JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 90, NO. A12, PAGES 12,183–12,194, DECEMBER 1, 1985

A New Type of VLF Emission Triggered at Low Altitude in the Subauroral Region by Siple Station VLF Transmitter Signals

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VLF wave data from the ISIS 2 satellite has revealed the existence of a new phenomenon in which coherent VLF signals from the Siple Station, Antarctica, VLF transmitter are observed to trigger a new type of VLF emission as these signals propagate upward to the satellite at 1400 km altitude through the ionosphere and low-altitude magnetosphere. The emissions have the form of band-limited impulses of approximately 20–30 ms duration. The bandwidth of the emissions is as much as 1 kHz and their amplitude is as much as 20 dB above that of the triggering signal. The emissions are thought to be the result of a rapidly evolving quasi electrostatic plasma instability triggered by the transmitter signals. The effect occurs generally when the transmitter signals lie just below a band of impulsive VLF hiss which is commonly observed to occur in the subauroral region poleward of the plasmapause. The impulsive VLF hiss band has a lower cutoff frequency in the range 3-4 kHz and appears to be the subauroral extension of the well-known auroral VLF impulsive hiss band. This phenomenon is possibly the transient analog of the recently reported spectral broadening effect [*Bell et al.*, 1983b] but the connection is not clear. In the present paper we show examples of this new phenomenon and delineate the conditions under which it occurs. The role of precipitating energetic particles in producing the phenomenon is discussed.

1. INTRODUCTION

The purpose of this paper is to report the existence of a new phenomenon in which coherent VLF signals from the Siple Station VLF transmitter (Antarctica, 76° S, 84° W) are observed to trigger a new type of VLF emission as these signals propagate upward through the ionosphere and low-altitude magnetoshere to the ISIS 2 satellite at 1400 km altitude.

Although the triggering of VLF emissions in the magnetosphere by signals from ground-based VLF transmitters is a well-known phenomena [*Helliwell and Katsufrakis*, 1974; *McPherson et al.*, 1974; *Dowden et al.*, 1978; *Bell et al.*, 1981, 1983*a*, *b*; *Kimura et al.*, 1983], most previous studies have indicated that these emissions were generated at high altitudes near the magnetic equatorial plane. Thus until recently it was commonly believed that transmitter signals propagating from the ground to a low-altitude satellite (altitude < 3000 km) did not interact with energetic particles in such a way as to trigger VLF emissions or even to alter the signal characteristics in any significant way. The signal distortions which were observed on these short paths, such as amplitude fading and bandwidth increases of a few hertz, appeared to be explainable on the basis of multipath propagation and small-angle scattering from small irregularities in the ionosphere [*Sonwalkar et al.*, 1984]. This situation was radically changed recently with the discovery of the spectral broadening effect [*Bell et al.*, 1983*b*].

Paper number 5A8746
0148-0227/85/005A-8746$05.00

In the spectral broadening effect, initially narrowband (~ 1 Hz) signals from ground-based VLF transmitters are observed on moving satellites to exhibit a significant apparent frequency bandwidth increase after propagating at low altitude through regions where energetic electron precipitation is thought to take place. The effect has been observed at satellite altitudes in the range 600–3800 km, and the frequency bandwidth increase can reach a value as high as 10% of the nominal frequency of the input signal. The bandwidth increase occurs only in the presence of impulsive VLF hiss and/or a lower-hybrid resonance (LHR) noise band [*McEwen and Barrington*, 1967; *Laaspere et al.*, 1971] with an irregular lower cutoff frequency, and only for signals whose frequency lies above the local LHR frequency at the satellite location. Dispersion in the sideband components of the affected pulses suggests that the apparent bandwidth increases may be due to a process in which the initial signal scatters coherently from large-scale plasma density irregularities at low altitude, and wave energy is scattered into quasi-electrostatic whistler mode waves with wave normal angles very close to the resonance cone. The large doppler shift associated with these short wavelength modes then produces the apparent increase in the bandwidth of the signal as observed on a moving satellite. Since impulsive VLF hiss and irregular LHR noise bands have been linked to energetic ($E < 1$ keV) electron precipitation in the past, it appears likely that the irregularities which scatter the injected signals are produced by the precipitating electrons [*Bell et al.*, 1983*b*; *Titova et al.*, 1984].

Although a passive scattering mechanism was initially proposed for the spectral broadening effect, active mechanisms also appeared to be possible. For instance, the irregularities which scatter the input signals could conceivably be

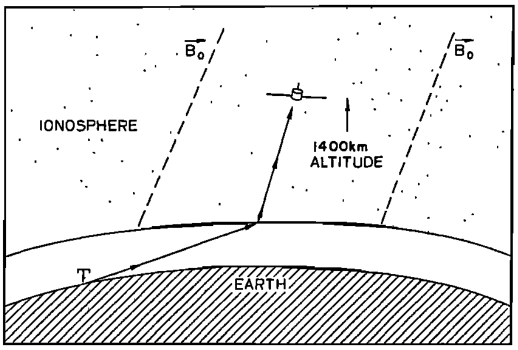

Fig. 1. Sketch showing the typical experimental configuration during periods in which ISIS 2 satellite data showed the presence of impulsive VLF emissions triggered by signals from the Siple Station VLF transmitter. In all cases the spacecraft was located in the southern hemisphere at a magnetic meridian within 10° of that of Siple Station. Distance in the earth-ionosphere wave guide between the subsatellite point and the transmiter (T) was generally less than 1000 km.

ion acoustic modes excited by the particle precipitation, and the sideband signals could possibly be produced through a nonlinear mode coupling process involving these modes. In this case the real frequency of the sideband waves would differ from that of the input signal and it could be said that the input wave had triggered "VLF emissions" during transionospheric propagation. In this process the free energy necessary to create the sidebands would derive ultimately from the energetic precipitating particles. Thus the discovery of the spectral broadening effect provided the first evidence that energetic particles might significantly alter the characteristics of coherent VLF waves propagating at low altitudes and suggested that the input waves might also trigger VLF emissions in this region.

In the present paper we present further and much stronger evidence that VLF emissions can be triggered at low altitudes by signals from ground-based transmitters. These emissions do not resemble the classic type thought to be triggered near the magnetic equatorial plane [*Helliwell and Katsufrakis*, 1974] but appear to be a new type of VLF emission not previously reported in the literature. The duration of this new type of triggered VLF emission is approximately 20–30 ms, much shorter than that the approximate 1 s duration of the classic form of triggered VLF emission. However the final amplitude level of the two types of emission appears to be roughly the same, being approximately 20 dB above the level of the input signal. The emissions are triggered generally when the transmitter signals lie just below a band of impulsive VLF hiss which is commonly observed to occur poleward of the plasmapause, with a lower cutoff frequency near 3 kHz. This phenomenon is possibly the transient analog of the spectral broadening effect [*Bell et al.*, 1983*b*] but the connection is not clear.

The band of impulsive VLF hiss which is associated with the impulsive emissions appears to be the subauroral extension of the impulsive auroral hiss bands which have in the past been linked with the precipitation of energetic electrons of energy less than 1 keV [*Gurnett and Frank*, 1972]. Thus there is reason to believe that the impulsive emissions may result from a rapidly evolving plasma instability which is driven by precipitating electrons.

The new type of triggered emission was discovered during joint VLF wave-injection experiments involving the Communications Research Centre at Ottawa, Canada, and the Stanford University STAR Laboratory. The joint wave-injection experiments have four main components: (1) broadband VLF/ELF receivers on the ISIS 1 and ISIS 2 satellites; (2) a broadband (1-20 kHz) controllable VLF transmitter located at Siple Station, Antarctica [*Helliwell and Katsufrakis*, 1974]; (3) various VLF navigation and communication transmitters, such as those of the world-wide Omega network; and (4) ground stations in the Antarctic and Canada.

The main goal of these, and similar, experiments is to acquire understanding of interactions between coherent VLF waves and energetic particles in the magnetosphere and ionosphere [*Helliwell and Katsufrakis*, 1974; *McPherson et al.*, 1974; *Dowden et al.*, 1978; *Bell et al.*, 1981*a*; *Bell et al.*, 1983]. Sources of the coherent waves involved in these studies include VLF transmitters, large-scale power grids, whistlers, and other natural coherent VLF signals.

The VLF wave source in the wave-injection study reported herein was the Siple Station VLF transmitter at L~ 4.2. One of the major advantages of the Siple transmitter is its ability to produce controlled VLF signals at frequencies in the range 1.5-6 kHz. This is the approximate range of the lower-hybrid resonance frequency (LHR) at ISIS 2 altitudes (~ 1400 km) on magnetic shells in the range $4 \leq L \leq 6$. Thus Siple transmitter signals can be used to study changes in wave characteristics that occur as the wave frequency is swept through the local LHR frequency. These changes include bandwidth increases, such as those of the spectral broadening effect [*Bell et al.*, 1983*b*], as well as amplitude increases.

It has been suggested that lower hybrid modes may be responsible for the acceleration of ions in auroral regions [*Chang and Coppi*, 1981]. Siple transmitter signals can possibly excite these modes as the signal frequency is swept through the LHR frequency.

Furthermore, the range 1.5-6 kHz generally includes the irregular lower cutoff frequency of the impulsive VLF hiss commonly seen in the auroral region as well as the subauroral region just outside the plasmapause [*Gurnett*, 1966; *Gurnett et al.*, 1969; *Jorgensen and Bell*, 1970; *Laaspere et al.*, 1971; *Gurnett and Frank*, 1972]. Thus the Siple signals can be used as probes to investigate the characteristics of the impulsive hiss, in particular to determine if the hiss may be generated at altitudes below the satellite as a result of a plasma instability.

The ISIS 2 spacecraft is in a nearly circular orbit at approximately 1400 km altitude with an inclination of 89° prograde. The 75-m (tip-to-tip) receiving dipole antenna feeds a VLF receiver operating in the 50 Hz to 30 kHz range. The receiver features a linear amplifier with an automatic gain control (AGC) providing a total dynamic range of 70 dB. Signals are telemetered to ground recording in real time using a conventional FM modulation scheme.

Receivers, recorders, and antennas necessary to acquire the telemetry signal from the analog portion of the ISIS 2 VLF wave experiment were installed at Siple Station in January 1982. Because of funding limitations equipment necessary to acquire the digital telemetry from the spacecraft was not available. As a result of this limitation, information concerning the absolute gain level of the satellite

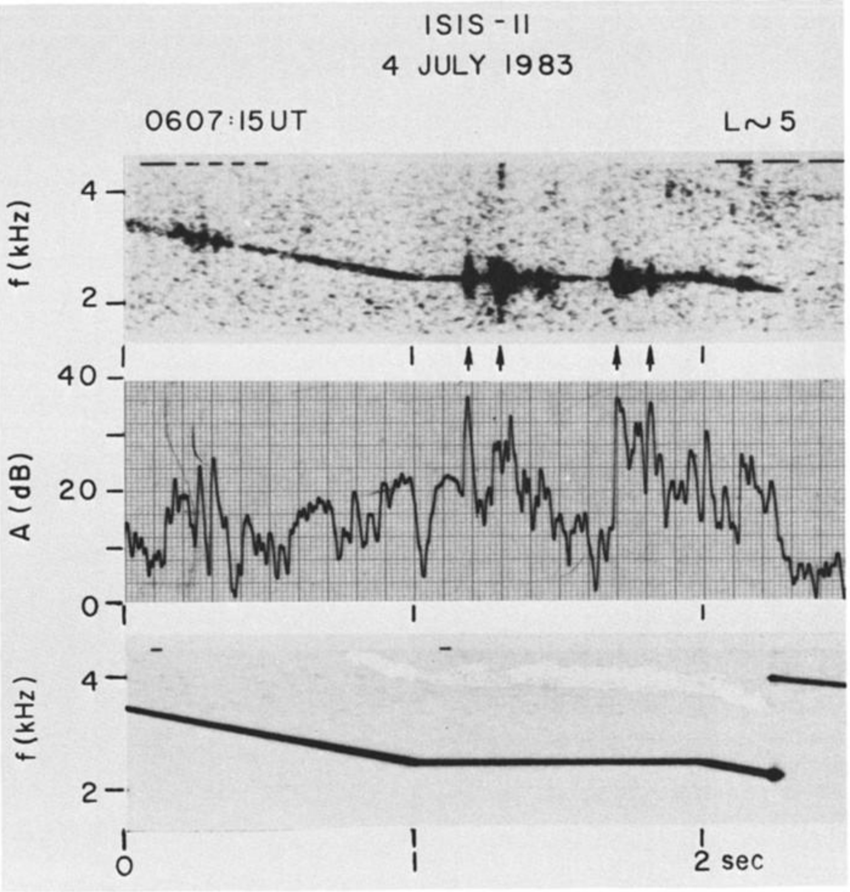

Fig. 2. Typical example of a Siple transmitter signal triggering impulsive VLF emissions.

VLF receiver was not recovered, although the wave spectral distribution was fully recovered. Furthermore, data from other operable spacecraft experiments, such as the topside sounder, which might have provided important correlative information, were also not recovered because they were carried on the digital telemetry signal. This situation continued through 1983, and as a consequence the absolute amplitude of the triggered impulsive emissions reported here could not be determined. However, their relative amplitude with respect to the triggering input signals was generally readily measured. Starting in 1986, ISIS 2 telemetry capability at Siple Station will include the digital telemetry signal. Thus both absolute wave amplitude and simultaneous correlative spacecraft measurements will be available for future planned experiments. In the following section we present new data from recent Siple Station wave injection experiments in which Siple signals trigger VLF emissions while propagating through ionospheric regions where subauroral impulsive VLF hiss is present.

2. OBSERVATIONS

Figure 1 shows the typical experimental configuration during periods in which triggered impulsive emission (IE) events were observed. In all cases the ISIS 2 satellite was located near the Siple Station magnetic meridian at an invariant latitude in the range 58° to 75° and at an altitude of approximately 1400 km. The distance in the earth ionospheric wave guide between the subsatellite point and the Siple transmitter location (T) was $\leq$ 1300 km.

Figure 2 shows high time resolution data of the frequency and amplitude of a Siple transmitter pulse during typical IE events. The upper panel shows a 1.5 to 4.5 kHz spectrogram of the pulse. The middle panel shows the pulse amplitude in a 300 Hz bandwidth centered on the instantaneous frequency of the pulse. The lower panel shows the frequency time format of the pulse. Arrows along the time axis of the spectrogram in the upper panel show the location of four events. (A few others, somewhat weaker, are not marked.) The events are characterized by impulsive increases in signal bandwidth and amplitude which endure for roughly 20-30 ms (based on a 10-dB-amplitude decreament). In general, bandwidth increases can reach as much as 1 kHz, and amplitude increases can exceed 20 dB. In the examples shown the maximum bandwidth of an IE is roughly 700 Hz and the amplitude of the IE events is roughly 10 to 20 dB above the signal level immediately preceding and following the events. During the duration of each of the events (20–30 ms) the satellite moved approximately 150–200 m along its orbit.

Figure 3 shows a series of IE events within the context of wideband wave observations made during an ISIS II pass near Siple station, Antarctica on July 4, 1983. Observations during this pass were typical of those made during our

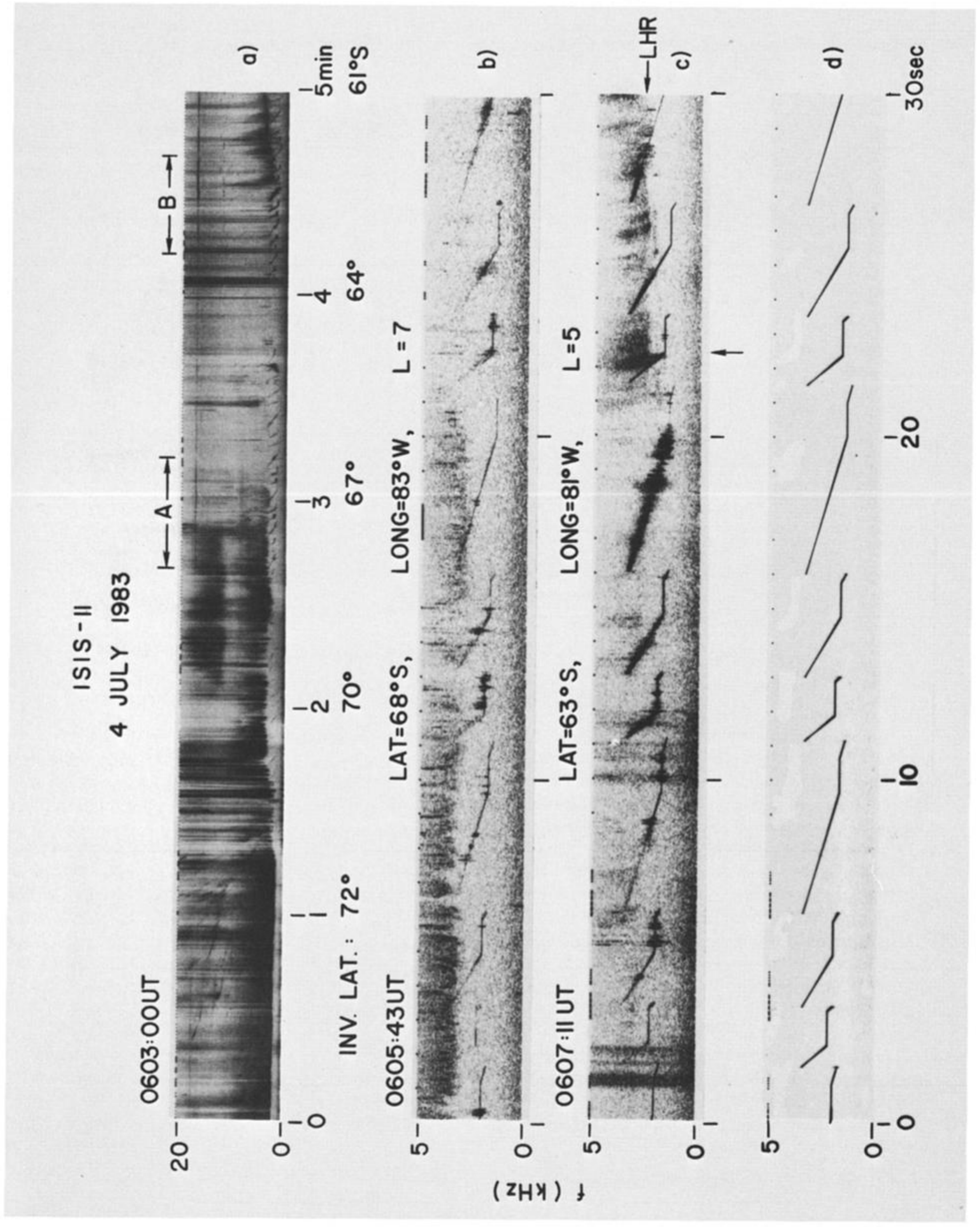

Fig. 3. Wideband VLF wave observations during a 5-min period in which Siple transmitter pulses triggered impulsive VLF emissions.

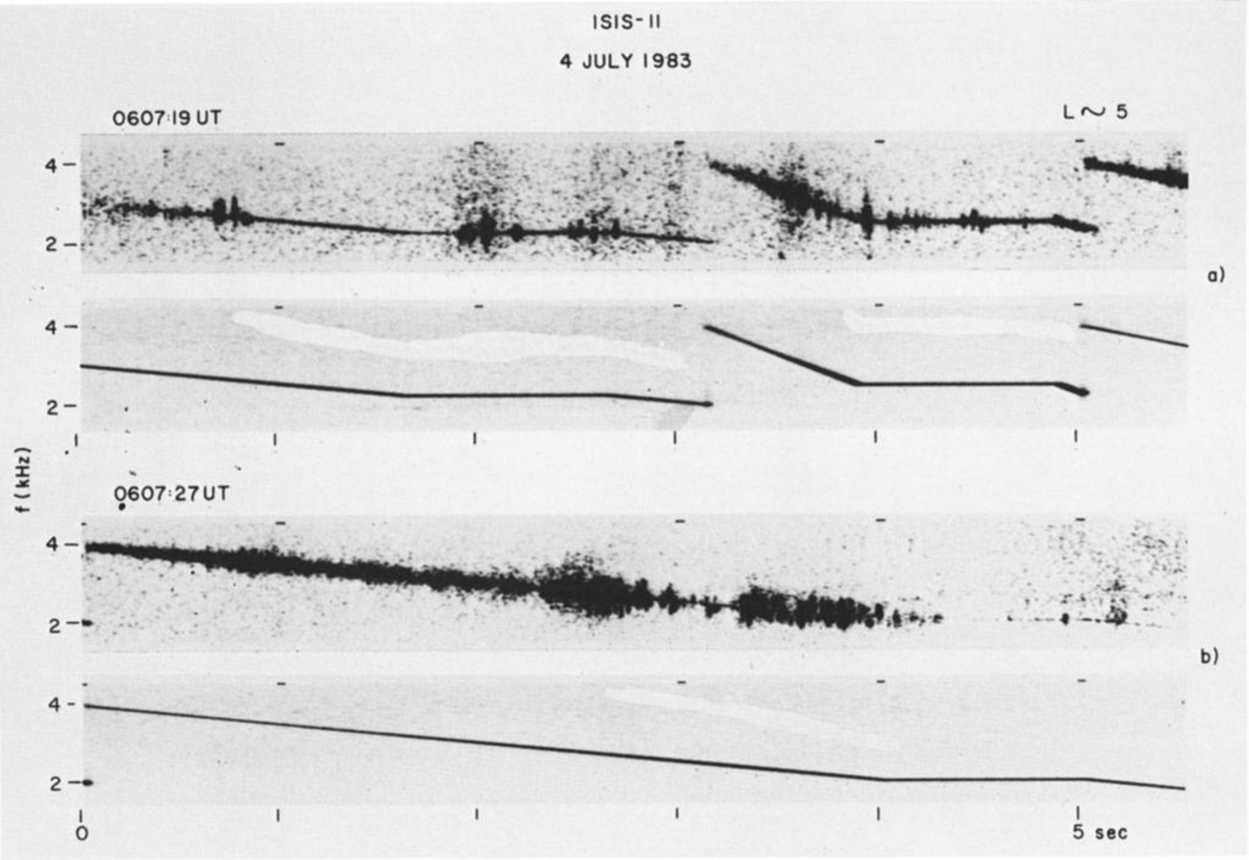

Fig. 4. High time resolution spectrograms of Siple transmitter pulses and triggered impulsive VLF emissions.

7-month study. Figure 3*a* shows a 0-20 kHz spectrogram of wave data acquired during a 5-min portion of the pass. During the first 2.5 min the satellite was located within the southern auroral region, and the wave activity was typical of this region, showing V-shaped auroral hiss forms (near 72° invariant latitude) [*Gurnett and Frank*, 1972; *Jorgenson and Bell*, 1970] and impulsive auroral hiss [*Gurnett*, 1966; *Laaspere et al.*, 1971; *McEwen and Barrington*, 1967] with a well defined lower cutoff frequency near 2 kHz. Shortly after the 1-minute mark the lower cutoff frequency of the impulsive auroral hiss began to rise and the impulsive hiss bursts tended to occur less frequently. At 0605 UT the lower cutoff frequency of the impulsive hiss had risen to ~ 3.5 kHz, and signals from the Siple station transmitter could be seen clearly in the data between 1 to 4 kHz. No IE events were associated with the transmitter signals observed at invariant latitudes (λ_I) above 68°S; however, as the satellite entered the subauroral region (outside the plasmasphere), a few isolated IE events were observed. A 30-s portion of the data in which IE events were first observed is marked as section A on the upper edge of the spectrogram of Figure 3*a*. This portion is shown with higher time and frequency resolution in Figure 3*b*. The IE events shown in Figure 3*b* occur in association with subauroral impulsive VLF hiss which resembles the impulsive auroral VLF hiss observed at higher latitudes. However, the subauroral impulsive VLF hiss is generally weaker than that in the auroral regions and decreases rapidly in amplitude below 67° latitude. (In the present work we define the subauroral region to consist of all latitudes between 60° and 67°.)

The IE events occurred more frequently as the spacecraft approaches the plasmapause position near $\lambda_I \sim 62°$. A 30-s portion of data bracketing the plasmapause position is marked as section B on the upper edge of the spectrogram of Figure 3*a*. This portion is shown with higher time and frequency resolution in Figure 3*c*. At this time the impulsive VLF hiss was no longer detectable. The IE events occurred more often and their signal bandwidth reached a maximum value of about 1 kHz near the 19-s mark. Near the 22-s mark (see arrow on time axis) a whistler arrived at the satellite and from its lower cutoff frequency the local LHR frequency could be determined (see arrow on frequency axis). Two instances of IE occurred near the 23-s mark where the pulse frequency lies below the local LHR frequency. Within the plasmasphere ($\lambda_I < 62°$S), signals lying within the LHR noise band exhibited a uniform spectral broadening similar to that reported previously [*Bell et al.*, 1983*b*]. The lower panel shows the transmitter pulse format corresponding to the satellite data in the two middle panels.

Figure 4 shows high time resolution spectrograms of Siple transmitter pulses exhibiting IE. The three pulses shown are part of the set shown in Figure 3. The impulsive nature of the bandwidth increases is clear. In these examples the duration of a typical isolated event is roughly equal to the filter response time (~ 50 ms). The lower portion of each panel shows the transmitted frequency time format.

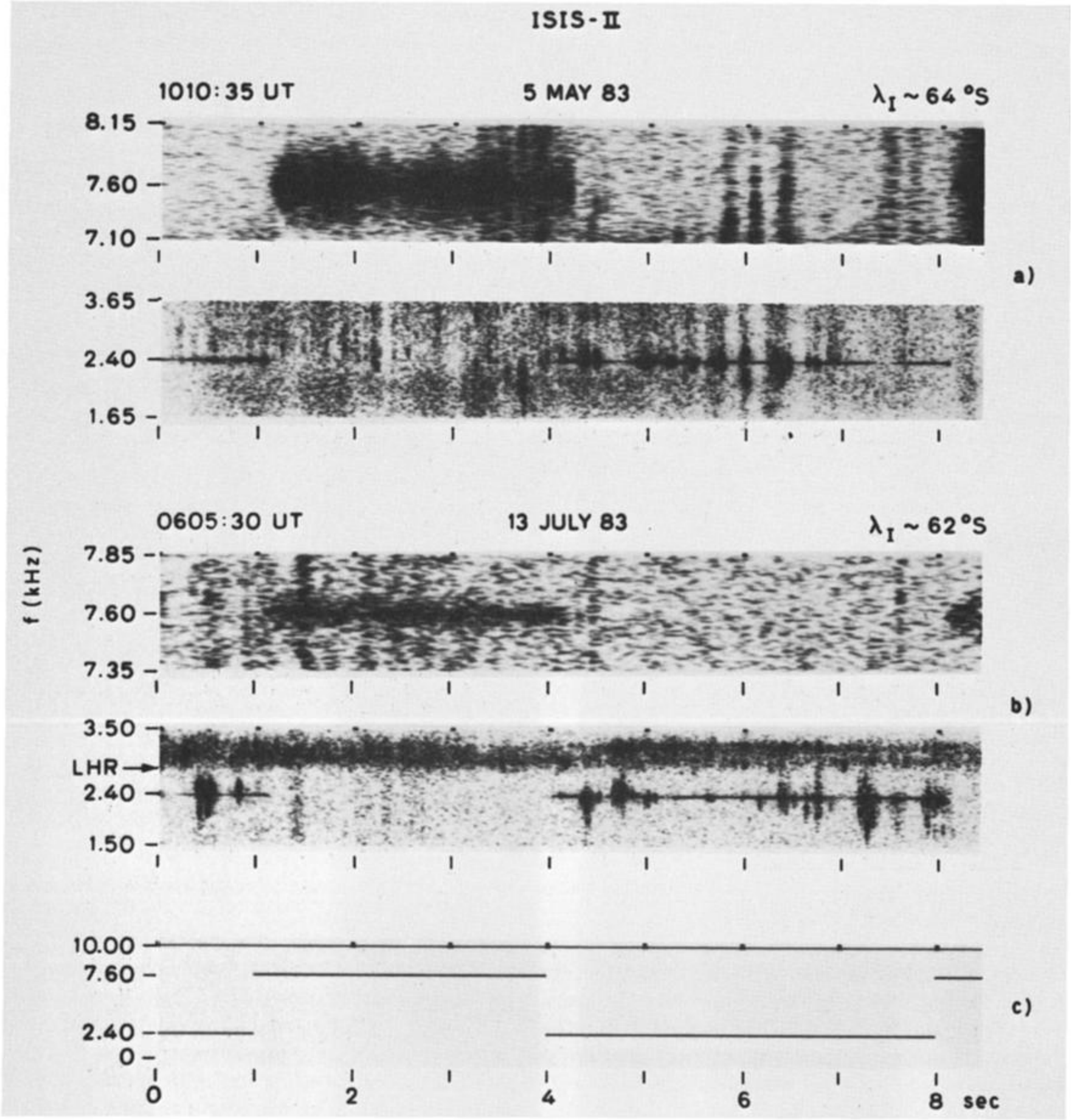

Fig. 5. High time resolution spectrograms showing the association between the spectral broadening exhibitied by transmitter pulses at 7.6 kHz and impulsive VLF emissions triggered by pulses at 2.4 kHz.

In order to study the relationship between the spectral broadening effect [*Bell et al.*, 1983] and the IE effect, a special transmitter format was employed in which fixed frequency pulses were transmitted alternately at 2.4 and 7.6 kHz. The pulses at 7.6 kHz were well above the normal frequency range of the local LHR frequency in the subauroral region, a necessary condition for the occurrence of the spectral broadening effect [*Bell et al.*, 1983*b*]. With the use of this format it was found that when the 2.4-kHz pulses exhibited IE the pulses at 7.6 kHz usually exhibited the spectral broadening effect. Examples of this association are shown in Figure 5.

Figure 5*c* is a 0 to 10 kHz spectrogram showing the transmitter format used in the experiments. The two high-frequency resolution spectrograms in Figure 5*a* show examples of the transmitted pulses as received on the spacecraft. The pulses at 7.6 kHz exhibit a spectral broadening of approximately 400 Hz, while the pulses at 2.4 kHz show a series of IE events. In the example of Figure 5*b*, the pulses at 7.6 kHz exhibit a spectral broadening of approximately 100 Hz, while the pulses at 2.4 kHz show a series of IE events. The lower spectrogram in Figure 5*b* shows the presence of an irregular LHR noise band with a lower cutoff frequency near 3 kHz (see arrow on frequency axis). The association of the spectral broadening effect with bands of irregular LHR noise is well established [*Bell et al.*, 1983*b*]. The association between the IE and spectral broadening effects suggests that the mechanisms for producing these phenomena may be similar. This point is discussed further in section 3.

Occasionally, the IE effect was observed to occur in the subauroral region in association with upward propagating whistlers. Figure 6 shows an example of this association as observed on August 18, 1982. On this day, near 0600 UT, whistlers were observed on the ground at Siple Station which had propagated from the conjugate hemisphere along plasmaspheric whistler mode ducts. The strongest whistler

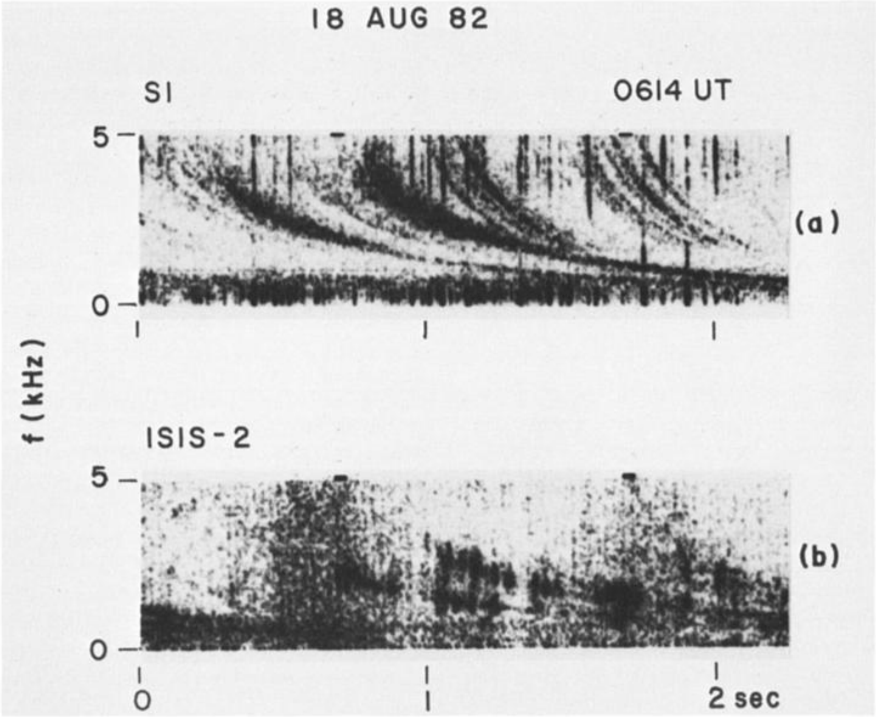

Fig. 6. Simultaneous ground and satellite data showing impulsive VLF emission events associated with whistlers observed on ISIS 2: (*a*) ducted whistlers received on the ground at Siple Station; (*b*) reflected whistlers and emission events observed on the spacecraft.

trace was associated with a duct near $L \sim 4$. For a period of approximately 2 min the strongest whistler trace was also observed on the ISIS 2 spacecraft while it was located in the subauroral region. However, the whistlers were observed on the spacecraft a short time (~ 50 ms at 3 kHz) after their observation on the ground. This fact suggests that the original ducted whistler wave packets were split into at least two components upon reaching the lower boundary of the ionosphere near Siple Station: a transmitted component which was observed on the ground and a reflected upward propagating component which was observed a short time later on the spacecraft. Observations of this type have been reported previously [*Farley and Dowden,* 1984].

As the satellite neared the plasmasphere, two strong whistler traces were observed and both traces were associated with IE events. This circumstance is illustrated in Figure 6, where Figure 6*a* shows the ground data and Figure 6*b* shows the simultaneous satellite data. The two strongest (darkest) whistler traces in Figure 6*a* correspond to the two traces in Figure 6*b*. Although the frequency range of the two strongest whistlers observed on the ground exceeds 4 kHz, the satellite whistlers cut off near 3 kHz. The association of the IE effect with upward propagating whistlers suggests that the IE mechanism can perhaps also be triggered by other types of coherent quasi monochromatic VLF signals such as power line radiation, magnetospheric lines, and narrowband chorus. A search for such events is presently underway.

The data reported here was acquired during the period April to October, 1983. A total of 92 satellite passes was involved, and the local time during the observations lay in the range 1800-0800 LT (through the night time sector). Impulsive bandwidth increases of Siple signals were observed on 39 of the 92 passes, giving an overall observational probability of roughly 42%.

Table 1 gives an accounting for each month of the total number of passes for which Siple transmissions were carried out, the number of passes on which IE was observed, and

TABLE 1. Monthly Occurrence Rate of Impulsive Emission Events

Month	Total Passes	Passes With IE	Occurrence Rate
April	11	2	~ 18%
May	13	6	~ 46%
June	14	14	~ 100%
July	20	10	~ 50%
August	10	3	~ 30%
September	15	4	~ 27%
October	9	0	~ 0%

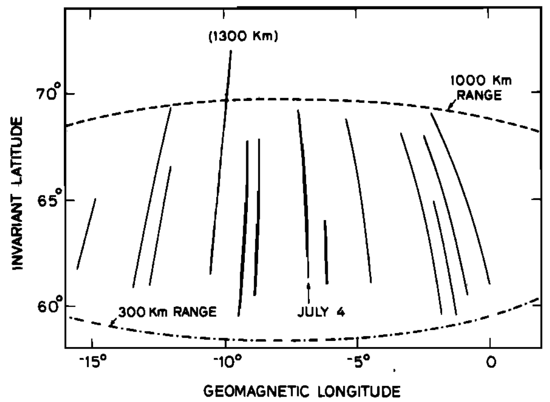

Fig. 7. Invariant latitude and geomagnetic longitude of the ISIS 2 satellite during passes in which Siple transmitter signals triggered impulsive VLF emissions.

the approximate probability of observation. The maximum occurrence rate was found in the month of June when IE were observed on all passes. The minimum occurrence rate was found in October when no IE events were observed. Furthermore, no IE events were observed after September 20, even though transmissions were carried out for a total of 19 passes after this date. The possible significance of this fact is discussed in section 3.

Figure 7 shows the invariant latitude and geomagnetic longitude of the ISIS 2 satellite for representative passes when IE events were observed. Most observations of the effect were made in the subauroral region poleward of the plasmapause location ($67^\circ > \lambda_I > 60^\circ$) and were spread with rough uniformity over 16° of geomagnetic longitude, centered approximately on the transmitter meridian.

In general, the propagation path from the transmitter to the satellite consisted of two parts: (1) propagation in the earth-ionosphere wave guide from the transmitter to the foot of the magnetic field line intersecting the satellite and (2) transionospheric propagation approximately along the earth's magnetic field to the satellite position. The locus of high latitude points for which the distance (range) in the earth ionosphere waveguide between transmitter and field line foot equals 1000 km is shown in the dashed curve of Figure 7. The locus of low-latitude points for which the range equals 300 km is also shown.

The bulk of the IE observations occurred for ranges less than 1000 km. The lack of observations at ranges > 300 km in the east-west direction is due to a bias in the selection of satellite passes for the experiments. To optimize the signal to noise ratio at the satellite, transmissions to the satellite were carried out generally only for orbits which fell within the longitude window shown in Figure 7. Occasionally, the IE events were associated with impulsive bursts of ELF noise below 500 Hz. However, in general the IE events were not well correlated with activity in the ELF band. During the observation of the IE events the planetary geomagnetic index, *Kp*, ranged from a low value of 0+ to a high value of 4+ and had an average value of 2+. Thus the IE events were observed mainly under conditions of low to moderate disturbance.

3. DISCUSSION

The band of impulsive hiss shown in Figure 3*b* can be described as a series of impulsive noise bursts with little or no dispersion and a lower frequency cut off of about 2-4 kHz. As such, it closely resembles the impulsive VLF hiss which exists in the auroral regions and which has been described by earlier workers. Spectrographic examples of this type of impulsive auroral VLF hiss have been given in a number of papers [*Gurnett,* 1966; *Laaspere et al.,* 1971; *Laaspere and Johnson,* 1973; *Gurnett and Frank,* 1972; *Mosier and Gurnett,* 1969, 1972; *Mosier,* 1971; *Jorgensen and Bell,* 1970; *Bell et al.,* 1983*b*.] The amplitude of this type of hiss reaches its highest levels in the dayside auroral zone [*Gurnett,* 1966; *Laaspere et al.,* 1971; *Gurnett and Frank,* 1972]. However, it appears to be common at lower intensity during all times of day [*Laaspere et al.,* 1971]. According to *Laaspere et al.,* the position of maximum intensity of the auroral hiss zone under magnetically quiet conditions extends from about 70° invariant latitude at magnetic midnight, through 75° invariant at 0600 and 1800 MLT to about 78° invariant at 1200 MLT. Thus the region of maximum intensity coincides with the region of maximum occurrence of "burst-type" lower-energy (~700ev) electrons observed by *Hoffman,* [1969]. Furthermore, in a number of studies a strong correlation was found between precipitating electrons with energy below 1 keV and auroral impulsive VLF hiss [*Gurnett and Frank,* 1972; *Hoffman and Laaspere,* 1972; *Laaspere and Hoffman,* 1976].

In view of the close similarity between the subauroral impulsive VLF hiss and the auroral impulsive VLF hiss it seems reasonable to suggest that the subauroral hiss may also be associated with low energy electron precipitation. This suggestion is supported by the work of *Gussenhaven et al.* [1983] which shows that the equatorward boundary of the diffuse auroral region lies in the range $\lambda_I \cong 62^\circ - 64^\circ$ in the 0000-0600 MLT sector during magnetically quiet conditions in which $K_p \sim 2$. Thus many of the IE events were observed at latitudes at which low energy ($E <$ 20keV) energetic electron precipitation is known to occur.

Estimates of the magnitude of this precipitation can be obtained from published Injun 5 observations [*Gurnett and Frank,* 1972] in which strong auroral VLF hiss was correlated with intense fluxes of low energy electrons. For the three cases concerning crossings of the southern auroral region near the dawn-to-dusk meridian it was found that near

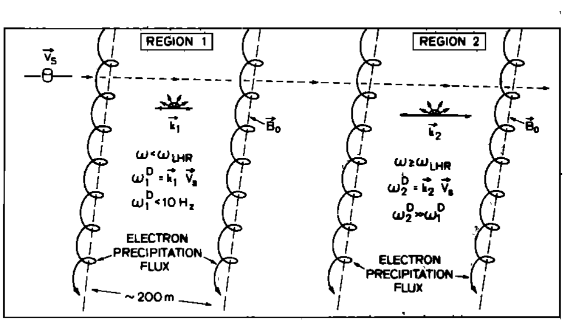

Fig. 8. Sketch of a possible mechanism for producing impulsive VLF emissions. Transmitter pulses are scattered coherently from magnetic field-aligned plasma irregularities of transverse scale approximately 200 m which are produced by energetic particle precipitation in the subauroral region. The scattered wave spectrum has components with wave normals nearly perpendicular to the earth's magnetic field, $\mathbf{B}_o$. Large doppler shifts of these components are observed in regions where the wave frequency equals or exceeds the local lower-hybrid resonance frequency. This doppler spread produces the observed impulsive bandwidth increase. The amplitude increase is thought to be caused by a quasi electrostatic coherent wave instability driven by the precipitating particles.

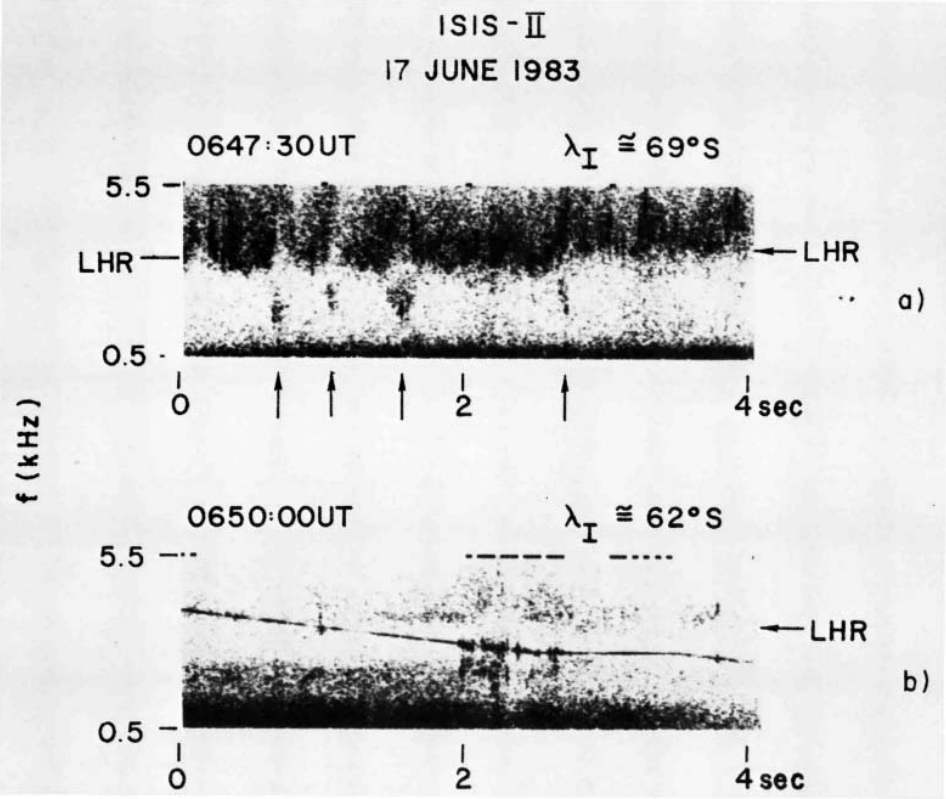

Fig. 9. Spectrograms of data suggesting a connection between large, impulsive decreases in the local lower-hybrid resonance (LHR) frequency and the onset of the triggering of impulsive VLF emissions by Siple transmitter pulses.

dawn, electrons in the energy range, $160 \leq E \leq 280$ev, exhibited a differential number flux in the range 10^3-10^4 electrons $(cm^{-2}s^{-1}sr^{-1}eV^{-1})$. These subauroral fluxes were roughly 2-3 orders of magnitude below the peak auroral fluxes measured on the same crossings. However, the presence of these relatively weak fluxes might be an important component of the IE mechanism.

It is believed that the lower cutoff frequency of the subauroral impulsive VLF hiss is approximately equal to the local lower-hybrid resonance (LHR) frequency [*McEwen and Barrington*, 1967]. In theory, the LHR frequency is dependent upon the three plasma parameters: local electron density, electron gyrofrequency, and ion composition. The variation in the observed LHR frequency (ω_{LHR}) with satellite position has been attributed to variations in one or more of these plasma parameters [*McEwen and Barrington*, 1967; *Laaspere and Taylor*, 1970; *Laaspere et al.*, 1969, 1971].

According to the cold plasma theory of whistler mode waves [*Stix*, 1962], whistler-mode wave components with frequency, ω, less than ω_{LHR} cannot achieve high refractive indices and remain essentially electromagnetic in character. However, wave components with $\omega \geq \omega_{LHR}$ can achieve high refractive indices when the wave normal is near the whistler mode resonance cone, in which case the waves are quasi-electrostatic in character. From the application of Snell's law at the boundary of a magnetic field aligned irregularity it can be shown that whistler mode waves which scatter coherently from the irregularity can excite quasi-electrostatic whistler mode waves within the irregularity as long as $\omega_H/2 > \omega > \omega_{LHR}$ within the irregularity where ω_H is the electron gyrofrequency. These circumstances suggest the following mechanism for the IE effect, which is similar in some respects to one of the mechanisms proposed for the spectral broadening effect [*Bell et al.*, 1983*b*].

We hypothesize that energetic electron precipitation in the subauroral region creates a multitude of magnetic field aligned irregularities of transverse scale of approximately 200 m in which the ion density and composition may differ from those of neighboring regions. As a result of these irregularities, the lower-hybrid resonance frequency is a rapidly varying function of position. The Siple pulses are scattered coherently from the irregularities and the scattered wave spectrum has components with wave normals nearly perpendicular to $\mathbf{B}_o$; this situation is illustrated schematically in Figure 8.

In irregularities in which the pulse frequency lies below the local ω_{LHR}, such as in region 1, large wave refractive indices and quasi electrostatic modes are not possible and scattered wave vectors, $\mathbf{k}$, perpendicular to $\mathbf{B}_o$ produce only small doppler shifts $\omega_1^D = \mathbf{k}_1 \cdot \mathbf{V}_s < 10$ Hz in the wave spectrum observed on the satellite, where $\mathbf{V}_s$ is the satellite velocity vector. In irregularities where the pulse frequency equals or exceeds ω_{LHR}, such as in region 2, quasi electrostatic whistler mode waves are excited with $\mathbf{k}$ near the resonance cone ($\sim \perp\mathbf{B}_o$). Because of their high refractive indices these modes are observed on the satellite with large doppler shifts, $\omega_2^D >> \omega_1^D$ thus producing the impulsive bandwidth increases associated with the IE events.

The large amplitude increase which generally characterizes each impulsive emission is hypothesized to occur as a result of a coherent-wave quasi electrostatic plasma instability which amplifies the high wave normal components of the

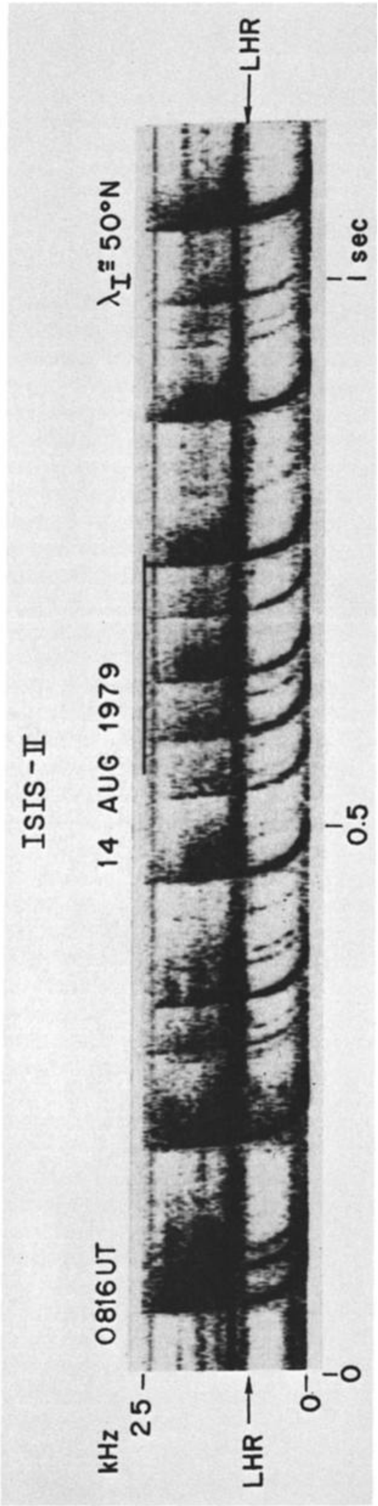

Fig. 10. Spectrogram of fractional-hop whistlers exhibiting anomalously large temporal dispersion at frequencies above the LHR frequency.

scattered signal. This instability might be analogous to the instability associated with lower hybrid waves in the presence of energetic electron beams [*Berger and Perkins*, 1976; *Papadopoulis and Palmadesso*, 1976]. If the causative instability reaches a nonlinear state, it is possible that the true frequency of the emission will differ from that of the input wave. However this shift could be obscured by the doppler shift effect.

The hypothesis that IE events are associated with rapid and short lived decreases in ω_{LHR} has some support in the data. In general, the lower cutoff frequency of the impulsive VLF hiss is a rapidy varying function of satellite position, with typical variations being of the order of ±200 Hz. This type of variation is shown in Figure 9*a*. Occasionally, however, and for short time periods, the lower cutoff frequency appears to decrease abruptly by as much as 2 kHz. Four instances of this behavior are marked by arrows on the time axis in Figure 9*a*; the data were acquired at the edge of the auroral region where the impulsive hiss was relatively strong and variations in the lower cutoff frequency were readily apparent. However, in the subauroral regions where most IE events were observed, the impulsive hiss was relatively weak and the lower cutoff frequency generally could not be measured. Figure 9*b* shows one of the few exceptions to this rule. In this panel a weak impulsive hiss band can be seen with a faint lower cutoff frequency. Near the 2-s mark the lower cutoff frequency appears to decrease abruptly to a value below the transmitter signal, and during the time of decrease a number of IE events occur. Although data such as that of Figure 9 does not provide strong evidence of a connection between IE events and abrupt decreases in ω_{LHR}, the assumption of such an association leads to a simple picture of the mechanism which produces the IE.

We have hypothesized that both the spectral boadening effect and the IE effect involve the scattering of the energy of the initial transmitter signal into quasi electrostatic whistler mode waves with wave normals near the resonance cone. The main evidence for this process comes from the characteristics of the pulses which exhibit spectral broadening [*Bell et al.*, 1983*b*] or the IE effect. However, further evidence can sometimes be found in natural signals which propagate to the satellite at times when spectral broadening is observed in transmitter pulses.

For instance, Figure 10 shows a high time resolution 0-25 kHz spectrogram of a cluster of fractional-hop whistlers [*Helliwell*, 1964], or sferics, which were observed on August 14, 1979, at a time when transmitter pulses from the Omega VLF transmitter in North Dakota were exhibiting spectral broadening (see Figure 7 of *Bell et al.* [1983*b*]).

The local LHR frequency at that time was approximately 11 kHz. The leading edge of each fractional-hop whistler trace exhibits a frequency time dispersion which is consistent with nomal whistler mode propagation from the ground to the satellite at 1400 km altitude. However, the temporal dispersion of each whistler for $\omega \geq \omega_{LHR}$ is very unusual. Portions of the traces below $\omega \geq \omega_{LHR}$ exhibit a temporal dispersion of approximately 10 ms, which is essentially the filter response time, while portions above ω_{LHR} exhibit a much larger dispersion of roughly 50 ms.

The temporal dispersion in the whistlers for $\omega > \omega_{LHR}$ is comparable to the maximum time delay between the carrier and sideband waves in the transmitter pulses which exhibited spectral broadening at this time [*Bell et al.*, 1983*b*]. Consequently, we interpret the data of Figure 10 as indicating that fractional-hop whistler components with $\omega > \omega_{LHR}$ excite quasi-electrostatic whistler mode waves as they propagate up to the satellite, presumably through a coherent scattering process. The relatively low group velocity of the excited quasi-electrostatic waves then results in large values of temporal dispersion in the total signal observed at the satellite.

During the 1983 campaign, only a few IE events were observed to occur within the plasmasphere, and these few occurred within a few degrees in latitude of the plasmapause position. There are a number of possible reasons for this circumstance. (1) ω_{LHR} tends to increase rapidly with decreasing latitude within the plasmasphere reaching values of 8 kHz or more a few degrees equatorward of the plasmapause. Thus abrupt decreases in ω_{LHR} of more than 4 kHz would have been necessary to satisfy the condition $\omega > \omega_{LHR}$ for the Siple pulses (whose frequency was always generally less than 4 kHz). Decreases of this magnitude were not observed in the data. (2) Lower-energy energetic electron precipitation flux is generally much lower within the plasmasphere than in the subauroral region. Thus if these particles drive the IE effect, much lower occurrence rates would be expected within the plasmasphere. (3) Local ion composition and density at 1400 km differs markedly between the plasmasphere and the subauroral region. Thus if a plasma instability is responsible for the IE effect, the necessary conditions for this instability may not exist within the plasmasphere. An example of a beam driven instability in lower hybrid waves which occurs only under conditions of low ion density is discussed by *Coppi et al.* [1981].

It is noteworthy that during most passes on which IE events were observed, the frequency of occurrence of IE events increased markedly as the satellite approached the plasmapause position; this circumstance is evident in the data shown in Figure 3. One interpretation of this variation is that there exists an input wave amplitude threshold below which IE events do not occur. If this is the case, it would provide a simple explanation of the general lack of observations of IE events in the auroral regions where impulsive VLF hiss bands with irregular lower cutoff frequency are a common feature of the data (see Figure 3). It is planned to carry out a test of the amplitude threshold hypothesis at Siple Station in 1986.

During the period September 21 to October 18, 1983, transmissions to the ISIS 2 satellite were carried out for 19 northbound passes over Siple Station. In each case the signals were received on the spacecraft but no IE events were observed. This abrupt cessation of IE events coincided with the precession of the northbound leg of the ISIS 2 orbit from the night side to the day side of the earth. Thus after September 20 the propagation of Siple transmissions to the spacecraft took place within a sunlit ionosphere.

The lack of IE events during daylight hours could possibly be due to the existence of an amplitude threshold for the IE effect. For instance, the daytime value of ionospheric absorption at 2.4 kHz is estimated [*Helliwell*, 1965] to be approximately 10 dB higher than that during night hours. In this case, the lower daytime signal amplitudes may be below the threshold level needed to trigger the IE events. Another possibility is that the IE effect occurs only in regions of low thermal ion density. This hypothesis is supported by the fact that the bulk of the IE events were observed to occur at local times and invariant latitudes consistent with the location of the main trough. As was mentioned above, this possibility could also explain why IE events are seldom observed within the plasmasphere.

It is well known that thermal ion densities in the trough region are generally much higher during daytime than during night time [*Taylor and Walsh*, 1972; *Titheridge*, 1976; *Brinton et al.*, 1978; *Ahmed et al.*, 1979]. Thus in this case the IE effect could be limited to night time hours if a threshold for ion density exists.

The existence of the IE effect lends credence to the idea that coherent VLF signals can act as catalysts to trigger natural plasma instabilities in the subauroral ionosphere and lower magnetosphere. Thus controlled studies of these instabilities may be possible. Furthermore, it suggests that the IE effect could be used as a diagnostic tool to study the characteristics of field aligned irregularities in the subauroral region, and to map out regions of precipitation of energetic electrons. Future studies should serve to establish the feasibility of these applications.

Acknowledgments. The authors acknowledge valuable discussions with D. L. Carpenter, U. Inan, R. A. Helliwell, and J. Yarbrough concerning the data discussed herein. The support in ISIS scheduling and data acquisition by the Satellite Controller and his staff at Communications Research Centre, Ottawa is deeply appreciated. The work of the first two authors was supported by the National Aeronautics and Space Administration under contracts NAS5-20871 and NGL-05-020-008. The work of the remaining author was supported by the Canadian Government through the Communications Research Centre. The spectrograms shown in this paper were produced by J. Yarbrough, the text was prepared by N. Leger, and typeset by K. Fletcher and G. Walker.

The Editor thanks R. L. Dowden and J. Chang for their assistance in evaluating this paper.

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(Received July 1, 1985;
revised August 19, 1985;
accepted August 20, 1985.)