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Rare Ground-Based Observations of Siple VLF Transmitter Signals Outside the Plasmapause

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Signals from the Siple, Antarctica ($L \sim 4.3$), VLF transmitter observed at the conjugate ground station Roberval, Canada, have previously been found to propagate either within the outer plasmasphere or within the region of steep plasmapause density gradients, but on paths with equatorial electron density that is within a factor of 2 of nearby plasmaspheric levels. We report here two cases in which propagation occurred just outside the plasmapause and at plasma trough density levels. In one case a series of 1-s pulses and frequency ramps was observed; many of the pulses triggered risers with slopes of ~10 kHz/s, much steeper than those usually observed within the plasmasphere. In the other case, no evidence of triggered emissions was seen on the Siple pulses, but instead efficient echoing occurred and noise band precursors to large wave bursts were initiated. The wave bursts were of a type that has been previously identified as driving transient bursts of electron precipitation into the ionosphere. Both cases occurred under magnetic conditions more disturbed than those typical of strong Siple signal propagation in the outer plasmasphere.

1. INTRODUCTION

Signals propagating from the Siple, Antarctica, VLF transmitter ($L \sim 4.3$) to the conjugate station Roberval, Canada, normally exhibit travel times and dispersion characteristics consistent with propagation either in the outer plasmasphere or in the region of steep plasmapause density gradients [*Carpenter and Miller,* 1976]. In the latter case, the equatorial electron density levels are usually within a factor of ~2 of levels in the nearby plasmasphere. The paucity of signal events outside the plasmapause is not surprising; during OGO 4 satellite receptions at ~600-km altitude of upgoing signals from high-power fixed-frequency transmitters, signal amplitude tended to be sharply reduced outside the plasmapause [*Heyborne et al.,* 1969]. Furthermore, it was found that whistlers propagating from the conjugate hemisphere to the Alouette 1 satellite at 1000 km tended to cut off abruptly as the satellite moved poleward through the plasmapause [*Carpenter et al.,* 1968].

It is desired to extend the ground-to-ground probing capabilities of the Siple transmitter into the low-density plasmatrough region. VLF wave activity is clearly present there, such as in the form of discrete chorus emissions. Ground-observed whistlers propagate there, albeit less frequently than in the plasmasphere and under specific conditions on local time and distance beyond the plasmapause [*Carpenter,* 1968]. Of special importance is the occurrence in the plasmatrough of burst correlations between natural VLF waves and precipitating electrons [e.g., *Rosenberg et al.,* 1971; *Helliwell et al.,* 1980; *Rosenberg et al.,* 1981]. The natural wave bursts as well as other types of emissions are frequently triggered by whistlers [*Helliwell et al.,* 1980; *Dingle and Carpenter,* 1981], and it is of interest to attempt to produce such effects under controlled conditions.

The purpose of this note is to present evidence that ground-to-ground propagation of signals from Siple to Roberval can be detected outside the plasmapause. Two examples have been identified thus far during reviews of data acquired in the years 1973, 1974, 1975 and 1977. In that period, transmissions were attempted on about 700 days, and signal detection at Roberval (plasmasphere propagation) was achieved on ~20% of the days. However, magnetic disturbance levels high enough to suggest that the plasma trough region was nearly overhead at Siple prevailed on only ~1/3 of the transmitting days. Thus the two examples represent ~1% of the days when the plasma trough region was "accessible" to the transmitter. The examples illustrate in different ways the special wave environment that exists beyond the plasmasphere. The results serve as a basis for further planning of experiments and as an additional justification for improvements in the performance characteristics of the transmitting system.

2. EXPERIMENTAL RESULTS

October 15, 1974. In this case the current Kp index was 3, but the Kp sum for the preceding 24 hours was 41, well above the values <20 found to be typical for cases of strong Siple signal propagation in the outer plasmasphere [*Carpenter and Miller,* 1976]. The Zeus VLF transmitter [*Helliwell and Katsufrakis,* 1974, 1978] was operated between 1500 and 2300 UT, and signals were detected at Roberval between ~1930 and 2030 UT (1430–1530 MLT). During a period of ~10 min near 1945 UT, relatively strong steeply rising chorus emissions were triggered by the transmitter signals. Figure 1 shows spectrograms of the activity in coordinates of frequency (3–8) kHz versus time. The transmitter format, consisting of frequency ramps and 1-s pulses in the range 3.95–4.95 kHz, is shown on the bottom panel. Radiated power at the upper band edge was ~1 kW, dropping to ~200 W at the lower edge. Roberval spectrograms for two intervals spaced 3 min apart are shown above. The transmitter format has been aligned in time with respect to the Roberval receptions. On each Roberval panel only the upper frequency range of the Siple format was observed against the strong impulsive noise background; within that range steeply rising emissions were repeatedly triggered. A

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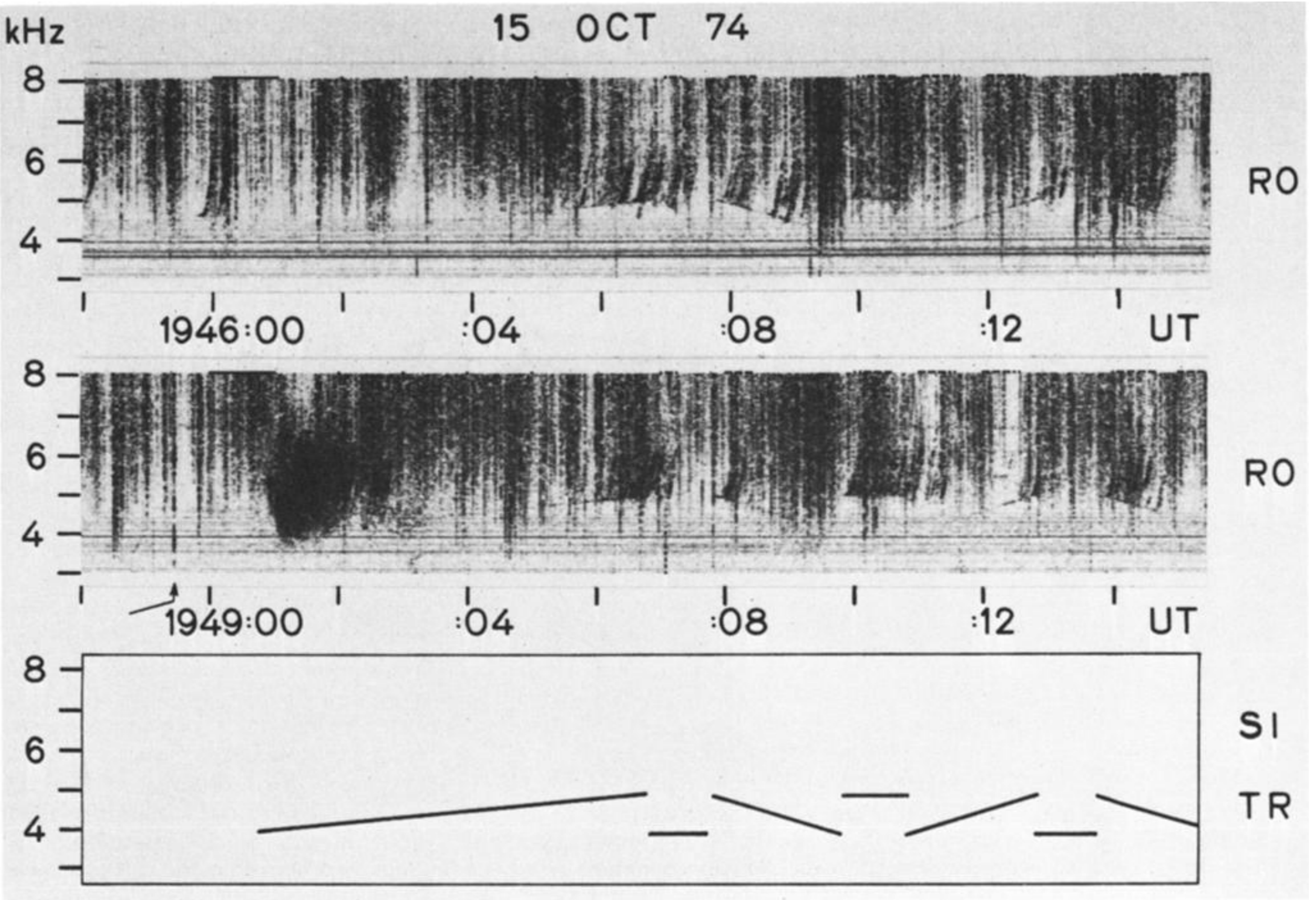

Fig. 1. Roberval spectrogram showing reception of Siple transmitter signals on October 15, 1974. The frequency-time format transmitted from Siple, Antarctica, delayed by the propagation time of ~0.8 s, is shown on the bottom panel. A two-hop whistler appeared near 1949:01: The time of its causative atmospheric is indicated by an arrow.

particularly well defined 1-s pulse appeared at ~1949:10 UT on the second panel.

A strong two-hop whistler, whose time of origin is indicated by an arrow, was received near 1949:01. This whistler had frequency-time features characteristic of whistlers propagating outside the plasmapause [e.g., *Carpenter,* 1978]; one such feature being the triggering of a burst of closely spaced chorus elements. Review of both Siple and Roberval records indicates that whistlers at this time were propagating on multiple paths; however the lack of multiple ramps in the received Siple signal suggests that the latter propagated essentially on a single path. The frequency range and rising tone characteristics of the whistler-triggered emissions are similar to those of the Siple signals, suggesting that they both propagated in the same field-line region.

The travel time of the Siple signals at 4.95 kHz was found to be 0.77 ± 0.02 s, as compared to the ~2 s usually observed at that frequency [*Carpenter and Miller,* 1976]. Comparison with one-hop whistler dispersion characteristics at Siple and two-hop whistlers at Roberval led to the following conclusions:

1. The plasmapause position, although not determined with precision, was at $L < 4$.
2. Siple signals traveled on an active whistler path located beyond the plasmapause at L ~4.2.
3. The electron density at L ~4.2, based on extrapolation from measurements on a path at L ~4, was 18 ± 10 el.cm^{-3}. The density analysis involved taking intermediate values between results from the DE and R^{-4} field-line models of plasma density discussed by *Park* [1972], an approach similar to that recommended by *Corcuff and Corcuff* [1982] on the basis of ground-satellite comparisons. The value of 18 el.cm^{-3} is in agreement with dayside plasmatrough values reported by *Angerami and Carpenter* [1966].

April 6, 1977. In this case, the current Kp index was 2-, and relatively deep quieting with respect to preceding moderately disturbed conditions was indicated (the preceding 24-hour Kp sum was 23 and the preceding two Kp values were 4 and 3).

The transmitter was operated in the 1.25 to 2.25-kHz range during the period 0800 to 1600 UT on April 6, 1977. Fifth harmonics of the transmitted fundamental were observed at Roberval during the period ~1100-1200 UT (0600-0700 MLT). This reception is interpreted as the result of the high harmonic content of the transmitter wave form in the low range being used (E. Paschal, personal communication, 1982) and the relatively greater efficiency of the Siple antenna at ~9 kHz (~4%) than at ~1.75 kHz (~0.02 percent) [*Raghuram,* 1974]. The estimated radiated power at 9 kHz was 135 W.

Natural noise bursts were also observed in the 1100-

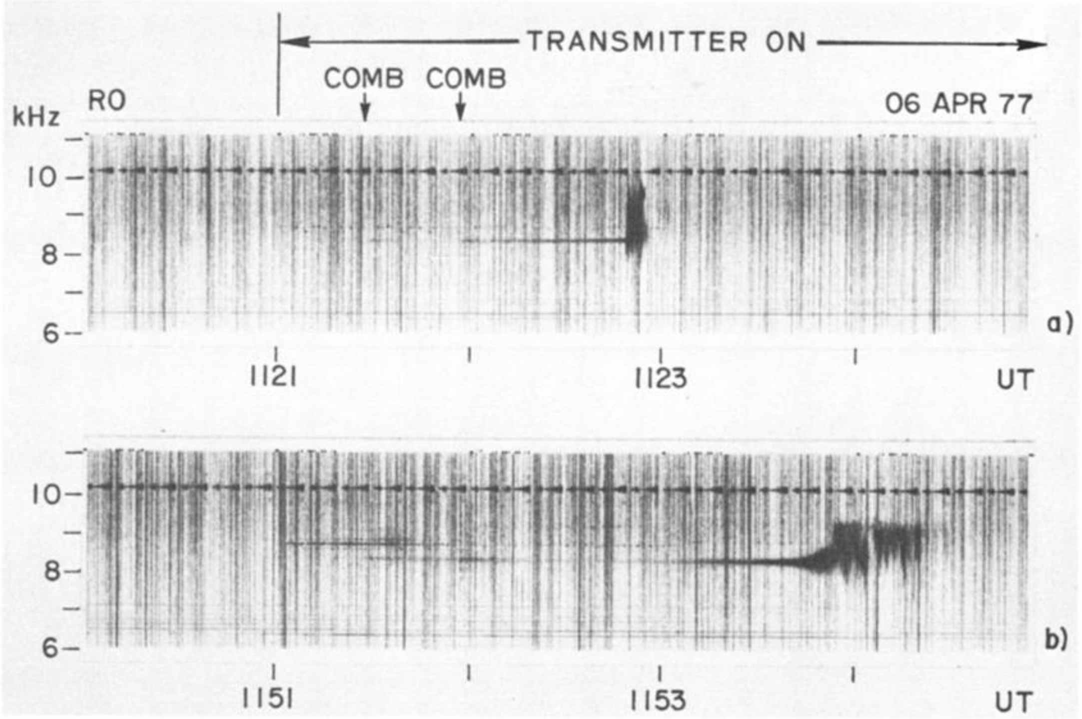

Fig. 2. Roberval spectrograms for April 6, 1977, showing receptions of Siple transmitter signals near 9 kHz, and the initiation of noise burst events during brief transmissions of a frequency comb.

1200 UT period. They were characterized by sudden (~1 s) increases in noise intensity and bandwidth following the appearance of narrow, nearly constant-frequency precursor bands, features previously found to be associated with wave burst propagation just outside the plasmapause [*Carpenter*, 1978]. Two of these bursts, received 30 min apart, are illustrated in Figure 2 on spectrograms of 6-11 kHz versus time.

In these two cases, Siple signals appeared to trigger the narrow-band precursors. The time of Siple transmitter operation is shown above the upper panel and applies to both panels. The received fifth-harmonic signals began at ~1121 and ~1151 UT with a series of pulses near 8.75 kHz, separated at intervals by rapidly varying (6 kHz/s) frequency ramps (see Figure 3, top panel at left). The pulses were particularly well defined on Figure 2*b* from ~1151:00 to 1151:45, while the ramps were not detected. Twice during this first minute a comblike spectrum was transmitted for a period of ~3 s. The times of comb transmission are shown at the top of Figure 2, while details of the frequency-time format are shown in Figure 3, top and bottom panels. The comb included a line at 9.125 kHz with principal sidebands at 9.175 kHz and 9.075 kHz and a line at 8.375 kHz with principal sidebands at 8.425 and 8.325 kHz, the sidebands being produced through 50-Hz square wave modulation.

In Figure 2*b*, a narrow noiseband at ~8.4 kHz appears to have been initiated at the time of the first comb. This band continued at constant frequency for ~1 min, faded, and then grew in amplitude until a broadband (~1-2 kHz) wave burst developed. In the upper panel a faint noise band at ~8.4 kHz appeared briefly following the first comb. At the time of the second comb, the narrowband activity recommenced and then a minute later developed into a broadband burst.

Figure 3 shows details of the onset of the precursors. The second and third panels show the Roberval spectra beginning at 1121:52 and 1151:22 UT, respectively. The corresponding Siple transmitter formats (fifth harmonic) are shown above and below, but have been delayed 0.9 s in time so as to be aligned with the received signals.

Under conditions of efficient multi-hop echoing of whistler-mode signals, an essentially continuous train of echoes can build up as the echoes of various order from preceding signals are superposed in time. This effect is particularly clear on the third panel of Figure 3, where nearly continuous lines appear at the transmitted frequencies 8.750 kHz and 8.825 kHz. In both the 1121 and 1151 cases, a pair of "echoing" lines at the center and lower sideband frequencies of the lower comb group (to within ±10 Hz measuring accuracy) appear to have originated at the time of the comb. Other records show that after ~20-40 s the line structure became less well defined and increasingly noiselike. However, it remained centered within ~50 Hz of the principal comb frequency at 8.375 kHz until the main bursts developed.

The comb pattern indicated in Figures 2 and 3 was transmitted at intervals of 7 or 8 minutes from 0800 to 1600 UT on April 6. The transmitter was operated at all intermediate times except for a 1 min key-up every 15 min, but there were no fixed-frequency signal components with fifth harmonic values closer in frequency to ~8.4 kHz than the pulses near 8.75 kHz shown in Figure 3. Two groups of noise bursts were observed at Roberval in the 1100-1200 UT interval. One, with starting frequencies in the range 9.4-9.8

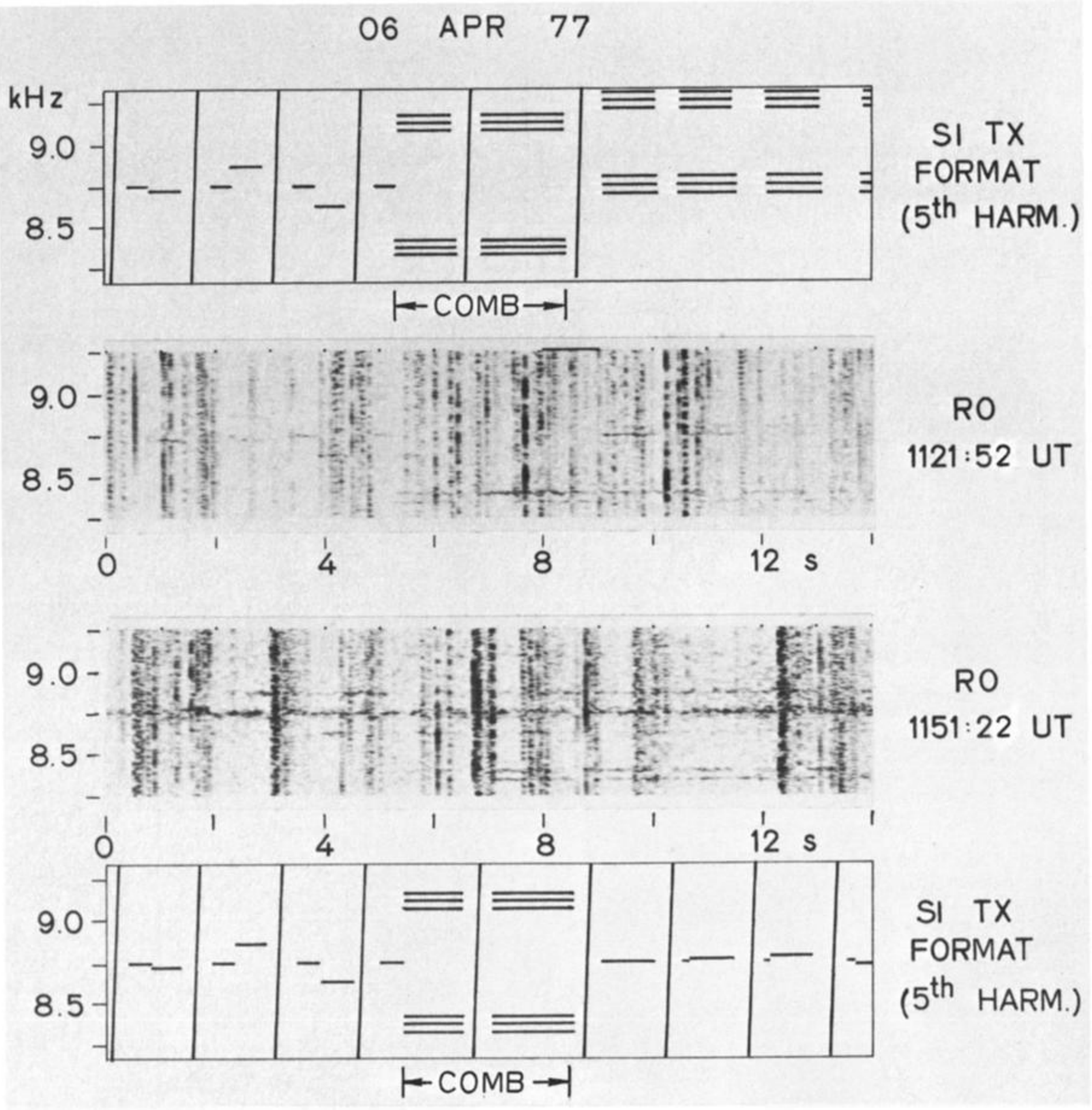

Fig. 3. Expanded portions of the Roberval spectrograms of Figure 2 near the times of initiation of the narrowband precursors. The corresponding frequency-time patterns of the Siple transmiter format are shown on the top and bottom panels. These have been delayed by the estimated 0.9 s propagation time from Siple, so as to be aligned with the received signals.

kHz, showed evidence of initiation by whistlers. The other, described here, started in the 8.2–8.4 kHz range. There were four such bursts; three (including the two illustrated) began at the time of the comb spectrum, while the fourth showed evidence of triggering by a whistler.

In this case whistlers were not sufficiently defined to permit determination of the plasmapause location. However, as noted, the noise bursts correlated with the comb transmissions were characteristic of propagation just beyond the plasmapause. Near 1133 and 1148 slow frequency ramps from Siple (1/3 kHz/s) were observed; their upper cutoff at ~ 9.2 kHz and increasing travel time with frequency in the 8-9 kHz range of observation are consistent with propagation at L ~3.6 and an equatorial density of 100 ± 50 el.cm^{-3}. This density level is a factor of ~5 below typical plasmasphere levels, and suggests propagation outside the plasmapause under conditions of partial recovery from preceding depletion [e.g., *Corcuff et al.*, 1972; *Carpenter and Park*, 1973].

3. DISCUSSION

Case of October 15, 1974. In this event the frequency-time slopes of the triggered chorus elements, ~10 kHz/s, were a factor of 3–4 steeper than those of typical emissions triggered by Siple signals within the outer plasmasphere. This is consistent with *Allcock and Mountjoy*'s [1970] finding of an increase with increasing magnetic activity in the slopes of chorus elements recorded at a middle latitude station. The increases appeared to depend mostly upon changes from one basic type of chorus emission to another, rather than upon continuous changes within a single type. One of their most commonly observed chorus types exhibited slopes comparable to those of Siple-triggered emissions within the plasmasphere (~ 1–2 kHz/s), while another agreed in slope with emissions outside the plasmapause reported here.

The Siple ramps and pulses in Figure 1 appeared weak compared to the level of the emissions they triggered. This is in contrast to Siple signals within the plasmasphere, which usually exhibit growth to a level comparable to that of the emissions that are produced [*Stiles and Helliwell,* 1977].

Direct triggering of emissions outside the plasmapause, such as in the October 15 case, will remain difficult because of the problems of ionospheric penetration mentioned earlier. However, the Siple long-wire antenna has recently been doubled in length to 42.4 km, so as to increase radiated power at 2.5 kHz by ~7 dB. Chorus emissions in the 2–4 kHz range have been found to propagate on paths overhead of Siple [*Helliwell et al.,* 1980]. The increase in radiated power, coupled with the ~7 dB power advantage of the present transmitter (Jupiter) over the Zeus system used in the reported cases, should increase the probability of successfully repeating the October 15 experiment.

Case of April 6, 1977. In a previous case study, wave bursts of the kind observed on April 6, 1977, including constant-frequency precursors, were found to have propagated just outside the plasmapause and to have occurred at several-min intervals during a multi-hour period of relatively deep quieting following moderate magnetic disturbance [*Dingle and Carpenter,* 1981]. The wave bursts were found to induce significant particle precipitation at 80 km altitude and were further found to have been triggered by whistler mode wave packets. The triggering waves were at times barely discernable on the records, much as in the present case involving Siple signals, where the evidence for triggering is the timing of the onset of the noiseband and the relation of its frequency to the frequency structure of the comb spectrum.

The essentially constant-frequency behavior of the noise precursors suggests the possibility of control by power-line harmonic radiation. However, as in the cases reported by *Dingle and Carpenter* [1981], such radiation was not at detectable levels on the records.

There appear to be characteristic differences in magnetospheric response to injected signals propagating inside and beyond the plasmapause. In the case of whistlers, the emissions triggered within the plasmasphere tend to contain a single element of duration 1 s or less, while those triggered outside often consist of multiple elements and may last for 10 s or more [*Carpenter,* 1978]. The result is that within the plasmasphere each succeeding whistler may trigger emissions, and the amount of wave energy may therefore be controlled by the rate at which whistlers occur. The same is true for the Siple transmitter; frequently the only magnetospheric signals detectable at a ground station are those induced by the transmitter, and each successive transmitter pulse produces an emission event. On the other hand, when noise bursts of the April 6 type occur outside the plasmapause, the injected signals may have far less control. There may be no evidence of wave growth on the signals themselves, and their relationship to the noise bursts may be only that of a frequency dependent trigger, as suggested by the data of Figures 2 and 3. The amount of energy released in individual wave bursts and the approximate time interval between bursts will tend to be essentially independent of the injected signal pattern. For example, the format shown in Figures 2 and 3 was transmitted six times between 1113 and 1152, but correlated bursts were initiated only at about 1114, 1122, and 1152. On the other hand, the specific timing of the bursts may be influenced by the timing of an injected signal, as illustrated in the figures.

Future possibilities for triggering noise bursts such as those of April 6, 1977, are favored by recent increases in radiated power, since path entrance points may be several hundred kilometers equatorward of Siple.

4. SUMMARY

Two quite different responses to Siple wave injection outside the plasmapause have been observed. In one case, on October 15, 1974, there was a direct triggering of discrete emissions whose slopes were a factor of 3–5 greater than those usually observed within the plasmasphere. In the other case, no evidence of triggered emissions was seen on the Siple pulses, but instead efficient echoing occurred and noiseband precursors to large wave bursts were initiated. In both cases, the Siple signals were relatively weak, as are typical whistlers in the outer region. Recent increases in transmitter power and antenna efficiency should facilitate future VLF probing of the complex plasmatrough region.

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