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DE-1 OBSERVATIONS OF VLF TRANSMITTER SIGNALS AND WAVE-PARTICLE INTERACTIONS IN THE MAGNETOSPHERE

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Abstract. A broadband VLF receiver on the DE-1 satellite measures signals injected into the magnetosphere by ground-based transmitters. VLF emissions triggered by these signals indicate that the waves interact strongly with trapped energetic particles in the magnetosphere. The propagation paths from the source to the satellite are deduced on the basis of the group time delay and Doppler shift. Although there are many different paths, emissions are triggered by the later-arriving pulses that have traversed the geomagnetic equator. First satellite-based observations of emission triggering by high-power communications transmitters and their possible implications are discussed.

Introduction

In situ satellite observations of coherent VLF waves from ground sources are an important component of experiments aimed at understanding wave-particle interactions in the magnetosphere. Ground sources include the experimental transmitter at Siple Station, Antarctica (76°W, 84°S) and various VLF navigation or communication transmitters. Previous observations on the IMP-6 and ISEE-1 satellites have shown that the injected signals are detectable continuously over large regions (in a ±50° longitude range around that of the source) in the plasmasphere [Inan et al., 1977; Bell et al., 1981]. In most cases the transmitter signals propagate up to the satellite along nonducted paths. While ducted waves propagate in field-aligned 'ducts' of enhanced ionization, nonducted raypaths are in general determined by the larger-scale gradients of the plasma density and the magnetic field. Such nonducted waves often exhibit high wave-normal angles and can reach a given satellite location either through 'direct' paths or along 'indirect' paths that include one or more magnetospheric reflections [Edgar, 1976]. Observations on the ISEE-1 satellite have shown that emissions were triggered only by the transmitter signals with the longer travel times, and that such triggering events were usually seen in the 0300-1000 LT interval. While these results were based mainly on observations of signals from the VLF transmitters of the Omega, N. D., transmitter (the ISEE-1 broadband VLF receivers covering the range of frequencies above 10 kHz was operationally limited to an observation window of ±50° in geographic longitude around that of the Siple transmitter (84°W)), in the present paper we report DE-1 observations of emission triggering by signals injected from other VLF transmitters that use similar formats but operate at higher radiated power. Our results indicate that for these cases triggering may occur more frequently and over a broader range of local times.

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Another important result of the ISEE-1 observations was the absence of triggering by signals from VLF communication transmitters such as NAA in Cutler, Maine, while the Omega transmitters with a factor of 20 dB less radiated power level were often seen to trigger strong emissions. This discrepancy is partly attributed to the fact that while the Omega transmitters employ pulsed modulation formats using 0.9-1.2 sec pulses, NAA usually employs a minimum shift keying (MSK) format consisting of short (25 ms) pulses that alternate in frequency. Experimental evidence shows that such short pulses do not produce significant growth and triggering [Helliwell and Katsufrakis, 1974]. Another factor is the relatively higher operating frequencies (16-25 kHz) of the communications transmitters compared to those of the Omega network (10.2-13.6 kHz) [Carpenter and Lasch, 1969]. In this paper, we present the first satellite observations of triggering by a high-power communication transmitter.

In the following, the VLF signals observed on DE-1 are associated with ground-based transmitters. The identification of the transmitters are mainly made on the basis of their operating frequency [International Frequency List, ITU, vol. 1, 1979 (hereafter referred to as Ref. 1); Cousins, 1972; J. P. Katsufrakis, private communication]. For the navigation transmitters with known formats, the time of origin (or transmission) of the signals is determined by measurement of the subionospheric signal at ground stations. Measurements of group time delay and Doppler shift of the transmitter pulses are used to determine the propagation paths. Our results show that the signals can reach the satellite through a variety of paths over which the time delays may vary from a few hundred ms up to a few secs.

Instrumentation

The Stanford University Linear Wave Receiver (LWR) on DE-1 is integrated into the Plasma Wave Instrument [Shawhan et al., 1981]. The receiver measures wave amplitude in the frequency range 1.5-16 kHz. All of the spectra shown in this paper were received on a magnetic loop (threshold sensitivity 6×10^{-7} $\gamma/\sqrt{\mathrm{Hz}}$ at 6 kHz). The gain of the amplifier can be set at 10 dB steps over a 70 dB range and can be varied automatically or can be commanded to remain fixed at any level. In the automatic mode the gain is updated every 8 secs. The response is linear over a 30 dB dynamic range in any gain position, thus facilitating accurate measurement of the signal intensity and temporal growth rate.

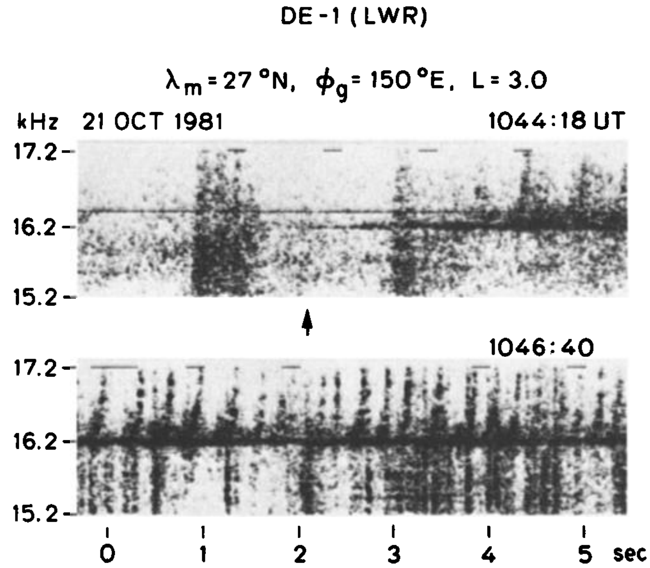

Fig. 1. Emission triggering by UMS. The satellite location is indicated by the geomagnetic latitude λ_m, geographic longitude ϕ_g, and L-value.

Observations

Figure 1 shows VLF emissions triggered by signals from a transmitter believed to be located in the eastern USSR (48°N, 135°E) using the call sign UMS. This transmitter operates alternately at 16.2 or 17.1 kHz and radiates $\sim$1000 kW, as determined from ground field strength measurements. In the case shown, the transmissions begin at approximately 1044:20 (see arrow), when the satellite is in the northern hemisphere and close to the meridian of the source. The exact time of keying is not known, but the one-hop delay from source to receiver at such a satellite location is expected to be a few hundred ms [Edgar, 1976].

In Figure 2 the 16.2 kHz transmitter signal begins to trigger emissions (as first evidenced by broadening of the signal spectrum) approximately 2 sec after the first component arrives (see arrow) at the satellite. This is consistent with results of raytracing in a model magnetosphere, involving wave travel to the opposite hemisphere, reflection from the lower boundary of the ionosphere, and return to the hemisphere of origin. The wave apparently triggers emissions as it crosses the wave-particle interaction region, believed to lie close to the geomagnetic equator [Helliwell, 1967; Inan et al., 1978]. The modulation format of the transmitter is not known, but is most likely a continuous wave (CW) transmission, as indicated by the first 2-sec portion of the signal. The lower panel shows that emissions are triggered at approximately 300-ms intervals, a common occurrence in experiments near 5 kHz [Helliwell and Katsufrakis, 1974]. The triggering event on 21 October lasted four minutes.

These are the first reported satellite observations of triggering by the relatively high-power communication transmitters, although triggering by such transmitters has been commonly observed on the ground [Helliwell, 1965]. Such triggering demonstrates the existence of a relatively strong resonant interaction between waves and particles, an important component of which would be pitch angle scattering, if we assume a cyclotron resonant interaction [Kennel and Petschek, 1966; Helliwell, 1967; Inan et al., 1978]. This evidence strengthens previous suggestions that these transmitters may induce significant amounts of particle precipitation and may play a role in the overall lifetimes of radiation belt particles [Inan et al., 1978; Vampola and Kuck, 1978; Imhof et al., 1981; Inan, 1981].

Figure 2 shows emissions triggered by 400 ms pulses from the navigational transmitter located in the USSR at Komosomolskamur (50°N, 136°E) [Ref. 1]; the format is shown in the lowest panel of Figure 2. The top panel shows the direct 12.65 kHz signal (400 ms long) as it arrives at the satellite $\Delta t = 0.3$ sec (at 12.65 kHz) after transmissions were observed at Roberval, Canada (47°N, 72°W), and South Pole, Antarctica. As expected, this direct signal does not show evidence of wave-particle interactions. Approximately 0.9 sec after the arrival of the direct signal, the reflected components, which have traveled to the opposite hemisphere and have been magnetospherically reflected [Edgar, 1976], begin to arrive. Their apparent duration is about three times that of the original signal (400 ms), indicating that there exist at least three paths through which the signal can reach the satellite. Emissions

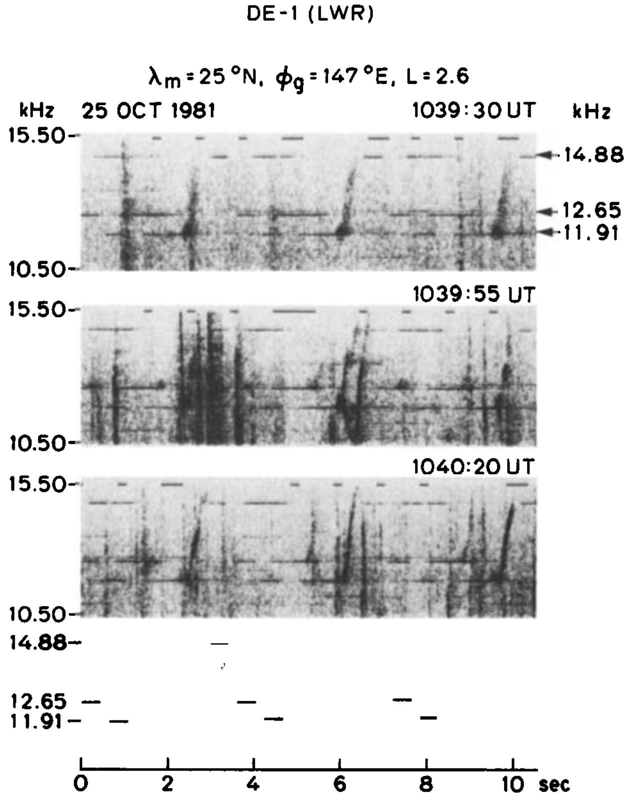

Fig. 2. Emission triggering by signals from the Komsomolskamur transmitter (50°N, 136°E). The modulation format shown in the lowest panel is shifted to the right by 0.3 sec (group time delay of the shortest path).

are repeatedly triggered along either one or a group of such paths that have very similar time delays. The latter possibility is suggested by the fact that the emissions of the top panel of Figure 2 are broadened as if by the superposition of two or more discrete components of similar slope but slightly different delay.

The distribution of path delays at all three transmitter frequencies in the top panel of Figure 2 is about the same. In terms of triggering, 11.9 kHz seems to be the most active frequency. Rising emissions were repeatedly triggered at this frequency during a 5-min period. In the first min of the event the 14.88 kHz signal was also seen to trigger emissions, although not as strongly as the 11.9 kHz signals, as shown in the lower panel of Figure 2. The middle panel shows the triggering of a 'hook' by the 11.9 kHz pulse.

Triggering events similar to that shown in Figure 2 were observed on 2 out of 4 passes of the satellite over the same region of space in the month of October 1981. The local time period of all passes was 2100-2200 LT, a time well outside the 0300-1000 LT sector in which most of the emission triggering by Omega, N.D., signals was observed on ISEE-1 [Bell et al., 1981]. Thus these results indicate that emission triggering may occur under more general conditions than previously thought. The data also indicate that the frequency of occurrence of emission triggering may also be significantly higher than the 15% observed on ISEE-1. One reason for this may be a difference in radiated power between the transmitters involved. Measurements of the observed levels of the subionospheric signals at the Roberval, Canada, station and the incorporation of the ionospheric propagation loss over the paths from the sources to Roberval indicate that the USSR navigational transmitters may operate at power levels as much as 15 dB above those of the Omega network.

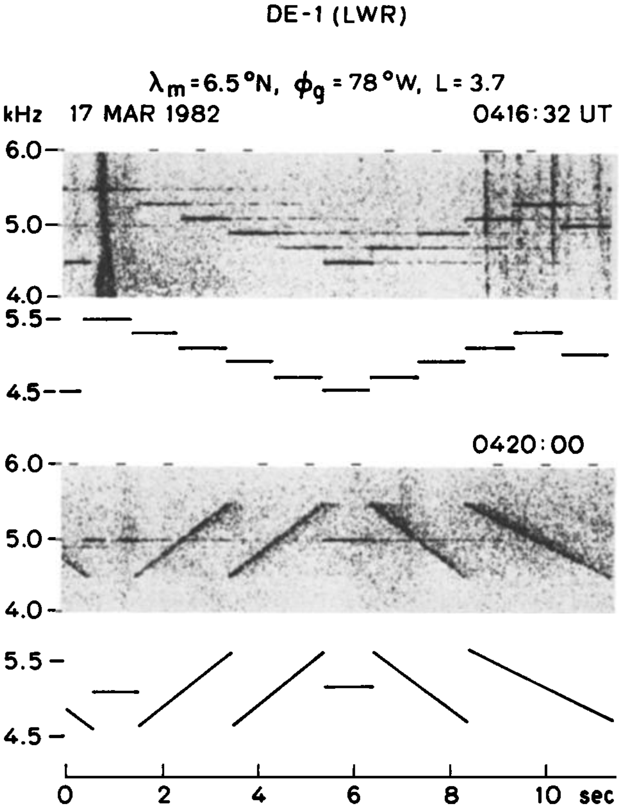

Fig. 4. Siple transmitter (76°S, 84°W) signals on DE-1 and corresponding transmitter formats, which are shifted by 0.9 sec, the time delay of shortest path from the source to the satellite.

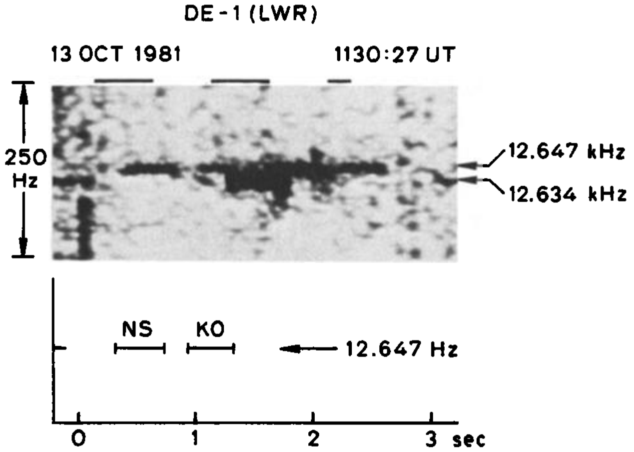

Fig. 3. Transmitter signal components that reach the satellite along different paths. The lower pulse at 12.634 kHz arrives at the 1.5 sec mark and with a 0.3 sec time delay. This signal comes from the Komsomolskamur (KO) transmitter and reaches the satellite through a path that enters the magnetosphere in the northern hemisphere. The first pulse at 12.647 kHz comes from the Novosibirsk (NS) transmitter (80°E, 55°N) and reaches the satellite over a path that enters the magnetosphere in the southern hemisphere. The second pulse from KO follows a similar path. The later pulses at 12.647 kHz are the reflected components of the earlier ones. The satellite location was $\lambda_m \simeq 34°S$, $\phi_g = 146°E$, $L \simeq 1.9$.

In order to illustrate the propagation characteristics of transmitter signals, we show in Figure 3 the reception in the southern hemisphere of the 12.65 kHz signal from the transmitter discussed in Figure 2. Twenty mins earlier the satellite was in a location similar to that shown in Figure 2, and emissions similar to those of Figure 2 were observed. The strong signal that arrives at the 1.5 sec mark has a frequency offset of -15 Hz compared to the nominal frequency of the transmitter (12.647 kHz) and is delayed approximately 0.3 secs. Both the time delay and frequency shift are consistent with raytracing results in a model magnetosphere. The signal enters the magnetosphere in the northern hemisphere and propagates over a nonducted path to the satellite, where its wave-normal angle with respect to the magnetic field is 80° (pointing towards higher latitudes). Since the satellite motion is at an angle to the wave normal direction, the observed signal frequency is Doppler Shifted by $\bar{k} \cdot \bar{v}$, where $\bar{k}$ is the wave number and v is the satellite velocity. Raytracing results show this Doppler shift to be in the range 10-30 Hz (negative), depending on the local cold plasma density. The spectral lines above the strong pulse at 12.634 kHz represent transmitter signals that propagate in the earth-ionosphere waveguide to the southern hemisphere, enter the magnetosphere and propagate to the satellite over a relatively short magnetospheric path. For a smooth model of the magnetosphere, the wave normal at the satellite location is approximately perpendicular to the satellite motion, thus resulting in $\bar{k}\cdot\bar{v}\simeq 0$ and negligible Doppler shift. The first 400 ms pulse is from the USSR navigational transmitter in Novosibirsk (80°E, 55°N) which operates at the same frequencies as the one in Komsomolskamur and in this case is keyed exactly 0.6 sec earlier (as determined by measurements of the subionospheric signal at ground stations). The second pulse at 12.647 kHz, from the Komsomolskamur transmitter, follows a similar path. Although the front portion of this pulse is not well defined, it arrives about 0.3 sec earlier than the 12.634 kHz signal, since the latter travels over a longer magnetospheric path (0.3 sec time delay) rather than a mostly subionospheric path.

The 12.65 kHz pulses that follow (from about 1.6 to 2.7 sec) the two pulses already discussed are either from another USSR transmitter in Krasnodar (33°E, 45°N) or are magnetospherically reflected components of the first two pulses. In the latter case, the reflected signals would be expected to be Doppler shifted in frequency. The lack of a shift indicates that the magnetospheric cold plasma distribution may be irregular.

To further illustrate the multiplicity of paths from a ground-based source to a high altitude satellite, we show in Figure 4 a typical example of DE-1 observations of Siple transmitter signals. For the case shown, the time delay of the leading edge of each pulse is approximately 0.9 sec. In addition to this path with the shortest time delay, there appear to be a number of other paths that reach the satellite with time delays ranging from 0.9 sec to 3.0 sec. This is evident both from the faint traces that follow the relatively strong 1-sec long portions of the pulses in the top panel and from the frequency ramps in the lower panel, which are followed by faint components that appear as diffuse spectra.

Summary

We have shown new evidence that VLF waves from ground transmitters propagate on a variety of paths and can be observed in the magnetosphere over large regions. Certain of these signals interact with the energetic radiation belt particles and trigger VLF emissions. We have also presented the first reported observation of emission triggering by high-power communication transmitters. Since triggering of emissions and pitch angle scattering of particles are the results of the same wave-particle interaction, this supports previous suggestions that man-made transmitter signals may interact with and therefore contribute to the precipitation of particles and thus may play a role in controlling energetic particle lifetimes in the magnetosphere.

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