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TRANSMITTER SIMULATION OF POWER LINE RADIATION EFFECTS IN THE MAGNETOSPHERE

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Abstract. Harmonic radiation from electrical power transmission lines is known to trigger strong emissions in the magnetosphere in the range of a few kilohertz. To study this phenomenon on a controlled basis, an experiment was conducted using a very-low-frequency transmitter at Siple, Antarctica ($L \simeq 4$) and a receiver at its conjugate station, Roberval, Quebec, Canada. Many important features of power-line-induced emissions including their frequency dependence, rapid amplitude variations, and spectral forms could be simulated by transmitting waveforms containing sidebands with 50 and 100 Hz frequency separations. It is found that power line effects can be simulated by radiating as little as 0.5 W at a given frequency. The results also demonstrate that the magnetosphere can generate sidebands at frequencies up to 25 Hz from the transmitter frequency. This explains why power-line-induced emissions sometimes show frequency components 20-30 Hz from exact multiples of the fundamental power frequency.

Introduction

Power line radiation (PLR) effects in the magnetosphere have been the subject of many recent papers, including Helliwell et al [1975], Park [1977], Luette et al [1977], Bullough et al [1976], Park and Helliwell [1978], and Park and Miller [1979]. Harmonic radiation from electrical power transmission lines leaks into the magnetosphere where it is greatly amplified and triggers new emissions that are much stronger than the triggering input wave. There is evidence that PLR-induced emissions contribute significantly to the overall magnetospheric wave activity in the range of a few kilohertz [Park and Miller, 1979].

Ground-based studies of PLR effects have have been based largely on data from three stations near L = 4; Siple (76°S, 84°W) and Eights (75°S, 77°W), Antarctica and Roberval, Quebec (48°N, 73°W) near the geomagnetic conjugate points of Siple and Eights. These stations afford excellent opportunities to study such effects because of relatively strong PLR sources in the industrialized areas of eastern Canada and the U. S.

PLR-induced emissions may appear in a wide variety of spectral forms, as shown in earlier papers by Helliwell et al [1975] and by Park [1977]. They also show rapid temporal variations in the general level of activity as well as in spectral forms with time scales of the order of a minute or less. Presumably these variations are due to a combination of factors that influence the source radiation intensity, propagation conditions in the ionosphere and magnetosphere, and wave particle interaction conditions near the equatorial plane. For a proper assessment of the role of PLR in magnetospheric dynamics, it is important to understand what magnetospheric conditions and what PLR intensity levels are required to trigger emissions that affect the behavior of trapped energetic electrons. In order to answer some of these questions, a series of controlled wave injection experiments have been conducted to simulate PLR, using an experimental transmitter at Siple and a receiver at Roberval. Preliminary results show that many properties of PLR-induced activity can be simulated with the Siple transmitter. In this paper, we report on some preliminary findings that bear on two main questions: (1) the amount of radiated power needed to produce PLR-like effects in the magnetosphere, and (2) the generation of sidebands in the magnetosphere that can sometimes cause confusion in the studies of PLR effects.

Experimental Facilities

The transmitter at Siple is a relatively low-power, solid-state device that can provide variable output up to 100 KW. The signal modulation is under the control of a mini-computer in conjunction with an accurate rubidium frequency standard. The antenna is a 21.2-km horizontal dipole, suspended a few meters above the snow surface. The thick (~2 km) layer of snow underneath the station keeps the antenna away from the lossy ground and increases its radiation efficiency. Details of the Siple transmitter and the receiving facility at Roberval have been described by Helliwell and Katsufrakis [1978].

One limitation of the Siple transmitter is that it can transmit only one carrier frequency at a time. Fortunately, however, it is possible to take advantage of the rapid frequency shifting capability of the transmitter and design a signal format that contains multiple sidebands at desired frequencies.

Experimental Results

Power line simulation experiment. For the purpose of simulating radiation from power lines,

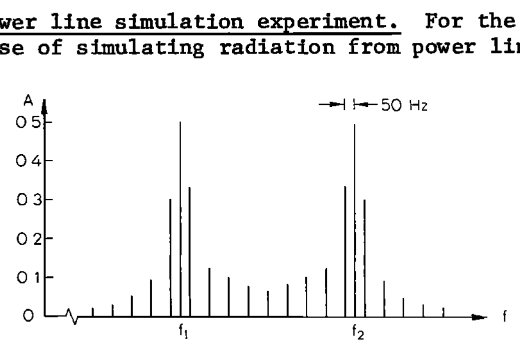

Figure 1. A sketch of the Fourier spectrum transmitted from Siple, Antarctica to simulate power line radiation. The waveform is a series of 10 msec pulses alternating between two frequencies, f_1 and f_2.

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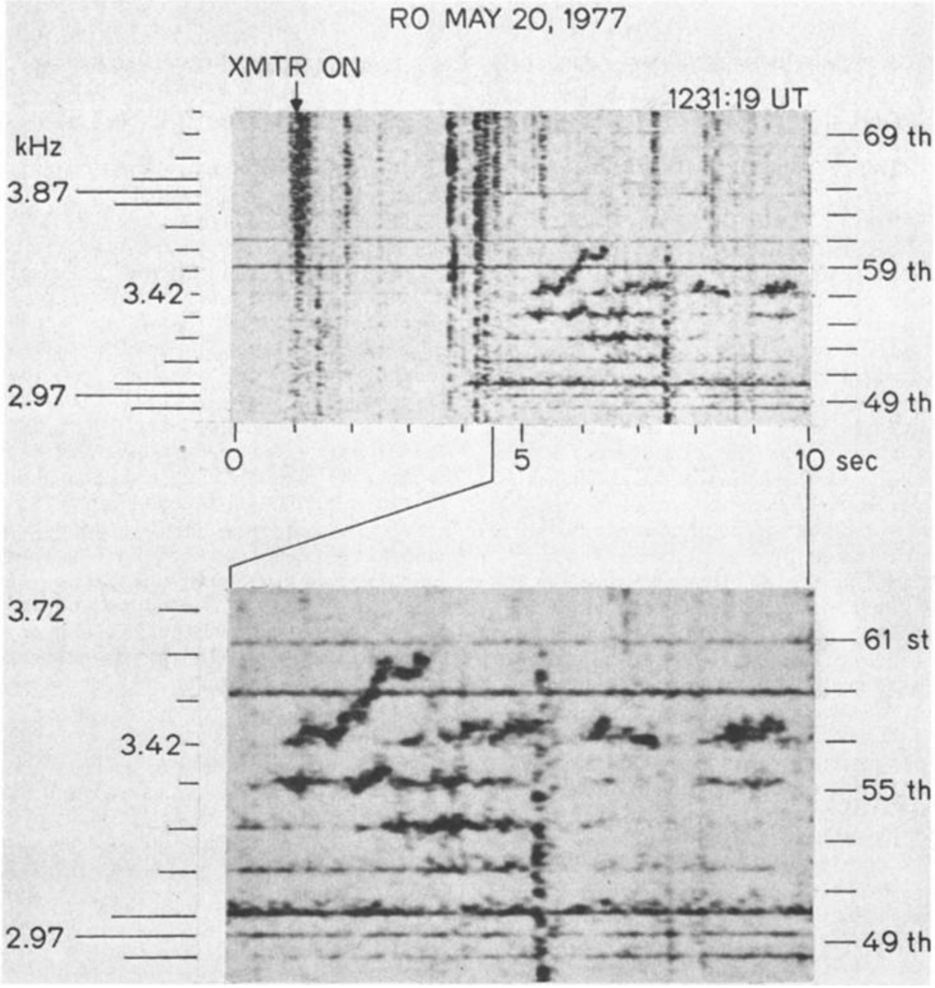

Figure 2. Spectrograms from Roberval, Quebec. The Siple transmitter was turned on at t = 1 sec. The horizontal bars at left show the frequency and relative amplitude of each transmitted sideband, while the bars at right show the harmonics of the 60 Hz power frequency in Canada.

the carrier was switched at 10 msec intervals between two frequencies, f_1 and f_2, 900 Hz apart. The Fourier spectrum of such a frequency-shift-keyed (FSK) signal is illustrated in Figure 1. The two pairs of sidebands about f_1 and f_2 are spaced 50 Hz from the carrier frequencies, while the other sidebands are 100 Hz apart.

It is generally accepted that VLF wave amplification and emission triggering take place through cyclotron resonance interaction between waves and energetic electrons. Since wave-particle interaction time is usually much longer than 10 msec, the electrons "experience" a time-averaged spectrum, as illustrated in Figure 1, instead of individual 10 msec pulses at f_1 and f_2 [Chang, 1978]. This transmitter format has produced a variety of wave-particle interactions that closely resemble PLR-induced effects, including frequency dependence, amplitude fading, and spectral forms. We now describe a few examples from this experiment.

The top panel of Figure 2 is a frequency-time spectrogram from Roberval. The horizontal bars at left show the frequency and relative amplitude of the sidebands transmitted from Siple (same as Figure 1). The transmitter was turned on at t = 1 sec. About 3 sec later, following whistler-mode propagation through the magnetosphere, the first detectable signal appears on the Roberval record at 3.87 and 3.02 kHz. The transmitted sidebands between 3.02 and 3.42 triggered emissions that resemble PLR-induced emissions. The vertical scale shows the odd harmonics of the 60 Hz power frequency. Two harmonics, the 59th and the 61st, are particularly strong and run throughout the record. These are believed to be local induction lines, although it is not possible to prove that they had not been amplified in the magnetosphere.

A portion of the top spectrogram is shown below in expanded scales. Several features are noteworthy in the figure. The signal intensity and emission activity observed at Roberval appear to depend more strongly on the frequency than on the transmitted power. For example, the sideband at 3.42 kHz with a minimum transmitted power stimulated strong emissions, while some of the nearby sidebands with larger power failed to produce detectable signals. This sideband frequency coincides with that of the 57th power line harmonic. This, however, does not appear to be a significant factor, since the most active sideband shifted to different frequencies later in the experiment, as discussed below (see

Figure 3). Two different spectral forms can be distinguished in Figure 2: extremely narrowband signals such as the sharp line at 2.97 kHz, and emissions with rather broad and turbulent spectra such as those near 3.42 kHz.

We can estimate the radiated power at each sideband frequency in the experiment illustrated in Figure 2. The total transmitter output was 20 kW for all sidebands combined. From the Fourier spectrum, we find that the power into the antenna was 100W at the 3.42 kHz sideband, which triggered strong emissions. Since the radiation efficiency of the antenna is ~0.5% at this frequency [Raghuram et al, 1974], the radiated power at 3.42 is estimated at 0.5W. It is difficult to estimate how much of this radiated power entered the magnetosphere and reached the wave-particle interaction region near the equator. However, a very rough estimate can be made as follows. If a VLF duct with 50 km diameter were positioned over Siple, the amount of power entering this duct would be 5% of the total radiated power (assuming the radiation pattern of a short dipole). This gives a power density of 6.4 x 10^{-12}W m^{-2} in the ionosphere. If we further assume that the power inside the duct remains constant with altitude, the power density would decrease by a factor of 110 from the bottom of the ionosphere to the equatorial plane in the magnetosphere. Thus we estimate that the input power into the wave-particle interaction region at 3.42 kHz was about 5.8 x 10^{-14}W m^{-2}. For a refractive index of 30, this corresponds to a wave magnetic field intensity of about 0.1 mγ.

Figure 3 shows two more examples of the same transmitter experiment, approximately 2 min and 18 min later. The transmitter format and power are identical to the case of Figure 2. The top spectrogram shows the most active sideband at 3.52 kHz, 100 Hz higher than the most active frequency in Figure 2. As in Figure 2, there is a mixture of sharp, narrowband signals and more diffuse, turbulent emissions. In the bottom spectrogram, most of the sidebands are inactive except the three at 3.87, 3.82 and 3.92 kHz. The two lines at 3.87 and 3.92 show deep and irregular fading. These examples illustrate the need for controlled experiments to investigate this complex and highly variable phenomenon.

Sideband generation in the magnetosphere. One puzzling aspect of PLR-induced emission is the fact that sometimes line emissions are observed at frequencies significantly different from exact multiples of the power frequency. A set of line emissions may appear with frequency spacings of only ~20-30 Hz. An example of this was shown in a paper by Helliwell et al [1975], who suggested magnetospheric sideband instability as a possible explanation. Controlled Siple transmitter experiments demonstrate that such sideband instability can be easily excited in the magnetosphere.

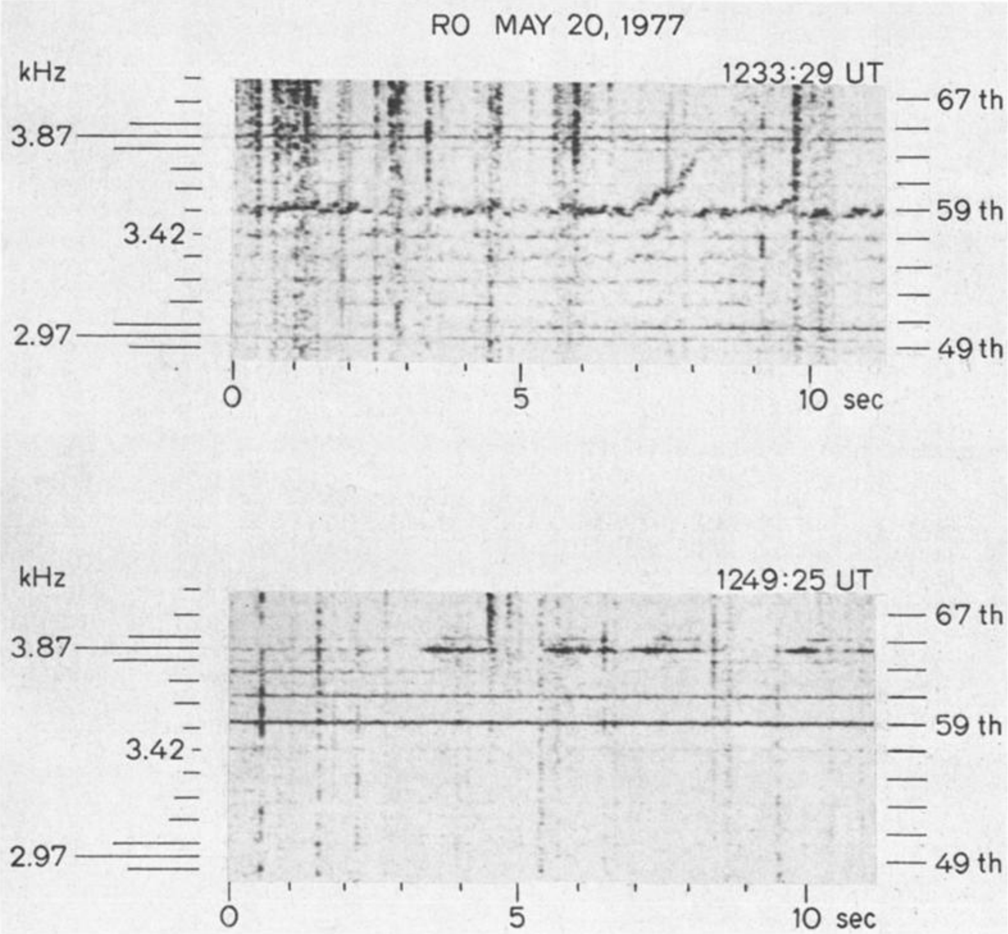

Figure 3. Spectrograms from Roberval during the same experiment as in Figure 2.

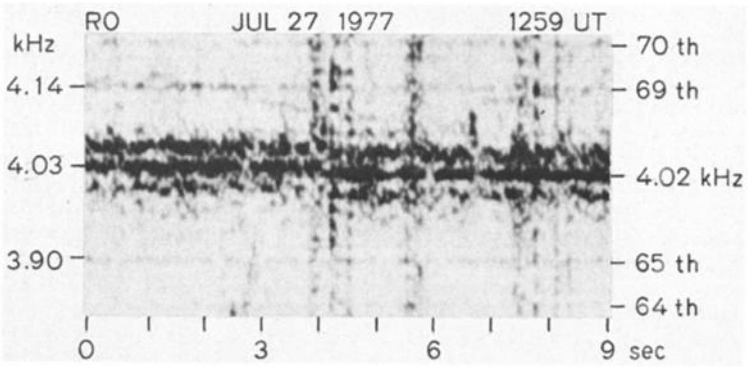

Figure 4. A spectrogram from Roberval illustrating sideband generation in the magnetosphere. The Siple transmitter was sending key-down signals with a 10 Hz frequency shift every 60 sec. One such shift is seen at t = 4 sec. Power line harmonics are indicated at right. The spectral analysis equipment was set for Δf = 6 Hz and Δt = 160 msec.

Bell and Helliwell [1971] observed amplitude pulsations (~0.5 s period) of constant-frequency transmitter signals, indicating the presence of sideband structures. Likhter et al [1971] reported on similar amplitude pulsations associated with long transmitter pulses. Whistler-mode sideband instability has also been discussed in several theoretical papers [Brinca, 1972; Nunn, 1974; Newman, 1977]. In our Siple experiments, sidebands appear to be a fairly common feature of long constant-frequency transmissions. Observed sideband frequency separations range from a fraction of a Hertz to several tens of Hertz, and the spectral structure often indicates the presence of both amplitude and frequency modulations. A detailed discussion of the sideband instability will be given in a separate report. Here we only give an example of stimulated sidebands that is relevant to the understanding of PLR-induced emissions.

The Siple transmitter was programmed to send constant-frequency signals with a 10 Hz shift each minute. Figure 4 shows an example of the signal received at Roberval. As the frequency shifts from 4.03 kHz to 4.02 kHz at t = 4 sec, the associated sidebands also shift down by 10 Hz. The sidebands are ~25 Hz from the carrier frequency and their amplitude is ~10 dB below the carrier amplitude. These results indicate that sideband instability can explain PLR-induced line emission with frequency separations less than the fundamental power line frequency.

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