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THE CONTROL OF THE MAGNETOSPHERE BY POWER LINE RADIATION

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Abstract. Evidence is presented that radiated power line harmonics leak into high-altitude regions of the magnetosphere with sufficient intensity to control the starting frequencies of chorus emissions. OGO-3 data from three passes show that the starting frequencies of all measurable chorus emissions were within a few hertz of power line harmonics. It is also found that emissions detected over Western Europe were controlled by harmonics of 50 Hz; over the eastern United States and Canada by 60 Hz; and along the Alaska-New Zealand meridian by harmonics of both 50 and 60 Hz. These results indicate that man-made VLF noise plays an important role in the generation of chorus, one of the commonly observed forms of wave activity in the outer magnetosphere.

Introduction

Power line radiation (PLR) effects in the magnetosphere have been discussed in a number of papers since they were first reported by Helliwell et al. [1975]. Ground-based observations show that radiated power line harmonics (PLH) in the kilohertz range are greatly amplified and trigger emissions that can on occasion completely dominate very-low-frequency (VLF) wave activity in the magnetosphere [Helliwell et al., 1975; Park and Helliwell, 1977, 1978]. The trapped energetic particles in the magnetosphere supply energy for wave amplification and triggered emissions. Many of the resonant particles are scattered into the loss cone and subsequently injected into and absorbed by the ionosphere. PLR-induced waves are important not only because they enhance the VLF noise level, but also because they are thought to enhance the precipitation of energetic particles in the magnetosphere through wave-particle interactions.

A satellite survey by Bullough et al. [1976] showed a pronounced peak in VLF activity over North America, which the authors attributed in part to the power line effect. In another satellite survey, the present authors examined the geographical distribution of chorus activity detected by the OGO-3 satellite [Luette et al., 1977]. The results showed that chorus activity tends to be maximum in regions threaded by geomagnetic field lines that intersect industrialized areas. This was again attributed to PLR that leaked into the magnetosphere with sufficient intensity to trigger chorus emissions.

In our previous study mentioned above, broadband spectrograms were used to distinguish chorus from other forms of VLF wave activity. However, unlike PLR-induced emissions observed on the ground, the OGO-3 spectrograms did not show clear evidence of triggering by PLR. It was suggested that since OGO-3 observed chorus activity mainly outside the plasmapause where wave-growth rates are large (200-2000 dB/s), the observed chorus could have been triggered by weak PLR waves that were below the threshold of detection. One way to test this hypothesis is to measure the starting frequency of individual chorus emissions. If the emissions were in fact triggered by PLR, their starting frequencies should be closely related to PLH frequencies. By contrast, spontaneous emissions should have random starting frequencies. The present study was undertaken to determine if the OGO-3 data used in our previous study [Luette et al., 1977] show control of chorus starting frequencies by PLR.

Analysis

The starting frequencies of chorus emission were measured on photographic spectrograms of broadband VLF data. Figure 1 shows an example of chorus activity included in this study. Note that the emissions start from a relatively narrow frequency range near 500 Hz. Such clustering of starting frequencies in a narrow frequency band is characteristic of chorus observed on satellites as well as on the ground. Some emissions such as the two in the middle of Figure 1 have well-defined starting frequencies, while others are blurred.

The ubiquitous UA-6B/H analyzer was used to process the spectrograms for this study. All of the data were limited to the 0 to 2.5-kHz band; however, segments were further band-limited when the activity dropped below 1.0 kHz. Portions of the spectra were expanded when the emissions were confined to a bandwidth of a few hundred hertz. As noted, many of the emissions were blurred and could not be included in this study. The resolution of some emissions was in part limited by the uncertainty principle $(\Delta f \Delta t) \geq 2\pi$. This principle describes the expected frequency resolution (Δf) for a given period of observation (Δt). Ubiquitous filter bandwidths (Δf) of 1 and 2 Hz were used during spectrum analysis. These bandwidths proved satisfactory because df/dt of the initial portion of the emissions were usually small and resulted in well-defined starting frequencies. Based on these techniques, the estimated uncertainty of the measurements is no greater than ±2 Hz. This estimate is confirmed by the histograms of measured starting frequencies which show standard deviations as small as 3 Hz.

Data from three satellite passes were selected for the present study on the basis of an abundance of well-defined chorus elements and are believed to be representative of any OGO-3 pass containing chorus emissions. One pass was over North America where the fundamental power frequency is 60 Hz, and another was over Europe where the power systems use 50 Hz. The third pass was over the Pacific near field lines that terminate in Alaska and New Zealand. Alaska uses 60 Hz, while New Zealand uses 50 Hz. A 7X optical comparator was used to measure the starting frequency of about 600 chorus elements that were sufficiently well

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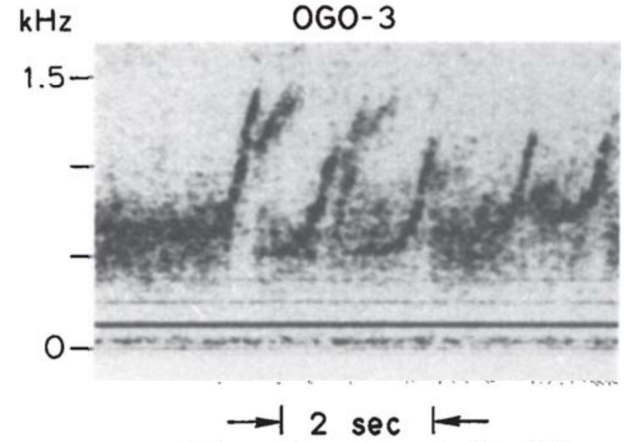

Fig. 1. Expanded portion of August 12, 1966, spectrogram showing two well-defined chorus emissions with 500-Hz starting frequencies. Constant-frequency lines at the bottom are instrumental and not PLR detected by the satellite. Strong chorus elements are seen to suppress the background through the AGC action of the receiver.

defined. This represents about 10 to 15% of all emissions observed during the three selected orbit periods. Figure 2 shows a 7X enlargement of the third emission from the left in Figure 1. The vertical frequency scale shows that the well-defined emissions can be measured to a high degree of accuracy. Accurate frequency calibration was provided by the spacecraft power converter frequency at 2461 Hz and the VLF receiver calibration signal at 1000 Hz. Doppler shift due to satellite motion is estimated to be less than 1 Hz in the frequency range of interest. For example, a Doppler shift of 0.52 Hz was calculated for a 550-Hz wave at $L = 7$ with a 70° wave normal with respect to the local static magnetic field. The satellite is assumed to be traveling 4 km/s and in opposite direction to the wave normal through a plasma density of 10 el/cm^3.

Results

The measured chorus starting frequencies are summarized in Figures 3, 4, and 5. In each figure the abscissa is the measured starting frequency minus the nearest integral multiple of 50 Hz or 60 Hz, depending on the satellite's location. The ordinate is the percentage of data samples that fall in each 5-Hz freqeuncy bin.

The data for Figure 3a were acquired March 23, 1967, from 0850 to 0950 UT while the satellite was passing over North America. The data were organized in multiples of 60 Hz, the predominant power line frequency in that sector. The measured frequencies range from 300 to 660 Hz, with about 65% falling within ±2 Hz of a 60-Hz harmonic. They favor odd harmonics over even harmonics by a ratio of about 4 to 1. For the 54 samples represented in this figure, all occurred within 12 Hz of a 60-Hz harmonic. There is one particularly active frequency at 540 Hz (the 9th harmonic of 60 Hz), with 44% of all measured starting frequencies falling within ±2 Hz of that frequency.

Figure 3b shows the data set acquired on October 10, 1966, from 1318 to 1358 UT when the satellite was in the European sector. Since most power systems in Europe operate at 50 Hz, the data are organized in terms of 50-Hz harmonics. A strong tendency for the starting frequencies to cluster around power line harmonics is clearly evident. The measured starting frequencies range from 300 to 1300 Hz and show no preference for odd or even harmonics.

The third data set shown in Figure 4 was acquired on August 12, 1966, from 2258 to 2330 UT when the satellite was in the Alaska-New Zealand sector. In this sector we have a mixture of 60-Hz power systems in Alaska and 50-Hz systems in New Zealand. Therefore the data were sorted in two different ways, according to deviation either from 60-Hz harmonics (Figure 4a) or from 50-Hz harmonics (Figure 4b). The results show a strong tendency for starting frequencies to cluster around harmonics of both 60 Hz and 50 Hz. However, unlike the previous two cases in Figure 3, there is a considerable spread in the data, which is to be expected from the presence of two sets of harmonics.

In Figure 5 we divided the same data in Figure 4 into two groups, depending on whether the measured starting frequency is closer to a multiple of 60 Hz or 50 Hz. The resulting histograms look similar to those in Figure 3.

A detailed study of the August 12, 1966, pass shows that the chorus starting frequencies were predominantly harmonics of 50 Hz near the beginning of the data sample, switched to a mixture of

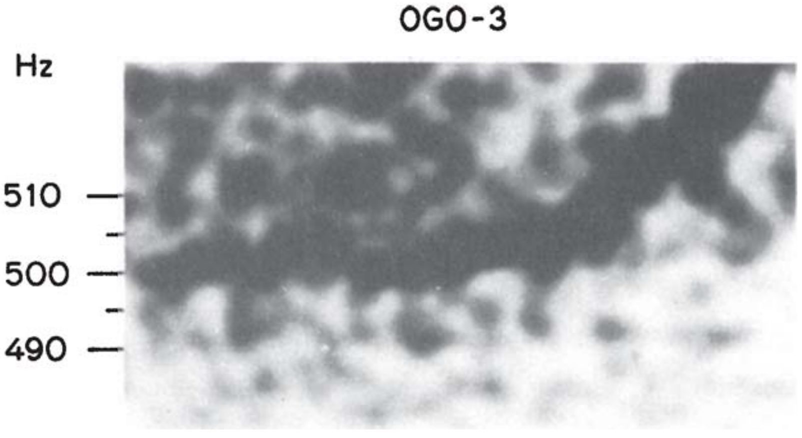

Fig. 2. A 7X enlargement of the third emission from the left in Figure 1.

both 50- and 60-Hz harmonics, and then finally become almost entirely 60-Hz harmonics toward the end of the data period. This is consistent with the satellite's orbit which first intercepted field lines connected to New Zealand and then later reached Alaska field lines at higher L values.

In Figures 3 and 5 there is a tendency for the histograms to be skewed to the high-frequency side. This can be explained as follows. Most chorus elements are rising tones whose amplitudes start from the background noise level and grow rapidly at typical rates of 200-2000 dB/s [Burtis and Helliwell, 1975]. Since the starting frequency is measurable at a point where the emission first becomes clearly detectable on the spectrogram, the measured starting frequency tends to be high.

Discussion

The results of the previous section clearly demonstrate that some of the chorus starting frequencies are closely controlled by power line harmonics. Does this mean that PLR stimulates emissions under conditions not conducive to the spontaneous emission generation? Or does PLR simply control the starting frequency of emissions that would have occurred even in the absence of PLR? We believe that PLR actually enhances the chorus activity level on the basis of an independent piece of evidence that the threshold of stimulated instability is significantly lower than that of spontaneous instability. The evidence is the observed fact that whistlers and transmitter signals can often stimulate strong emissions in an otherwise quiescent magnetosphere [e.g., Storey, 1953; Helliwell, 1965]. This is true even when the stimulating waves are too weak to be detectable on normal spectrographic records. Chorus in the 2- to 4-kHz band observed at Siple, Antarctica, shows a pronounced low level of activity on Sunday which corresponds to the weekly minimum in power production and consumption near the magnetic conjugate [Park and Miller, 1979]. While chorus emissions were clearly visible on the spectrograms, the triggering PLH could not always be found. An important question that needs to be investigated is whether and under what conditions the magnetosphere reaches the threshold of instability in the presence of continuous leakage of PLR from below.

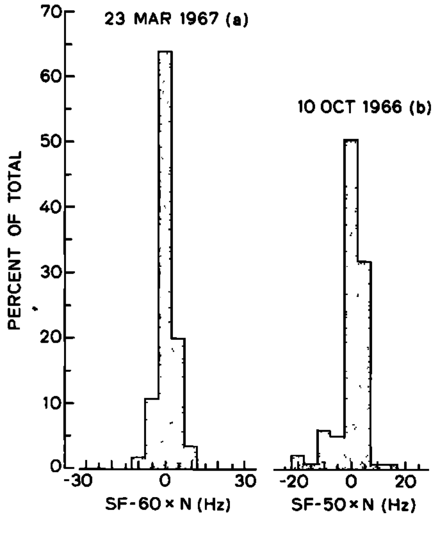

Fig. 3. Measured starting frequencies, OGO-3: (a) March 23, 1967; time interval 0830-1000 UT; trajectory: altitude 8.1 to 5.5 R_E, dipole latitude -2° to -10°, dipole longitude 27° to 15°. Magnetic activity Kp = 0, Kpm = 1; 55 samples. (b) October 10, 1966; time interval 1318-1358 UT; trajectory: altitude 3.9 to 2.1 R_E; dipole longitude 138° to 158°. Magnetic activity Kp = 0, Kpm = 3; 133 samples.

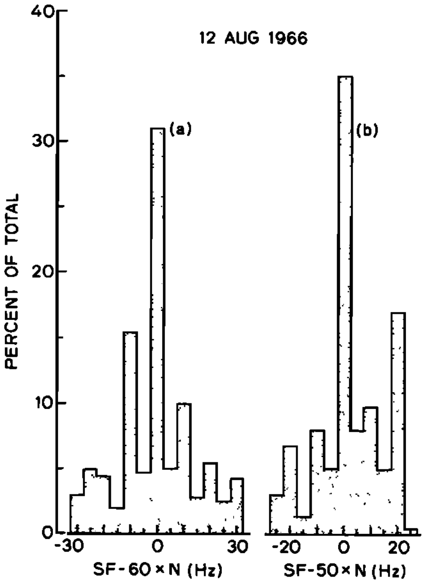

Fig. 4. Measured starting frequencies OGO-3: August 12, 1966; time interval 2258-2330 UT; trajectory: altitude 2.7 to 4.0 R_E; dipole latitude 31° to 36°; dipole longitude 270° to 283°. Magnetic activity Kp = 2; Kpm = 4; 370 samples. Samples correlated with harmonics of (a) 60 Hz and (b) 50 Hz.

Although only 10 to 15% of the emissions were sufficiently well-defined to be measured, all chorus elements display the same general behavior. We suggest that the remaining 85-90% of the emissions were not spontaneously generated because the earlier study [Luette et al., 1977] showed that the occurrence of chorus was correlated with industrialized activity. A high percentage of spontaneous emissions would have masked any dependence of chorus activity on geographic areas.

The spectrograms of OGO-3 data used in this study show no clear evidence of the stimulating power line radiation, even when strong emissions are triggered at power line harmonic frequencies. This is attributed to the limited sensitivity of the broadband receiver, a common problem with such systems flown on satellites. With the receiver connected to the magnetic loop antenna (26.4 m^2 area), which was the normal mode of operation, the maximum sensitivity ranged from 30 mγ at 300 Hz to 30 μγ at 12.5 kHz. This sensitivity is not sufficient to detect PLR under normal circumstances. Also, the absolute sensitivity of the broadband receiver was modulated by a log-compression circuit which functioned as a fast automatic gain control (AGC). During periods of low wave activity which usually occurred at large L values the receiver operated at maximum sensitivity. However, as the wave intensity increased

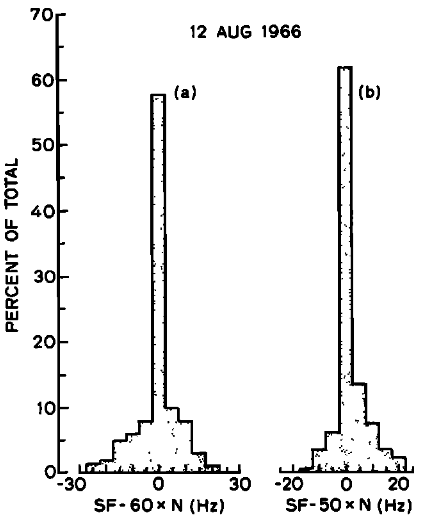

Fig. 5. Divided data set (see text) correlated with multiples of (a) 60 Hz and (b) 50 Hz.

the sensitivity was reduced and controlled by the strongest signal in the passband of the receiver. At all altitudes PLR had to compete with the more intense chorus, hiss, and whistlers. Data from the more sensitive OGO-3 digital sweeping receivers, which did not incorporate an AGC, showed that PLR intensities for frequencies below 1500 Hz at an altitude of 4-5 R_E were of the order of 0.3 mγ. This level is below the threshold of the broadband receiver.

The OGO-3 digital receiver results can be checked by examining data taken with the same type of receiver on the low-altitude (400-900 km) OGO-4 satellite. The PLR intensities should be stronger at the lower altitude. A preliminary survey of these data shows that PLR intensities of 1 to 10 mγ have been observed. Figure 6 shows an example of PLR data from an OGO-4 pass over South America. The signal amplitude in units of decibels below 1 γ is plotted against frequency. The spectral peaks, spaced 100 Hz apart and 20-30 dB above the background noise level, show harmonic radiation from the 50-Hz power systems in South America. A global survey of PLR intensities using OGO-4 is now underway, and the results will be reported separately.

The PLR intensities shown in Figure 6 are below the threshold of detection of the broadband receiver system on the same satellite. Only a few strong peaks that exceed -50 dB γ are barely discernable on a broadband spectrogram. There is an obvious need for improved broadband systems for future satellite studies of PLR phenomena.

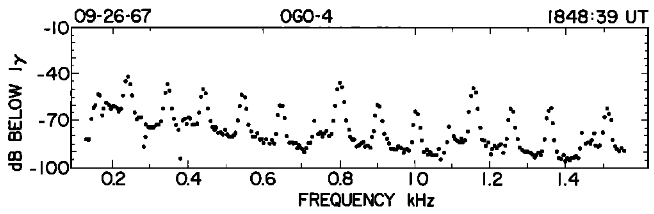

Fig. 6. Spectrum of 50-Hz PLR measured by OGO-4 sweeping receiver. Lines 1-5 and 9-11 are odd harmonics, while lines 6-8 are even harmonics. The last line is a whistler and was not present on successive frames. Satellite's location: altitude 500 km; dipole latitude 4°; dipole longitude 338°.

Conclusions

This study has shown that the starting frequency of some chorus emissions is strongly correlated wit harmonics of power line frequencies. We interpret this evidence to mean that power line radiation leaks into the magnetosphere where it stimulates the generation of VLF chorus. Since chorus is one of the most commonly observed electromagnetic waves in the magnetosphere, we conclude that power line radiation has significant effects on the wave intensity level in the magnetosphere, which in turn affects the orbits and lifetimes of trapped energetic particles through wave-particle interactions.

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