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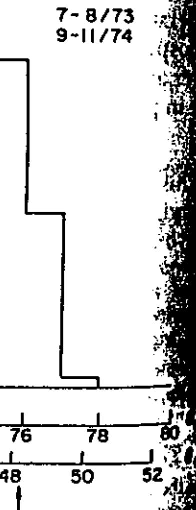

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The path concentration should facilitate experiments in which path location is of particular importance, such as the search (using balloon-borne x-ray counters, riometers, etc.) for the effects of wave-induced precipitation of energetic electrons into the lower atmosphere. Further, magnetospheric phenomena of interest tend to move in a way that permits the various important states of the system to be scanned through sufficiently long-enduring observations near given field lines; this is illustrated in figure 1. In one case (circles) the Siple signal probes conditions well inside the plasmapause, while in the other case it probes the region of steep plasmapause density gradients.

The transmitter signals have been used to advantage in a recent (June and July 1975) test of VLF direction finding on signals emerging from the ionosphere in the vicinity of Roberval. Participants from Japan, the United Kingdom, and the United States benefited from the availability of signals of known frequency in a known signal format, propagating within an expected north-south range.

This research was supported by National Science Foundation grants GV-41369 and DES 75-07707.

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Satellite observations of nonducted signals from the Siple transmitter

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In a circular region with a radius of about 500 kilometers, a substantial portion of the energy radiated by the Siple transmitter enters the ionosphere and propagates into the magnetosphere in the whistler mode. The path of propagation in the magnetosphere may be either ducted or nonducted. Ducted signals follow geomagnetic field-alined paths and may emerge from the ionosphere and be observed at ground stations (Helliwell, 1965). Nonducted waves follow more complicated paths: they tend to remain above the lower boundary of the ionosphere, and are not usually observed on the ground (Smith and Angerami, 1968).

The properties of ducted signals are by far the best understood; most of our knowledge about whistlers, very low frequency (VLF) emissions, and wave-particle interactions in the magnetosphere derives from their study. The nonducted mode nonetheless is important; about 90 percent of the energy radiated by a VLF ground transmitter will propagate through the magnetosphere in this mode.

It generally can be expected that the nonducted waves from the Siple transmitter will interact with energetic particles in the magnetosphere and will produce VLF emissions and particle scattering in the same manner as ducted waves. The nonducted

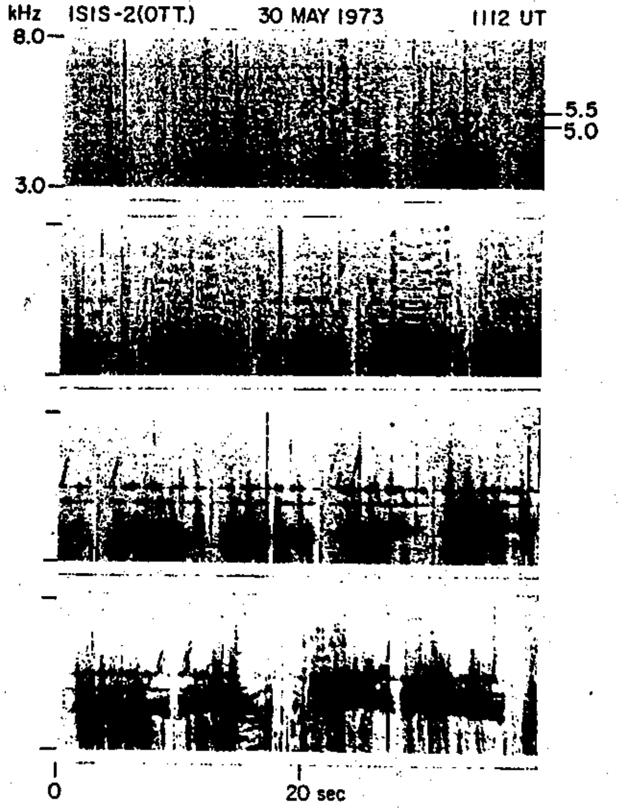


Figure 1. Very low frequency (VLF) spectrogram showing Siple transmitter pulses and stimulated emissions as observed over the Northern Hemisphere by the polar-orbiting satellite ISIS-2.

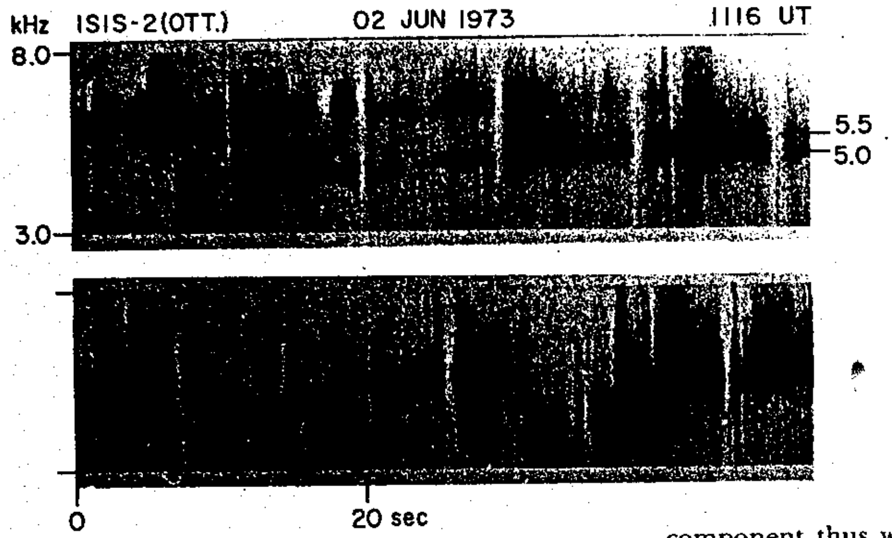
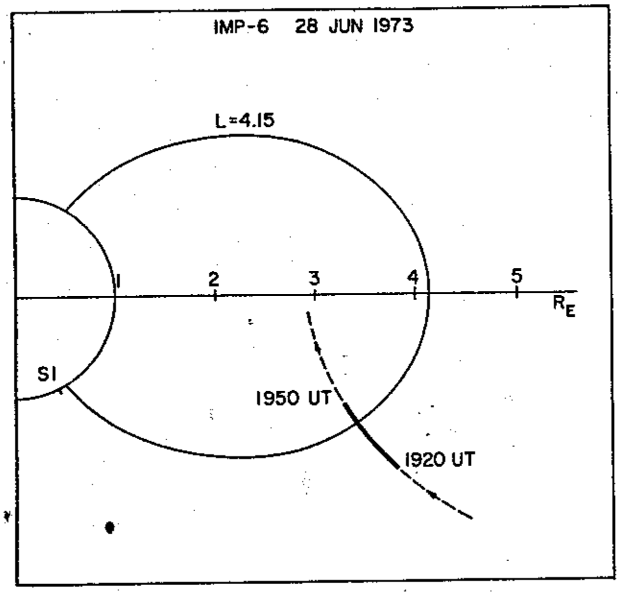


Figure 2. VLF spectrogram showing doppler shift of Siple transmitter pulses as observed over the Northern Hemisphere by ISIS-2.



component thus will be valuable in the study of wave-particle interaction phenomena. Since the nonducted modes are not detectable from ground-based stations, it is necessary to use satellites to make *in situ* measurements of the transmitted wave spectrum and of the associated emissions.

Observations of nonducted signals from the Siple transmitter thus far have been carried out using three satellites: ISIS-2, Explorer-45, and IMP-6. Measurements of wave spectra from the polar-orbiting satellite ISIS-2 have shown many interesting triggering events as well as large doppler shifts associated with the nonducted transmitter signal. Spectrograms illustrating these effects are shown in figures 1 and 2. In figure 1, the four panels represent about 2 minutes of continuous data taken near the conjugate point. At the time of reception, the

Figure 3. Magnetic-meridian-plane projection of an IMP-6 satellite pass on 28 June 1973. The heavy-lined portion denotes the 6,000 kilometer path along which strong Siple signals were observed.

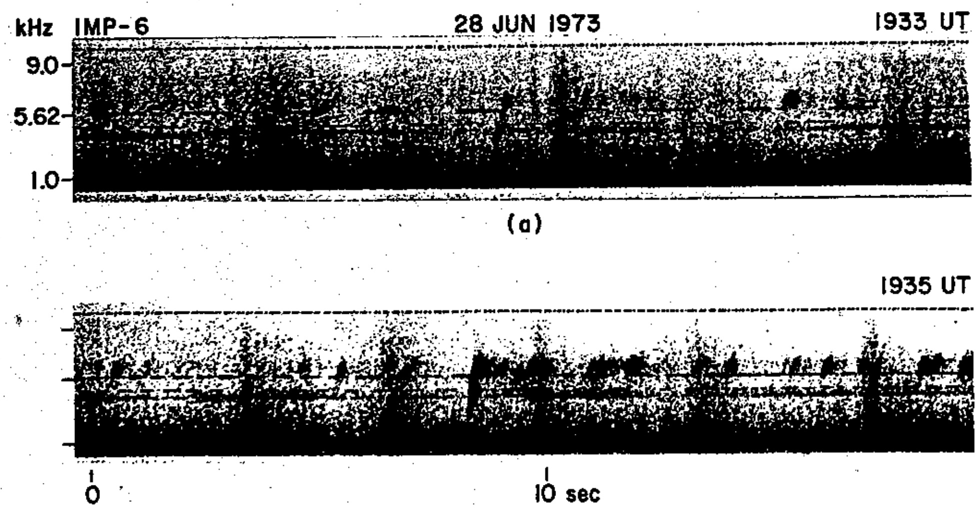


Figure 4. VLF spectrogram showing Siple signal reception outside the plasmapause on the IMP-6 pass of figure 3.

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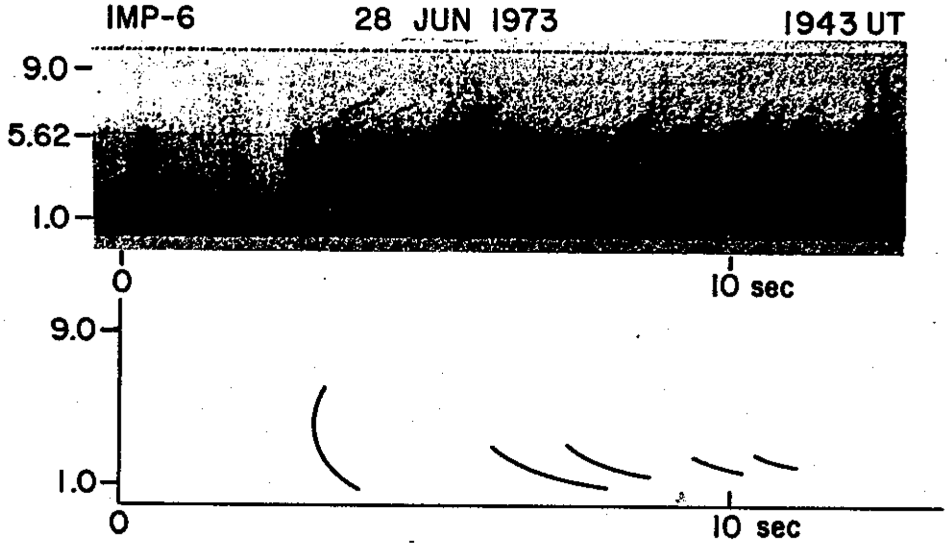

Figure 5. VLF spectrogram showing Siple signal reception inside the plasmapause on the IMP-6 pass of figure 3.

Siple transmitter was sending 1-second-long pulses in frequency shift key (FSK) format, alternating between 5.0 and 5.5 kilohertz. Individual pulses generally are clearly visible, except when obscured by interference from a high-frequency satellite transmitter. The emission activity is weak in the first two panels, consisting of falling tones near the ends of a few pulses. The activity becomes much stronger in the last two panels, and almost every pulse at 5.5 kilohertz shows signs of amplification and emission triggering.

Figure 2 illustrates the doppler shift phenomenon; again, the transmitter format is FSK with 1-second-long pulses at 5.0 and 5.5 kilohertz. On the upper panel an extra set of pulses appears about 300 hertz above the pulses at 5.5 kilohertz, and is delayed about 200 milliseconds with respect to these pulses. The extra set of pulses is interpreted as follows: The transmitter signals at 5.5 kilohertz can reach the satellite by at least two separate nonducted paths through the magnetosphere, a short-time-delay path and a long-time delay path. At the satellite position, the wave refractive index on the long-delay path is generally much longer than on the short-delay path. Further, the direction of the wave normal is generally parallel or antiparallel to the satellite direction. The doppler shift due to satellite motion is thus much larger for the long-time-delay dignal, and in this particular case places it a few hundred hertz in frequency above the short-delay signal. This type of data clearly shows the multipath nature of nonducted signals from the Siple transmitter.

Measurements of wave spectra on the equatorial-orbiting satellites Explorer-45 and IMP-6 have shown that the Siple transmitter illuminates a large volume of the magnetosphere and that within this region emission-triggering events can be readily observed. Figure 3 shows a magnetic-meridian-plane projection of an inbound pass of IMP-6 on 28 June 1973. During this pass signals from the Siple transmitter were received over a 6,000-kilometer section of the orbit (as shown by the heavy line in figure 3). The dipole field line extending to 4.15 equatorial earth radii, the approximate inward edge of the plasmapause at that time, is also shown. Spectra recorded outside the plasmapause are presented in figure 4. Here the transmitter signal at 5.62 kilohertz is strong while the natural signals, such as whistlers, are relatively weak and occur infrequently. In the lower panel a few natural emissions can be seen near the upper transmitter frequency of 5.62 kilohertz.

Figure 5 shows spectra recorded inside the plasmapause. The transmitter signal is still readily observable but the whistler amplitude and frequency of occurrence have increased dramatically from their values in figure 4. In the lower part of figure 5 is a sketch of a multihop whistler train that appears in the data panel directly above. The multihop event shows the presence of a whistler that is guided along the surface of the plasmapause boundary. A final example of emission triggering by nonducted transmitter signals is given in figure 6, which shows spectra received by Explorer-45 on 13 July 1973. On this occasion the transmitter operated at 7.8 and 7.1 kilohertz. Although the 7.8 kilohertz signals are not in evidence, the 7.1 kilohertz signals are strong and give rise to strong rising emissions. The transmitter signals are located slightly above a very intense band of natural noise. consisting of rising emissions.

Since the satellite observations show that nonducted signals are readily observable throughout large volumes of space, they serve to put the Siple wave injection experiment on a firm footing with respect to *in situ* measurements. We now plan to use satellite measurements more extensively to map

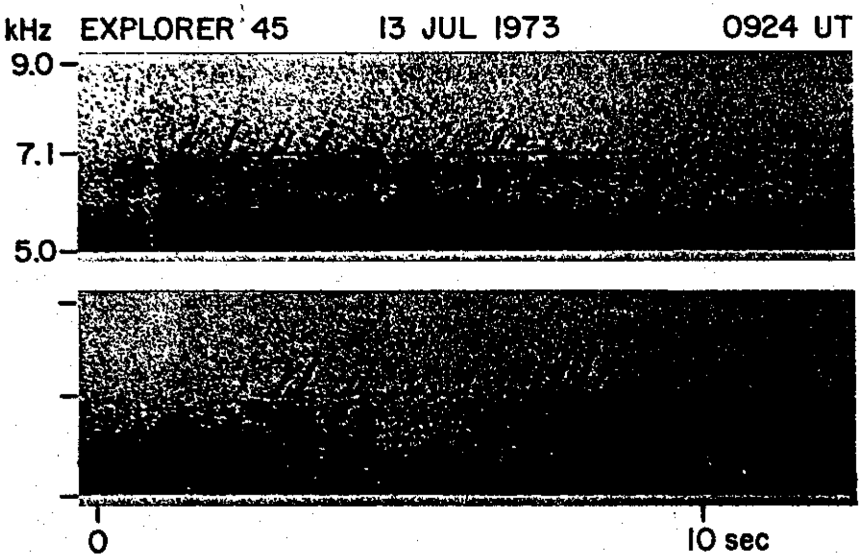

Figure 6. VLF spectrograms from Explorer-45, near the magnetic equator, showing triggering of emissions by nonducted signals from the Siple transmitter.

out the regions where VLF emissions are produced and to measure in the interaction region itself the correlation between input wave characteristics and energetic particle characteristics. Satellite measurements of this nature, which make use of the Siple transmitter, are an important part of future space missions. In particular, the Mother/Daughter spacecraft of the International Sun-Earth Explorer missions and the Electrodynamic Explorer spacecraft will be involved in VLF wave injection experiments using the Siple transmitter. Experimenters on the GEOS satellite, soon to be launched by the European Space Research Organization, are interested in VLF wave-injection experiments, possibly involving the Siple transmitter. These measurements should serve to elucidate the physics of wave-particle interactions in the magnetosphere and to give us a clearer understanding of the nature of the plasma envelope that surrounds earth.

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A possible new type of whistler-induced VLF propagation disturbance

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One fascinating side effect of lightning discharges is the modulation they sometimes produce on radio waves. This phenomenon is the result of a long chain of events. Radiation from the lightning stroke travels into the magnetosphere where it propagates as a whistler wave. The whistler encounters the energetic electrons of the earth's radiation belts and scatters them in such a way that some of them rain out of the magnetosphere into the underlying ionosphere. When these rapidly moving electrons collide with molecules of the dense neutral atmosphere, they produce considerable ionization, significantly increasing the free electron content of a localized region of the ionosphere. The result is a depression in the top surface of the natural waveguide formed by the earth's surface and the ionosphere. Very low frequency (VLF) radio waves, such as signals from various U.S. Navy transmitters, propagate worldwide in this waveguide. The bump in the guide alters the local propagation characteristics and perturbs the amplitude and phase of the signals received at distant points.

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