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Probing properties of the magnetospheric hot plasma distribution by whistler mode wave injection at multiple frequencies: Evidence of spatial as well as temporal wave growth

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Abstract. This is the second of two papers on the use of whistler mode wave injection to investigate properties of the magnetospheric hot plasma. Paper 1, [*Sonwalkar et al.*, this issue] emphasized the use of signals at a single frequency to identify longitudinal structures ranging from 100 to 25,000 km in extent in ~1-10 keV electrons drifting azimuthally through whistler ducts. This short paper discusses and illustrates the use of wave injection at multiple discrete frequencies to study temporal changes in magnetospheric hot electrons with parallel (gyroresonant) velocities in various nonoverlapping ranges. As in paper 1, the data studied were acquired during a special 9-hour period of 1.9 - 2.9 kHz VLF transmissions from Siple Station, Antarctica, to Lake Mistissini, Canada, on January 23-24, 1988. The amplitudes of the leading edges of constant frequency pulses at 1900, 2150, and 2400 Hz were found to vary independently with time. This is interpreted as evidence of a spatial amplification process that accompanied the well known and more readily identifiable phenomena of exponential temporal growth to a saturation level. Evidence of wave-hot plasma interactions showed a dependence on df/dt of the input signal frequency versus time format; in general, the slow frequency ramps showed the highest amplitudes and the fast ramps and parabolas the lowest, in agreement with past work.

1. Introduction

This and a companion paper by *Sonwalkar et al.* [this issue] (hereinafter referred to as paper 1) discuss the use of whistler mode wave injection as a means of studying otherwise unobservable properties of the magnetospheric hot plasma. Paper 1 shows how information on longitudinal structure in the ~1-10 keV electrons may be obtained from signal reception at a single frequency (2400 Hz), while the present paper considers additional information that is obtainable from measurements at multiple frequencies.

As in paper 1, the data studied were acquired during a special 9-hour period of transmissions from Siple Station, Antarctica, to Lake Mistissini, Canada. A special 1-min-long signal format centered at 2400 Hz was transmitted every 5 min. Readers are referred to paper 1 for a description of the experimental setup, transmission format, overall features of the data, and results on the passive propagation conditions prevailing. These last included identification of a principal propagation path of field-aligned duct in the outer plasmasphere at L=5.1, with equatorial density 276 electrons/cm^3.

Gyroresonance wave-particle interactions have long been considered to be the underlying mechanism for the coherent wave instability (CWI) [see *Carlson*, 1987, and references therein], which is believed to be responsible for nonlinear and quasi-coherent interaction between whistler mode signals and energetic electrons [*Helliwell*, 1988]. The CWI is highly selective in frequency; it has been demonstrated experimentally that the outcomes of wave-particle interactions involving a particular signal can be strongly influenced by the presence of another signal within 100 Hz. In contrast, signals separated in frequency by more than about 100 Hz behave independently wih respect to wave-particle interactions [*Helliwell et al.*, 1986] and can therefore be used to probe different regimes of the electron distribution function. In this paper we investigate experimentally how the wave particle interaction parameters depended on wave frequency and investigate the temporal variations of these parameters at several different transmitted frequencies.

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In our case study the magnetospheric responses to injected waves at frequencies separated by 250 Hz were uncorrelated, thus supporting our expectation that signals at different frequencies are responsive to different parts of the electron distribution function.

2. General Features

Figure 1a shows a spectrogram of three 200-ms pulses at 2400, 2150, and 1900 Hz that were used to study the frequency dependence of the wave-particle interaction parameters. This staircase of three pulses was transmitted once every 5 min as part of the special 1-min diagnostic format (see Figure 3 in paper 1). The descending tone near the trailing edges of the pulses was not transmitted but was in fact a falling emission initially triggered by the 2400 Hz pulse and then either entrained or retriggered by the 2150-Hz pulse. The falling tones near t=2 and t=3 s were transmitted as linear frequency ramps from 2.9 to 1.9 kHz, the first at full power and the second at -6 dB. Note near t=2 s the continuation of the ramp below 1.9 kHz as a falling tone emission. The dark horizontal lines on the record represent interference from the local power grid at the Lake Mistissini receiving site. Amplitude charts such as those shown in Figure 1b were used to measure the initial levels and growth rates at the three frequencies.

3. Normalization of the Input Power to a Magnetospheric Path

In order to evaluate the magnetospheric response to wave injection as a function of frequency it is necessary to rescale or normalize the levels of the received signals

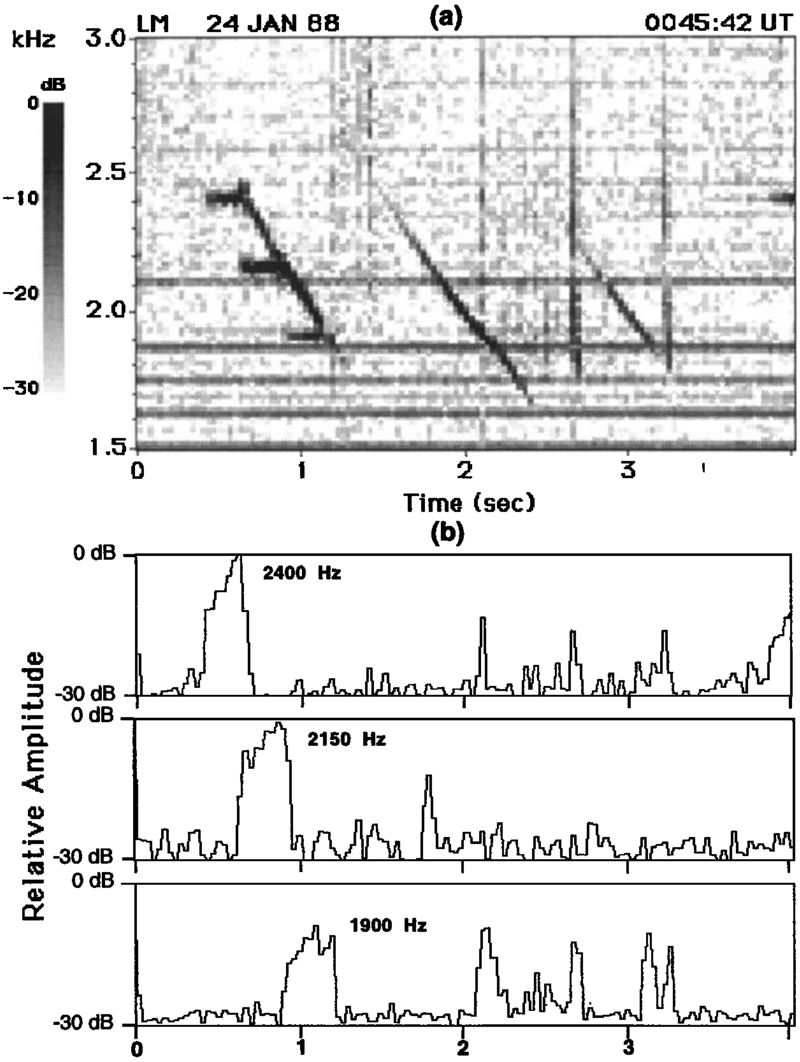

Figure 1. (a) Spectrogram from Lake Mistissini, Canada, illustrating the reception of 200-ms pulses transmitted from Siple, Antarctica, at 2400, 2150, and 1900 Hz. The pulses were used to study the frequency dependence of wave-particle interaction parameters during a 9-hour period on January 23-24, 1988. The descending tone at the trailing edges of the pulses was actually a triggered emission. The descending tones near t = 2 s and 3 s were transmitted as linear freqency ramps at 0 dB and -6 dB, respectively. The first of these was one of the signals used to study the effects of df/dt on wave growth. The horizontal lines represent interference from the power grid near the receiving station. (b) Charts showing amplitude versus time at the three pulse freqencies. These were used to measure pulse initial levels and growth rates.

so as to account for variations with frequency in the amplitude of signals coupled into the magnetospheric duct. These variation occurred principally because (1) the transmitter/antenna system was tuned to resonate at a center frequency (in this case 2400 Hz), and (2) the antenna radiation efficiency over ice was a function of frequency [*Raghuram et al.*, 1974].

The Siple antennas were crossed NS and EW horizontal dipoles capable of phased excitation so as to achieve arbitrary polarization in the upward direction. For the 200-ms pulses of interest and most other elements of the 1-min format, right-hand (RH) circular polarization was used for most efficient coupling into the whistler mode in the overhead ionosphere.

The following points were considered in estimating the factors by which the received signals should be normalized.

1. Estimate the power input to the antenna in the RH mode. Input real powers P_{EW} and P_{NS} to the EW and NS antennas, respectively, were measured at the site at 1900, 2400, and 2900 Hz. Small differences in the P_{EW} and P_{NS} were such that a small amount of power was input in the left-hand (LH) or nonpropagating mode (assuming upward propagation). Figure 2 shows the input power results for RH (solid circles) and for LH (solid squares) polarizations.

2. Estimate the power radiated from the antenna in the right hand mode. The radiation efficiency of the 42-km-long antennas as a function of frequency was calculated using the results of *Raghuram et al.* [1974], values at the key frequencies of 1.9, 2.15, and 2.4 kHz being 0.19%, 0.39%, and 0.59%, respectively. Figure 2 shows by open circles and open squares the radiated power for RH and LH polarizations, respectively.

Other factors that play a role in determining the power that couples into a duct at different frequencies are the ionospheric reflection and absorption losses and the coupling of energy into the duct at the duct entrance altitude, assumed to be located at ~1000-2000 km [*Bernhardt and Park*, 1977]. Because the duct of interest (at L=5.1) was located poleward of Siple by of order 300 km, the RH polarized transmitted wave would be expected to experience some reflection loss because of the obliquity of the angle of incidence on the ionosphere. However, we have assumed this reflection loss to be roughly the same for each of the frequencies of interest. A small amount of power from the radiated left-hand mode signals can couple to the right-hand mode when the left-hand signal impinges on the Earth-ionosphere boundary at an oblique angle [*Mielke et al.*, 1992]. In our case, this contribution to the right-hand signal power was small and can be neglected (see Figure 2).

The ionospheric absorption losses at $L = 5.1$ for signals at 1900, 2150, and 2400 Hz during the noon to dusk observation period are estimated to be the same within 1 or 2 dB [*Helliwell*, 1965; *Scarabucci*, 1970]. The coupling of energy into the duct can also be expected to be the same for signals at the three frequencies, because this coupling, determined by propagation factors, should not be strongly dependent on frequency as long as the duct is several wavelengths wide at each of the frequencies of interest. This latter condition should be easily satisfied, since duct width at 1000 km is believed to be a few tens of kilometers [*Angerami*, 1970], whereas the whistler mode wave length at 2 kHz is a few kilometers [*Helliwell*, 1965].

4. Observations

Figure 3 shows examples of the 200-ms pulses and following frequency ramps received at 15-min intervals during the 0015-0130 UT period of greatest multifrequency activity. Changes with time in the frequency response of the magnetosphere are qualitatively indicated by the pulse intensities (not normalized) as well as by changes in the occurrence of falling tones triggered by the pulses. In the first and fourth panels such tones

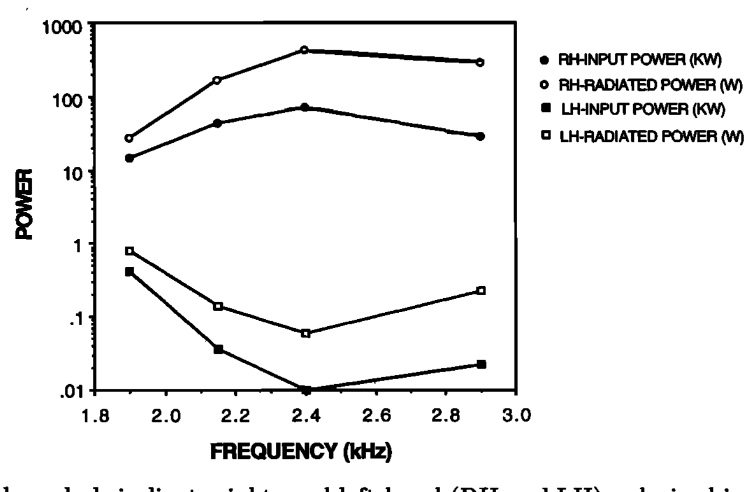

Figure 2. Solid symbols indicate right- and left-hand (RH and LH) polarized input power to the Siple antennas as a function of frequency between 1.9 and 2.9 kHz during the 9-hour transmission period, based upon measurements of real power to the two crossed 42-km horizontal antennas. Input power is shown in kilowatts. Open symbols show estimated RH and LH radiated power in watts, based upon calculations by *Raghuram et al.* [1974].

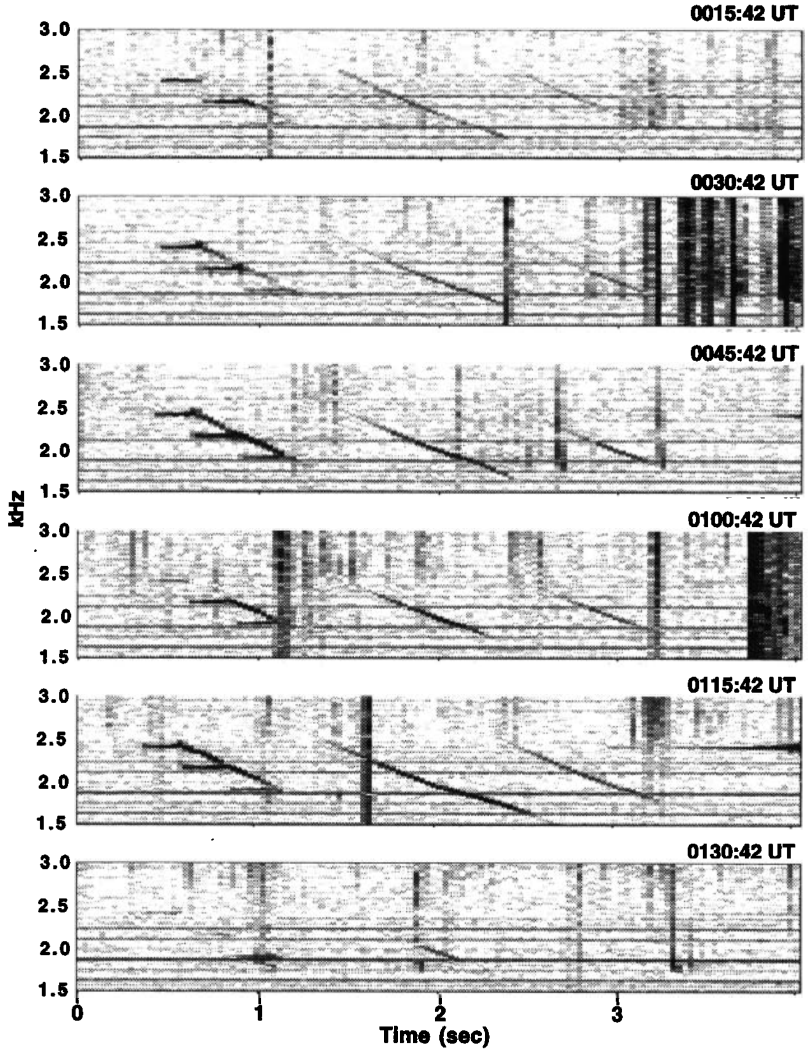

Figure 3. Spectrograms similar to that of Figure 1a showing variations with time in the magnetospheric response to signals injected at 2400, 2150, and 1900 Hz on January 24, 1988.

were not triggered by the first (2400 Hz) pulse, while in the sixth panel neither the first nor the second pulse triggered an emission.

Figure 4 shows the occurrence of 200-ms pulses at the three frequencies as detected from inspection of spectrographic records for the entire 9-hour 1700-0210 UT period. A zero means that a pulse was transmitted but could not be visually identified. Because a response at all three staircase frequencies was detectable during most recordings in the 0000-0200 period, that subinterval was used for detailed measurements of pulse amplitude profiles such as those shown in Figure 1b.

Figure 5 shows the initial or leading edge amplitudes and the growth rates for the 200-ms pulses at the three frequencies during the interval 0015–0210 UT. The amplitudes have been normalized to the same radiated power (27.8 W). In most of the 1-min recordings the initial signal level increased with decreasing frequency, whereas the growth rate tended to decrease. (Note in Figure 5 and other similar figures that signals were transmitted throughout the period indicated. In the case of amplitude measurements, a zero implies that any signal present was below the noise level of the record, which in most cases was a few decibels. In the case of growth rate, a zero implies that the measurement could not be made.)

In paper 1, no correlation was found between the initial level of a 2-s pulse at 2400 Hz and its growth rate. Inspection of the trends for the 200-ms pulses in Figure 5 reveals a similar lack of correlation at all three of the staircase frequencies. This is also illustrated by the scatterplot of Figure 6. Both the leading edge amplitudes and growth rates showed variations on a 5-15 min timescale (Figure 5). However, the temporal variations among the three frequencies during the 0000-0210 UT period of detailed study were not correlated. For example, as shown in Figure 5a, while the leading edge amplitude of the 1900 Hz pulse remained between 15 and 20 dB in most cases, the leading edge amplitude of the pulse at 2400 Hz varied between 2 and 15 dB. The

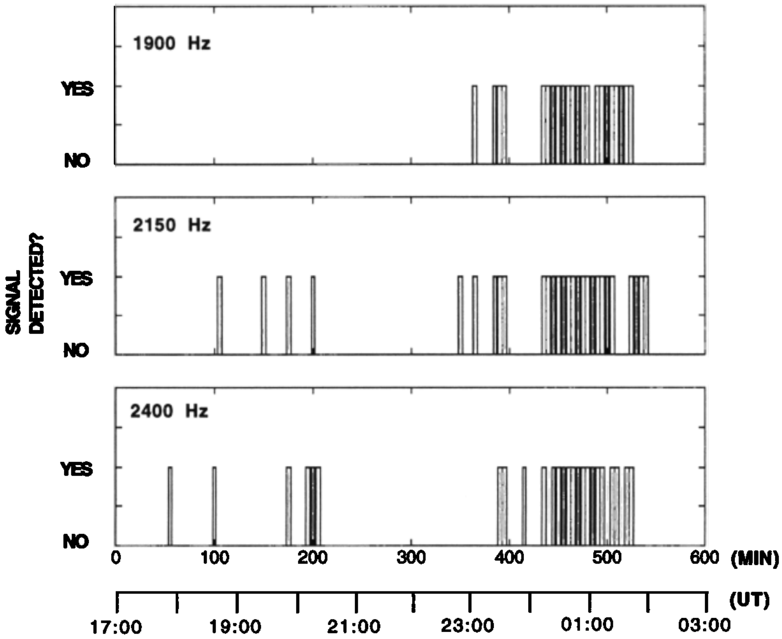

Figure 4. Histogram showing the times of detection of pulses (signal 6) at 1900, 2150, and 2400 Hz during the 9-hour transmission period on January 23-24, 1988. The staircase of pulses was transmitted once every 5 min during that period.

scatterplot of Figure 7a show the lack of correlation between initial levels at 2150 and 2400 Hz and those at 1900 Hz.

The lack of correlation between growth rates at the various frequencies indicated in Figure 5, also illustrated by the scatterplot of Figure 7b, is not surprising, because particles with nonoverlapping $V_{\parallel}$ values are expected to interact with different frequencies. However, it is interesting that the initial levels also showed no correlation; if it is assumed that the initial edges of the

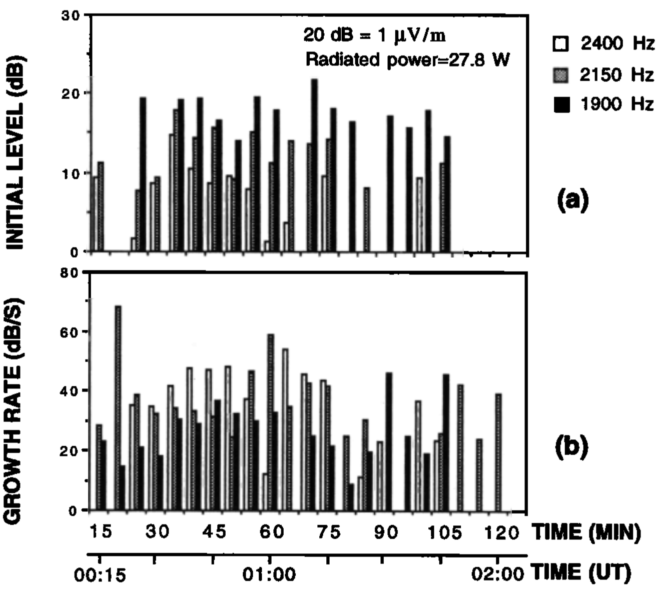

Figure 5. Histograms comparing the (a) initial received levels (in decibels) and (b) the growth rates (in decibels per second) of the 200-ms pulses (signal 6) at 2400, 2150, and 1900 Hz during the active period 0015-0200 UT on January 24, 1988. The initial levels were normalized to the same radiated power (27.8 W) so as to account for differences in radiated power with frequency.

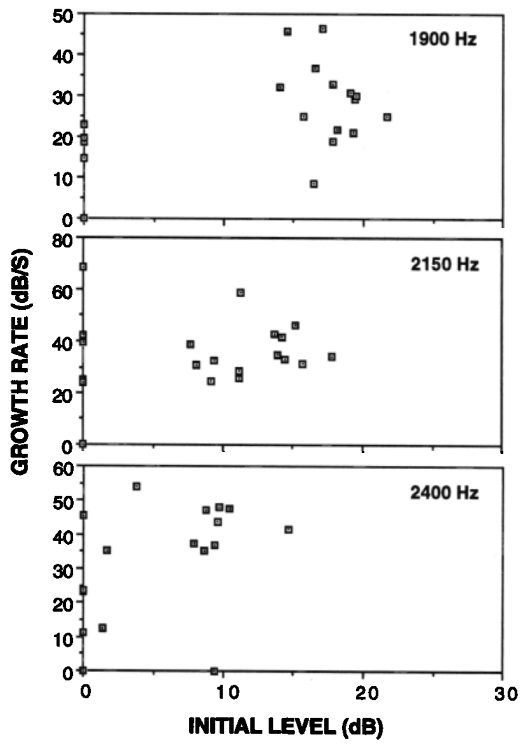

Figure 6. Plots of measured growth rate in decibels per second versus initial level in decibels for the three 200-ms pulses (signal 6) at 1900, 2150, and 2400 Hz during the period 0000-0210 UT, showing a lack of correlation.

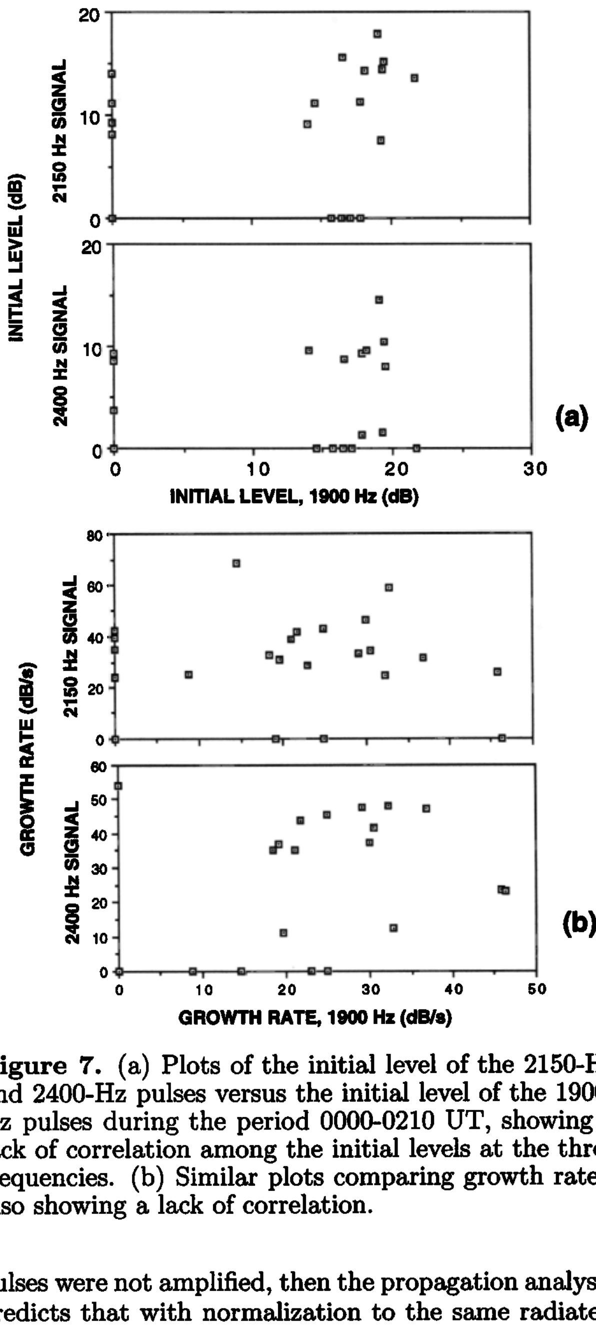

Figure 7. (a) Plots of the initial level of the 2150-Hz and 2400-Hz pulses versus the initial level of the 1900-Hz pulses during the period 0000-0210 UT, showing a lack of correlation among the initial levels at the three frequencies. (b) Similar plots comparing growth rates, also showing a lack of correlation.

pulses were not amplified, then the propagation analysis predicts that with normalization to the same radiated power, the initial levels at the three frequencies should have remained within 1-2 dB of each other.

We can eliminate the possibility that ionospheric losses changed during the 200-ms period between pulses at the different staircase frequencies. A doublet signal, composed of simultaneous 4-s-long 2140- and 2160-Hz pulses, was transmitted $\sim$ 4 s after the 2150-Hz 200-ms pulse, and at the same power level. It exhibited the same initial amplitude within 1-2 dB as that of the 200-ms pulse at 2150 Hz. This result, illustrated in Figure 8, and our finding that, as expected, the doublet signal did not show evidence of temporal growth, implies that the entire doublet signal underwent spatial amplification comparable to that experienced by the leading edge of the 2150-Hz 200-ms pulse. The underlying process must have been linear, because the doublet signal showed no distortion in the time domain, and no new frequencies were generated.

A brief comparison was made of the effect of varying the slope of the input signal frequency format on the wave-particle interaction parameters. Previous work has shown a dependence of those parameters on df/dt [*Carlson et al.*, 1985]. Figure 9 shows the peak amplitudes reached at 2150 and 2400 Hz in a 100-Hz band for four different signals: (1) 200-ms pulses ($df/dt = 0$ Hz/s), (2) slow ramp (signal 4, $df/dt = -92.5$ Hz/s), (3) fast ramp ($df/dt = -1$ kHz/s) , and (4) parabolic transmissions ($df/dt \sim 2$ kHz/s). In general the slow ramps showed the highest amplitudes and the parabolas the lowest. *Helliwell* [1970] and *Carlson et al.* [1985] have suggested that the df/dt dependence of wave-particle interactions may be interpreted in terms of an off-equatorial position of the interaction region. It is, however, difficult to interpret the data on the varying df/dt cases because the signal durations were different in each case and transmitter power varied with frequency.

5. Concluding Remarks

A study has been made of variations with frequency in the magnetospheric response to waves injeced from Siple Station, Antarctica, during a special 9-hour period on January 23-24, 1988. The 1000-Hz-wide transmission format, centered at 2400 Hz, included 200 ms pulses at 1900, 2150, 2400, 2650, and 2900 Hz, but as reported in paper 1, a cutoff occurred near 2500 Hz such that only the lower three pulse frequencies were detectable (this cutoff was attributed to a lack of electrons with the appropriate parallel velocities for resonance with the 2500-2900 Hz waves).

The magnetospheric responses at the three observed frequencies were compared both in terms of changes with time and in terms of absolute amplitude. Estimates of the latter required rescaling observed amplitudes to account for differences with frequency in radiated power.

The growth rates of the 200-ms pulses at 1900, 2150, and 2400 Hz were found to be uncorrelated, implying that the different frequencies interacted with different portions of the particle distribution function and there-

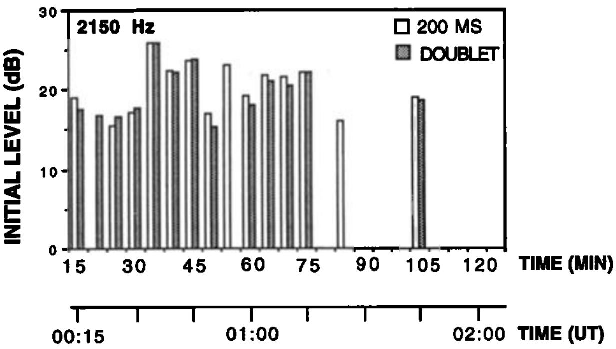

Figure 8. Comparison of the initial amplitude of the 200-ms pulse at 2150 Hz and that of a frequency doublet beginning about 5 s later on January 24, 1988. The doublet consisted of constant frequency tones at 2140 and 2160 Hz and was transmitted at essentially the same total power level used for the 2150-Hz pulse.

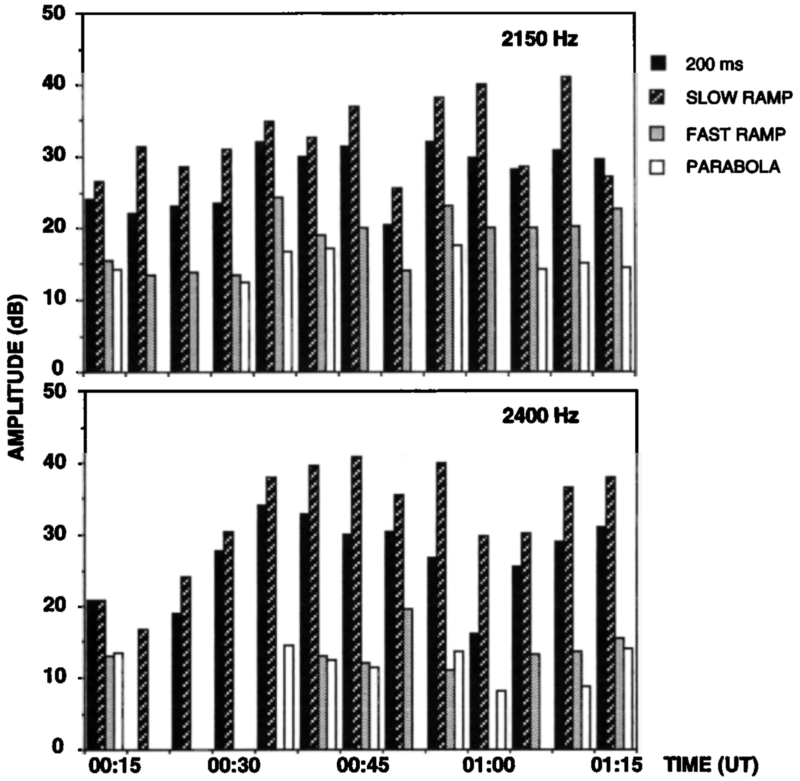

Figure 9. Histograms comparing the peak amplitudes at 2150 and 2400 Hz of Siple transmitter signals with various frequency-time slopes. See text for details.

fore, as expected, could be used to study variations in the particle distribution function with energy and/or pitch angle. Figure 10 is a diagram of different regimes of electron parameters that are expected to resonate with different frequencies. Since the interaction bandwidth has been found to be about 100 Hz [*Helliwell et al.*, 1986], signals separated by 250 Hz may be expected to interact with essentially nonoverlapping ranges of $V_{\|}$.

Most of the detectable 200-ms pulses at 1900, 2150, and 2400 Hz were observed during the same 2-hour period when the strongest signals at the transmitter center frequency, 2400 Hz, were observed, as reported in paper 1. However, during the subinterval 0000-0210 UT, both the leading edge amplitudes and growth rates of the pulses showed variations on a 5-15 min timescale, and the temporal variations of signals at the three frequencies were not correlated. This finding, taken together with results from paper 1, indicates that the hot plasma was amplifying the initial edge as well as the main body of each signal element and hence that nontemporal as well as temporal amplification was important. Interpreted as such, both types of amplification peaked within the same 2-hour period, but within that period were uncorrelated on 5-15 min timescales, as indicated by lack of correlation of the initial edges and growth rates. Nontemporal amplification, assumed to be spatial in nature, appears to have been identified for the first time in Siple transmitter data. It should be accessible for further study both in past data and by future probing experiments.

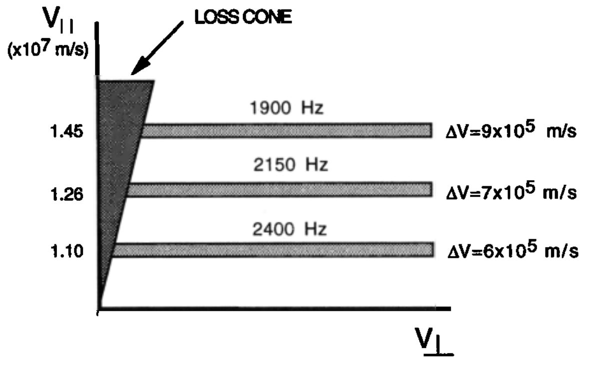

Figure 10. Diagram showing the different regimes in electron velocity space to which the Siple pulses at 1900, 2150, and 2400 Hz were sensitive through gyroresonant interactions.

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