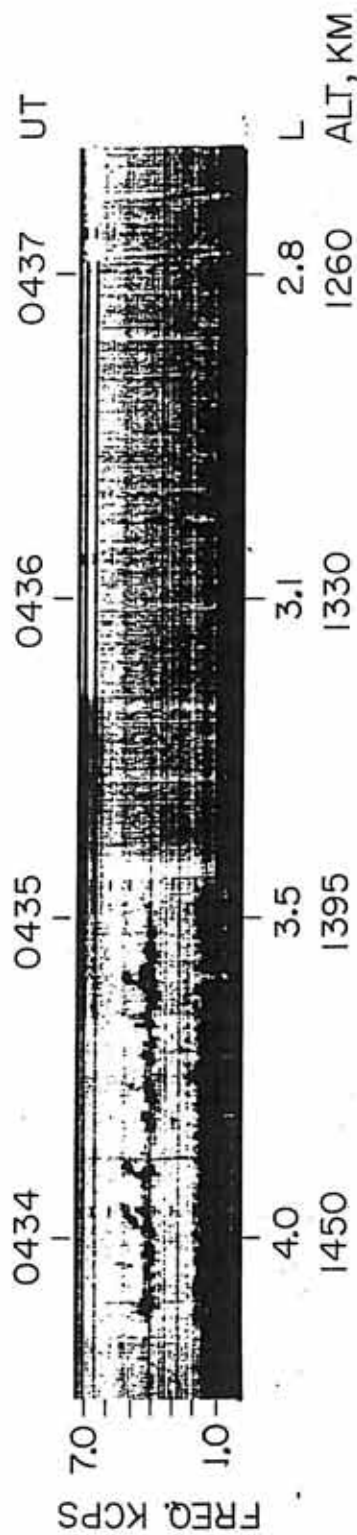


Figure 24