Observed Correlations between Auroral and VLF Emissions

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This paper presents a series of simultaneous observations of very-low-frequency radio noise by the Injun 5 satellite and of visual aurora along the same geomagnetic-field line by the Fort Churchill Auroral Observatory. Seven observations from the period of August 29, 1968, to March 4, 1969, are discussed. In 5 of the 7 events studied VLF hiss is observed in association with auroral-light emissions. These observations typically show the occurrence of VLF hiss in the general region of the auroral arc, with significant changes in the VLF spectrum sometimes observed in the immediate vicinity of the auroral arc. One event for which the associated charged-particle fluxes have been analyzed is investigated in detail. The VLF radio noise intensity for this event is among the largest observed with Injun 5 and is much greater than can presently be explained by an incoherent Cerenkov radiation mechanism.

Visual aurora and magnetospheric radio phenomena have been studied for many years [see Chamberlain, 1961; Helliwell, 1965; McCormac and Omholt, 1969]. However, relatively little is known about the simultaneous occurrence and association of these phenomena. Simultaneous ground-based observations of aurora and VLF ‘auroral hiss’ have been reported by Martin et al. [1960], Jørgensen and Ungstrup [1962], Morozumi [1962], and Harang and Larsen [1965]. Ungstrup [1966] has also observed chorus and other discrete VLF emissions in association with certain auroral forms. Often during the more intense auroral events VLF emissions are not observed on the ground. This anticorrelation is believed to be due to the increased absorption of VLF waves at the base of the ionosphere caused by the auroral charged-particle precipitation [Martin et al., 1960; Morozumi, 1963]. Since many of the magnetospheric radio waves may also undergo total internal reflection at the base of the ionosphere, ground-based observations provide only very limited information on the association between aurora and magnetospheric radio noise.

Also, previous studies [Gurnett, 1966; Gurnett and Frank, 1971] suggest that auroral-light emissions are generated by precipitating particles having different energies than those particles which generate VLF radio emissions. Thus, good local correlations are not necessarily to be expected in any particular precipitation event unless the precipitating particles have a sufficiently broad energy spectrum. The limitations of ground-based observations discussed above are largely overcome by satellite measurements of VLF phenomena, although at the expense of much greater difficulty in coordination of the simultaneous ground and satellite observations.

The first simultaneous satellite observations of aurora, VLF radio noise, and charged-particle precipitation were reported by Gurnett [1966], who used data from the Injun 3 satellite, which carried an auroral photometer viewing downward approximately parallel to the geomagnetic field. Although several excellent correlations were found in the Injun 3 data between aurora and VLF hiss events, it was also found that not all auroral-light emissions could be associated with VLF hiss.

This paper presents the results of a program of simultaneous observations of VLF radio noise made by using the NASA and University of Iowa Injun 5 satellite and all-sky observations of aurora at the Auroral Observatory in Fort Churchill, Manitoba, Canada. These measurements were performed on a prearranged schedule over a period of about 6 months and

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have resulted in the simultaneous observation, by all-sky camera and the Injun 5 satellite, of portions of 7 auroral events. Five of these events are of a quality suitable for a detailed analysis and are presented in this report. The charged-particle fluxes observed on one of these events are discussed in a companion paper by Ackerson and Frank [1972].

The limited number of events available for this study is due to the stringent conditions that must be satisfied at both observing points. Since both the aurora and the VLF radio noise are presumed to be associated with precipitating charged particles, the aurora and radio observations should be performed on the same geomagnetic-field line. Thus, for a given ground-based auroral observation, there exists a very small ‘window’ in latitude and longitude within which the satellite measurements must be made. Typically only about one pass per week occurs within this window. Furthermore, the auroral observations are dependent on local weather and light conditions and the satellite measurements must satisfy various telemetry and operation limitations. The net result is that the chances of obtaining simultaneous ground-based and satellite observations of the same event are quite small.

DATA ANALYSIS AND SURVEY OF OBSERVATIONS

The Injun 5 satellite was launched on August 8, 1968, into an elliptical polar orbit with an inclination of 80.66°, an apogee altitude of 2528 km, and a perigee altitude of 677 km. The VLF experiment on Injun 5 includes an electric dipole antenna, a magnetic loop antenna, and two wide-band (30 Hz to 10 kHz) receivers. (For a detailed description of the Injun 5 VLF experiment, see the paper by Gurnett et al. [1969].) The Injun 5 data used in this study were acquired by the North Liberty Radio Observatory of the University of Iowa in real time, since the 2.5-kHz bandwidth of the Injun 5 tape recorder is not sufficiently broad for auroral-hiss observations.

The Fort Churchill Auroral Observatory, which provided the all-sky camera observations for this study, is located at geographic coordinates of 58°45′25″ north latitude and 266°01′00″ east longitude, approximately 2100 km north of the telemetry receiving site. If it is assumed that the aurora occurs at an altitude of 100 km, then the all-sky camera viewing angle of 155° results in a field of view (at 100 km altitude) covering approximately 56.5° to 61.0° north latitude and 257° to 275° east longitude. The Fort Churchill all-sky observations were started on August 29, 1968, with the observing schedule being determined from the satellite orbit predictions supplied by NASA, and were continued through March 4, 1969. During the scheduled observation periods all-sky photographs were made at the rate of 1 frame every 12 to 13 sec.

For the period from August 29, 1968, to March 4, 1969, simultaneous auroral and VLF data were obtained for 7 events. Of these 7 events, 5 have auroral and VLF radio noise events of a quality suitable for a correlative comparison. Of the remaining 2 events, one exhibited no detectable VLF radio noise in the vicinity of the aurora and the other has not been suitable for meaningful study owing to the weak auroral intensity.

Since very few observations of this type are available owing to the above difficulties, we will discuss each of the 5 events investigated in order to give an over-all view of the correlations, and absence of correlations, found. The all-sky photographs and the frequency-time spectograms of the VLF electric and magnetic fields for these 5 observations are illustrated in Figures 1 through 5. In 2 of these events, for which the all-sky photographs are of too low contrast for photographic reproduction, the auroral forms are shown by line drawings.

To compare the auroral intensity and other phenomena along the same geomagnetic-field line, the position in longitude and latitude of the geomagnetic-field line passing through the satellite is computed at an altitude of 100 km, the assumed altitude of the aurora, using the Jensen and Cain [1962] expansion for the geomagnetic field. These latitude and longitude coordinates are plotted on the all-sky photographs, indicated by the arrows in Figures 1 through 5, by using a computer-generated overlay grid for the latitude and longitude at an altitude of 100 km as viewed by the all-sky camera. In this manner, two simultaneous observations along the same geomagnetic-field line can be compared. The range of $L$ values covered by the Fort Churchill all-sky photographs is approximately 6.6 to 11.8. It should be noted
here that field-aligned currents that flow above auroral displays [Zmuda et al., 1970; Armstrong and Zmuda, 1970] will cause the real field to distort from the Jensen-Cain expansion. However, for Injun 5 altitudes (less than 2500 km) these distortions will cause errors of the order of 0.1 or less in \( L \), which is roughly the accuracy limit of the auroral position determinations in this study. Thus such currents will not significantly affect the results presented here and have been ignored in the analysis.

**Observations of September 15, 1968.** A quiet homogeneous auroral arc observed on September 15, 1968, is shown in Figure 1 with the more intense portions of the arc indicated by shading. As the satellite traverses the sky from the southern horizon to the northeast, it passes over the homogeneous arc at approximately 03h 31m 09s UT. The frequency-time spectrograms for this pass show a band of VLF hiss with a weak magnetic-field component and a lower cutoff frequency of about 6 to 8 kHz. This VLF hiss emission is present for about 2 min before the satellite passes through the auroral arc and continues until the end of the pass approximately 1 min later. As the satellite passes through the auroral arc, from about 03h 31m 08s to 03h 31m 10s UT, the frequency of the VLF hiss decreases abruptly to about 3 kHz. The intensity of the VLF hiss band does not show any evident association with the location of the auroral arc.

Since the VLF hiss band in this case extends for many hundreds of kilometers on either side of the auroral arc and since the intensity does not correlate with the location of the auroral arc, it is concluded that this noise is not generated in the immediate vicinity of the aurora and is probably not directly associated with the auroral-light emission. The decrease in the frequency of the VLF hiss band near the auroral arc may be due to a change in the local lower

**Fig. 1.** All-sky photograph reproductions and VLF spectra for the auroral event of September 15, 1968. Satellite position along geomagnetic-field line is plotted on all-sky data with circle and identified by arrow.
hybrid resonance frequency, which is believed to be related to the lower cutoff frequency of this type of noise [McEwen and Barrington, 1967].

Observations of November 18, 1968. Figure 2 illustrates a homogeneous arc or band and two localized auroral patches observed near the northwest horizon on November 18, 1968. The satellite begins to pass over the patch structure at about 06h 37m 51s UT. The northernmost patch appears to intensify between 06h 37m 51s and 08h 38m 04s, as the satellite passes over it. At 06h 38m 17s the satellite is located above the second patch structure to the south, and at 08h 38m 30s the satellite is beyond the auroral activity. The VLF radio noise observed in the region of the patch structure is very broad band, extending from approximately 1 to about 20 kHz, and is typical of auroral-zone VLF hiss of the type discussed by Gurnett [1966], Jørgensen [1968], Laaspere et al. [1971], and Gurnett and Frank [1972]. The maximum VLF hiss intensity occurs at about 06h 37m 50s UT, approximately coincident with the time that the satellite is over the northernmost auroral patch. The magnetic-field strength of the VLF hiss in this event is quite weak and cannot be seen in the magnetic-field spectrogram in Figure 2 because of the poor ratio of telemetry signal to noise during this portion of the pass. The VLF hiss intensity decreases considerably after about 06h 38m 20s UT and is undetectable after about 06h 38m 30s UT.

Observations of November 27, 1968. In the event of November 27, 1968, shown in Figure 3, a diffuse auroral band extends over most of the northern horizon with the most intense portions occurring near the northeastern and western horizons. At 05h 41m 42s UT the satellite is passing over the most intense region near the western horizon. Between 05h 41m 42s and 05h 42m 04s UT the aurora becomes more intense below the satellite. Between 05h 42m 04s and 05h 42m 30s UT the intensity of the aurora...
decreases, and at 05h 42m 30s UT the satellite is over a relatively less intense portion of the band. The VLF noise observed during this pass consists of a band of VLF hiss below about 2 kHz, with a pronounced decrease in the noise intensity from about 05h 42m 06s to 05h 42m 25s UT. The decrease occurs during the same time period in which the intensity of the auroral band is decreasing.

Observations of December 21, 1968. A large, weak, homogeneous auroral arc observed on December 21, 1968, is shown in Figure 4. For this event the satellite passed over the arc from about 01h 52m 30s to 01h 52m 50s UT. This auroral arc occurs essentially coincident with a V-shaped VLF hiss event of the type described by Gurnett [1966]. V-shaped VLF hiss events are characterized by a lower cutoff frequency, which initially decreases with decreasing latitude, reaching a minimum of about 1 to 4 kHz, and then increases with decreasing latitude, giving a characteristic V-shaped appearance on a frequency-time spectrogram. The time (distance) scale of V-shaped VLF hiss events is typically about 1 min (500 km) for the Injun 5 orbit. The V-shaped VLF hiss event in Figure 4 is somewhat unusual in that the low-latitude portion of the event has an abrupt change in the lower cutoff frequency at about 01h 52m 48s UT, giving a very asymmetrical appearance (one-half of a V) on the frequency-time spectrogram. The maximum VLF hiss intensity for this event occurred from about 01h 52m 36s to 01h 52m 47s UT, essentially coincident with the passage of the satellite over the auroral arc.

Observations of February 17, 1969. A quiet homogeneous arc observed near the western horizon on February 17, 1969, is illustrated in Figure 5. Only a single frame of all-sky auroral data is available for this event. The VLF radio noise observed on this pass consists of an intense band of VLF hiss with little or no magnetic-field component.

Fig. 3. All-sky photographs and VLF spectra for the auroral event of November 27, 1968.
Fig. 4. All-sky photograph reproductions and VLF spectra for the auroral event of December 21, 1968.

Further Analysis of the December 21, 1968, Event

Of the 5 simultaneous aurora/VLF radio noise observations investigated, the event on December 21, 1968, provides the best example for a detailed analysis. The VLF radio noise intensity for this event is the largest of all the examples found, and the data quality is very good. During this pass the spacecraft is in the high bit rate mode of operation (24,000 bits/sec), and thus very high temporal resolution measurements of charged-particle fluxes are available from the Low-Energy Proton and Electron Differential Energy Analyzers (Lepedeas) on Injun 5. The charged-particle fluxes observed during this event are discussed in detail in a companion paper by Ackerson and Frank [1972] and are summarized below for comparison with the VLF radio noise observations.

The energy-time spectrogram given by Ackerson and Frank [1972] for the precipitated electron flux observed during this event shows that the auroral-light emission is produced by electrons with energies primarily less than 10 kev and maximum electron fluxes of about $4 \times 10^6$ electrons (cm$^2$ sec ster)$^{-1}$. The low-energy electron precipitation region, which extends from 01h 52m 32s to 01h 53m 00s, agrees well with the region of auroral-light emission shown in Figure 4. The energy-time spectrogram for this event has an inverted 'V' form typical of the auroral electron precipitation events observed by Injun 5 [Frank and Ackerson, 1971]. The electron energy spectrum for this event is very broad with intense fluxes extending from less than 100 ev up to several kev. Detailed energy-time spectra for this event are given by Ackerson and Frank [1972]. As discussed by Ackerson and Frank [1972], the auroral arc is located on the poleward side of the electron $E > 45$ kev trapping boundary. The time of maximum electron energy flux, approximately 01h 52m 45s UT, corresponds well with the
time at which the maximum VLF hiss intensity occurs. The abrupt change in the low-frequency cutoff of the VLF hiss at 01h 52m 48s UT, from approximately 1.5 kHz on the poleward side to about 4 kHz on the equatorward side, corresponds very closely (±1 sec) with a change in the angular distribution of the electron flux, from strongly peaked downward along the geomagnetic field on the poleward side to approximately isotropic on the equatorward side.

From the simultaneous electric- and magnetic-field measurements on Injun 5, the Poynting flux direction of the VLF hiss, up or down the geomagnetic field, has been determined by using the correlation techniques described by Mosier and Gurnett [1971] and Gurnett et al. [1971]. The Poynting flux direction of the VLF hiss event in Figure 4 is observed to be primarily downgoing with occasional upgoing components. As discussed by Gurnett and Frank [1972], a lower limit on the average Poynting flux along the geomagnetic field is given by the correlation

\[ \langle E_z H_y \rangle = |E_z| |H_y| \langle \cos \phi \rangle \]

between the electric and magnetic fields \( E_z \) and \( H_y \), where \( \langle \cos \phi \rangle \) is the average value of the cosine of the phase angle between the electric- and magnetic-field signals. At the time of maximum VLF hiss intensity for this event, approximately 01h 52m 47s UT, the broad-band (300 Hz to 10 kHz) electric- and magnetic-field strengths are 8.4 mv (meter\(^{-1}\)) and 22.0 m\(\gamma\), respectively, and the cosine correlation, \( \langle \cos \phi \rangle \), has been measured from the wide-band telemetry to be approximately 0.5. Using an effective noise bandwidth for the emission of 5 kHz, the corresponding lower limit on the VLF power flux for this event is \( 1.5 \times 10^{-11} \) watts (m\(^2\) Hz\(^{-1}\)). This event is among the most intense VLF hiss events observed with Injun 5.

**Discussion**

The data presented in this study provide further examples of the observed association between aurora and VLF ‘auroral’ hiss. Al-

![Fig. 5. All-sky photograph reproductions and VLF spectra for the auroral event of February 17, 1969.](image-url)
though in several instances VLF hiss was observed in association with aurora, it is also significant that two events were observed for which the auroral-light emission is not associated with any detectable VLF hiss emission. These findings are consistent with the earlier results of Gurnett [1966], who found that not every auroral-light emission could be associated with a VLF hiss event, thus indicating that VLF hiss and auroral-light emissions are produced by electrons of somewhat different energies. Gurnett and Frank [1972] have shown that VLF hiss is closely associated with the occurrence of intense fluxes of electrons with energies on the order of 100 ev. Auroral-light emissions, however, are generally attributed to somewhat higher electron energies, on the order of 1 to 10 kev, because of the greater energy flux contributed by these particles. Thus, depending on the detailed energy spectrum of the precipitated electron flux, there may be a predominance of low-energy (\(\sim 100\) ev) electrons which leads to the generation of VLF hiss but which does not contribute greatly to the auroral-light emission. On the other hand, for more energetic electron precipitation events there may be little VLF hiss generated, but strong auroral-light emissions can be observed. If the precipitated electron energy spectrum is sufficiently broad, such as for the event shown in Figure 4, both VLF hiss and auroral-light emissions are observed over the auroral arc.

The correlation between changes in the lower cutoff frequency of the VLF emissions in the region of the auroral arc, such as evident in Figures 1 and 4, is believed to be due to a modification of the local plasma density and composition by the precipitating particles. In Figure 1, for example, the lower cutoff frequency of the electric-field noise band is believed to be associated with the lower hybrid resonance (LHR) frequency of the local plasma [McEwen and Barrington, 1967]. The abrupt decrease in the frequency of the noise band from approximately 03h 31m 08s to 03h 31m 10s UT, which is coincident with the passage of the satellite over the aurora, is believed to be due to the change in the LHR frequency caused by the change in the local electron and ion density within the electron precipitation region.

Ellis [1957] first proposed that auroral-zone VLF hiss emissions are produced by incoherent Cerenkov radiation from the charged particles that produce auroras. Detailed model calculations have been performed by Jørgensen [1968] for the VLF power flux generated by Cerenkov radiation from large, but plausible, fluxes of electrons with energies on the order of 1 kev. Jørgensen's calculations, which assume a density of 8 electrons cm\(^{-3}\) with energies from about 1 to 16 kev and exact guiding of all the Cerenkov radiation along the geomagnetic field from the magnetosphere into the ionosphere, predict a maximum VLF power flux of \(10^{-11}\) watts (m\(^2\) Hz\(^{-1}\)). As discussed by Gurnett and Frank [1972], the observed power fluxes of VLF hiss, which are sometimes as large as \(10^{-11}\) watts (m\(^2\) Hz\(^{-1}\)) for electron fluxes and densities comparable to those used by Jørgensen, indicate that present models of incoherent Cerenkov radiation are inadequate to explain the generation of VLF hiss by this process. The December 21, 1968, event in Figure 4 provides a further example of these difficulties. The VLF power flux for this event is at least \(1.5 \times 10^{-11}\) watts (m\(^2\) Hz\(^{-1}\)), a factor of 2000 greater than the maximum VLF power flux obtained from Jørgensen's model calculations. Also, in this event the VLF hiss is observed over a latitudinal distance approximately 5 times the latitudinal width of the electron precipitation region, thereby further reducing the power flux computed by Jørgensen owing to the spreading of the VLF wave energy away from the flux tube within which the noise is generated. The energy spectra given by Ackerson and Frank [1972] for this event are significantly softer than the energy spectrum used by Jørgensen, although the total density of precipitating electrons, \(E > 100\) ev, for this event (~4.5 electrons cm\(^{-3}\)) is comparable to the number density used by Jørgensen (8 electrons cm\(^{-3}\)). Since the electron energy spectra now being observed in association with VLF auroral hiss are significantly softer than that used by Jørgensen, a definitive evaluation of the incoherent radiation mechanism will require further calculations using these softer electron energy spectra.

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