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# Explorer 45 and Imp 6 Observations in the Magnetosphere of Injected Waves From the Siple Station VLF Transmitter

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This paper reports the first results of a Stanford University–University of Iowa joint experiment in which VLF waves from the Siple Station transmitter in Antarctica are injected into the magnetosphere along the earth's magnetic field lines and are detected near the magnetic equatorial plane by the Explorer 45 and Imp 6 spacecraft. The purpose of this experiment is to conduct a controlled in situ study of VLF wave-particle interactions, in particular, to determine the propagation characteristics of the injected waves in the magnetosphere, to determine the regions where VLF emissions are produced, and to determine the effective volume of the magnetosphere illuminated by the Siple transmitter. During the first 3 months of the joint experiment, transmissions to the two spacecraft were attempted on 25 separate occasions when the satellites were within ±30° longitude of the magnetic field line linking Siple Station and its conjugate point at Roberval, Canada. Measurable signals were produced during 10 of these 25 passes, and these signals were observed as much as 20°E and 15°W of the Siple longitude and on various $L$ shells between 2.9 and 5. On one pass a strong, well-defined signal was present over a 6000-km-long orbital section between $L \sim 4$ and $L \sim 5$, indicating that the transmitter can illuminate a large volume of the magnetosphere. Emissions stimulated by the transmitter pulses were observed on three passes, and there was evidence on one of these passes that emission stimulation and/or wave entrainment effects were taking place far from the magnetic equator. Signal amplitude measurements were available on only one pass, but these were obtained over a wide region. Amplitudes varied from $10^{-5}\,\gamma$ outside the plasmapause at $L = 5$ to $10^{-4}\,\gamma$ just inside the plasmapause at $L \sim 4$. On the basis of these first results of the Stanford University–University of Iowa joint experiment we conclude that important possibilities exist for meaningful in situ high-altitude satellite wave measurements during VLF wave injection experiments.

## INTRODUCTION

This paper reports the first results of a Stanford University–University of Iowa joint experiment in which VLF waves from the Siple Station transmitter in Antarctica are injected into the magnetosphere along the earth's magnetic field lines and are detected near the magnetic equatorial plane by the Explorer 45 and Imp 6 spacecraft. The purpose of this experiment is to conduct a controlled in situ study of VLF wave-particle interactions, in particular, to determine the propagation characteristics of the injected waves in the magnetosphere, to determine the regions where VLF emissions are produced, and to determine the effective volume of the magnetosphere illuminated by the Siple transmitter. The results are presented in two parts. The first part, reported in this paper, discusses the general results and interpretation of data. The second part, reported in a companion paper [*Inan et al.*, 1977], focuses on the data from one exceptionally good day and reports on a new diagnostic technique to determine cold plasma densities in the magnetosphere.

In what follows, we first briefly describe the Stanford University wave injection experiment at Siple Station in Antarctica and the University of Iowa VLF experiments on the Imp 6 and Explorer 45 spacecraft. We then discuss the results.

*Siple wave injection experiment.* The Stanford University VLF wave injection experiment at Siple Station has been described in recent papers [*Raghuram et al.*, 1974; *Helliwell and Katsufrakis*, 1974], so a brief summary will suffice here. The Siple wave injection experiment is an active experiment designed to study VLF wave-particle interactions in the magnetosphere. One goal of the experiment is to learn how to control the energetic particles by the injected waves.

Once control is established, the energetic particles can then be used as tools to study other important processes. For example, the control of energetic particle precipitation would permit controlled studies of X ray, ionization, and radiation emission processes in the ionosphere. Furthermore, modulation of precipitation flux might provide a means to produce Pc 1 ULF waves [*Bell*, 1976] on a controlled basis. Numerous applications can be envisioned.

The basic mode of operation of the wave injection experiment is as follows. VLF signals from the Siple transmitter are radiated from the 21.2-km-long antenna and propagate through the ionosphere above the antenna and into the magnetosphere. Once they are in the magnetosphere, the signals follow the earth's magnetic field lines, and as they approach the magnetic equatorial plane, they begin to interact strongly with energetic electrons through gyroresonance. During the interaction the energetic particles are scattered in pitch angle, and VLF emissions may be produced. After the interaction the injected waves travel along the field lines until they reach the ionosphere above Roberval, the ground station conjugate to Siple. If the injected waves have been propagating in field-aligned whistler ducts, they will arrive in the lower ionosphere with nearly vertical wave normals and will be transmitted through the ionosphere and will be received at Roberval. If, on the other hand, the injected waves have been propagating in the unducted mode, they will arrive in the conjugate ionosphere with wave normals inclined almost 90° to the vertical and will not be transmitted through the ionosphere or received at Roberval. Since whistler ducts occupy only a small fraction of the inner magnetosphere, it is clear that most of the radi-

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ation from the transmitter will not be observed at ground stations in the conjugate hemisphere but instead will remain trapped within the magnetosphere until it is absorbed.

Despite the fact that the bulk of the injected energy is not detected on the ground, the interactions that are produced by the small ducted component are so rich in new detail that the wave injection experiment has to date been quite successful. However, it is clear that there are a number of important questions which cannot be answered by using ground data alone:

1. What is the volume of the magnetosphere illuminated by the Siple transmitter, and what is the distribution of wave amplitude?
2. What is the exact location of the interaction region where VLF emissions are produced?
3. What is the relative efficiency of nonducted waves in producing emissions?
4. What is the magnitude of the energetic particle scattering due to the injected waves and stimulated emissions?

All of these questions involve quantities which at our present state of knowledge can only be measured in situ by satellites. Thus an important component of the wave injection experiment is the measurement by satellites of the characteristics of waves and particles in the magnetosphere during the wave injection process. The purpose of the present paper is to report the first results of high-altitude satellite measurements of the Siple signals and to demonstrate the feasibility of attempting in situ measurements of the injected wave characteristics.

## UNIVERSITY OF IOWA PLASMA WAVE INSTRUMENTATION ON EXPLORER 45 AND IMP 6

*Explorer 45.* The University of Iowa VLF plasma wave instrumentation on Explorer 45 has been discussed in detail in a previous paper [*Anderson and Gurnett,* 1973]. The electric dipole antenna consists of two graphite-coated spheres, 14 cm in diameter, mounted on booms such that the center-to-center distance between the spheres is 5.08 m. The electronics instrumentation consists of two principal elements: (1) a step frequency spectrum analyzer and (2) a wide band receiver. Owing to the failure of a spacecraft converter as of April 1973, only the wide band receiver was available to detect signals from the Siple transmitter. This receiver employs automatic gain control (AGC) covering an 80-dB dynamic range and has a bandwidth of about 100 Hz to 10 kHz. The minimum detectable sine wave signal for the AGC receiver was 10 $\mu$V rms, measured at the input terminals of the preamplifier.

*Imp 6.* The Imp 6 spacecraft was launched on March 13, 1971, from the Eastern test range at Cape Kennedy, Florida, into a highly eccentric earth orbit with initial perigee and apogee geocentric radial distances of 6613 and 212,630 km, respectively, an orbit inclination of 28.7°, and a period of 100.3 hours. Imp 6 was spin-stabilized with the spin axis ($z$ axis) oriented approximately perpendicular to the ecliptic plane. The nominal rotation period was about 11 s.

The University of Iowa plasma wave experiment on Imp 6 detects plasma wave phenomena in the frequency range from 20 Hz to 200 kHz. The principal elements of the instrumentation for this experiment are three mutually orthogonal 'long' electric dipole antennas, three mutually orthogonal magnetic loop antennas, two identical frequency spectrum analyzers, and two broad band AGC receivers. Two of the long electric antennas, $E_x$ and $E_y$, are perpendicular to the spacecraft spin axis with tip-to-tip lengths of 54.0 and 93.2 m, respectively. The third long antenna, $E_z$, is parallel to the spin axis and has a tip-to-tip length of 7.7 m. Each magnetic loop antenna consists of a one-turn loop with an area of 0.81 m$^2$. The loop antenna assembly is mounted on a boom which extends approximately 4 m from the body of the spacecraft. Any of these antennas can be connected to either of two identical spectrum analyzers and two wide band receivers [*Gurnett and Shaw,* 1973].

Each of the two spectrum analyzers consists of 16 channels with center frequencies from 36 Hz to 178 kHz. The filter for each channel has a bandwidth of approximately 15% of the center frequency, and there are four filters per decade of frequency. Each filter channel has two detectors, a peak detector and an average detector. The peak detector measures the largest signal strength observed during each sample interval of 5.11 s, has a time constant of 0.1 s, and is reset to zero at the start of each new sample interval. The average detector measures the average signal strength over one sample interval and has a time constant of 5.11 s. Each filter channel has a dynamic range of 100 dB and an rms sensitivity of about 10 $\mu$V for a sine wave signal applied to the input terminals of the preamplifier. The output of each detector is a dc voltage which is approximately proportional to the logarithm of the input signal amplitude.

When a spectrum analyzer is connected to one of the long electric dipole antennas, electric field strengths as low as 0.2 $\mu$V/m can be measured. The sensitivity of the magnetic loop antennas is a function of frequency and varies from about 2.0 m$\gamma$ at 36 Hz to about 10.0 $\mu\gamma$ at 16.5 kHz.

The wide band receivers employ automatic gain control and provide broad band coverage of the frequency ranges from 10 Hz to 1 kHz and from 650 Hz to 30 kHz, depending on the particular mode of operation selected. Several combinations of antennas and frequency ranges are possible and are selected by commands. The analog signals from the wide band receivers are transmitted to the ground via the special purpose analog transmitter. These wide band signals are used for a high frequency-time resolution analysis of transient and narrow band wave phenomena.

Imp 6 reentered the atmosphere in October 1974.

*Joint experiment.* The Stanford University-University of Iowa joint experiment consisted of transmissions of special programs by the Siple transmitter for reception by Explorer 45 and Imp 6. These transmissions were carried out during the time period May 1973 to June 1974 and consisted of a wide variety of programs, including frequency shift keying (FSK) at multiple frequencies, CW pulses of variable duration, and combinations of signals with constant frequency-time slope, i.e., frequency ramps. Various frequencies in the 2- to 8-kHz range were utilized, the transmitter-radiated power varying from approximately 100 W at 2 kHz to 4 kW at 8 kHz. In all, approximately 500 hours of transmissions were involved. The present paper reports results from the initial 3-month period of the joint experiment.

During this initial period, transmissions to the two spacecraft were attempted on 25 separate occasions when the satellites were within ±30° longitude of the field line linking Siple and Roberval. Of these 25 periods of transmission (23 for Explorer 45 and 2 for Imp 6), 10 (8 Explorer 45 passes and 2 Imp 6 passes) produced a measurable signal at the satellite location. This relatively small sample suffices to demonstrate many important features of the wave injection experiment.

In the following we report a general qualitative survey of data from all passes, presenting our observations and indicating their importance and possible implications.

*Illumination area of the Siple transmitter.* The Explorer 45 satellite had a nearly equatorial orbit, which lay within 3° of the earth's equator. The Imp 6 spacecraft, on the other hand, had an orbit of moderate inclination which in 1973 intersected the equatorial plane at approximately 25° latitude at 4 $R_E$. The detection of the Siple signals by these spacecraft provided an opportunity to determine the volume of the magnetosphere illuminated by the Siple transmitter. Figure 1 shows 8 of the 10 satellite passes projected upon the equatorial plane. Two Explorer 45 passes are not shown because these satellite paths coincide with others and hence complicate the figure. The portions of the passes where signals from Siple were received are shown with heavy lines. The direction in which the satellite was moving on each pass is indicated by an arrow. In all cases shown the Siple signal frequency lay in the 4- to 8-kHz range, while the transmitter-radiated power lay approximately in the 1- to 4-kW range.

The local times of the subsatellite points during the periods of reception tended to group in either the dawn sector (3 cases in the 0400–0600 local time range), the noon sector (5 cases in the 1000–1300 local time range), or the late afternoon sector (2 cases in the 1600–1800 local time range).

The bulk of the receptions occurred during periods of quieting following magnetic disturbance, and the *Kp* value during the times of reception ranged from 0 to 4−, the average *Kp* value being 2+.

Receptions generally occurred inside the plasmapause with the exception of two cases, one of which (June 28) is discussed in detail below.

The above data concerning local time of observation, degree of magnetic disturbance, and reception location with respect to the plasmapause are generally consistent with the findings concerning ducted transmissions between Siple Station and its conjugate, Roberval [*Carpenter and Miller,* 1976]. However, there appears to be an anticorrelation between receptions on the satellites and receptions of ducted signals at Roberval.

For instance, of the 10 periods when the Siple signal was observed on the spacecraft, only two gave evidence of simultaneous reception of ducted signals at Roberval. This anticorrelation suggests that the spacecraft detect predominantly unducted waves and that the presence of ducts is not an essential factor in satellite reception of injected VLF waves.

Figure 1 shows the path segments where the Siple signal was received by the broad band receivers on the satellites. No information is given here regarding the absolute signal intensity during the receptions, since this information was not available on Explorer 45. However, signal intensity measurements on one Imp 6 pass are reported later in the paper. In general, it was not difficult to identify the signal in the presence of the natural background noise (hiss and chorus). However, there were cases in which strong background noise, generally chorus, suppressed the transmitter signal through the AGC action of the receiver and allowed the signal to appear only occasionally. The signal was assumed to be present in such cases. In Figure 1 the location of Siple Station is indicated by a circled cross, as is the intersection with the equatorial plane of the Siple-Roberval magnetic field line. It is clear from the figure that the injected signals can illuminate a large volume of the magnetosphere. For instance, signals were observed as much as 20°E and 15°W of the Siple geographic longitude (84°W) and on various *L* shells between 2.9 and 5. Since these receptions were not made simultaneously, it cannot be concluded that the transmitter can illuminate this entire region at any one time. However, on the basis of the June 26 Imp 6 pass, which showed the presence of strong, well-defined signals over a 6000-km-long orbital section, it is safe to conclude that the injected waves on occasion can illuminate large volumes of the magnetosphere. This finding is important in that it establishes the general feasibility of in situ high-altitude satellite wave measurements during VLF wave injection experiments.

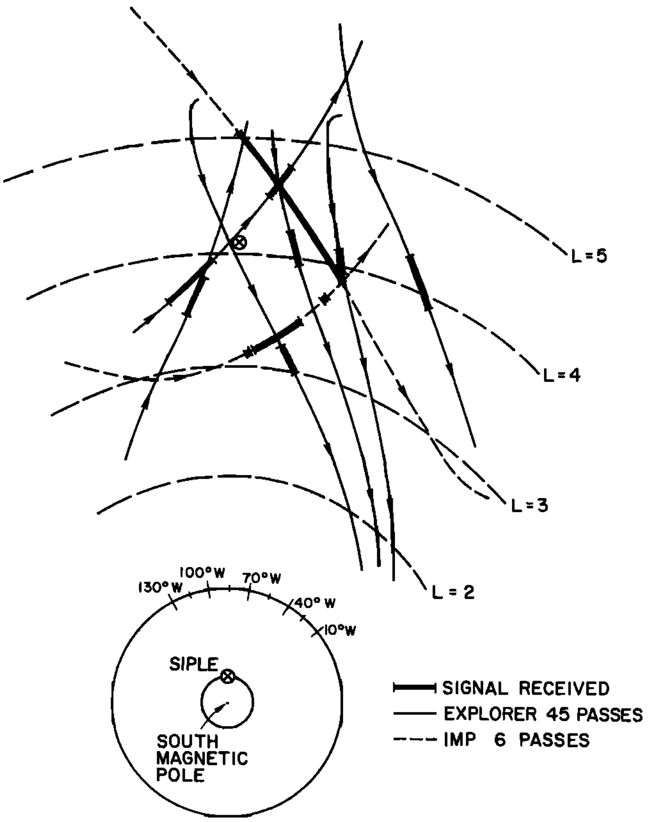

Fig. 1. Viewing area of the Siple transmitter, plotted in the geomagnetic equatorial plane in a centered dipole system. The scale gives the geographic longitude.

*VLF emission activity.* VLF emissions triggered by the transmitter pulses were detected during 3 (2 for Explorer 45 and 1 for Imp 6) of the 25 periods of transmission considered here. Figure 2 shows an example of strong triggered emissions observed on Explorer 45. In this pass the injected signals were observed during a 5-min period (0920–0925 UT) of transmitter operation. The transmission format was a 5 min on–5 min off sequence at 7.6/7.1 kHz, employing a variable pulse length FSK program, pulse lengths varying from 1 to 8 s in 1-s steps. The type of triggered emission illustrated in Figure 2 was observed on 53 occasions during the 0920–0925 UT transmission period but was not seen during intervals of no transmissions. The evidence that the emissions are triggered by the transmitter pulses is supported in Figure 2 by the fact that the risers are triggered at the transmitter frequency and are not present just below it. The fact that the risers were not seen when the transmitter was turned off also implies that the emissions are triggered by the transmitter signals.

Although the triggering of artificially stimulated emissions (ASE's) by ducted VLF waves is well documented, very few cases of triggering by nonducted waves have been reported [*Angerami and Bell,* 1971]. Since the probability that the satellite is in a duct is small, the propagation to the Explorer 45 spacecraft is most likely nonducted, and the data shown in Figure 2 may be some of the few reported observations by a

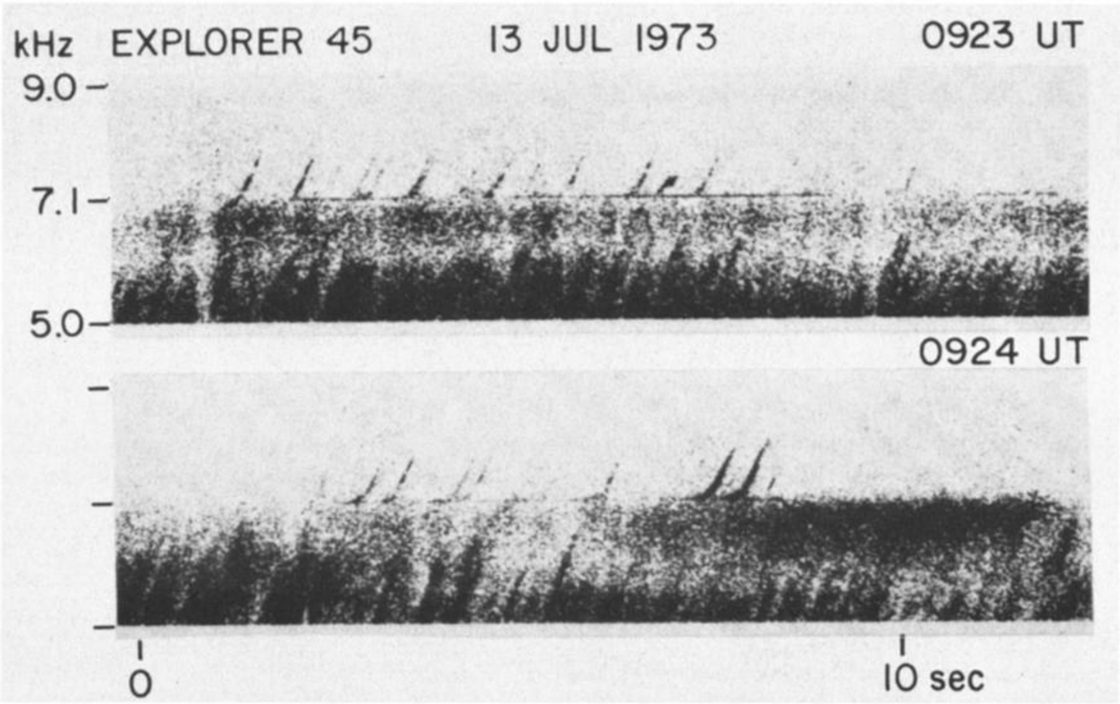

Fig. 2. Triggered emissions observed on Explorer 45. The Siple transmitter was transmitting a 7.6/7.1-kHz FSK variable pulse length program, the pulse length varying from 1 to 8 s. Only the lower frequency is observed on the satellite. The upper spectrogram shows emissions triggered by an 8-s-long pulse, whereas the lower one shows a slightly later event involving a 6-s pulse.

high-altitude spacecraft of nonducted triggering of ASE's in the magnetosphere.

The data from the Imp 6 pass on June 28, 1973, are diverse and rich in implications. Throughout the 25-min period (1920–1945 UT) studied from this pass, strong Siple signals were observed. Emissions with rising frequency (i.e., 'risers') were also observed quite often, especially in the period 1925–1940 UT.

Figure 3 shows, in a magnetic meridian plane projection, the portion of the June 28 pass over which the transmitter signal was observed. The reception occurred near local noon under relatively quiet conditions. In the 30-min interval from 1920 to 1950 UT the satellite moved from magnetic dipole coordinates $\theta$ = 24.3°S, $L$ = 5.04 to $\theta$ = 18.4°S, $L$ = 3.84 while moving from a geographic longitude of 81.5°W at 1920 UT to 65.8°W at 1950 UT.

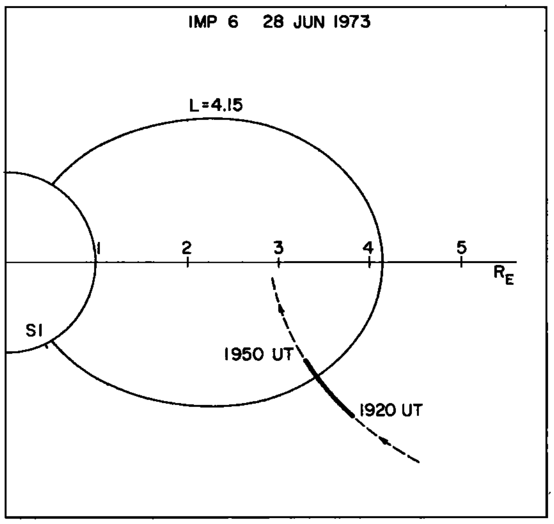

Fig. 3. Portion of the inbound pass of Imp 6 on June 28, 1973, plotted in a magnetic meridian plane projection. The $L$ = 4.15 field line, which is the location of the inner edge of the plasmapause, is also shown.

The transmissions from the Siple transmitter started at exactly 1920 UT. The special program of transmissions to Imp 6 was as follows:

| | |
|---|---|
| 1920 | Frequency shift keying 5620/4620 Hz, 1-s pulses for 4.5 min. |
| 1925 | Variable pulse length program, 5 each of 50- to 400-ms pulses with 50-ms steps repeated 15 times, equal to 4.5 min. |
| 1930 | Back to 1-s pulses and so on, alternating every 5 min until 1952. |

Figure 4 shows the frequency-time plots of the two formats. Note from the above that the transmitter stops transmitting for the last ½ min of every 5 min.

It was observed that within a few seconds after the start of transmissions, Imp 6 began to receive the transmitter pulses. The transmitter signals were then observed continuously for about 30 min. Figure 5 shows two portions of data illustrating the reception of both formats transmitted. As can be seen in Figure 5, the higher-frequency, i.e., 5620-Hz, signal was considerably better defined than the lower-frequency one throughout this period. The relative weakness of the signal at 4620 Hz is most probably due to the fact that the transmitter was tuned exactly to 5.62 kHz and the radiated signal at 4.62 kHz was lower in intensity by approximately 3 dB.

An interesting feature of Figure 5*b* is the occurrence of a periodic emission which starts off at about 1935:10 UT. The components of the emission are indicated by the arrows in the figure.

It has been hypothesized that periodic emissions are generated when a triggering emission, echoing between hemispheres in the whistler mode, triggers a second emission somewhere

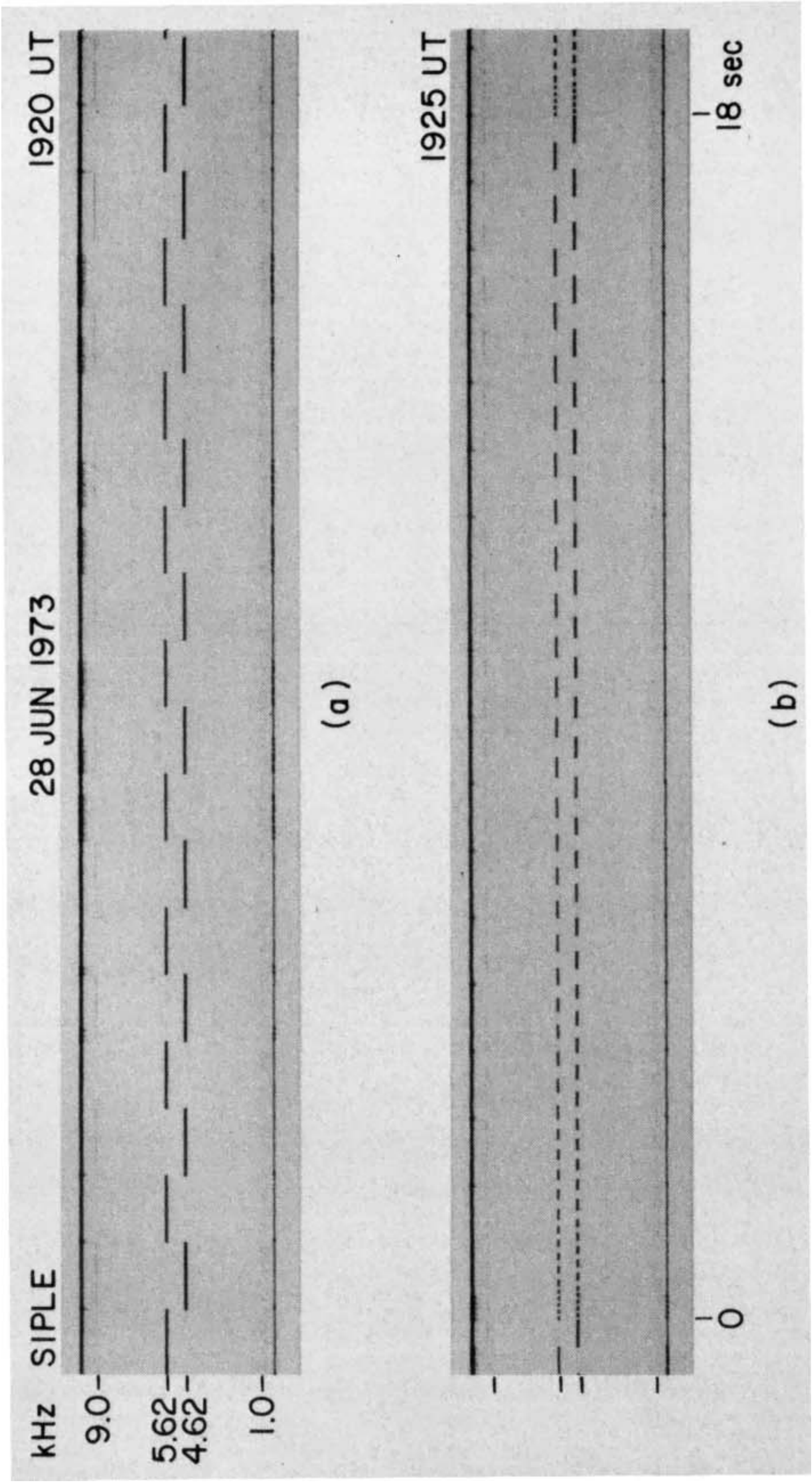

Fig. 4. Program of transmissions to Imp 6.on June 28, 1973. (*a*) FSK 5620/4620 Hz with 1-s pulses. (*b*) FSK 5620/4620 Hz with pulse lengths varying from 50 to 400 ms.

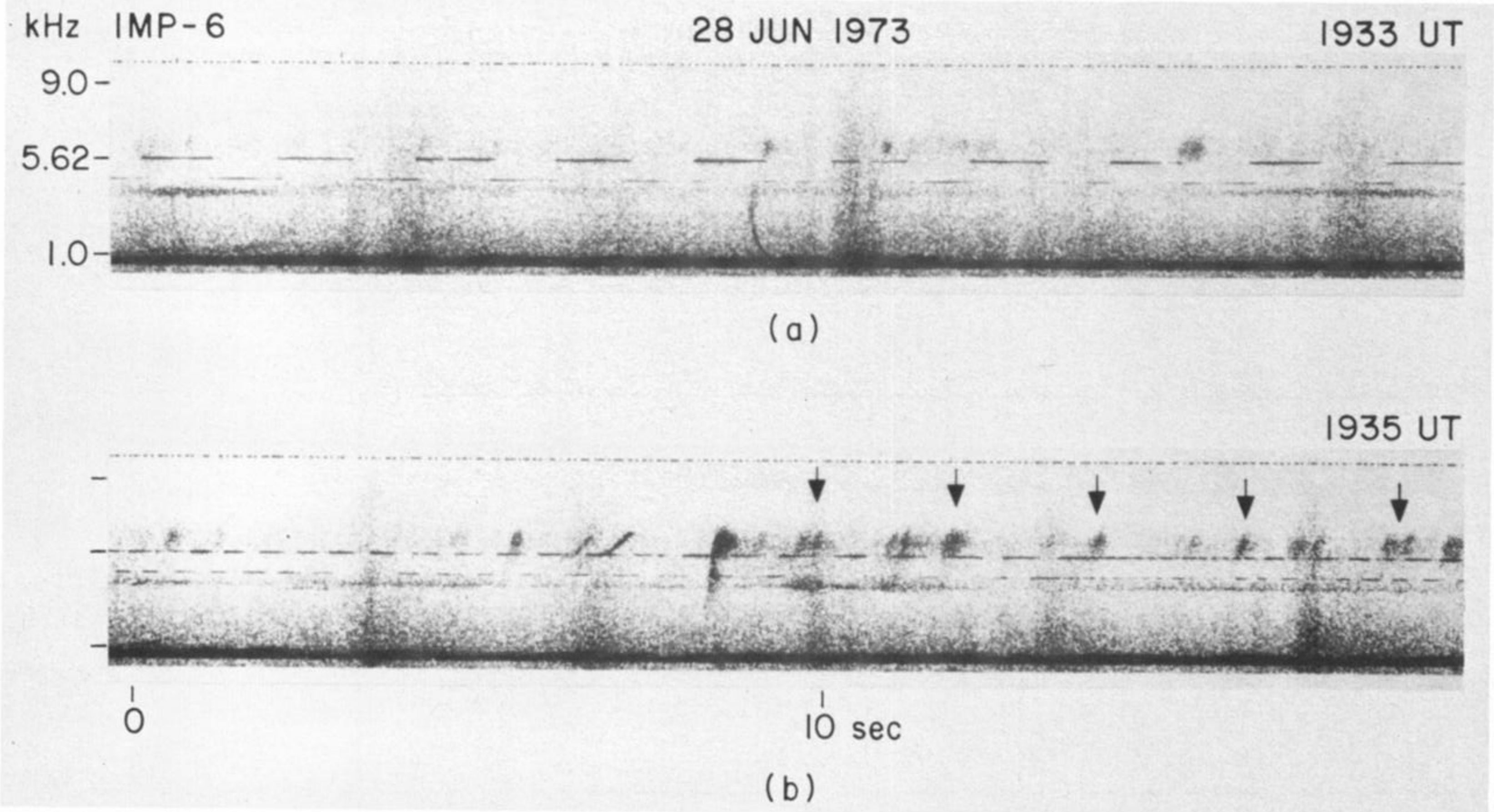

Fig. 5. Reception of the transmitter signals on Imp 6. (*a*) FSK with 1-s pulses. (*b*) FSK with variable pulse length. The arrows on the lower spectrogram show the components of the periodic emission that started off at about 1935:10 UT.

near the magnetic equatorial plane. This new emission echoes in the whistler mode between hemispheres and repeats the triggering process, as does each subsequent triggered emission. The net result is a set of periodic emissions in which the period is equal to the whistler mode two-hop group time delay at the triggering frequency [*Helliwell*, 1965]. This hypothesis is based on the experimental ground data on periodic emissions, which show that the period between emissions is indeed equal to the whistler mode two-hop group time delay. Since the two-hop whistler mode time delay measurements pertain only to ducted signals, it is implied that the periodic emissions are also ducted. Thus the satellite may be located inside a whistler duct at approximately 1935 UT when the periodic emission is observed.

Examples of the emission activity observed on Imp 6 are given in Figure 6. Figure 6*a* shows the transmitter signals and a few risers observed when the satellite was at $L \sim 4.7$. These emissions are typical of those seen early in the pass and appear to originate close to the transmitter frequency. However, it is not clear from this example whether the emissions are triggered by the transmitter pulses. Figure 6*b* shows the activity at a slightly later time when a similar type of rising emission is observed even though the transmitter is no longer operating. In this example, transmissions were stopped at 1929:30 UT (marked by arrow), and two rising emissions appear 5–10 s later. Examples of this sort indicate that not all, and perhaps none, of the risers seen early in the pass are associated with the transmitter pulses. Later in the pass, as the satellite moved further inward, the emissions became stronger and better defined. Typical examples of the emissions observed later in the pass are shown in Figure 6*c*. These data were recorded at $L = 4.3$. Although the rising emissions appear to originate at the transmitter frequency, the presence of more than one ray path to the satellite makes it difficult to identify the location in time of the transmitter pulses with respect to the emissions, and it is not immediately clear that the emissions and pulses are correlated. However, if these emissions are actually triggered by direct signals from the transmitter, then the finding will have a significant effect upon presently accepted models of the emission generation mechanism. These implications are discussed in detail later in the paper; first, we wish to establish the correlation between the transmitter pulses and the emissions. This task requires that we determine the actual paths followed by the transmitter pulses in reaching the satellite and the group time delays along the paths. The path determination requires the measurement of pulse time delay, the construction of a realistic plasma density model, and the computation of ray paths in the model medium. These tasks are taken up in a companion paper [*Inan et al.*, 1977] hereafter referred to as paper 2; we merely quote the results below.

1. The pulses of Figure 6*c* reached the satellite by direct paths between transmitter and satellite similar to those shown in Figure 7. It was not possible for the pulses to reach the satellite in the MR (magnetospherically reflected) mode [*Edgar*, 1972] after being reflected once in the northern hemisphere.
2. The time delay of the pulses from transmitter to satellite varied from 0.27 s on the shortest path to 0.37 s on the longest path.
3. The emissions of Figure 6*c* were detected at a time when the satellite was in a low plasma density region just outside the plasmapause.

These results are applied below.

Figure 8 shows an enlarged version of a portion of the spectrogram of Figure 6*c*. Unfortunately, the individual transmitter pulses are not clearly distinguishable because of enhanced background noise and multipath effects. Below the emissions are plotted the transmitter pulses as they would have been observed on the satellite according to the ray-tracing analysis of paper 2. In plotting the transmitter signals a time delay of 0.27 s is used. This is a typical group delay measured at around 1938 UT, as given in Figure 7 of paper 2, and is also the lowest time delay predicted by the ray-tracing analysis. When pulses with different time delays overlap, the resulting single pulse will have a time delay equal to the shortest of the group delays. The portions of the pulses as they were transmitted are shown by heavy lines. However, since more than one path reaches the satellite and since each path has a different time delay, the apparent duration of the pulses will be longer than that transmitted. These additional portions of the transmitter pulses are shown by light lines.

We have now identified the individual pulses, and it is clear from Figure 8 that at least three of the emissions appear to originate from one of the pulses. For instance, the first and third emissions appear to be triggered from the trailing edge of the second and fifth pulses, respectively, while the fourth emission, a hook, appears to be triggered from the trailing edge of the sixth pulse. On the other hand, it is not clear that the second emission can be associated with any of the pulses, and in fact, it may be of the variety shown in Figure 6*b*. Thus only three of the four emissions give the appearance of having been triggered by the transmitter pulses. This picture is somewhat confused by the fact that the first and third rising emissions may be viewed as continuations of rising emissions coming from the noise band at around 4.0 kHz. This can be seen from Figure 6*c*. However, even if this is the case, a strong interaction with the transmitter pulse is still taking place, since the slope of the riser changes abruptly after it encounters the pulse. It is well known that the rate of change of frequency of an emission can change abruptly when its instantaneous frequency equals that of a second signal present in the same space. This type of interaction has been called 'wave entrainment' [*Helliwell and Katsufrakis*, 1974]. Thus the first and third 'emissions' in Figure 8 may actually be produced through the wave entrainment process. However, the fourth emission in Figure 8, which looks like a well-defined 'hook,' cannot be viewed as a continuation of any signal other than that from the transmitter.

Thus the data of Figure 8 suggest that Siple pulses far from the magnetic equator either have triggered emissions, including a 'hook,' or have produced wave entrainment effects and triggered a 'hook.' In either case a strong VLF wave-particle interaction would be involved. In spite of the suggestions of Figures 8 and 6*c* it is important to stress that the data cannot be construed as proof that emission triggering or wave entrainment effects have been produced by the transmitter pulses. The element of repeatability is lacking; subsequent portions of the data showed no clear correlation between the pulse spacing and the spacing of the emissions. Thus the possibility cannot be ruled out that coincidence has led to the interesting correlation seen in Figure 8.

*Signal amplitude measurements.* For the Imp 6 pass on June 28, 1973, it was possible to measure the transmitter signal amplitude by using the wave amplitude data from the multichannel spectrum analyzer. Since the transmitter signal was observed on the satellite for almost 30 min, it was also possible to observe the variation of the wave amplitude over a large region of the magnetosphere. Figure 9 shows a plot of wave

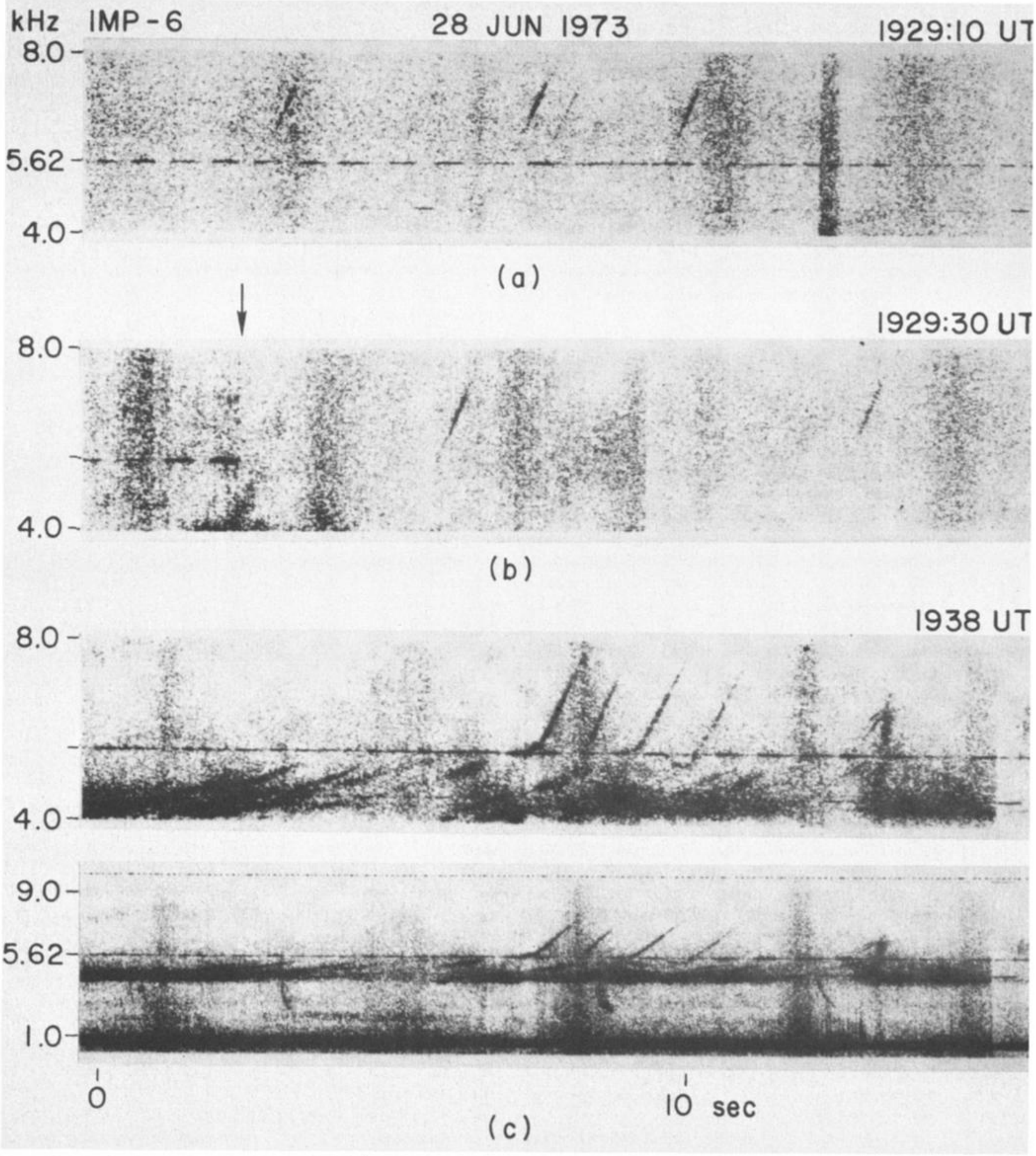

Fig. 6. Rising emissions observed on Imp 6. Part *c* shows the same time period with both 4- to 8- and 1- to 9-kHz frequency ranges.

magnetic field amplitude versus time as the satellite moves inward from $L = 4.8$ to about $L = 4.0$. The portions of the curve where the signal amplitude has apparent dips are those times when transmissions from Siple were stopped. The depth of these dips gives a measure of the noise background. It can be seen that the signal level lies approximately 3–5 dB above the noise.

It is clear from Figure 9 that the signal amplitude increases as the satellite comes closer to the plasmapause. This is expected, since the large plasmapause gradients act to focus the waves inside the plasmapause and defocus the waves outside [*Inan and Bell*, 1976; paper 2].

The absolute magnitude of the wave magnetic field is of special interest. We see from Figure 9 that inside the plasmasphere the wave amplitude is of the order of a few tenths of a milligamma. If it is true, as some theories [*Helliwell*, 1967; *Nunn*, 1974] suggest, that VLF waves are only amplified close to the magnetic equator, then the amplitudes of Figure 9 must

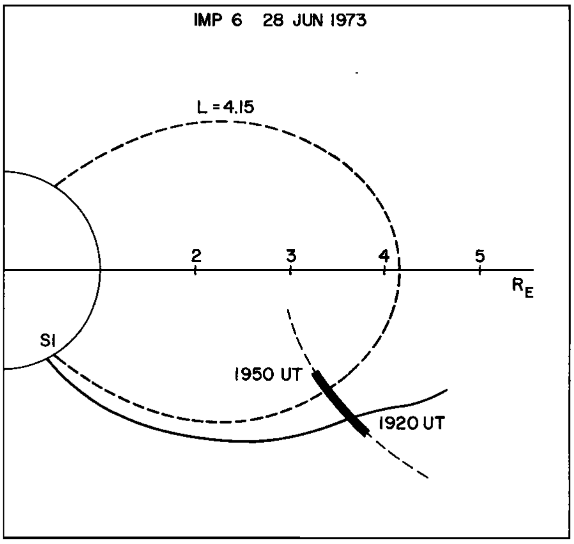

Fig. 7. Typical computed ray path from the ground to the satellite.

represent unamplified wave amplitudes. It has been demonstrated that during the emission generation mechanism the wave amplitude can grow by as much as 30 dB [*Stiles and Helliwell*, 1975]. Therefore after amplification and triggering at the equator the wave amplitude (extrapolated from Figure 9) may be as large as 7–8 mγ. Since no absolute measurements of VLF transmitter signal amplitudes in the high-altitude magnetosphere have previously been published, there has been a major controversy about the determination of realistic signal amplitudes to use in VLF emission theories. The theory given by *Helliwell* [1970] and *Helliwell and Crystal* [1973] has used wave amplitudes in the range 1–10 mγ, which agrees with our estimate of amplified wave amplitude. For the theory of *Nunn* [1974], however, it is crucial to have signal amplitudes of at least 50–60 mγ, since that theory requires at least a few trapping periods for the emission generation to start. Our estimate of this amplified wave amplitude is an order of magnitude lower than Nunn's requirement, and we conclude that the data support Helliwell's theory better than Nunn's theory.

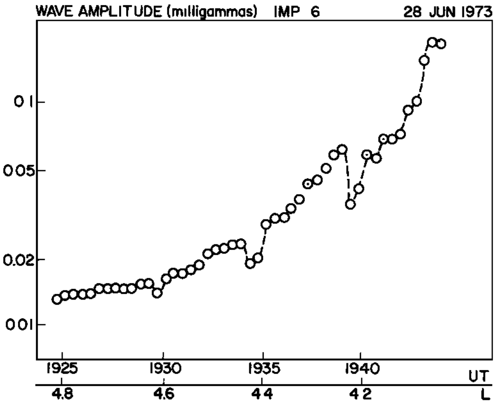

Fig. 9. Wave magnetic field in milligammas versus time as observed on Imp 6.

## DISCUSSION AND CONCLUSIONS

We have reported the results of the analysis of the first part of the data from the Stanford University–University of Iowa joint experiment. We have shown that a large volume of the magnetosphere can be illuminated by the Siple transmitter. For instance, during the Imp 6 pass on June 28, 1973, the transmitter signal was observed on the satellite for 30 min over a distance of 6000 km ($L$ = 5–3.5). These data demonstrate the general feasibility of in situ high-altitude satellite wave measurements of signals from ground transmitters during VLF wave injection experiments.

It is important to point out here how our work differs from that of past experimenters. For instance, a decade ago the results from the satellite Ogo 1 [*Heyborne*, 1966] demonstrated the feasibility of detecting at high altitudes the VLF signals (17.8 and 18.6 kHz) from high-power transmitters (radiated power of >250 kW). However, the format of the transmitted signals was not under the control of the experimenters and in general was not appropriate for a study of wave-particle interactions. Furthermore, the relatively high frequency of the signals prevented the injected waves from probing the magnetosphere along field lines beyond $L \sim 3$. Results from the Ogo 3 satellite (J. Angerami, private communication, 1972) demon-

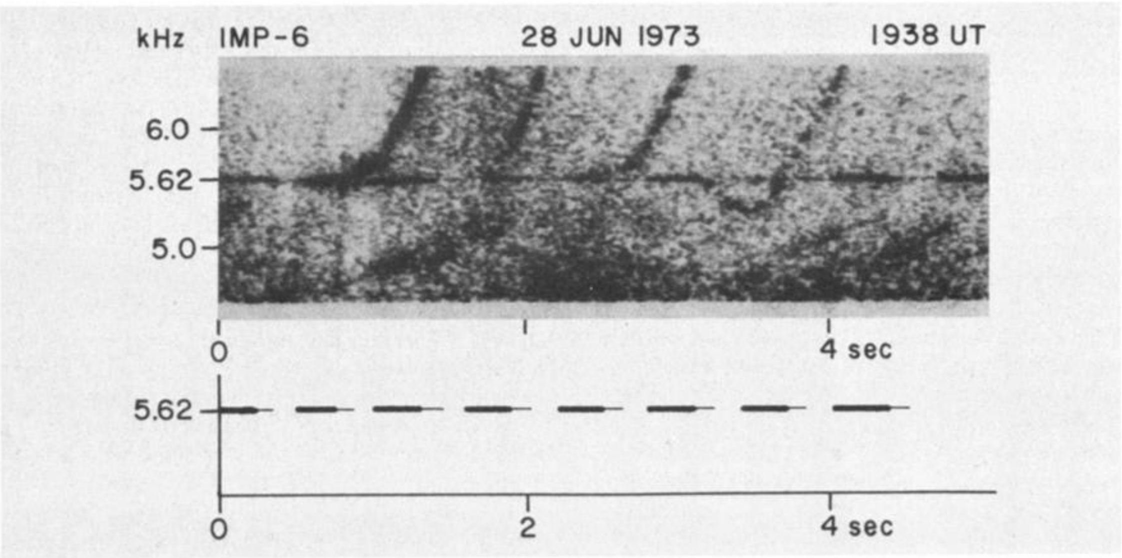

Fig. 8. Enlarged view of unusual emissions observed at 1938 UT. The reconstructed transmitter pulses are shown below the spectrogram. The lengths of the pulses as transmitted are shown by heavy lines. Additional portions due to multipath effects are shown by light lines.

strated the feasibility of detecting the VLF signals (10.2 and 11.33 kHz) at high altitudes from a moderate-power transmitter (2 kW radiated). However, again the format of the transmitted signals was not under the control of the experimenters, and the relatively high frequency of the signals prevented the injected waves from probing the magnetosphere along field lines beyond $L \sim 3.5$. Thus although these early experiments established the feasibility of probing a small portion of the magnetosphere with high- to moderate-power VLF transmitters, they gave little clue as to the feasibility of probing more distant portions of the magnetosphere ($3 < L < 8$), where important wave-particle interactions are known to take place and where lower wave frequencies (1–8 kHz) are required. To investigate this question, the Siple transmitter facility was established in 1972. As a result of low antenna efficiencies at lower wave frequencies the radiated power from the Siple transmitter is low, ranging from 100 W at 2 kHz to 4 kW at 8 kHz. Because of this low output power it was not clear at the outset that the nonducted injected waves would have sufficient amplitude to be detected on high-altitude satellites. However, the present work demonstrates the general feasibility of this detection and indicates that high-altitude satellite measurements can play an important part in VLF wave injection experiments. The importance of this finding is underscored by the fact that a low-power VLF wave injection experiment will be included in the International Earth-Sun Explorer satellite program and others have been planned for the Electrodynamics Explorer satellite program, the Geos satellite program, and the space shuttle based Atmospheres, Magnetospheres, and Plasmas in Space Laboratory.

We note that the transmitter signals were detected on the satellites on 10 of the 25 days which make up our sample. Assuming that our sample is representative, we can then conclude that the probability is roughly 40% that an equatorially orbiting satellite on a given day will encounter detectable Siple signals in the magnetosphere within the $L$ range 3–5 and within ±20° longitude of the Siple-Roberval meridian.

It is interesting to compare this satellite reception probability with the results obtained for ground station reception. In a 2-year study of ducted VLF whistler mode transmissions between Siple and Roberval stations it was found that Siple signals were detected during 72 of the 374 days when transmissions were carried out [*Carpenter and Miller*, 1976]. Thus the probability of ground station reception was approximately 19%, or roughly one-half the probability that we have found for satellite reception. There are at least two reasons why the satellite reception probability might be higher than that for ground station reception. Ground station reception depends upon the presence of active whistler mode ducts near the Siple-Roberval meridian, and these active ducts are not always present. Satellite reception, on the other hand, occurs generally through nonducted ray paths, and these paths are always 'present' in the medium. Thus on days when active ducts are absent near Siple and reception at Roberval is not possible, satellite reception may still be possible. A second reason why satellite reception probability might be higher than ground station reception probability is that nonducted waves can apparently be detected over a wider $L$ range than ducted waves. For instance, *Carpenter and Miller* [1976] found that the signal path $L$ shells for ducted waves between Siple and Roberval were concentrated in the range $L = 3.5$–$4.5$. In contrast to this finding it can be seen in Figure 1 that the satellite receptions covered a larger $L$ range, $L = 2.9$–$5$, and that a significant number of examples (3) lie beyond the $L = 3.5$–$4.5$ range.

In addition to the above factors there are a number of other factors which complicate the probability calculation; for example, wave amplification may be stronger on ducted paths than on nonducted paths, background noise levels may differ markedly at the two receiver locations, and the defocusing losses of nonducted waves may be high. Thus in practice it is not a simple matter to interpret our results. However, we can conclude that if, as our results suggest, the probability of satellite reception is at least as high as the probability of ground reception, then the importance of in situ high-altitude satellite wave measurements during VLF wave injection experiments will be considerable.

Up to the present time a number of mechanisms have been proposed to explain the phenomenon of VLF emissions [*Helliwell*, 1967; *Das*, 1968; *Sudan and Ott*, 1971; *Matsumoto and Kimura*, 1971; *Dysthe*, 1971; *Nunn*, 1971, 1974; *Brinca*, 1972; *Roux and Pellat*, 1976]. Two of the most widely accepted theories are those of *Helliwell* [1967] and *Nunn* [1974].

We have stated that if the emissions of Figure 6*c* were triggered by direct signals from the Siple transmitter, then this fact would have a profound effect upon presently accepted models of the emission generation mechanism. In order to appreciate this point it should first be noted from Figure 3 that the satellite position at 1938 UT is close to the Siple-Roberval field line and at a magnetic latitude of approximately 20°S. Thus if direct signals from the Siple transmitter gave rise to ASE's, these ASE's must have been produced somewhere between the ground and the satellite location at southern latitudes greater than 20°S. Thus the generation region will be located far from the equatorial plane. Next, it will be noted from Figure 6*c* that of the emissions shown, the first three are rising emissions (i.e., risers), and the fourth is an emission that first falls and then rises (i.e., a hook). These observations do not fit into the framework of accepted theories of VLF emissions. For instance, the theories of *Helliwell* [1967] and *Nunn* [1974] predict that all ASE's are produced within a few degrees of the magnetic equatorial plane (given currently accepted models of the thermal plasma distribution). Furthermore, the same theories predict that hooks can be produced only at the equator. Both of these predictions will be at variance with the satellite observations if it is true that the emissions of Figure 6*c* are ASE's and are generated somewhere on the direct path between the transmitter and the satellite location. Given that the emissions of Figure 6*c* might have been produced through a wave entrainment process rather than an emission-triggering process, the data nevertheless give the first evidence that strong VLF wave-particle interaction may occur far from the magnetic equator.

It should be noted here that most experimental data on natural magnetospheric emissions, such as VLF-ELF chorus and ELF hiss, suggest that these natural noise bands are triggered at or close to the equator [*Burtis*, 1974; *Tsurutani and Smith*, 1974; *Thorne et al.*, 1973]. However, there is no direct evidence suggesting that artificially triggered emissions originate at the equator. One difference between natural and artificially triggered emissions is the fact that the former are highly incoherent wide bands of noise, whereas the latter are usually highly coherent narrow band signals [*Stiles and Helliwell*, 1975].

As is shown in paper 2, the emissions of Figure 6*c* occurred in the low-density region just outside the plasmapause. It is in this same region that whistlers are sometimes observed to display unusual characteristics. For instance, the upper cutoff frequency of whistlers which propagate just outside the plasmapause is sometimes seen to be as high as 0.9 of the equatorial gyrofrequency [*Carpenter*, 1968*a*]. The normal upper cutoff frequency of whistlers is approximately 0.5 of the equatorial gyrofrequency [*Carpenter*, 1968*b*], and it can be shown that higher-frequency components cannot propagate in the whistler duct to the opposite hemisphere. Thus the high upper cutoff frequency of whistlers propagating just outside the plasmapause is unexplained. It is possible that the modes of wave propagation and emission generation in this region differ from those in the region inside the plasmapause. If this is the case, the theories of Helliwell and Nunn may not apply to this region.

On the basis of these first results from the Stanford University-University of Iowa joint experiments we conclude that exciting possibilities exist for meaningful in situ satellite wave and particle measurements during future VLF wave injection experiments. This should be especially true for missions such as that of the Electrodynamics Explorer, where the satellite orbit can be adjusted to maximize the time spent near field lines linking the VLF ground transmitter.

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