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GROUND OBSERVATIONS OF POWER LINE RADIATION COUPLED TO THE IONOSPHERE AND MAGNETOSPHERE*

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Abstract. Ground-based VLF observations show evidence that strong whistler-mode waves in the magnetosphere are often stimulated by harmonic radiation from electrical power transmission lines. These stimulated emissions sometimes dominate the wave activity in the kHz range. A VLF transmitter at Siple, Antarctica has been used to simulate these power line effects with ~ 0.5 W radiated power at a given frequency. Occurrence statistics of power line effects are also summarized.

1. Introduction

Harmonic power line radiation (PLR) in the kHz range has been observed to stimulate strong wave-wave interactions in the magnetosphere (Helliwell *et al.*, 1975; Park, 1977). As a result of such interactions, the PLR wave may be amplified by ~ 30 dB during one passage through the interaction region and when the intensity exceeds a certain threshold level, may trigger free-running emissions whose frequency may deviate from the stimulating PLR frequency by hundreds of Hertz or more. PLR waves also interact with other man-made or naturally-occurring waves by entraining them or cutting them off.

The amplified PLR waves and triggered emissions often echo from hemisphere to hemisphere inside whistler ducts. Each time these waves pass through the wave-particle interaction region near the equator, they may be further amplified or trigger new emissions, thus adding to the complexity of the spectra of received signals. It should be pointed out that without amplification, magnetospherically propagating PLR waves are usually below the threshold of detection on normal broadband spectrograms. When they are amplified up to detectable levels, the nonlinear amplification process results in frequency broadening that clearly distinguishes magnetospheric PLR from monochromatic induction lines originating in local transmission lines.

In the next section, we shall review several different spectral forms of PLR-induced wave activity in the magnetosphere, including some wave-wave interaction effects. In Section 3 we shall present some results from VLF transmitter experiments that were designed to simulate PLR effects. Section 4 summarizes the PLR statistics, followed by discussion and conclusion in Section 5.

2. Examples of PLR-Induced Wave Activity

PLR-stimulated waves in the magnetosphere show a variety of spectral characteristics, some of which are illustrated in this section. Figure 1 shows simultaneous records from

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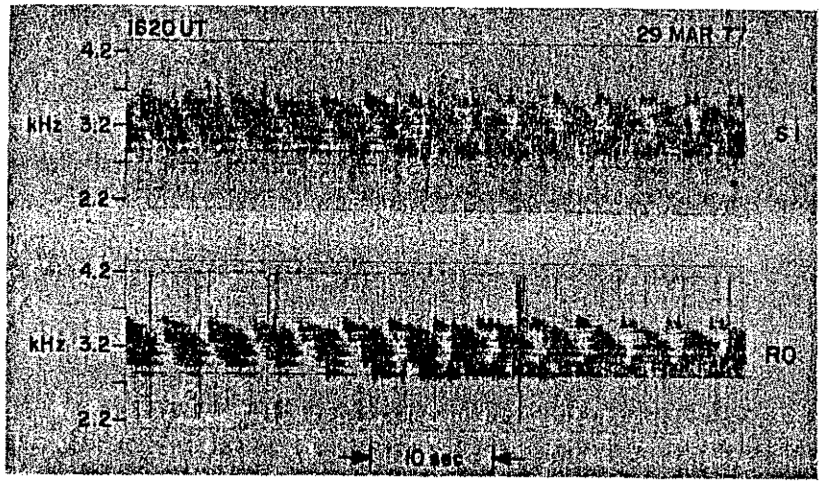

Fig. 1. Magnetospheric line radiation observed simultaneously at the conjugate stations, Roberval and Siple. The period of amplitude modulation is the two-hop whistler-mode echo period.

conjugate stations Siple, Antarctica (76° S, 84° W) and Roberval, Quebec (48° N, 73° W). Line radiation is seen to alternate between the two stations with the whistler echo period.

Figure 2 illustrates another type of line radiation recorded at Siple and Roberval showing continuous lines at several frequencies. Roberval records show the contrast between sharp, local induction lines and magnetospheric lines that have been broadened and shifted upward by nonlinear amplification process. Helliwell *et al.* (1975) studied

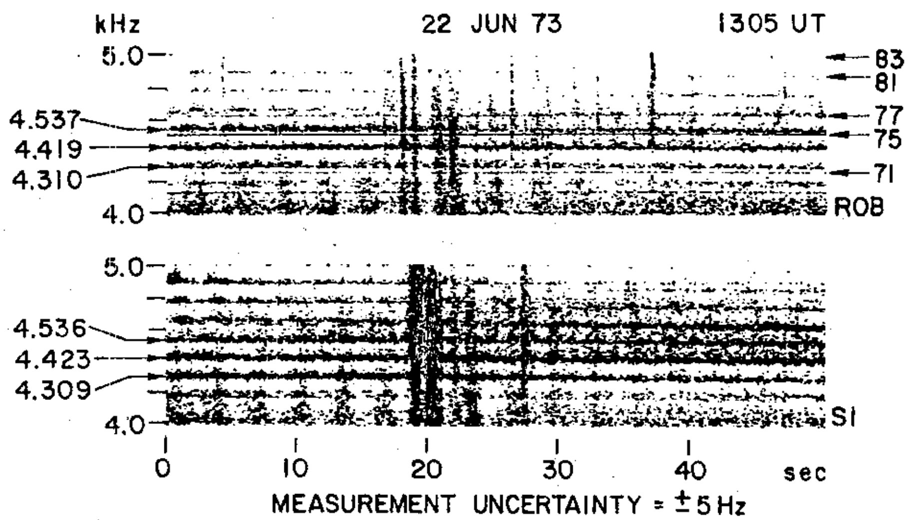

Fig. 2. Simultaneous VLF records from Roberval and Siple showing magnetospheric line radiation. The Roberval record also shows local induction lines (from Helliwell *et al.*, 1975).

this event in detail and found that the distribution of frequency spacings between adjacent magnetospheric lines had a mean value of 129 Hz, a median value of 125 Hz, and half-maximum values of 105 Hz and 135 Hz.

Amplified PLR can also trigger emissions whose frequencies are no longer controlled by triggering PLR waves. An example of this is shown in Figure 3, where rising tone emissions, starting at several power line harmonic frequencies, merge to form broad noise bursts.

A more subtle form of PLR effects involves wave-wave interactions in which PLR waves, often below the threshold of detection in frequency-time spectrograms, modify the behavior of other naturally occuring or man-made waves by entraining them or cutting them off. Figure 4 shows an example of a long enduring emission triggered by the experimental VLF transmitter at Siple. The emission undergoes several inflections at power line harmonic frequencies as indicated by local induction lines. Wave-wave interactions can also 'turn on' PLR, as illustrated in Figure 5. In this example, the long enduring multi-frequency PLR event can be traced back to a whistler at $t = 40$ s. Short segments of echoing PLR near the beginning of this event show how they are amplified during successive passes through the magnetosphere. They are not even discernable

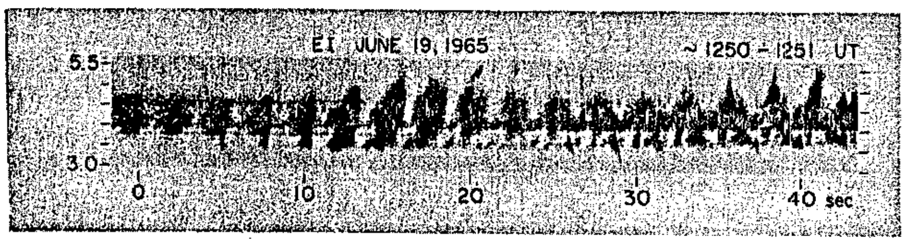

Fig. 3. An example of magnetospheric emissions triggered by power line radiation recorded at Eights, Antarctica (after Park, 1977).

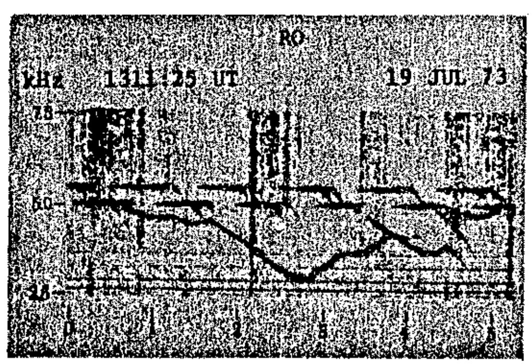

Fig. 4. Siple transmitter signals as received at Roberval. The transmitter format was frequency shifting between 5.0 and 5.5 kHz every 0.5 s (from Helliwell *et al.*, 1975).

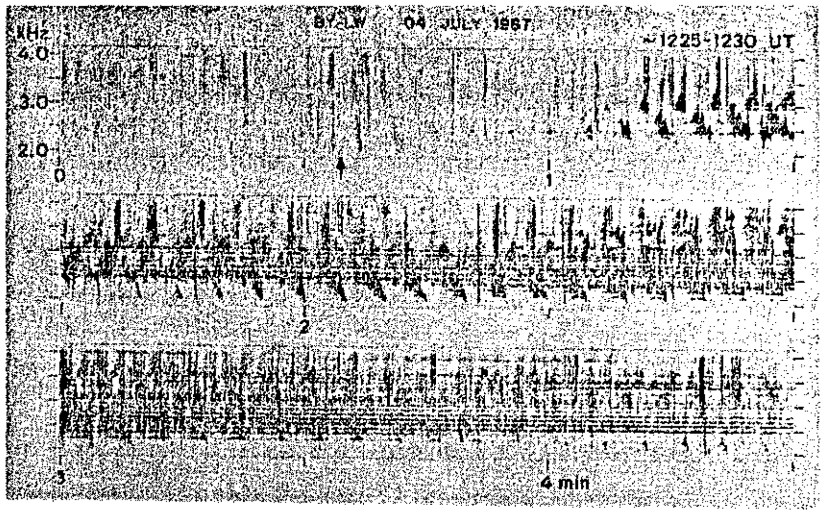

Fig. 5. VLF recording made with a 21 km dipole antenna at Byrd, Antarctica (80° S, 120° W). The vertical arrow marks the time of lightning discharge in the northern hemisphere that produced the whistler which in turn stimulated the magnetospheric PLR lines.

until several passes through the magnetosphere but once they reach a certain intensity level they trigger emissions, which in turn appear to stimulate adjacent PLR lines. Note the falling tone emission near t = 1 min 40 s, that echoes and turns on new PLR lines in a manner similar to the whistler at t = 40 s.

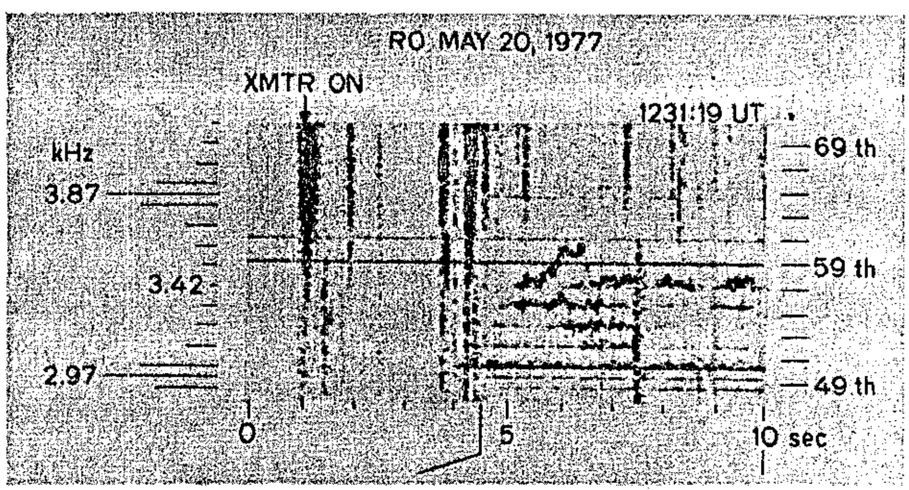

Fig. 6. A spectrogram from Roberval showing the results of a power line simulation experiment using the Siple transmitter. The numbers on the right indicate the harmonics of 60 Hz power frequency.

3. Transmitter Simulation of PLR Effects

Little is known about the amount of VLF power radiated into the magnetosphere by electrical transmission lines and how it varies with location and time. In an attempt to learn how much power is needed to produce the observed PLR effects, the Siple transmitter has been used to simulate PLR. Figure 6 shows an example of the simulation result. The horizontal bars on the left-hand side of the figure represent the relative amplitude of the Fourier components of the transmitted signal. The discrete frequencies are separated by 50 Hz and 100 Hz. Note that the magnetospheric output intensity observed at Roberval shows little relationship to input power. For example, the most active line at 3.42 kHz had the minimum transmitted power that was estimated to be ~ 0.5 W (Park and Chang, 1978). The intensity of the input wave entering the wave-particle interaction region in the equatorial magnetosphere is of the order $10^{-13}\,T$ (0.1 mγ). The spectrum of the output wave varies greatly with time scales of less than a minute.

Figure 7 shows another example in which a single constant frequency transmission from Siple produced several sidebands spaced about 20 Hz apart. Sidebands may appear in a great variety of spectral shapes; they may be symmetric or asymmetric about the carrier and may appear continuously, periodically or randomly in time. These results may explain the fact that PLR-induced line emissions often show fine structures with line spacings less than the fundamental power line frequency.

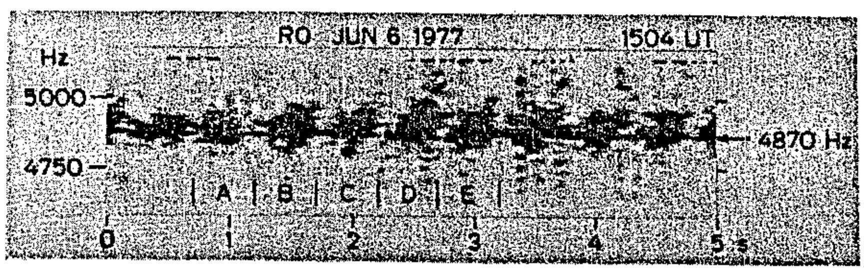

Fig. 7. A spectrogram from Roberval showing several sidebands generated by a key-down transmission from Siple at 4870 Hz.

4. Statistics of PLR Events

Figures 8–10 summarized the statistics of PLR effects observed at Siple and Eights (75° S, 77° N) in Antarctica. The distribution of PLR frequency in Figure 8 shows a pronounced peak near 3.5 kHz. In Figure 9 the local time variation of PLR occurrence has broad maximum between 5 and 15 hr. Figure 10 shows that the probability of observing PLR is reduced on Sundays when the power consumption is lower than the rest of the week.

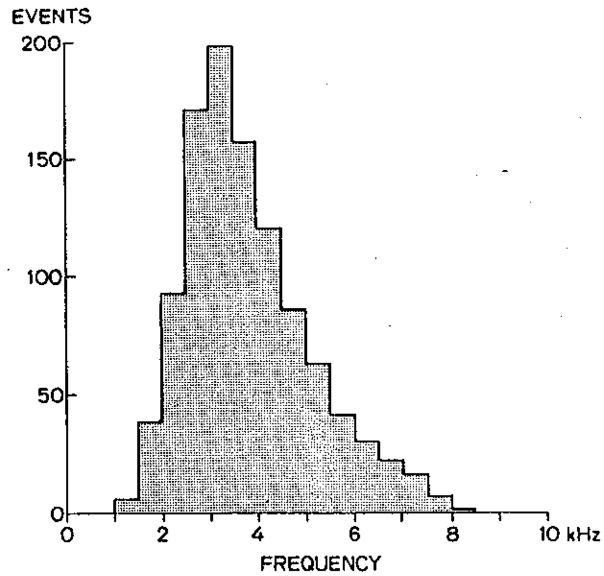

Fig. 8. Frequency distribution of PLR-induced magnetospheric VLF emissions observed at Siple and Eights, Antarctica (from Park and Helliwell, 1978).

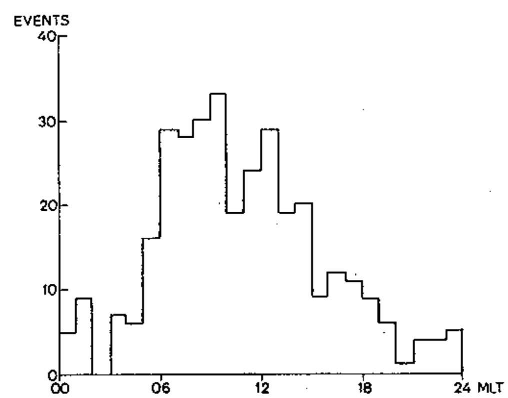

Fig. 9. Magnetic local time distribution of PLR-induced VLF wave events observed at Siple and Eights, Antarctica (from Park and Helliwell, 1978).

5. Discussion and Conclusion

The data presented here came from Eights and Siple Stations that are located in a region conjugate to eastern Canada and the United States. The combination of low local noise level and strong PLR sources in the conjugate region makes this part of Antarctica ideal for detecting magnetospheric PLR effects. Search for PLR effects should be extended to other longitudes and into space in order to obtain a global picture of PLR effects.

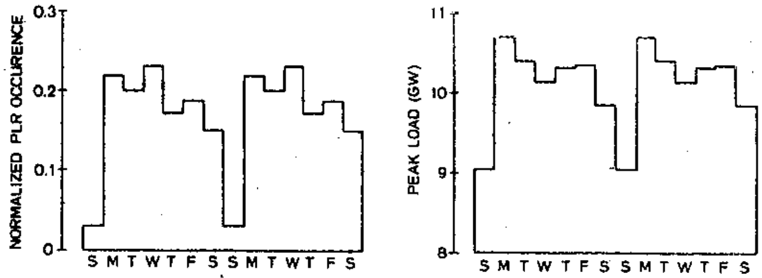

Fig. 10. The occurrence of PLR events at Simple and Eights as a fraction of the day of the week compared with variations of the peak electric load on Hydro Quebec, a major supplier of electricity in Quebec (from Park and Helliwell, 1978).

Little is known at present about the harmonic currents flowing in power grids and the radiation intensity in the VLF range. We need to understand the geographical distribution of PLR source intensity and its temporal variations.

Amplified PLR undoubtedly affects the trapped energetic electrons in the magnetosphere. If wave-particle interaction takes place through cyclotron resonance, as is generally believed, some of the interacting electrons would be scattered into the loss cone and be precipitated into the ionosphere. How important PLR effects are in ionospheric and magnetospheric dynamics has been a topic of recent discussion (Park and Helliwell, 1978; Thorne and Tsurutani, 1979). More systematic studies need to be conducted before this question can be answered quantitatively.

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