

Reprint from

EARTH'S PARTICLES AND FIELDS

*Proceedings of the NATO Advanced Study
Institute held at Freising, Germany
July 31 — August 11, 1967*

Edited by

Billy M. McCormac
*Physics Division, IIT Research Institute
Chicago, Illinois*

Copyright© 1968 by
REINHOLD BOOK CORPORATION
All rights reserved

REINHOLD BOOK CORPORATION
A subsidiary of Chapman-Reinhold, Inc.
New York Amsterdam London

SATELLITE OBSERVATIONS OF VLF EMISSIONS AND THEIR ASSOCIATION WITH ENERGETIC CHARGED PARTICLES

Donald A. Gurnett

*Department of Physics and Astronomy
University of Iowa
Iowa City, Iowa*

Introduction

Very-low-frequency (VLF) emissions are naturally occurring VLF radio noises generated by energetic charged particles in the earth's magnetosphere. These emissions have been extensively investigated using ground-based VLF receivers. Systematic classifications of VLF emissions according to their frequency-time form have been given by GALLET (1959) and more recently by HELLIWELL (1965). Studies of the region of occurrence for various types of VLF emissions have been carried out by numerous investigators including, ELLIS (1959), MARTIN *et al.* (1960), POPE (1963), LAASPERE *et al.* (1964), and JØRGENSEN (1966).

Ground-based observations of VLF phenomena, however, have a number of serious disadvantages compared to satellite measurements. These disadvantages include: (1) variable and unknown absorption and transmission losses through the base of the ionosphere, (2) total internal reflection of VLF waves at the base of the ionosphere, and (3) difficulty in determining the latitude of a VLF emission because of propagation in the earth-ionosphere waveguide over long distances. These are all largely overcome by satellite measurements of VLF phenomena.

A summary of recent satellite observations of VLF emissions are presented. The intensities and regions of occurrence for various types of VLF emissions are summarized and simultaneous charge particle fluxes and VLF measurements available from the INJUN III satellite are compared.

The Broadband Intensity of Magnetospheric VLF Emissions

The VLF experiment on the INJUN III satellite was used to obtain a preliminary evaluation of the intensity and region of occurrence of VLF emissions

(see GURNETT and O'BRIEN, 1964). The broadband (0.2 to 7 kHz) magnetic field strength was investigated as a function of invariant latitude (INV-Arccos $L^{-1/2}$) (McILWAIN, 1961) and magnetic local time (MLT) (CHAMBERLAIN, 1961) without regard to altitude (perigee, 236 km; apogee, 2785 km) or to the type of emission. To provide proper normalization of the data MLT and INV were divided into blocks, 1 hour by 1 degree. On a given revolution the first data point within a given block was taken to be representative of the entire block for that revolution. Approximately 48,000 broadband magnetic field strength measurements were used in the data analysis: one measurement per MLT-INV block per revolution. The largest field strength found was 30 milligammas. Only 825 measurements, or 1.7 per cent exceeded 4.0 milligammas,

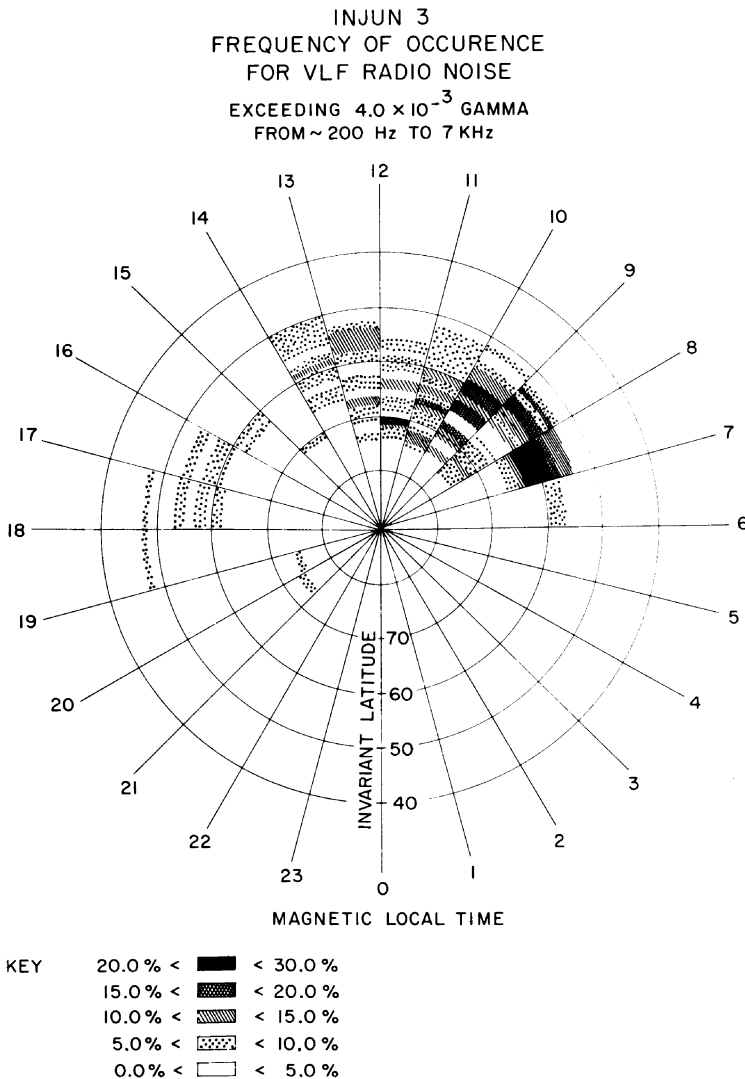


FIGURE 1. Normalized frequency of occurrence for broadband magnetic field strengths exceeding 4.0 milligammas.

and 5,300 measurements, or 11 per cent, exceeded 1.5 milligammas (approximately twice the receiver noise level). Figures 1 and 2 show the normalized frequency of occurrence for broadband magnetic field strengths exceeding 4.0 and 1.5 milligammas, respectively, as a function of INV and MLT.

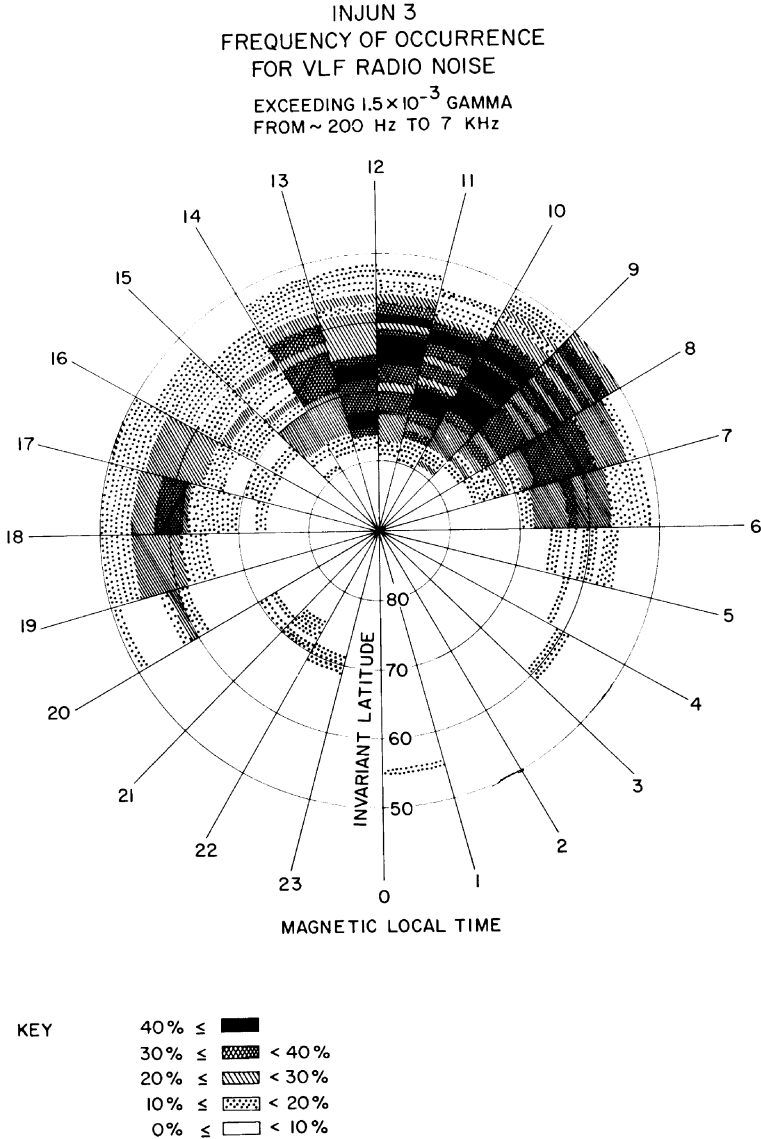


FIGURE 2. Normalized frequency of occurrence for broadband magnetic field strengths exceeding 1.5 milligammas.

It is evident from Figures 1 and 2 that the most intense VLF emissions activity is confined to INV between approximately 50 to 70° and to MLT during local day. The region of maximum VLF emission activity occurs during local morning and is centered on approximately 65° INV and about 8 to 10

hrs MLT for the 4.0 milligammas threshold, and about 9 to 12 hrs MLT for the 1.5 milligammas threshold.

Figure 3 is a reproduction of the INJUN III median omnidirectional intensities of precipitated 40 keV electrons given by FRANK *et al.* (1964) for comparison with the occurrence contours of VLF emissions. Figure 3 illustrates a

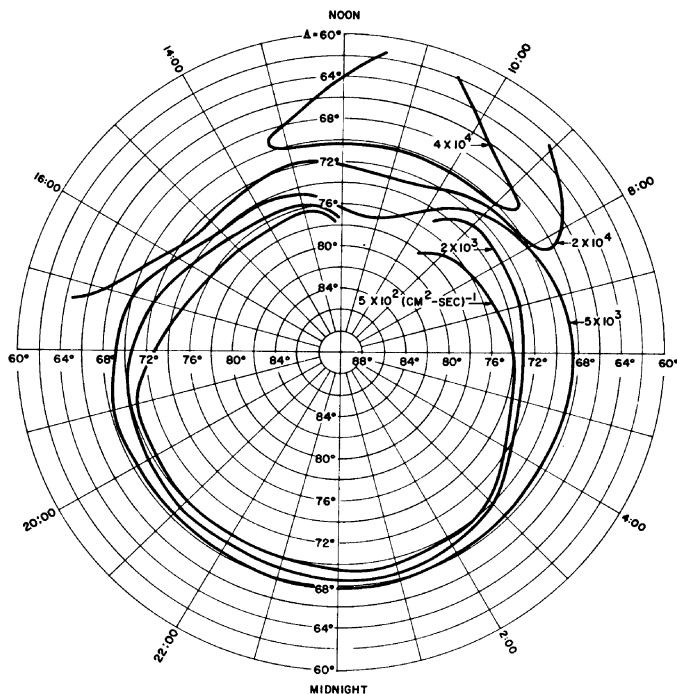


FIGURE 3. Intensity contours for precipitated 40 keV electrons (FRANK *et al.*, 1964).

general peak in the precipitation of 40 keV electrons (the $4 \times 10^4 \text{ cm}^{-2} \text{ sec}^{-1}$ contour) centered on approximately 66° INV and 11 hrs local time. A comparison of Figures 1, 2, and 3, reveals that statistically the region of maximum VLF emissions activity and the region of most intense 40 keV electron precipitation are nearly coincident.

ELF Hiss and Chorus

To determine the type of VLF emission responsible for the daytime maximum in VLF emission activity shown in Figures 1 and 2 we have studied the frequency-time spectra of all the events exceeding 1.5 and 4.0 milligammas (TAYLOR and GURNETT, 1968). The type of VLF emission most commonly found among these events consisted of broadband hiss having frequencies from a few hundred cycles per second up to one or two kilocycles per second. We call this noise *ELF hiss*. Examples of the frequency-time spectra of ELF hiss are shown in Figure 4. The ELF hiss spectra often have a sharply defined

lower frequency cutoff ranging from about 200 Hz (the lowest frequency received) to 600 Hz (BURNS and GURNETT, 1967). This low-frequency cutoff is believed to be due to a reflection condition for down-going waves at the ion-ion cutoff frequency occurring between the proton and helium ion gyrofrequency.

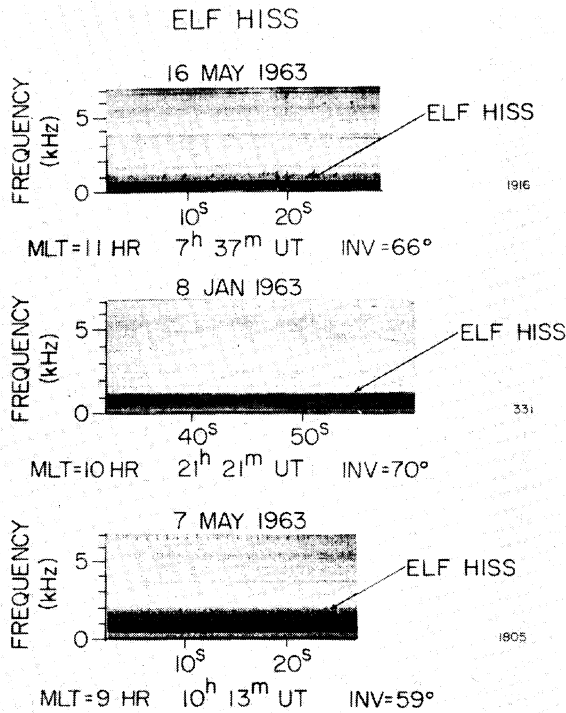


FIGURE 4. Frequency-time spectra of ELF hiss.

ELF hiss was present for 92 per cent of the field strength measurements exceeding 4.0 milligammas (Figure 1) and for 59 per cent of the field strength measurements exceeding 1.5 milligammas (Figure 2). Thus, ELF hiss is the principal type of VLF emission producing the broadband magnetic field strengths shown in Figures 1 and 2.

Chorus is the second most common type of VLF emission contributing to the VLF field strengths in Figures 1 and 2. Chorus consists of closely spaced randomly occurring discrete noise bursts, usually rising in frequency in the range 0.5 to 6 kHz, with the individual bursts typically having a duration of a few tenths of a second. Frequency-time spectrograms of typical chorus bursts are shown in Figure 5. Chorus was present for 52 per cent of the field strength measurements exceeding 4.0 milligammas (Figure 1), and for 50 per cent of the field strength measurements exceeding 1.5 milligammas (Figure 2). Quite often both chorus and ELF hiss occur together as in Figure 5, with the chorus bursts appearing to rise out of the top of the ELF hiss spectrum. Usually the highest frequency component of the ELF hiss and chorus emissions decreases

with increasing latitude and is usually less than 1.5 kHz above 75° INV. A typical latitudinal dependence of the ELF hiss and chorus spectrum is shown in Figure 6, with chorus and ELF hiss emissions extending to about 3 kHz at the

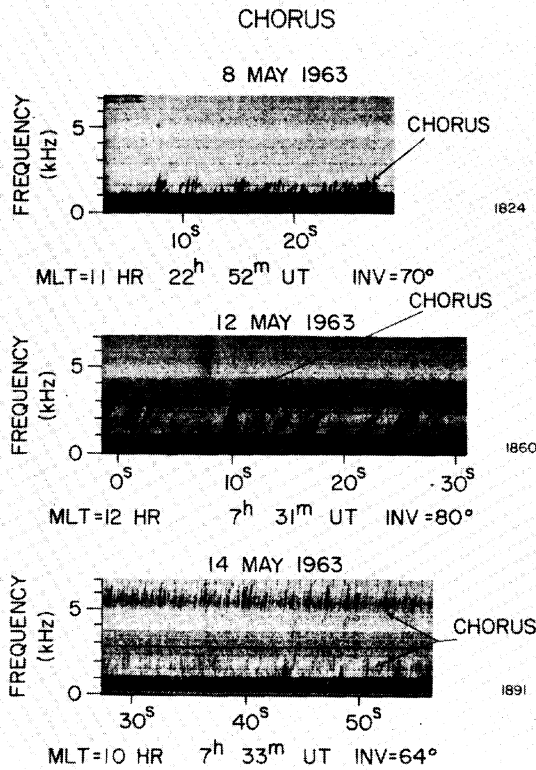


FIGURE 5. Frequency-time spectra of chorus.

start of the pass (68° INV) and decreasing in frequency as the satellite moves to higher latitudes. At high latitudes these ELF hiss and chorus emissions are believed to correspond to the "700 cps noise band" reported by AARONS *et al.* (1960) and to "roar" or "polar chorus" reported by UNGSTRUP and JACKEROTT (1963).

Measurements of VLF emissions by the OGO-1 satellite at high L values near the magnetic equator have been reported by DUNCKEL and HELLIWELL (1966). They report that the most intense chorus observed by OGO-1 occurred at $L = 5$ (INV = 64°) during local day with a broadband intensity of about 60 milligammas, approximately six times the maximum intensity of chorus observed by INJUN III at lower altitudes.

An interesting association was found in the INJUN III data between chorus bursts and 40 keV electron microbursts. Electron microbursts are randomly occurring, very rapid (~ 0.25 sec), impulsive increases in the flux of precipitated energetic (few tens of keV) electrons (ANDERSON and MILTON, 1964; OLIVEN *et al.*, 1967). Electron microbursts and simultaneous VLF chorus

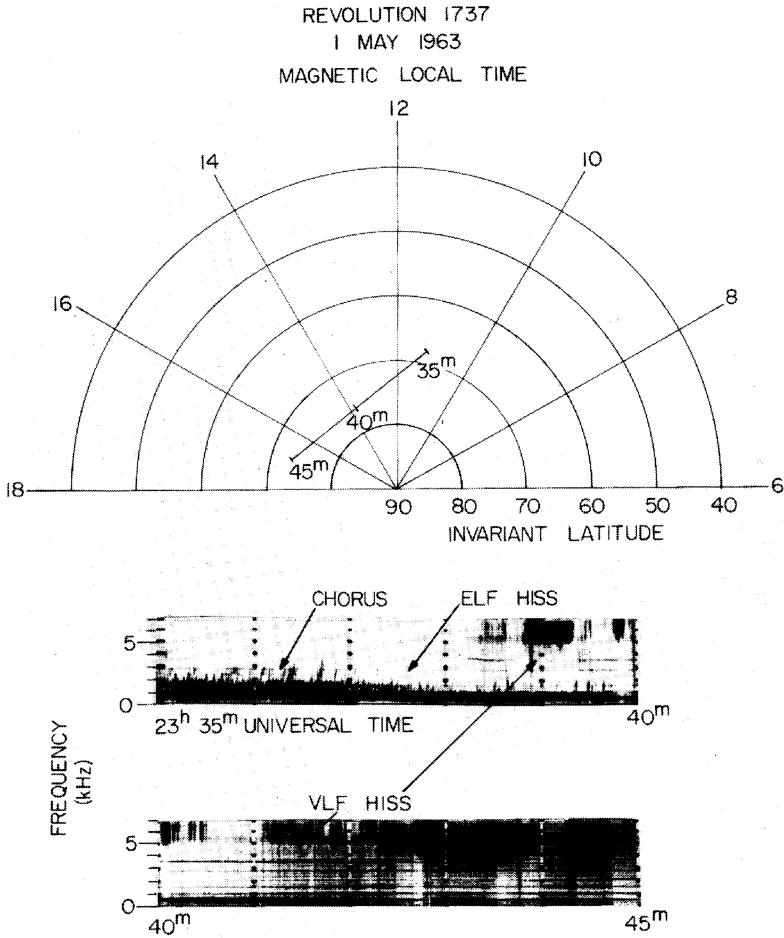


FIGURE 6. Latitude and local time dependence of ELF hiss and chorus spectra.

bursts observed by INJUN III are shown in Figure 7. Although it is not possible to establish a one-to-one correspondence between individual chorus bursts and individual electron microbursts it is evident from Figure 7 that the time scale of the two phenomena is very similar. From an investigation of 400 revolutions during which electron microbursts occurred it is found that electron microbursts are *always* accompanied by VLF chorus emissions, but chorus bursts are not always accompanied by electron microbursts. Such a correspondence would be very unlikely if the two phenomena occurred independently (OLIVEN and GURNETT, 1967). Thus, it appears that there is a close association between chorus and precipitating 40 keV electron microbursts.

Auroral Zone VLF Hiss

Auroral zone VLF hiss is commonly found in satellite VLF data (GURNETT, 1966; McEWEN and BARRINGTON, 1967; JØRGENSEN, 1967). The frequency spectra of auroral zone VLF hiss is typically a flat noise spectrum extending from a lower frequency limit of about 2 to 4 kHz to possibly several tens of

kilohertz. In Figure 8 we show the frequency-time spectra of three auroral zone VLF hiss events selected to illustrate the types of spectral forms observed.

The region of occurrence of auroral zone VLF hiss as determined from a

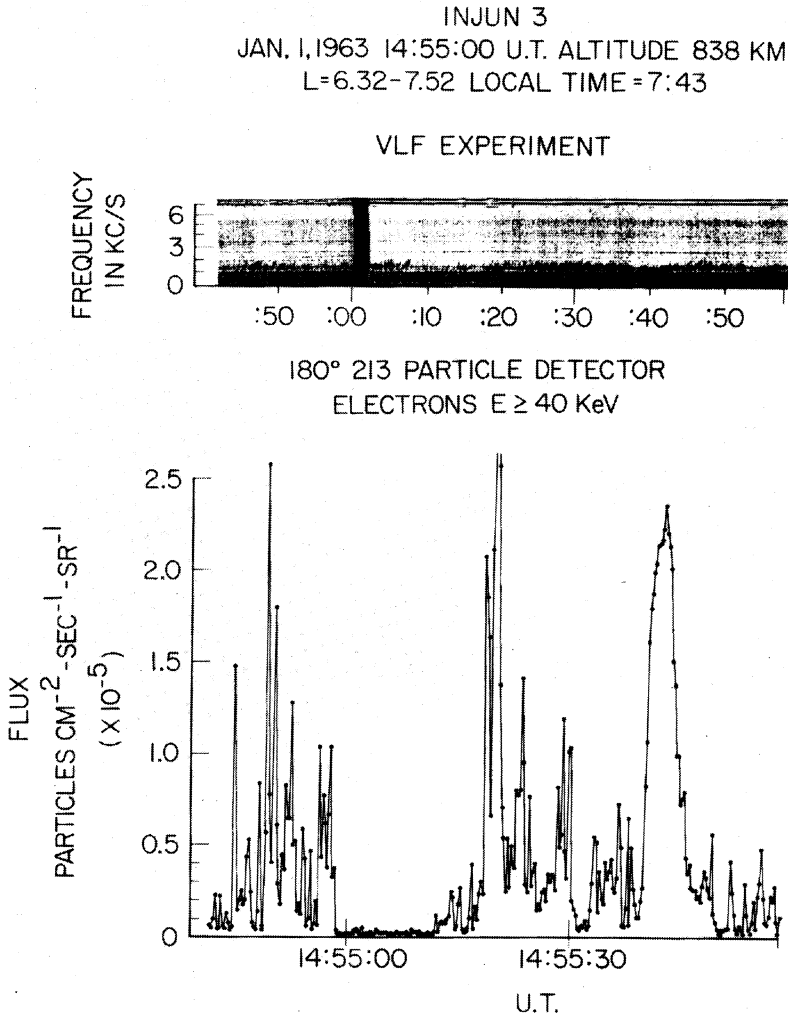


FIGURE 7. Simultaneous occurrence of chorus and 40 keV electron microbursts.

study of INJUN III data is shown in Figure 9. For details of this study see GURNETT (1966). Figure 9 shows that the auroral zone VLF hiss occurs over a relatively narrow range of invariant latitudes near the auroral zone and predominately during local afternoon and evening, from 12.0 to 24.0 MLT. Generally, the broadband (0.2 to 7.0 kHz) intensity of auroral zone VLF hiss is less than that of ELF hiss and chorus; consequently, auroral zone VLF hiss does not contribute significantly to the broadband signal strength plots in Figures 1 and 2.

Ground-based observations of VLF hiss above 2 kHz near the auroral zone have been reported by numerous investigators including MARTIN *et al.* (1960),

VLF HISS SPECTRA

3238
3066
3129

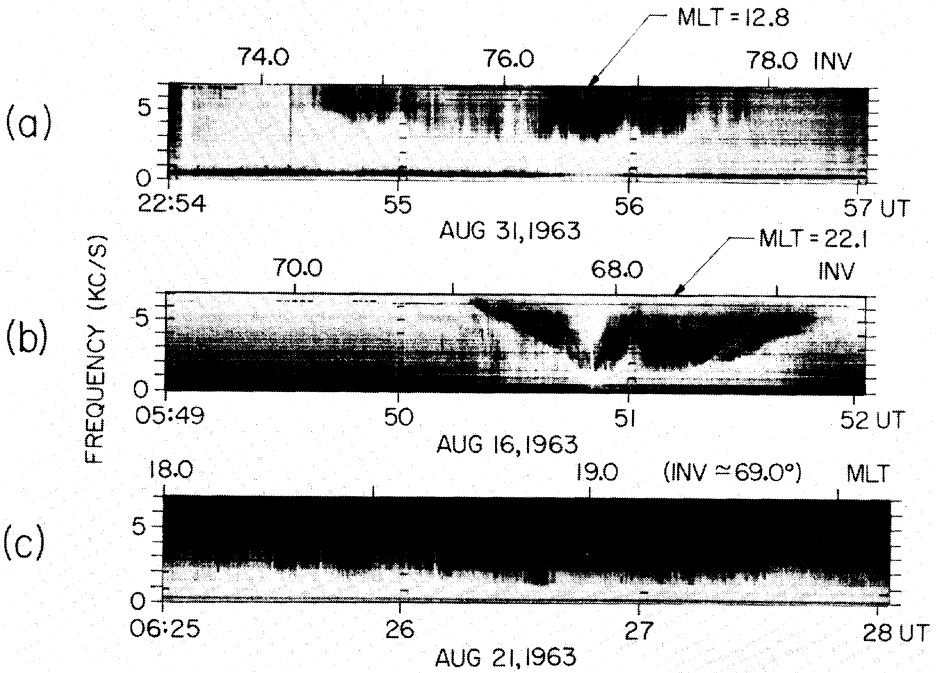


FIGURE 8. Frequency-time spectra of auroral zone VLF hiss.

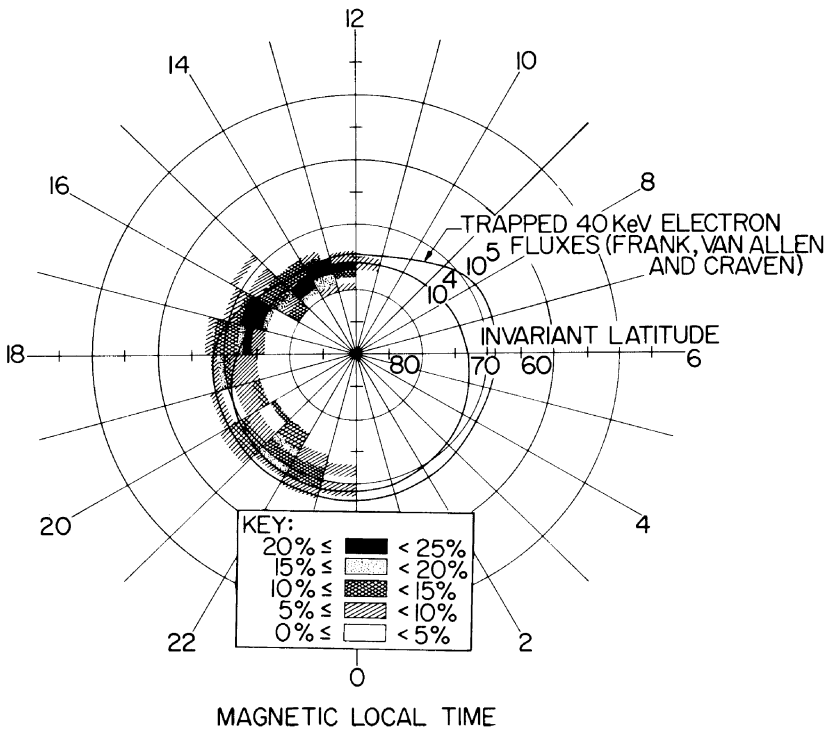


FIGURE 9. Frequency of occurrence of auroral zone VLF hiss as a function of INV and MLT for INJUN III.

MOROZUMI (1965), and JØRGENSEN (1966), and have been variously called hiss, VLF hiss, and auroral hiss. The relationship between the auroral zone VLF hiss observed on the ground and by satellites is not entirely clear, although in some cases VLF hiss observed by a satellite cannot be observed by nearby ground stations.

A comparison of the auroral zone VLF hiss region and the INJUN III median intensities for trapped 40 keV electrons given by FRANK *et al.* (1964) is shown in Figure 9. Statistically, the VLF hiss region begins near the high-latitude limit of trapping and extends to higher geomagnetic latitudes. During local evening, particularly, the region of maximum VLF hiss occurrence is several degrees poleward of the 40 keV trapping boundary and is within a region relatively void of electrons with energies greater than 40 keV. These statistical results have also been verified by individual pass studies. There are many

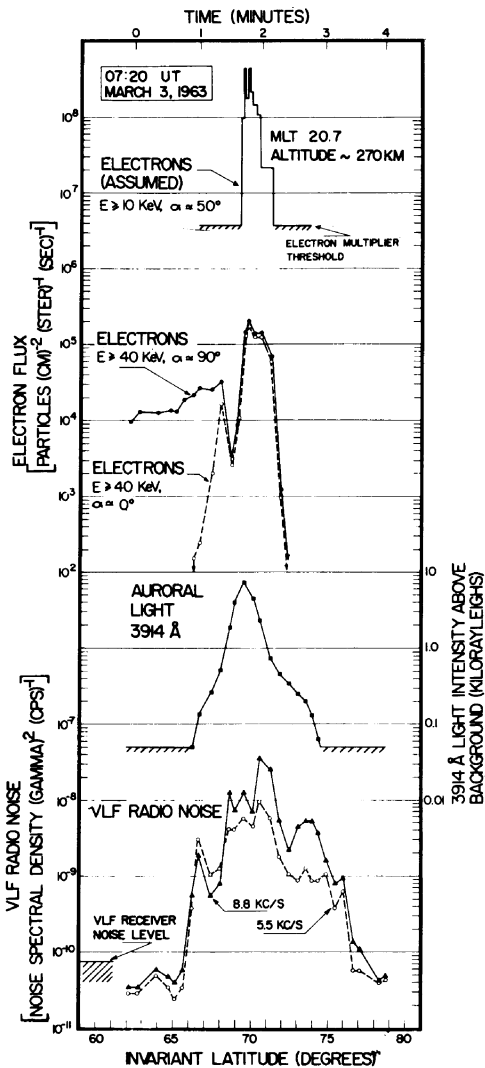


FIGURE 10. Simultaneous occurrence of auroral zone VLF hiss, auroral optical emission, and intense 10 keV particle precipitation.

cases in which the 40 keV electron flux never exceeds 10^3 ($\text{cm}^2 \text{sr sec}$) $^{-1}$ over the entire latitude range of a VLF hiss event.

The occurrence of auroral zone VLF hiss is, however, closely associated with the occurrence of intense fluxes of electrons with energies greater than about 10 keV detected by the electron multiplier on INJUN III, particularly when the energy spectrum is very soft (FRITZ and GURNETT, 1965, and GURNETT, 1966). In Figure 10 we show one such event which illustrates the simultaneous occurrence of VLF hiss, an auroral optical emission at 3914\AA , and an intense flux of precipitating 10 keV electrons. The association between VLF hiss and the 10 keV electron flux shown in Figure 10 is often found in the INJUN III data.

Lower Hybrid Resonance Noise Bands

One of the common features of VLF data from the ALOUETTE 1 satellite, which used an electric dipole antenna, is the occurrence of noise bands with a sharp lower frequency cutoff varying in frequency from about 2 to 20 kHz (BARRINGTON *et al.*, 1963). There is considerable evidence that the lower frequency cutoff of this noise band is the lower hybrid resonance (LHR) frequency of the ambient plasma (BRICE and SMITH, 1965). This band is called the *LHR noise band*.

The occurrence of LHR noise bands in the ALOUETTE data shows two distinct latitude regions where LHR noise bands occur most frequently (MCEWEN and BARRINGTON, 1967). In the lower latitude region, from about 45 to 60° INV, the lower cutoff frequency varies smoothly with satellite position, usually decreasing in frequency with increasing latitude. In the higher latitude region, from about 70 to 85° INV, the lower cutoff frequency is erratic and shows rapid fluctuations.

In the lower latitude region the LHR noise bands are observed as much as one half of the time by ALOUETTE 1 but are extremely rare in the INJUN III VLF data, presumably because this electrostatic resonance has a very small magnetic field component.

In the high-latitude region the general description of the LHR noise bands observed by ALOUETTE 1 and the auroral zone VLF hiss observed by INJUN III is very similar. Although simultaneous observations have not been made, it is entirely possible that these two phenomena are identical. No correlations of LHR noise bands with charged particle fluxes have been made.

Discussion

The most intense VLF emissions observed by the INJUN III satellite were found to occur between about 50° to 70° INV and during local day, with the maximum intensity occurring at about 65° magnetic latitude and during local morning from about 8 to

10 hrs MLT. The principal types of VLF emissions occurring in this region are ELF hiss and chorus, with the ELF hiss usually being the most intense.

The observation that the region of most intense VLF emission activity and the region of most intense precipitation of 40 keV electrons are nearly coincident suggests a close association between VLF emissions and 40 keV electron precipitation. The simultaneous occurrence of 40 keV electron microbursts and chorus bursts provides further evidence of such an association. Possible mechanisms relating VLF emissions and electron precipitation have been considered by KENNEL and PETSCHKE *et al.* (1966) and are discussed in following papers.

Auroral zone VLF hiss was also commonly found in the INJUN III data although less frequently than ELF hiss and chorus. The occurrence of auroral zone VLF hiss did not appear to be related to the intensity of electrons with energies greater than 40 keV, but did appear to be associated with intense fluxes of soft electrons with energies of about 10 keV or less commonly found during early evening.

Acknowledgments The author wishes to express his thanks to Dr. S. Shawhan for his helpful comments on this paper and to Messrs. W. Taylor, M. Oliven, and T. Burns who contributed to the studies in this paper. Research supported in part by the Office of Naval Research under Contract Nonr 1509(06) and by NASA Grant NGR-16-001-043.

References

- AARONS, J., GUSTAFSON, G., and EGELAND, A., 1960, *Nature* **185**, 148.
 ANDERSON, K. A. and MILTON, D. W., 1964, *J. Geophys. Res.* **69**, 4457.
 BARRINGTON, R. E., BELROSE, J. S., and KEELEY, D. A., 1963, *J. Geophys. Res.* **68**, 6539.
 BRICE, N. M. and SMITH, R. L., 1965, *Nature* **203**, 926.
 BURNS, T. B. and GURNETT, D. A., 1967 (to be published in *J. Geophys. Res.*)
 CHAMBERLAIN, J. W., 1961, *Physics of the Aurora and Airglow*, Academic Press, New York.
 DUNCKEL, N. and HELLIWELL, R. A., 1966, Paper 4.4-3, Spring URSI Meeting, April 18-21, Washington, D. C.
 ELLIS, G. R. A., 1959, *Planet. Space Sci.* **1**, 253.
 FRANK, L. A., VAN ALLEN, J. A., and CRAVEN, J. D., 1964, *J. Geophys. Res.* **69**, 3155.
 FRITZ, T. A. and GURNETT, D. A., 1965, *J. Geophys. Res.* **70**, 2485.
 GALLET, R. M., 1959, *Proc. IRE.* **47**, 211.
 GURNETT, D. A. and O'BRIEN, B. J., 1964, *J. Geophys. Res.* **69**, 65.
 GURNETT, D. A., 1966, *J. Geophys. Res.* **71**, 5599.
 HELLIWELL, R. A., 1965, *Whistlers and Related Ionospheric Phenomena*, Stanford University Press, Stanford, Calif.
 JORGENSEN, T. S., 1966, *J. Geophys. Res.* **71**, 1367.
 JORGENSEN, T. S., 1967, Paper 4.1-3, Spring URSI Meeting, May 23-26, Ottawa, Canada.
 KENNEL, C. F. and PETSCHKE, H. E., 1966, *J. Geophys. Res.* **71**, 1.
 LAASPERE, T., MORGAN, M. G., and JOHNSON, W. C., 1964, *Proc. IEEE.* **51**, 554.
 McEWEN, D. J. and BARRINGTON, R. E., 1967, *Canadian J. of Phys.* **45**, 13.
 McILWAIN, C. E., 1961, *J. Geophys. Res.* **66**, 3681.
 MARTIN, L. H., HELLIWELL, R. A., and MARKS, K. R., 1960, Stanford Electronics Lab. Tech. Rept. No. 1, Stanford University, Stanford, Calif.
 MOROZUMI, H. M., 1965, *Rept. Ionosphere and Space Res. Japan* **19**, 286.
 OLIVEN, M. N., VENKATESAN, D., and MCCracken, K. G., 1967, Department of Physics and Astronomy Res. Rept. 67-19, University of Iowa, Iowa City, Iowa (to be published in *J. Geophys. Res.*)

- OLIVEN, M. N. and GURNETT, D. A., 1967, Department of Physics and Astronomy Res. Rept. 67-39, University of Iowa, Iowa City, Iowa (to be published in *J. Geophys. Res.*)
- POPE, J. H., 1963, *J. Geophys. Res.* **68**, 83.
- TAYLOR, W. W. L., and GURNETT, D. A., (to be published in *J. Geophys. Res.*)
- UNGSTRUP, E. and JACKEROTT, I. M., 1963, *J. Geophys. Res.* **68**, 2141.

Discussion

The altitude variation of the ELF hiss implies that this emission is going down into the ionosphere from the exosphere. The VLF hiss propagation direction, however, cannot be determined at present.

The ELF emission seems to be associated with high-energy particles while VLF emission is associated with low-energy particles. This inverse correlation of emission frequency with particle energy may be because resonance with a low-energy particle is at the gyrofrequency (VLF) but that resonance with a high-energy particle can be at a lower frequency (ELF).

The frequency vs time behavior of the dawn chorus was emphasized to be characteristic of the source mechanism, not of the dispersion of the propagation medium.