JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 95, NO. A1, PAGES 225–231, JANUARY 1, 1990

Whistler Precursors on a VLF Transmitter Signal

E. W. PASCHAL

STAR Laboratory, Stanford University, Stanford, California

Whistler precursors are discrete emissions which are occasionally seen just before two-hop whistlers. Most theories of precursors assume they are triggered emissions and focus on creating a triggering signal with the proper time delay from the causative sferic. Whistler precursors have now been seen on a signal from the Siple VLF transmitter. Phase analysis shows that these precursors are caused by a rapid increase in growth activity, and not by a triggering signal.

1. INTRODUCTION

Whistler precursors are discrete emissions, usually rising tones, that are observed to precede two-hop whistlers echoes [*Helliwell*, 1965; *Laaspere and Wang*, 1968]. The group delays of echoing precursors are the same as those of their associated whistlers, implying that they propagate in the same magnetospheric ducts. The whistler nose frequency f_n or frequency of minimum dispersion is determined by the magnetic latitude of the path and is given in terms of the equatorial electron gyrofrequency as $f_n = 0.37 f_{Heq}$. The initial frequencies of precursors, typically 2–4 kHz, fall in the range $0.04\text{–}0.20 f_{Heq}$ [*Dowden*, 1972, Figure 2]; that is, at or below half the whistler nose frequency. Precursors are delayed from the causative sferic by just a bit more (0.1–0.3 s [*Park and Helliwell*, 1977]) than the one-hop whistler delay at their initial frequency; that is, they start a bit later than halfway between the sferic and the returning two-hop echo. The intensity of the precursor may exceed that of the associated two-hop whistler [*Laaspere and Wang*, 1968].

Precursors are generally assumed to be triggered emissions created by the same lightning strokes that cause the whistlers. They show amplitude growth and frequency behavior similar to other types of triggered emissions. However, their triggering mechanism has not been satisfactorily explained. Ordinary triggered emissions are believed to be caused by cyclotron resonance between waves and energetic electrons at the top of a duct near the equatorial plane [*Helliwell*, 1967]. In this interaction, an external triggering signal phase-bunches electrons traveling in the opposite direction along the field line; these electrons then radiate, creating an emission which travels in the same direction as the triggering wave. The difficulty with precursors as triggered emissions is that the triggering whistler, on its first pass through the magnetosphere, must somehow create an emission moving in the opposite direction in order for the precursor to arrive back at the receiver before the two-hop whistler echo.

Helliwell [1965] and *Dowden* [1972] proposed that precursors are emissions triggered by hybrid whistlers. A hybrid whistler is one which propagates subionospherically from the site of a lightning stroke to the opposite hemisphere before entering a magnetospheric duct and returning. The difficulty with this model is that hybrid whistlers are only rarely observed. And as far as I know, the only published example of a hybrid whistler associated with a precursor is that given by *Rietveld* [1980, Figure 3].

Molchanov and Chmyrev [1970] proposed that a strong whistler is scattered through a nonlinear interaction with a low-frequency ion-acoustic wave to generate a backward moving whistler mode wave. They claimed that the backward moving wave is seen on the ground as the precursor itself. *Reeve and Boswell* [1976] proposed a similar model where a strong whistler decays parametrically into a backward moving whistler mode wave and an ion-acoustic wave. The backward moving whistler mode wave then triggers the precursor. *Reeve and Boswell* [1976] explained that the backward moving wave is never seen because it may be very narrowband and indistinguishable from the precursor it triggers. The scattering or decay in these models is not instantaneous but grows over an interval of, say, 100 ms at a given frequency and is plausible only at the low-frequency tail where the whistler is well dispersed.

Reeve and Rycroft [1976] postulated that an unducted whistler is magnetospherically reflected at the end of its first hop and enters a duct midway through its second hop to trigger a precursor, slightly ahead of the two-hop ducted whistler. This process seems to require a combination of particular conditions, and its overall probability is unknown.

Park and Helliwell [1977] presented *f-t* spectrograms purporting to show that precursors observed in North America start at frequencies which are multiples of 60 Hz. They argued that this is evidence of the effects of power line harmonics (putative signals at harmonics of the power line frequency radiated by the power grid). They proposed a model in which the outgoing whistler undergoes longitudinal resonance with costreaming energetic electrons and perturbs the electron energy distribution. This perturbed distribution then amplifies, through cyclotron resonance, a power line harmonic moving in the opposite direction. The amplified power line harmonic triggers an emission which arrives before the two-hop whistler echo. *Tkalcevic* [1982] studied the details of the longitudinal interaction, and supported the plausibility of this model.

Rietveld [1980] studied a particular narrowband type of precursor he called a "monochromatic precursor start," as observed in New Zealand. This is a single-frequency signal which lasts for up to 200 ms and may then trigger the rising emission of typical precursors. He used phase analysis to show, unlike *Park and Helliwell* [1977], that the frequencies of these signals are not related in any statistical way to harmonic frequencies of the power grid, either multiples of 50 or 60 Hz. (Phase analysis involves using the phase of spectral components as well as their magnitudes, and is more

Paper number 89JA01209.
0148-0227/90/89JA-01209$02.00

accurate than *f-t* spectrograms for measuring instantaneous frequency. *Rietveld* [1980] used the "phasogram" technique of *Dowden et al.* [1978].) He proposed that a monochromatic precursor may be an emission, perhaps triggered by a hybrid whistler, which becomes entrained by a power line harmonic (hence the monochromatic aspect) but is offset from it by up to 100 Hz as other emissions sometimes appear to be offset from their triggering signals.

The purpose of this paper is to present examples of a new type of whistler precursor and interpret them in the light of existing theory. The VLF transmitter at Siple Station, Antarctica, has been used for a number of years as a controlled source of whistler mode signals to study various aspects of magnetospheric propagation, particularly wave growth and wave-particle interactions. In the records presented here, Siple was sending two-tone signals to a receiver at the conjugate point in Roberval, Quebec. The two-tone transmission format tends to suppress cyclotron-resonance growth, and the phase-stable signals received in Roberval were used to monitor slow changes in path phase delay associated with hydromagnetic waves [*Andrews,* 1977; E. W. Paschal et al., Correlation of whistler mode phase delay with transient hydromagnetic waves, submitted to *Journal of Geophysical Research,* 1989]. The 11-min transmission occurred during a time of strong two-hop whistler activity. Many of the whistlers were preceded by brief perturbations in the amplitude and phase of the transmitted signal. The unexpected occurrence of whistler precursors on a transmitted signal and the availability of phase analysis have provided a chance to apply new experimental methods to the precursor problem.

2. OBSERVATIONS

Figures 1, 2, and 3 show portions of a transmission from the VLF transmitter at Siple Station as recorded at Roberval. The transmission is the two-tone LICO1 (line coupling, version 1) format, a continuous signal containing two equal-amplitude components at 3950 and 3980 Hz. The upper half of each figure shows an *f-t* spectrogram, and the lower half shows a gray-scale phase plot of the same recording over a restricted frequency range including the LICO1 signal. The phase plot shows both the magnitude and phase of the outputs of successive analysis filters. Trace width is proportional to signal magnitude, and trace deflection is proportional to relative phase (phase with respect to an oscillator at the center frequency of the filter), one revolution full-scale. Filters in the phase plot are spaced 10 Hz apart, but each has a 3-dB bandwidth of 20 Hz. Leakage into adjacent filters causes the chevron patterns surrounding strong components. Recorded signals have been corrected for frequency and timing errors due to tape wow and flutter by using a constant-frequency pilot tone [*Paschal and Helliwell,* 1984].

The whistler mode LICO1 signal is visible in each spectrogram as the constant-frequency signal just below 4 kHz. Other constant-frequency signals at 2.5 kHz and below were interference at the receiver induced from local power lines, and were not magnetospheric signals. The top of a band of magnetospheric chorus is seen extending to frequencies just over 1 kHz. In the left of each figure is the vertical stripe of a strong sferic due to a lightning flash in the northern hemisphere, followed after a few seconds by many two-hop whistler components. The LICO1 signal had a group delay of $t_g = 2.1$ s, determined by measuring the time delay at Roberval from the known beginning of the transmission. There were also whistler components with that delay, the first strong components in Figure 1 with a two-hop time of 4.2 s. We will assume that those whistler components and the LICO1 signal travelled on the same path (as is typically the case [*Carpenter and Miller,* 1976]). Note that the Siple transmission was very close to the nose frequency of the whistler components, which was approximately $f_n = 4000$ Hz. Using standard whistler analysis, we find from *Park* [1972] a path L value of 4.32 and a hemispheric tube content of $N_T = 3.5 \times 10^{13}$ cm^{-2}, or equatorial electron density of $N_{eq} = 275$ cm^{-3}, typical of the outer plasmasphere under magnetically quiet conditions [*Park et al.,* 1978].

The phase plots in the bottom of Figures 1–3 show the phase-coherent nature of the LICO1 signal. Both components, as received at 3950 and 3980 Hz, were relatively constant in frequency most of the time and very close to the transmitted frequencies, as expected. (A signal at the exact center frequency of an analysis filter shows as a horizontal line.) The very slow drifts in phase (Doppler shift less than ±0.2 Hz) seen in Figures 1–3 were mostly due to motion of the whistler mode duct associated with hydromagnetic waves, as discussed by E. W. Paschal et al. (1989). At some times, particularly in Figure 2, coherent signals are also seen 30 and 60 Hz both above and below the transmitted components. These were sidebands caused by cyclotron resonance between the LICO1 signal and energetic electrons near the top of the path [*Helliwell et al.,* 1986]. Finally, another weak but coherent signal can be seen in Figures 1 and 2 near 3900 Hz. This was interference induced at the receiver due to local power line currents at the 65th harmonic of 60 Hz. Note that the phase behavior of this signal was unrelated to that of the LICO1 components and their sidebands.

About 1 s before before each two-hop whistler in Figures 1–3, the Siple LICO1 signal showed considerable amplification—a precursor. In each case the amplification lasted for about 1 s. Other significant precursors occurred in this transmission at 1609:14, 1610:45, 1611:53 UT, and there were probably additional, though weaker, events.

During each precursor, the two transmitted tones and their sidebands grew in amplitude, usually with a noticeable phase advance. In most cases the phase advance amounted to, say, 1/3 rev. However, in the precursor in Figure 1 the 3950 Hz tone advanced 2 revs in 0.5 s (+4 Hz offset), the 3980 tone advanced 1 rev, and the first upper sideband at 4010 Hz advanced about 0.5 rev. In each case, the transmitted tones and sidebands decreased in magnitude after the precursor. The phase of each component resumed its previous behavior as if the precursor had not happened.

There was a peculiar null in the magnitude of the upper Siple tone in the middle of each precursor. In Figure 1 this appears as the tone undergoes a phase reversal as if from interference or fading. Shortly after the null a weak rising emission was triggered. In Figure 2 the null occurs without any marked phase effect, though it seems to precede (trigger?) a burst of growth on the lower tone and the sidebands. And in Figure 3 the null coincides with a short burst of signal growth at nearby frequencies.

There was also a certain variability in the timing of the precursors from one event to the next. In Figure 1 the precursor started 3.1 s after the sferic, in Figure 2 it started

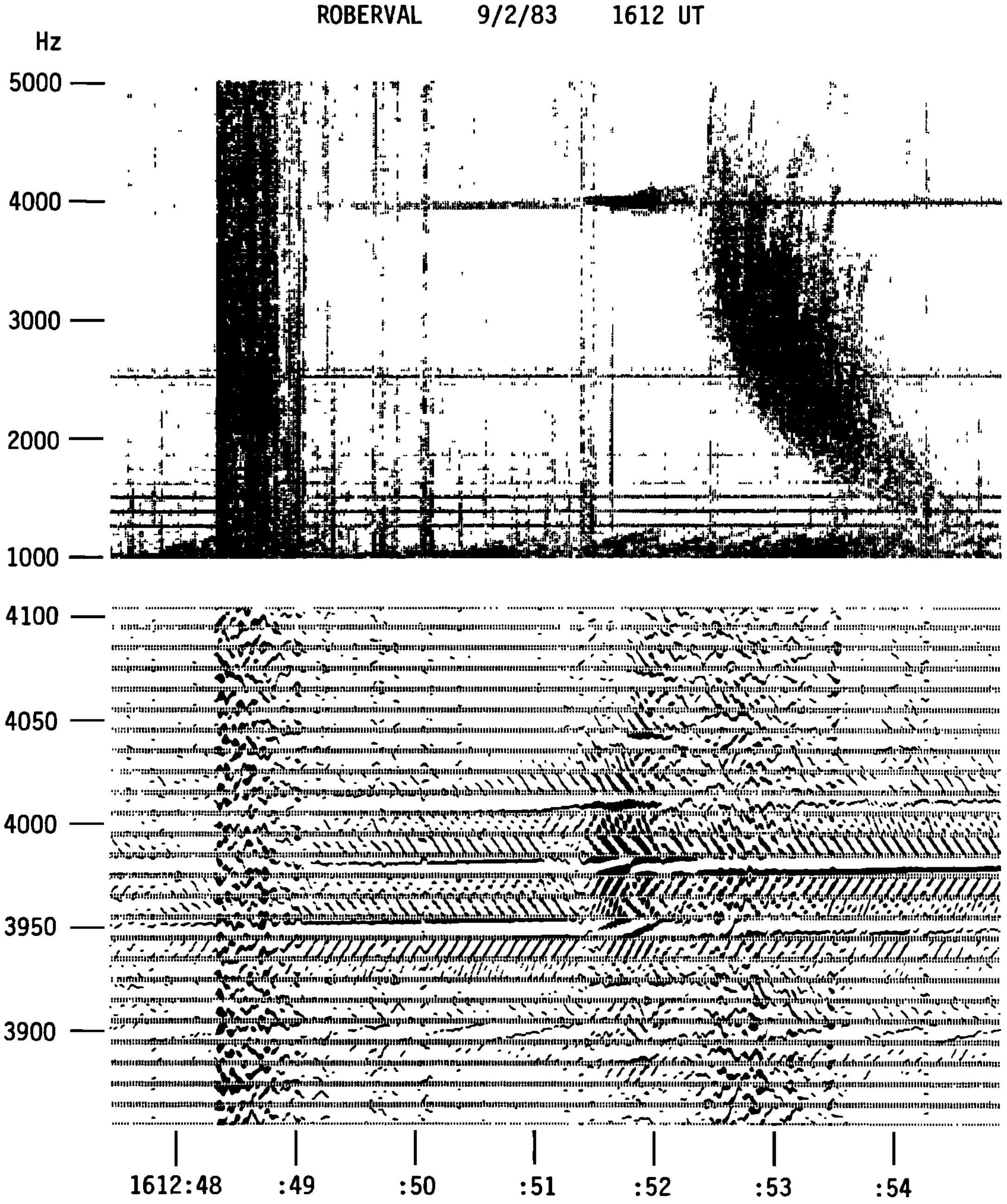

Fig. 1. Spectrogram and phase plot of a whistler precursor on a LICO1 transmission from Siple Station as received at Roberval, Quebec. The phase plot displays analysis filter outputs with trace width proportional to signal magnitude and trace deflection to relative phase, one revolution full scale. Shortly before the whistler arrives, the two transmitted signal components at 3950 and 3980 Hz experience amplification and phase advance. Sidebands at ±30, ±60, and +90 Hz are enhanced. A weak rising emission is triggered. After the precursor, signal components resume their previous behavior.

3.3 s after the sferic, and in Figure 3 it started only 2.6 s after it. The corresponding times from the sferic to the magnitude null were 3.5 s, 3.6 s, and 3.1 s, respectively. This variability has been noted before in whistler precursors by *Helliwell* [1965, Figure 7-53] and *Laaspere and Wang* [1968, Figure 5].

Note that the precursors started 0.5–1.2 s after the one-hop whistler group delay of $t_g = 2.1$ s. This delay from the one-hop time is greater than the 0.1–0.3 s mentioned in the introduction as being typical of natural whistler precursors. The excess delay may be significant, or it may just reflect differences in paths and frequencies between previously observed natural whistler precursors and the signals in this case. Natural precursors previously studied propagated on L shells from 2.5–3.8 [*Dowden,* 1972] versus $L = 4.32$ in this case, were associated with whistlers with nose-frequency group delays less than 1.7 s versus $t_n = 2.1$ s here, and started at frequencies usually below half the nose

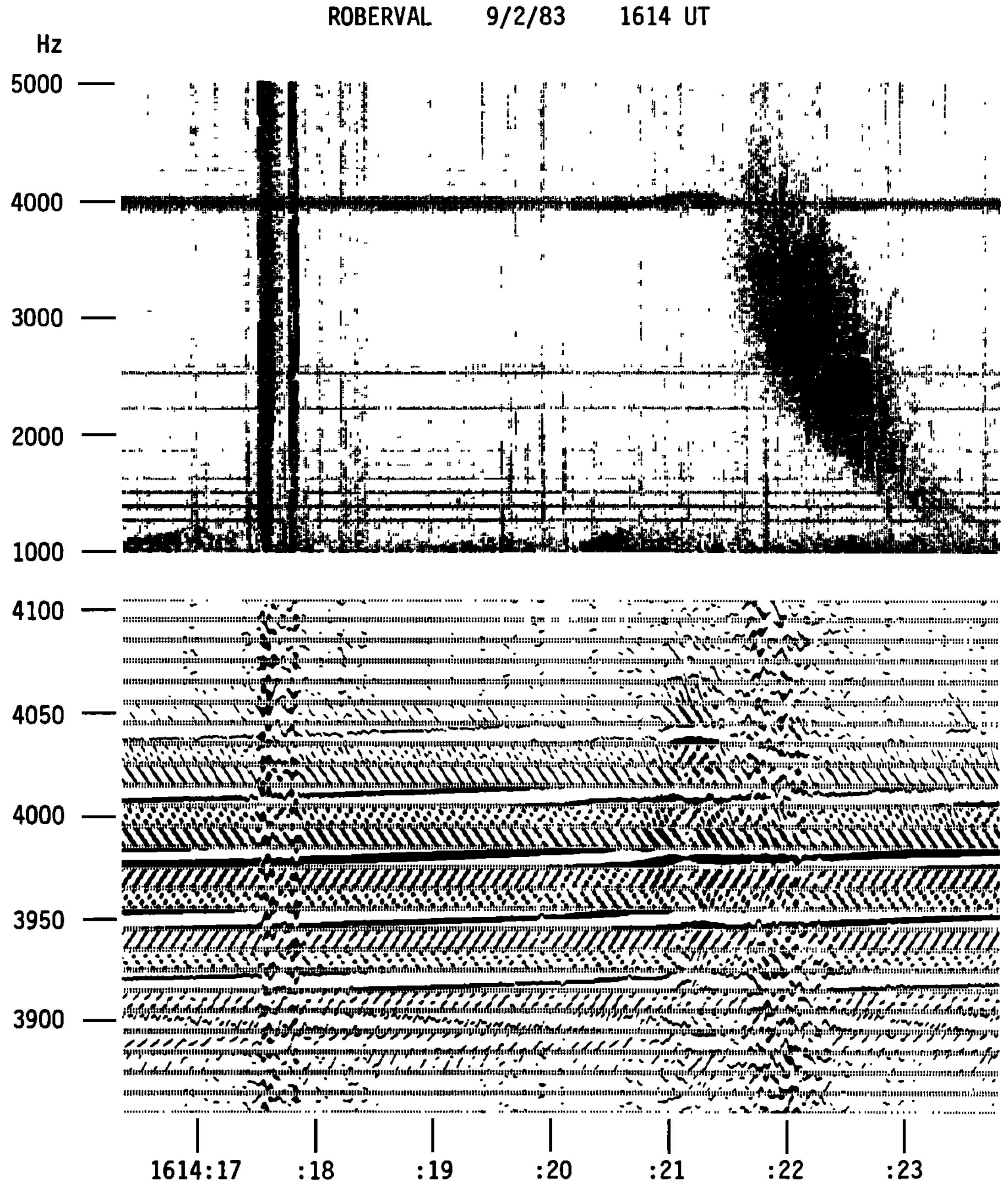

Fig. 2. A second whistler precursor on a two-tone transmission, as in Figure 1. The phase advance caused by the precursor is much smaller, only a fraction of a revolution. Existing sideband components due to cyclotron resonance show phase changes as well. The upper transmitted tone at 3980 Hz has a null in the middle of the precursor. An unrelated signal at 3900 Hz is local power line interference.

frequency $(0.04\text{–}0.20 f_{H_{eq}})$ instead of at the nose frequency itself $(f_n = 0.37 f_{H_{eq}})$.

In two cases in this transmission, at 1611:55 and 1615:33 UT, a second amplification event lasting about 1 s also occurred after the whistler, a "postcursor." At 1611:55 UT the postcursor started about 0.8 s after the first whistler component, or 2.0 s after the precursor (which itself occurred about 3.0 s after the spheric). At 1615:33 UT (Figure 3) the postcursor started about 1.4 s after the whistler or 2.7 s after the precursor. The postcursors may be related to the precursors (though with even more variability in timing), but they may also be effects caused by emissions triggered from the tops of the whistlers. Unfortunately, we do not have sufficient information about the postcursors to discuss them further.

3. Discussion

The examples in Figures 1–3 show whistler-related effects occurring on the transmitted LICO1 signal approximately one second before the two-hop whistler echoes. These effects were the momentary amplification of the LICO1 signal, a corresponding phase advance of 0.5 rev or so, and the enhancement of its various magnetospherically generated 30 Hz sidebands. Temporal growth, phase advance,

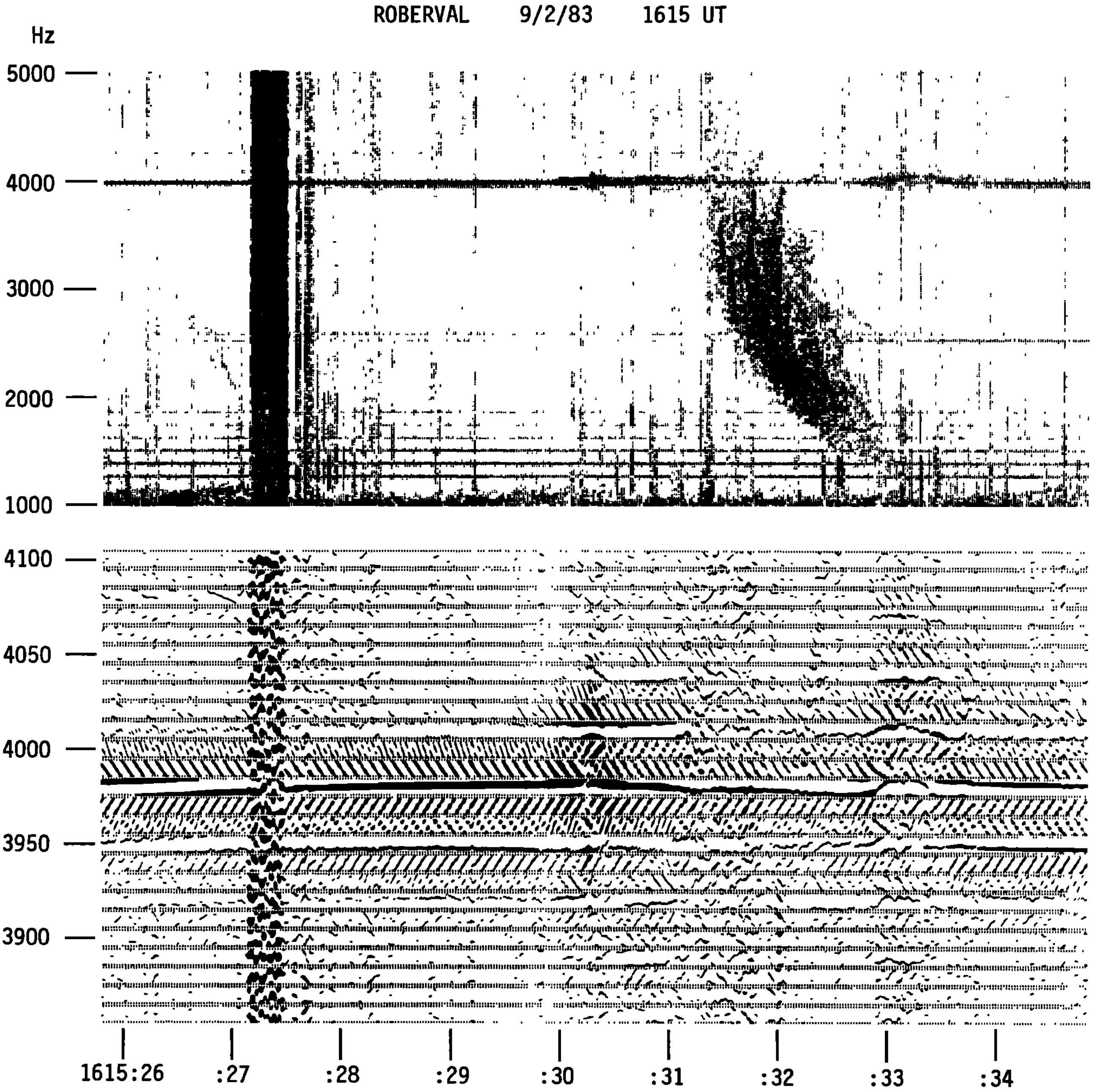

Fig. 3. A third whistler precursor as in Figure 1. The precursor occurs slightly earlier in this case. There is a "postcursor" shortly after the whistler as well, though whether this is caused by the same mechanism as the precursor is not known.

and sideband generation are the characteristic features of cyclotron-resonance interactions with energetic electrons [*Paschal and Helliwell*, 1984; *Helliwell et al.*, 1986]. The precursor behavior in Figures 1–3 indicates a sudden increase in cyclotron-resonance growth activity. In fact, growth was strong enough in Figure 1 that the amplified LICO1 signal even triggered an emission. This is, to my knowledge, the first time precursors have been reported on a transmitter signal. The case is also unique in that the frequencies of the precursors were so high relative to the associated whistlers, near the whistler nose frequency rather than below half of it.

The models of *Helliwell* [1965] and *Dowden* [1972] (hybrid whistler), *Molchanov and Chmyrev* [1970] and *Reeve and Boswell* [1976] (parametric decay), and *Reeve and Rycroft* [1976] (magnetospherically reflected whistler) each assumed that conditions were ripe for the growth of an emission, and the thrust of each model was to produce a triggering signal that had the right time delay with respect to the causative sferic and the two-hop whistler. However, the precursors in Figures 1–3 are not triggered emissions. The problem here is not to find a triggering signal but to find a mechanism that momentarily increases growth activity. None of these three models can do that. In addition, the parametric decay model can be ruled out because it only works at the low-frequency tail of a whistler, not at the nose frequency.

It might be argued that a triggering signal *is* being created as in one of the three models above, but that its effect is altered by the presence of the LICO1 signal. That is, perhaps the precursors are the result of entrainment of the triggering signal by the LICO1 signal. Entrainment occurs when an input wave (the entraining signal), moving along a whistler mode path, reaches the wave-particle interaction region where some growth process, such as the generation of an emission (the entrained signal), is already in progress. Even if the input signal is as much as 20 dB weaker than the emission, it may take control of the growth process, causing a sudden change in slope df/dt from that of the emission to that of the input signal [*Helliwell,* 1979]. However, we cannot have entrainment of a precursor triggering signal by the LICO1 signal because that requires reversing the physical locations of the two waves. It is the LICO1 signal which is due to existing wave-particle interactions (LICO1 growth, though somewhat suppressed, is occurring since 30-Hz sidebands are being generated prior to the precursor), and it is the supposed triggering signal that enters up wave of the interaction region. We could conceivably have entrainment *of* the LICO1 interaction by a triggering signal, but that would appear as a change in slope df/dt from that of the LICO1 signal to that of the triggering signal, which was not what we saw here.

To explain the precursors in Figures 1–3, we need a mechanism other than an electromagnetic signal that produces increased growth. The growth rate for cyclotron resonance is governed by the number of energetic electrons which are available to resonate with a wave at any time given. Note that electrons moving in one direction along a field line resonate with waves moving in the opposite direction, assuming cyclotron resonance. The LICO1 precursors seem to have been due to momentary changes in the distribution function of energetic electrons moving south through the cyclotron-resonance interaction region at the top of the path. Longitudinal resonance between the outgoing (south moving) whistler before it reached the equatorial plane and costreaming electrons might have enhanced the flux of relevant electrons sufficiently to have increased the growth of the north moving LICO1 signal, as in the model of *Park and Helliwell* [1977] and *Tkalcevic* [1982]. To this extent our observations support their model over earlier ones that merely produce triggering signals. However, it may be difficult using their model to account for the long delays of these precursors, especially the one in Figure 2 (1.2 s after the one-hop delay), without moving the cyclotron-resonance interaction region so far south of the equator that it is beyond the point where we would expect effective resonance with the LICO1 signal.

Park and Helliwell [1977] also argued that a precursor occurs when a magnetospheric power line signal is amplified due to the enhancement in electron flux and becomes intense enough to trigger an emission. About this mechanism our observations have little to say. The precursors we observed started, and remained for the most part, at the frequency of the LICO1 signal. We did not observe triggered emissions suddenly beginning up to 100 Hz above the transmitter signal, as would be required to reconcile *Rietveld*'s [1980] observations with the frequencies of power line harmonics. This may be because the two-tone LICO1 signal with 30 Hz separation suppressed growth and emission triggering. A magnetospheric power line harmonic, if there be such, would not be self-suppressed and might be more likely to trigger an emission, possibly somewhat offset in frequency. The real test of power line harmonics as triggers for natural precursors must be a statistical analysis of precursor starting frequencies. The only study so far, *Rietveld* [1980], found no particular correlation with power line harmonics, either at multiples of 50 or 60 Hz.

Finally, we come to the more general question of the role of triggering signals in the generation of emissions. Must we always have a external triggering signal in order to stimulate an emission; or may emissions sometimes arise spontaneously or, which amounts to the same thing, be triggered by local noise? This question is important because if an external trigger is not always required, then the mechanism of electron flux enhancement through longitudinal resonance is by itself sufficient to explain precursors; there is no need to invoke power line radiation. The answer may be connected with the power threshold effect observed on signals from the Siple transmitter, as reported by *Helliwell et al.* [1980]. They found a level of transmitted power below which received signal amplitude was proportional to input amplitude, and only above which did temporal growth and emission triggering occur. The threshold level varied widely with time and was different for different ducts. While the mechanism behind the threshold effect was not understood, they suggested that the threshold at any given time reflects the balance between the influx of energetic electrons into a given duct and the depletion of those electrons through scattering during wave growth; an increase in particle flux decreasing the threshold for growth. If this is the case, the momentary increase in flux due to longitudinal resonance with a whistler may decrease the threshold sufficiently that existing magnetospheric noise will be enough to stimulate a precursor emission, and an explicit trigger may not be necessary.

4. CONCLUDING REMARKS

Whistler precursors have been seen for the first time on signals from a VLF transmitter. They were similar to ordinary precursors in their timing with respect to the causative sferic and the two-hop whistler echo, starting shortly after the one-hop delay (though somewhat later than natural precursors), but they occurred at the nose frequency of the whistler instead of at lower frequencies. Phase analysis shows that the precursors consisted of the amplification and advance in phase of components in the transmitted signal, together with the generation of coherent sidebands. Most previous models have assumed that precursors are triggered emissions due to cyclotron-resonance interactions between the transmitted waves and energetic electrons which occur near the top of the magnetospheric path; these models have attempted to explain the appearance of a triggering wave at the proper place and time. The new results show that precursors are actually due to a sudden but momentary increase in wave-particle growth activity in the interaction region, and not just the presence of a triggering signal. This increase in activity is presumably due to a change in the distribution function of energetic electrons, perhaps caused by their earlier longitudinal resonance with the outgoing whistler. If growth activity is sufficiently enhanced, the threshold for emission triggering may decrease enough that existing magnetospheric noise can initiate a precursor emission, and no external trigger signal may be required.

Acknowledgments. The author thanks D. L. Carpenter and R. A. Helliwell for valuable comments. Much of this work was done as part of a Ph.D. thesis at Stanford University. The analysis equipment used was funded by the Division of Polar Programs of the National Science Foundation under grant DPP76-15678. Additional support was provided by the Division of Polar Programs of NSF under grant DPP86-13783.

The Editor thanks Y. Omura and M. T. Rietveld for their assistance in evaluating this paper.

REFERENCES

Andrews, M. K., Magnetic pulsation behaviour in the magnetosphere inferred from whistler mode signals, *Planet. Space Sci.*, *25*, 957–966, 1977.

Carpenter, D. L., and T. R. Miller, Ducted magnetospheric propagation of signals from the Siple, Antarctica, VLF transmitter, *J. Geophys. Res.*, *81*, 2692–2700, 1976.

Dowden, R. L., Trigger delay in whistler precursors, *J. Geophys. Res.*, *77*, 695–699, 1972.

Dowden, R. L, A. D. McKay, L. E. S. Amon, H. C. Koons, and M. H. Dazey, Linear and nonlinear amplification in the magnetosphere during a 6.6 kHz transmission, *J. Geophys. Res.*, *83*, 169–181, 1978.

Helliwell, R. A., *Whistlers and Related Ionospheric Phenomena*, Stanford University Press, Stanford, Calif., 1965.

Helliwell, R. A., A theory of discrete VLF emissions from the magnetosphere, *J. Geophys. Res.*, *72*, 4773–4790, 1967.

Helliwell, R. A., Siple Station experiments on wave-particle interactions in the magnetosphere, in *Wave Instabilities in Space Plasmas*, edited by P. J. Palmadesso and K. Papadopoulos, pp. 191–203, D. Reidel, Hingham, Mass., 1979.

Helliwell, R. A., D. L. Carpenter, and T. R. Miller, Power threshold for growth of coherent VLF signals in the magnetosphere, *J. Geophys. Res.*, *85*, 3360–3366, 1980.

Helliwell, R. A., U. S. Inan, J. P. Katsufrakis, and D. L. Carpenter, Beat excitation of whistler mode sidebands using the Siple VLF transmitter, *J. Geophys. Res.*, *91*, 143–153, 1986.

Laaspere, T., and C. Y. Wang, Whistler precursors, *Radio Sci.*, *3*, 213–218, 1968.

Molchanov, O. A., and V. M. Chmyrev, Possible generation mechanism of the precursors of whistlers, *Geomagn. Aeron.*, *10*, 816-820, 1970.

Park, C. G., Methods of determining electron concentrations in the magnetosphere from nose whistlers, *Tech. Rep. 3454-1*, Radiosci. Lab., Stanford Electron. Labs., Stanford Univ., Stanford, Calif., 1972.

Park, C. G., and R. A. Helliwell, Whistler precursors: A possible catalytic role of power line radiation, *J. Geophys. Res.*, *82*, 3634–3642, 1977.

Park, C. G., D. L. Carpenter, and D. B. Wiggin, Electron density in the plasmasphere: Whistler data on solar cycle, annual, and diurnal variations, *J. Geophys. Res.*, *83*, 3137–3144, 1978.

Paschal, E. W., and R. A. Helliwell, Phase measurements of whistler mode signals from the Siple VLF transmitter, *J. Geophys. Res.*, *89*, 1667–1674, 1984.

Reeve, C. D., and R. W. Boswell, Parametric decay of whistlers—A possible source of precursors, *Geophys. Res. Lett.*, *3*, 405–407, 1976.

Reeve, C. D., and M. J. Rycroft, A mechanism for precursors to whistlers, *J. Geophys. Res.*, *81*, 5900–5910, 1976.

Rietveld, M. T., Monochromatic precursor starts, *J. Geophys. Res.*, *85*, 2027–2036, 1980.

Tkalcevic, S., Nonlinear longitudinal resonance interaction of energetic charged particles and VLF waves in the magnetosphere, *Tech. Rep. E4-2311*, Radiosci. Lab., Stanford Electron. Labs., Stanford Univ., Stanford, Calif., 1982.

E. W. Paschal, STAR Laboratory, 324 Durand Building, Stanford University, Stanford, CA 94305.

(Received December 13, 1988;
revised May 23, 1989;
accepted June 12, 1989.)