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Testing Radio Bursts Observed on the Nightside of Venus for Evidence of Whistler Mode Propagation From Lightning

VIKAS S. SONWALKAR AND D. L. CARPENTER

Space, Telecommunications and Radioscience Laboratory, Stanford, California

R. J. STRANGEWAY

Institute for Geophysics and Planetary Physics, University of California, Los Angeles

Radio burst events recorded on the nightside of Venus by the orbiting electric field detector (OEFD) on Pioneer Venus Orbiter (PVO) have been interpreted as originating in subionospheric lightning. This lightning source interpretation has been subject to repeated challenges. During many of the burst observations, activity occurred in the lowest, or 100 Hz, filter band channel only, while in a smaller number of cases, activity occurred at two or more of the four filter band frequencies 100 Hz, 730 Hz, 5.4 kHz, and 30 kHz. Previous work with the data has been primarily statistical in nature. In some studies, only events with activity limited to the 100-Hz channel were considered; 100 Hz had been found to be lower than typical values (~100-1000 Hz) of the ambient electron gyrofrequency, and such cases appeared to be candidates for whistler mode propagation from lightning sources to the satellite. In general it was recognized that if the higher-frequency signals were of subionospheric origin, their observation from PVO would require an ionospheric penetration mechanism other than the conventional one associated with excitation of the cold plasma whistler mode at the lower ionospheric boundary. In the present work, methods have been developed for testing the hypothesis that particular burst events were the result of whistler mode propagation of signals from subionospheric lightning sources. The tests allow prediction of the resonance cone angle, wave normal direction, refractive index, wave dispersion, and wave polarization and are believed to represent an improved way of categorizing OEFD burst data for purposes of investigating source/propagation mechanisms. The tests, which are capable of refinement, were applied to observations from 11 periods along seven orbits. Most of these cases had been illustrated in the literature in support of conflicting interpretations of the observations. The key wave normal test was applied to each of the 11 cases, and the dispersion and polarization tests were also applied to the limited extent that the properties of the particular data sets would permit. The results obtained from the limited data sample indicate that there are at least two main categories of burst events, one for which the assumed vertical wave normal angle was within the allowed cone of angles for whistler mode propagation and one for which this was not the case. Lightning is thus considered to be a candidate source for at least some of the OEFD bursts. Its further assessment as a source must await studies of additional events and, in particular, examination of cases to which the more stringent dispersion and polarization tests can be applied. Four of the five burst events that were found to be inconsistent with the hypothesis of whistler mode propagation from lightning involved receptions at multiple OEFD filter band frequencies, while one involved 100 Hz only. A search for the cause of such events should include possible mechanisms of ionospheric wave penetration at frequencies both above and below the gyrofrequency, as well as plasma instability mechanisms local to the spacecraft.

1. INTRODUCTION

A spirited and now protracted debate has arisen in the literature over the extent to which certain wave bursts observed on the nightside of Venus from the Pioneer Venus Orbiter (PVO) can be interpreted as evidence of lightning in the Venusian atmosphere [*Russell et al.*, 1988*a*, *b*, 1989*a*, *b*; *Russell*, 1989; *Scarf et al.*, 1987; *Scarf and Russell*, 1988; *Taylor and Cloutier*, 1986, 1988; *Taylor et al.*, 1985, 1988, 1989]. A key element in the debate is the fact that the orbiting electric field detector (OEFD) on PVO was limited by telemetry considerations to the measurement of signals within four narrow (~30%) frequency bands centered at 100 Hz, 730 Hz, 5.4 kHz, and 30 kHz. That limitation precluded the type of wideband spectrum analysis that in the Earth's environment has permitted researchers to distinguish relatively easily between signals of lightning origin and others that appear to originate in plasma instabilities of various kinds. Lacking the desired wideband information, the OEFD investigators designed their instrument so that, under the plasma conditions that were expected to prevail at Venus, there could be at least a limited registration of signals that might propagate to the spacecraft from lightning sources [*Taylor et al.*, 1979; *Scarf et al.*, 1980]. In particular, the lowest frequency channel was set at 100 Hz, a frequency expected to be low enough to propagate through the Venusian ionosphere in the so-called whistler mode.

The debate thus far has been dominated by the results of statistical studies [*Russell et al.*, 1988*a*, *b*, *c*; *Scarf et al.*, 1987; *Taylor et al.*, 1985, 1989; *Scarf and Russell*,1983, 1988; *Taylor and Cloutier*,1987, 1988; *Singh and Russell*, 1986; *Russell*, 1989], although attention has also been given to details of the instrument response to wave bursts [*Taylor et al.*, 1979; *Scarf et al.*, 1980; *Taylor and Cloutier*, 1988], to

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the direction of the background magnetic field [*Scarf et al.*, 1980; *Scarf and Russell*, 1983], and to polarization analysis of signals received along individual orbits [*Scarf and Russell*, 1988]. In doing statistics, it has been recognized that because the upper limiting frequency of the whistler mode in a dense plasma is $f \sim 28B$, where f is in hertz and B is the local magnetic field magnitude in nanoteslas, waves at the OEFD frequencies 5.4 kHz and 30 kHz would regularly be in a range above the whistler mode cutoff and thus would not be expected to propagate freely. During the ongoing debate, critics have pointed out that many of the 100-Hz wave bursts attributed by the experimenters to lightning were detected within localized depletions or troughs in ion density, and they have suggested that those wave bursts originated in plasma instabilities associated with such irregularities [*Taylor et al.*, 1985, 1987; *Taylor and Cloutier*, 1986]. On the other hand, defenders of the lightning interpretation have argued that the significance of the density troughs lies in the fact that in such regions the magnetic field tends to be locally enhanced, thus permitting whistler mode propagation to occur at a frequency below the local gyrofrequency [*Scarf and Russell*, 1988].

The present report is the result of a guest investigator study conducted by two of us in collaboration with the current principal investigator for the OEFD (R.S.). As guest investigators, we have sought to understand the positions taken on both sides of the debate, while devoting our main efforts to acquiring new understanding of the OEFD data. To this end, we have developed a series of tests of the data that provide additional physical grounds, other than the previously used ratio of observed frequency to gyrofrequency, for determining whether particular burst observations exhibit properties that would be expected of signals propagating in the whistler mode from remote lightning sources. As we show in the following section, there are three such tests, an initial one, the wave normal test, that can be applied in most cases, and two others, the dispersion and polarization tests, which are applicable only under certain conditions. The tests have thus far been applied to a few selected events only, and the results are primarily limited to the outcomes of the wave normal test. They nevertheless suggest that there are at least two main categories of bursts, one that exhibits one or more properties consistent with whistler mode propagation from subionospheric lightning sources and another that does not.

2. ANALYSIS APPROACH

The method of analysis is based on a formalism recently developed to analyze wave data received on a satellite [*Sonwalkar*, 1986]. In this formalism the kinetic constraints arising from the physics of the medium, i.e. properties such as cutoffs, dispersion, polarization of the modes of propagation, and the kinematic constraints arising from the measurement process, i.e. motion of the satellite, response of the detector, receiver characteristics, sampling rate of the data, are explicitly taken into account to predict certain quantities that can be tested experimentally. The method may be used in situations such as that of the OEFD data, in which tests of a given hypothesis that are more direct in nature are not possible due to experimental limitations. We make use of PVO data on cold plasma density N_e (OETP), background vector magnetic field $\mathbf{B}_0$ (OMAG), electric field in four narrow band (OEFD) channels (100 Hz, 730 Hz, 5.4 kHz, and 30 kHz), orbiter position and motion, orientation of the spacecraft spin vector, and orientation of the electric field antenna in the spin plane. By combining these measurements with known theoretical results on wave propagation in a magnetoplasma, it is possible to devise quantitative tests of the hypothesis that impulsive subionospheric sources of electromagnetic waves are responsible for the burstlike responses in the electric field detector of the PVO.

The analysis is based on the following three assumptions.

1. The Venusian ionosphere is spatially uniform over length scales larger than the wave-lengths (λ) in question and temporally uniform over time scales larger than the wave periods concerned.

2. The Venusian ionosphere is, on average, locally horizontally stratified.

3. Subionospheric wave sources are impulsive (wideband), occur randomly in time, and produce signals that vary randomly in intensity.

Assumption 1 is believed to be justified because the refractive index in the Venusian ionosphere is large and the wave lengths are small ($\leq$ 1 km). Furthermore, the wave periods of interest are short ($\leq$ 10 ms). By analogy with Earth's ionosphere, at least at low altitude, the Venusian ionosphere can be expected to be horizontally stratified (assumption 2). *Brace et al.* [1980] compared measurements of plasma electron density during inbound and outbound parts of orbits and found that the nightside ionosphere of Venus is horizontally stratified to a significant degree up to $\sim$ 1000 km altitude. Assumption 3 is appropriate if the subionospheric source is lightning that resembles lightning on Earth to the extent of being impulsive in character and random in time of occurrence [*Uman*, 1987].

We begin with the supposition, illustrated in Figure 1, that a signal observed by the OEFD originates in a subionospheric lightning source and propagates through the Venusian ionosphere in an "allowed" propagation mode. The impulsive signals from such a source are assumed to propagate in a free space mode to a lower ionospheric boundary near 140 km altitude [*Brace et al.*, 1980], after which some penetrating portion of the signal propagates through the ionosphere to the satellite. In the ionosphere, we assume that propagation takes place in the two modes predicted by cold electron plasma propagation theory. For typical values of plasma parameters in the Venusian ionosphere (plasma frequency $f_{pe} \sim$ 100 kHz, gyrofrequency $f_{He} \sim$ 1000 Hz, lower hybrid resonance frequency $f_{LHR} \sim$ 20 Hz, electron temperature $T_e < 1$ eV) and for the frequency range 100 Hz to 30 kHz of interest, use of cold electron plasma propagation theory is well justified [*Stix*, 1962]. Using this theory,

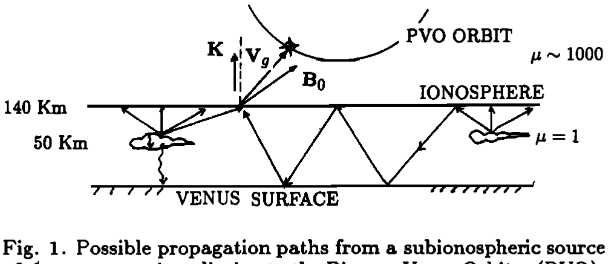


Fig. 1. Possible propagation paths from a subionospheric source of electromagnetic radiation to the Pioneer Venus Orbiter (PVO).

one can calculate two values of refractive index, which are functions of the wave frequency (f) and of the medium parameters plasma density (N_e) and the direction and magnitude of the magnetic field (**B**). In order for this theory to apply, it is necessary that the medium be uniform locally (assumption 1).

Table 1 gives values of the two refractive indices N_1 and N_2 for propagation at the four OEFD frequencies. Two limiting conditions are considered; in one the angle θ between the wave normal and **B** is $0°$, in the other, $90°$. The magnitude of the **B** field is assumed to be 20, 30, or 40 nT and the plasma density to be 10^3 el-cm^{-3}, typical values reported for nightside observations near 150 km altitude. Three principal effects are evident in Table 1: (1) only one mode, N_2, called the whistler mode, can propagate freely (i.e. the refractive index is real), (2) for the propagating mode the refractive index is very large, $\sim$ 1000, and (3) the propagation is a strong function of frequency and of the wave normal angle with respect to the ambient magnetic field. In general, a wave of frequency f and wave normal angle θ will propagate freely only if $f \cos\theta < f_{He}$, where f_{He} is the electron gyrofrequency. For the propagating mode N_2, there is therefore a limiting wave normal angle θ_{res}, tabulated at the right. This angle, depending as noted upon frequency and the value of magnetic field, is such that waves with wave normal angle $\theta > \theta_{res}$ are evanescent. For typical values of magnetic field in the Venusian ionosphere, only 100 Hz and 730 Hz have a nonzero resonance cone angle (θ_{res}), so that only these two channels can be expected to register a subionospheric signal. If the wave normal angle is larger than the resonance cone angle for each of the four frequencies, both modes are heavily attenuated (i.e. ~50 dB/km), and the attenuation is roughly the same at all four OEFD frequencies (see values of N_2 for $\theta = 90°$).

TABLE 1. Values of Refractive Indices N_1 and N_2 for Propagation at the Four Orbiting Electric Field Detector Frequencies

	$\theta = 0°$		$\theta = 90°$		
Frequency, Hz	N_1	N_2	N_1	N_2	$N_2(\theta_{res})$
			$B = 20$ nT		
100	1107i*	1322	2840i	2864i	79°
	20.14 dB/km†	λ=2.27 km††	51.68 dB/km	52.12 dB/km	
730	292i	805i	389i	389i	0°
	37.96 dB/km	104.65 dB/km	50.57 dB/km	50.57 dB/km	
5,400	55i	50i	52i	52i	0°
	53.9 dB/km	49.0 dB/km	50.96 dB/km	50.96 dB/km	
30,000	9.3i	9.5i	9.4i	9.4i	0°
	50.78 dB/km	51.87 dB/km	51.32 dB/km	51.32 dB/km	
			$B = 30$ nT		
100	928i	1041	2840i	2896i	83.16°
	16.88 dB/km	λ=2.88 km	51.68 dB/km	52.70 dB/km	
730	265i	1002	389i	389i	29.65°
	34.45 dB/km	λ=0.41 km	50.57 dB/km	50.57 dB/km	
5,400	49i	57i	53i	53i	0°
	48.02 dB/km	55.86 dB/km	51.94 dB/km	51.94 dB/km	
30,000	9.3i	9.5i	9.4i	9.4i	0°
	50.78 dB/km	51.87 dB/km	51.32 dB/km	51.32 dB/km	
			$B = 40$ nT		
100	815i	886	2840i	2942i	84.87°
	14.83 dB/km	λ=3.38 km	51.68 dB/km	53.54 dB/km	
730	244i	532	389i	389i	49.32°
	31.72 dB/km	λ=0.77 km	50.57 dB/km	50.57 dB/km	
5,400	58i	59i	52i	52i	0°
	47.04 dB/km	57.82 dB/km	50.96 dB/km	50.96 dB/km	
30,000	9.2i	9.6i	9.4i	9.4i	0°
	50.23 dB/km	52.42 dB/km	51.32 dB/km	51.32 dB/km	

*i indicates that the refractive index is imagninary.

†Attenuation in decibels per kilometer when the refractive index is imaginary.

††Wavelength in kilometers when the refractive index is real.

Assumption 2, in conjunction with the large refractive index of the propagation mode in the ionosphere and Snell's law, allows us to take the local vertical direction as the direction of the wave normal. With this assumption and the known medium parameters (N_e, $\mathbf{B}_0$), cold electron plasma propagation theory [*Stix*, 1962] allows us to predict wave propagation properties for a plane wave of arbitrary frequency. We can predict the propagation behavior of an arbitrary wave, since assumption 1 permits us to consider an arbitrary wave to be composed of individual plane waves. In particular, the resonance cone angle, refractive index, wave dispersion, and wave polarization can be predicted. The known wave normal angle and the calculated resonance cone angle then provide us with an initial test for propagation from a subionospheric source. If such propagation is found possible in a particular case, the observed waves must then exhibit the dispersion and polarization predicted by theory. Dispersion is measured in terms of differences in the time of arrival of signals in different frequency channels, and polarization in terms of antenna spin modulation. Assumption 3, about the impulsive nature of the source and about the randomly varying source intensity, requires us to average spin fading over several events in order to compare the observed polarization with the predicted one.

Based on the foregoing, the hypothesis that we consider is that an observed signal propagated from a subionospheric lightning source to the PVO in the whistler mode. The following three tests can then be applied to the OEFD data from individual orbits.

Test 1: Wave normal direction. In this key test the wave normal angle θ, a measurable quantity (from data on the $\mathbf{B}$ direction with respect to the local vertical), is compared to the predicted resonance cone angle $[\theta_{res} = \cos^{-1}(f/f_H)]$ to see if whistler mode propagation is possible ($\theta < \theta_{res}$). Figure 2 shows two examples of a wave penetrating a highly refracting ionosphere from a free space region below. In both cases the magnetic field is assumed to be oriented at some angle with respect to the local vertical, while the wave normal is directed along the vertical because of the Snell's law matching requirements at the boundary. In Figure 2*a*, the wave normal direction (k direction) lies within the resonance cone (i.e., $\theta < \theta_{res}$), and whistler mode propagation is expected, while in Figure 2*b*, $\theta > \theta_{res}$, and we expect strong attenuation, such as that indicated in Table 1.

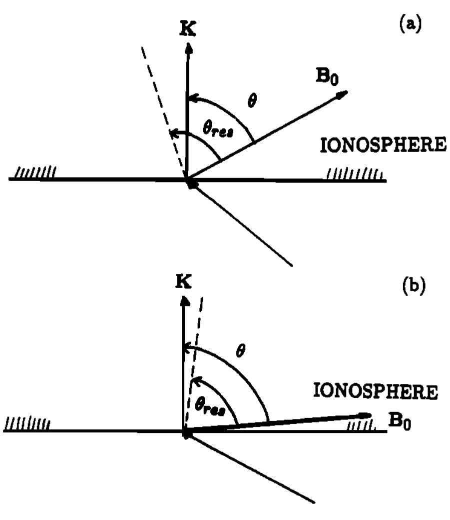


Fig. 2. (*a*) A wave incident on the ionosphere from a subionospheric source when the wave normal angle θ is less than the resonance cone angle θ_{res}. In this case the wave can propagate in the ionosphere. (*b*) Case in which $\theta < \theta_{res}$. The wave in the ionosphere is evanescent.

Test 2: Dispersion. The dispersion of whistler mode waves arriving at PVO from a subionospheric source should be a pronounced effect in the OEFD data, but one difficult to measure directly. If the two lowest OEFD channels, 100 Hz and 730 Hz, meet the wave normal test for whistler mode propagation, they may be expected to exhibit differences in arrival time that are consistent with differences in the expected group velocity v_g at the two frequencies Figure 3*a* shows the expected group velocity in kilometers per second versus frequency for two wave normal angles, 0° and 40°, and for N_e=1000 el-cm^{-3} and B=30 nT. In addition, due to the 30% bandwidth of each channel, individual incident signals (assumed to be impulsive with duration $\sim$ 1 ms) should show temporal broadening. The sampling rate for data in the high-resolution mode is 250 ms. Thus the difference in arrival times for signals in the 100-Hz and 730-Hz channels and the broadening of signals due to the finite bandwidth of each of the channels will be measurable effects if they exceed 250 ms in duration.

Figures 3*b* and 3*c* show the expected relative amplitude of whistler mode wave pulses observed in the 100-Hz and 730-Hz channel for 0° and 40° wave normal angles respectively. The source impulse is assumed to occur at 0 s, and the whistler mode signals are assumed to propagate a distance D=10 km (in altitude) through a medium where N_e =1000 el/cm^3 and B =30 nT. The time difference between the leading edges of the pulses in the 100-Hz and 730-Hz channels gives the expected time difference in the arrival of the two signals (100 Hz arriving first). Figures 3*b* and 3*c* show that the time difference effect is measurable (>250 ms) at 40° wave normal angle while the pulse broadening effect in the 730-Hz channel is detectable both at 0° and at 40° wave normal angle. Another effect of the pulse broadening is that the peak intensity should be reduced. If we assume that the subionospheric source has a uniform spectrum over the 100- to 730-Hz range, then it can be shown that the amplitude (in volts per meter) of the pulse due to frequency components arriving after delay t_g is given by

$$A(t_g) = \frac{K}{\sqrt{\mu(f)\partial t_g/\partial f}}, \qquad (1)$$

where $\mu(f)$ is the whistler mode refractive index and the constant K depends upon the strength of the lightning stroke. Since the dispersion in the 730-Hz channel is much larger than that in the 100-Hz channel, the expected amplitude in the 730-Hz channel is comparatively lower. Figures 3*b* and 3*c* show that the peak intensity occurs at the leading edge of the pulse. Thus we can define the pulse width as the time interval between the leading edge and the time when the amplitude is reduced to 10% (-20 dB) of the peak value.

From (1), we calculate the ratio of the observed peak amplitudes (in volts per meter per squareroot hertz) in the 100-Hz and 730-Hz channels, obtaining

$$\frac{A_{peak}(100Hz)}{A_{peak}(730Hz)} = \left[\frac{730(\mu(f)\partial t_g/\partial f)_{peak(730)}}{100(\mu(f)\partial t_g/\partial f)_{peak(100)}}\right]^{1/2} \quad (2),$$

where a factor corresponding to the ratio of the two frequencies is included to account for the 30% bandwidth of each channel. This ratio is dependent on the medium parameters and wave normal only; it is not a function of altitude, since the broadening increases in proportion to distance similarly for both channels. Note that (2) assumes that the source spectrum is uniform over the 100- to -730 Hz frequency band. Under this assumption, as shown below, the 730-Hz signal would be expected to be 20–80 dB below the 100-Hz signal, for typical Venusian plasma parameters. Thus even if

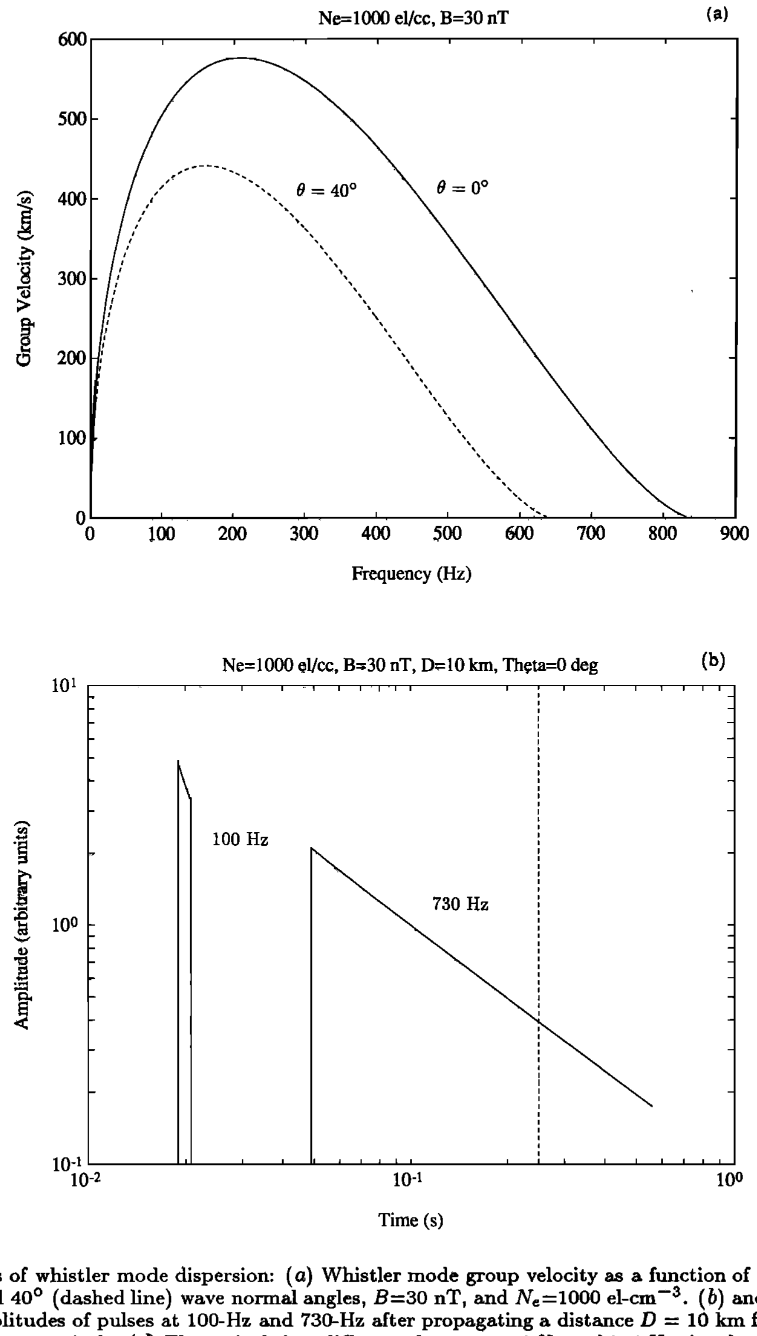


Fig. 3. Effects of whistler mode dispersion: (*a*) Whistler mode group velocity as a function of frequency for 0° (solid line) and 40° (dashed line) wave normal angles, B=30 nT, and N_e=1000 el-cm^{-3}. (*b*) and (*c*) The arrival times and amplitudes of pulses at 100-Hz and 730-Hz after propagating a distance D = 10 km for wave normals of 0° and 40°, respectively. (*d*) The arrival time difference between 100-Hz and 730-Hz signals after propagating a distance D = 10 km, as a function of wave normal angle. Three values of the magnetic field, 25, 30, and 35 nT, are considered. (*e*) The corresponding pulse widths at 100-Hz and 730-Hz. (*f*) The corresponding ratios in decibels of the peak amplitude at 730-Hz to peak amplitude at 100-Hz. The electron density is assumed to be 1000 el-cm^{-3}. The dashed horizontal lines in Figures 3*d* and 3*e* show the limits on temporal resolution (250 ms) imposed by the sampling rate.

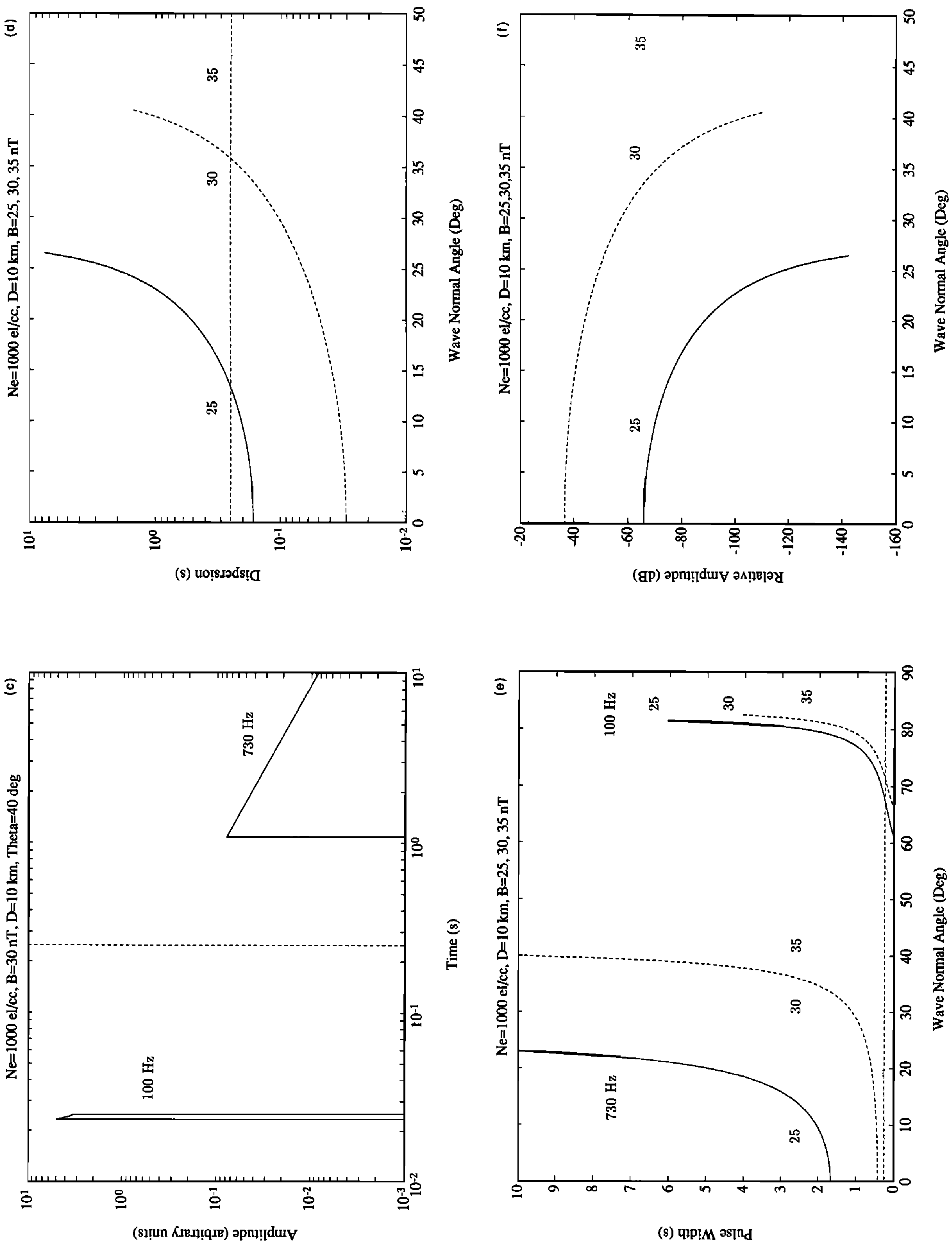


Fig. 3. (continued)

the source spectrum were not uniform, (2) may be taken to predict, at least qualitatively, the ratio of the two channel intensities.

Figures 3*d*, 3*e*, and 3*f* show, respectively, the travel time difference between 100-Hz and 730-Hz signals, the pulse widths at the two frequencies, and the relative amplitude of the 730-Hz channel signal with respect to the 100-Hz channel as a function of wave normal angle for Ne=1000 el-cm^{-3}, background magnetic fields of 25, 30, and 35 nT, and a propagation distance D of 10 km in altitude. These figures demonstrate that dispersion effects are sensitive to both the magnetic field value and the wave normal direction. They were found to be only weakly dependent on the plasma density N_e, however.

There are difficulties in applying the dispersion test to OEFD data. From Figure 3*d*, if we assume an ionospheric boundary at 140 km, the travel time difference effect should be detectable (> 250 ms) at 150 km or above if $\theta >\sim 15^\circ, \sim 35^\circ$, and $\sim 45^\circ$ for background magnetic field strengths of 25, 30, and 35 nT, respectively. Figure 3*e* shows that pulse broadening should be observable (i.e., >250 ms) at 150 km or above for the 730-Hz channel at all wave normal angles (for B equal to 25 and 30 nT), while it should be observable for the 100-Hz channel only when the wave normal angle is close to the resonance cone angle. Since group delay and pulse broadening are both incremental with altitude, we do not need to know the altitude of the bottom of the ionosphere to apply these tests. However, Figures 3*d* and 3*f* show that in order for the dispersion to exceed 250 ms and hence be detectable, the wave normal will be so high that ~70 dB of relative attenuation of the 730-Hz waves is expected. Thus only at relatively low altitudes (< 150 km) and only in those cases for which the source impulse contained a strong component at 730-Hz, may we hope to apply the dispersion test to a detectable 730-Hz signal.

Test 3: Polarization. For each propagating cold plasma mode, and given information on **B** and electron density N_e, the polarization properties of the mode are uniquely predictable as functions of frequency and wave normal direction. In general, the polarization is elliptical. If a plane wave propagating in a given direction is intercepted by a spinning spacecraft, the recorded wave amplitude should exhibit a perfect sinusoidal variation. The phase and modulation depth of this variation can be predicted, given information on the wave normal direction and on the orientation and direction of motion of the satellite. For a plane wave, the envelope of the observed voltage [*Sonwalkar*, 1986; *Sonwalkar and Inan*, 1986] is given by

$$< V(t)V^*(t) >= \frac{1}{4}L_{eff}^2 A[1 + M\cos(2\omega_s t - \alpha)], \quad (3)$$

where M and α give the depth and phase of fading that occurs at twice the spin frequency ω_s, and are dependent only on the medium parameters N_e and **B** and the wave parameters f and θ. The amplitude parameter A depends on the medium and wave parameters as well as on the strength of the plane wave. L_{eff} is the antenna effective length. Figure 4 shows a hypothetical example of three cycles of the variation that might be expected in the case of a plane wave signal.

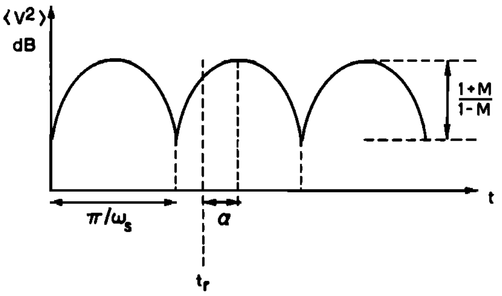


Fig. 4. Schematic of the voltage received on a spinning satellite for a plane wave. The fading parameters M and α are functions of the medium parameters, the wave frequency, the wave normal angle with respect to **B**, the spin axis, and the phase of the antenna vector in the spin plane.

In the case of signals hypothesized to come from a series of impulsive subionospheric sources, each received signal is too short in duration and unpredictable in intensity to provide evidence of the fading pattern. Further, the automatic gain control (AGC) receiver aboard PVO has a decay constant(τ) of 500 ms. Thus, depending on the occurrence time of source impulses and the times at which the data are sampled, the receiver will introduce a factor $D = D_0 e^{(-t/\tau)}$. Therefore (2) is modified as follows:

$$< V(t)V^*(t) >= \frac{1}{4}L_{eff}^2 D(t)A(t)[1 + M\cos(2\omega_s t - \alpha)], \quad (4)$$

where $A(t)$, and $D(t)$ are randomly varying parameters due to random variations in the intensity and occurrence patterns of the source impulses (assumption 3).

If wave bursts occur in close succession, the randomness in their individual amplitudes and occurrence times can be averaged out, provided that the medium parameters remain constant over the averaging period. That is, if the wave normal is constant (**B** constant) and N_e is constant (or effectively, if predicted spin parameters M and α are constant) during several spin cycles, averaging the data from these cycles should permit recovery of the predicted spin pattern, i.e.,

$$\{< V(t)V^*(t) >\}_{(n-cycles)} = \frac{1}{4}L_{eff}^2 \{D(t)A(t)\}_{(n-cycles)} \cdot [1 + M\cos(2\omega_s t - \alpha)]. \quad (5)$$

The quantity $\{D(t)A(t)\}_{(n-cycles)}$ is assumed to average out to some constant value due to the random occurrence pattern and intensities of the assumed subionospheric sources.

A proper test of the steadiness of the wave normal is the extent to which an average of several cycles of the predicted fading replicates the expected fading for a single cycle. Of course, necessary to any successful polarization test is the occurrence of signals sufficient in number to make the averaging over several cycles meaningful. In the next section we describe application of this test to the one candidate case among seven in which suitable conditions for averaging were present.

3. RESULTS OF DATA ANALYSIS

Our study of the PVO data included a general survey of the data from orbits 475-526 in season 3 and a detailed study of the nightside data from seven orbits, numbers 68, 86, 501, 502, 503, 515, and 526. In a typical case, the satellite spent ~16-20 min under nightside conditions of eclipse by the planet, moving from altitudes near 2000 km to periapsis below 170 km and back on a north-south trajectory. Bursts tended to occur in groups lasting from ~30 s to ~4 min. On three of the orbits, 502, 503, and 526, only one group was detected, while on four orbits, 68, 86, 501, and 515, there were two main groups, well separated in time. Thus a total of 11 burst groups from the seven orbits were studied. Five of the burst groups occurred below 200 km, near periapsis, while two occurred near 200 km and four above 300 km altitude.

Nine of the 11 burst groups, two each from orbits 68, 86, and 515 and one each from 501, 502, and 526, were chosen from among those that had previously been illustrated and discussed in the literature. An additional burst group from orbit 501 was selected, and a case from 503 was chosen simply because that orbit followed two others on our list. Seven of the 11 cases involved 100-Hz only. Five of these, two from orbit 68 and one each from 86, 515, and 526, had been illustrated as examples of data interpreted in terms of whistler mode propagation from lightning sources [*Scarf et al.*, 1980; *Ksanfomality et al.*, 1983; *Singh and Russell*, 1986; *Scarf and Russell*, 1988; *Russell et al.*, 1988*a*]. Several of these same cases had been illustrated in papers that challenged this interpretation [*Taylor et al.*, 1985, 1987; *Taylor and Cloutier*, 1986, 1987]. Of the four burst groups involving multiple frequencies, the ones from orbits 86, 501, and 515 had been illustrated by, respectively *Singh and Russell* [1986], *Russell et al.* [1989*b*], and *Russell et al.* [1988*a*], as examples of a body of events that the authors interpreted as originating in lightning, but which required a mechanism of ionospheric penetration other than that associated with conventional models of whistler mode excitation at a lower ionospheric boundary. The multifrequency case from orbit 86 was also illustrated in papers that challenged this lightning source interpretation [*Taylor and Cloutier*, 1986, 1987]; *Taylor et al.*, 1987].

We now describe the outcomes of our attempts to apply the three tests described above to the data.

The Wave Normal Test

The upper panels of Figures 5*a*-5*k* show the electron density in el-cm^{-3}/10^4, the ambient magnetic field magnitude in nT/10^3, and the wave electric field in Vm^{-1}Hz$^{-1/2}$ in the OEFD channels during intervals when burstlike signals were observed. The electron density data are 12-s averages; the others represent sampling every 250 ms.

The periods displayed vary in length according to the duration of the individual groups or clusters of bursts. At the upper right above the panels are indicated the starting and ending altitudes for the interval displayed. When periapsis occurred during the interval, its time is indicated by an arrow under the upper panel.

In the lower panels of Figures 5*a*-5*k*, the wave normal direction is compared with the resonance cone angle θ_{res}. The great variability of θ is due to its dependence on the direction of **B**; the less variable θ_{res} depends only upon the ratio of wave frequency to the magnitude of **B**. whistler mode propagation should have been possible for a given wave normal direction θ provided that $0° < \theta < \theta_{res}$ or provided that $(180° - \theta_{res}) < \theta < 180$. The resonance cone angle θ_{res} and the complementary angle $(180° - \theta_{res})$ are shown for 100-Hz and 730-Hz. In some cases, such as Figure 5*c*, the resonance cone angle was 0° for 730 Hz and therefore is not visible on the figure. $\theta_{res} = 0°$ essentially implies that no propagation could take place at the frequency in question.

In terms of this key test, we find that the data can be divided into two broad categories, each of which can be further divided into two subcategories:

Category 1. These are data consistent with the hypothesis that the signals had propagated in the whistler mode from subionospheric lightning sources.

1. The wave normal was inside the resonance cone for the 100-Hz channel, but outside for the 730-Hz channel ($\theta_{res}(730) < \theta < \theta_{res}(100)$). Only the 100-Hz signal was observed, as expected. The wave normal condition for the hypothesis was therefore fulfilled. Four such cases were found (Figures 5*a*, 5*b*, 5*d*, and 5*j*). These occurred, respectively, on orbits 68 near 200 km altitude inbound and 200 km outbound, on orbit 86 above 400 km, and on orbit 515 above 300 km.

2. The wave normal was inside the resonance cone for both 100 Hz and 730 Hz, i.e. $\theta < \theta_{res}(730) < \theta_{res}(100)$. Signals were observed in the 100-Hz channel only. Two such cases were found (Figures 5*g* and 5*k*). These occurred, respectively, on orbit 502 above ~ 400 km and on orbit 526 below ~200 km. Detectable signals at 730-Hz would not necessarily have been expected in these cases, as discussed below in the section on the dispersion test.

Category 2. These are data not consistent with the hypothesis that the signals had propagated in the whistler mode from subionospheric sources.

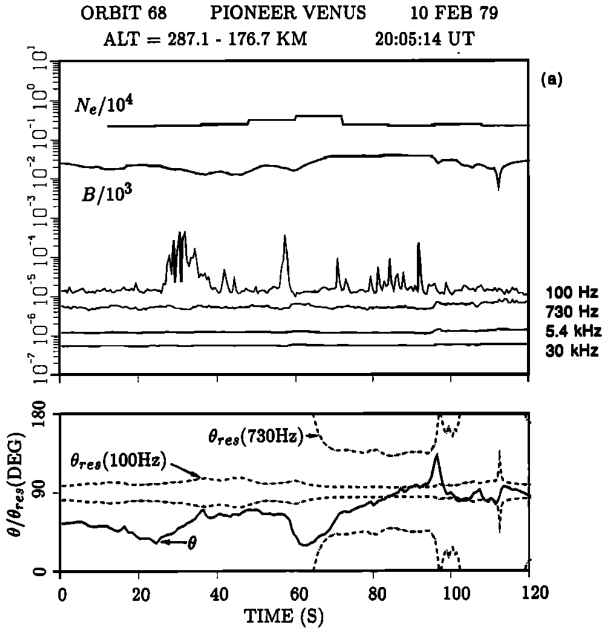
1. The wave normal was outside the resonance cone angle for 100 Hz (and therefore for the frequencies of the other channels), i.e., $\theta > \theta_{res}(100)$. Signals were detected in the 100-Hz channel only. One such case was found (Figure 5*f*, from orbit 501 above 350 km).

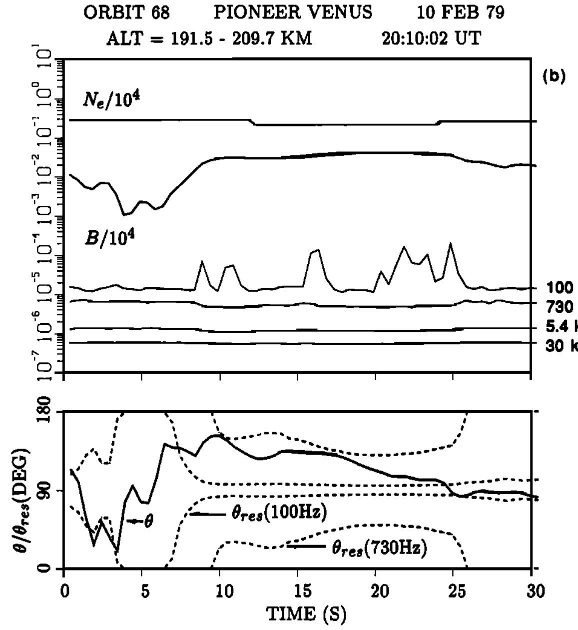
2. The wave normal angle was outside the resonance cone for 100 Hz ($\theta > \theta_{res}(100)$). Signals were observed at 100-Hz as well as in higher frequency channels. Four such cases were found (Figures 5*c*, 5*e*, 5*h*, and 5*i*). These occurred, respectively, on orbits 86, 501, 503, and 515, at altitudes below 200 km.

One interesting point is that 100-Hz signals were observed in all the cases.

The Dispersion Test

Among the cases that were consistent with the whistler mode-propagation-from-lightning hypothesis according to the wave normal test (Category 1 above), there were none with bursts at both 100 and 730 Hz. The wave normal condition was met for both 100 Hz and 730 Hz only for the cases of Figures 5*g* and 5*k*, during which the magnetic field was between 30 and 40 nT. The wave normal angle was between 15° and 28° for orbit 502, and between 15° and 39° for or-





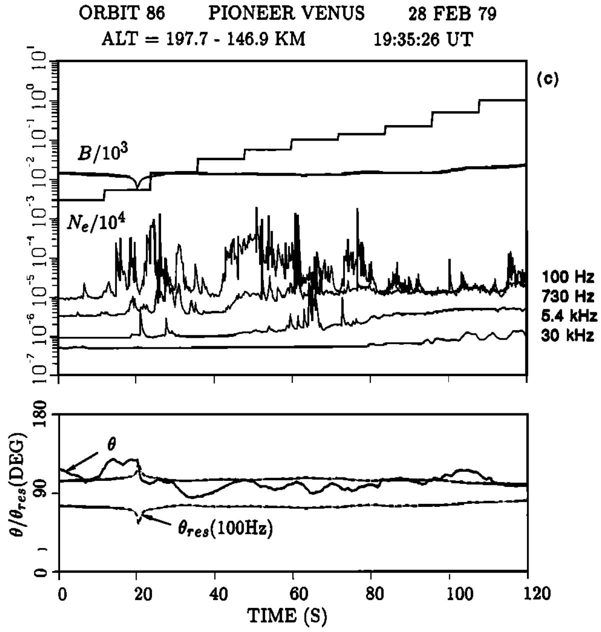


Fig. 5. (a)-(k) The top panels show the electron density in el-cm$^{-3}/10^4$, the ambient magnetic field magnitude in nT/10^3, and the wave electric field in Vm^{-1}Hz$^{-1/2}$ in the OEFD channels during intervals when burstlike signals were observed. The electron density data are 12-s averages; the others represent sampling every 250 ms. The bottom panels show the wave normal angle with respect to the local magnetic field direction. The dashed curves indicate the resonance cone angles for 100-Hz and 730-Hz. Propagation is allowed only for wave normal angle θ such that $0 \leq \theta < \theta_{res}$ or $(180° - \theta_{res}) < \theta \leq 180°$. In some of the figures, the resonance cone angle for 730-Hz is 0°, indicating that no propagation was possible at any wave normal angle.

bit 526, giving $(A_{peak}(100)/A_{peak}(730))$ ~20–50 dB. Under these conditions, observable whistler mode signal at 730 Hz would not necessarily have been expected, but the predicted group delay differences between 100-Hz and 730-Hz signals were only ~250 ms, about the order of the temporal resolution of the OEFD data, and hence the dispersion test could not be directly performed.

The Polarization Test

The polarization test was applied to all six cases in category 1 above. In several of the cases, relatively deep fading was expected if the data were to be consistent with the whistler mode hypothesis. However, because of temporal fluctuations in the wave normal and corresponding changes in the expected envelope from spin cycle to spin cycle, there was only one case, that of orbit 526, in which an average over multiple spin cycles preserved the predicted single cycle pattern. In this case the polarization condition was met, as illustrated in Figures 6*a* and 6*b*. Figure 6*a* shows the predicted sinusoidal spin fading for a plane wave propagating with the wave normal indicated in the bottom panel of Figure 5*k*, and with the plasma parameters of orbit 526.

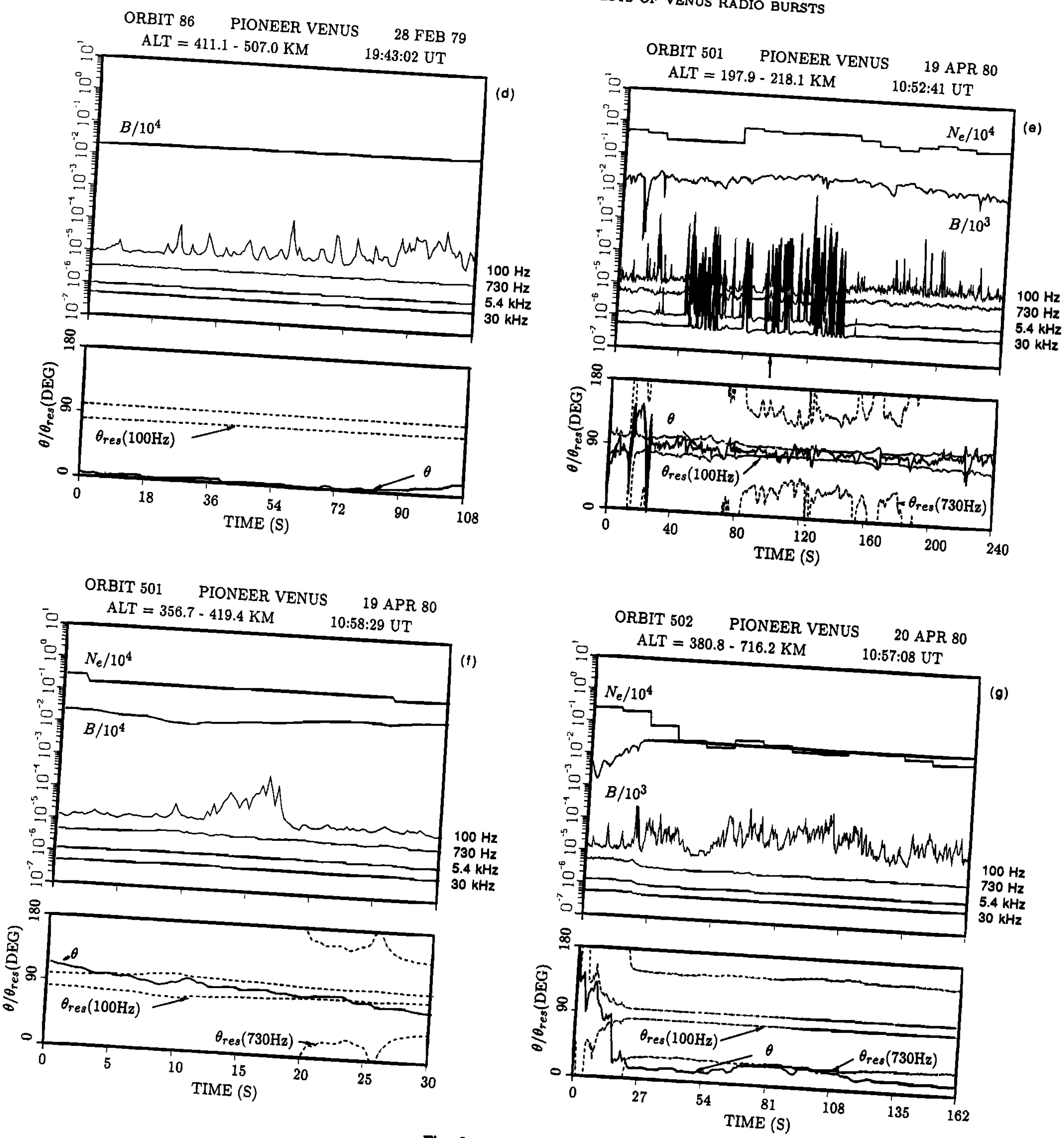


Fig. 5. (continued)

The predicted fading is shown by the dashed curve, while the behavior of the data is shown by the solid lines. Figure 6b shows the predicted spin fading and data when both are averaged over four spin cycles (or over eight fading cycles). The patterns are similar, except for a phase shift which might be explained by the slow (0.5 s) time constant of the AGC amplifier.

We note that data from this orbit were previously analyzed for polarization information by *Scarf and Russell* [1988], using a different method, and were reported to be consistent with whistler mode propagation. In that work the amplitude of the 100-Hz signal was plotted with respect to the projection of **B** in the spacecraft spin plane.

The difficulty in other cases in doing the required averaging over spin cycles is illustrated in Figure 7. Figure 7a shows the predicted fading pattern and the observed data for an ~ 2-min period from orbit 86 (see also Figure 5d). Relatively deep modulation appears in both curves, but following

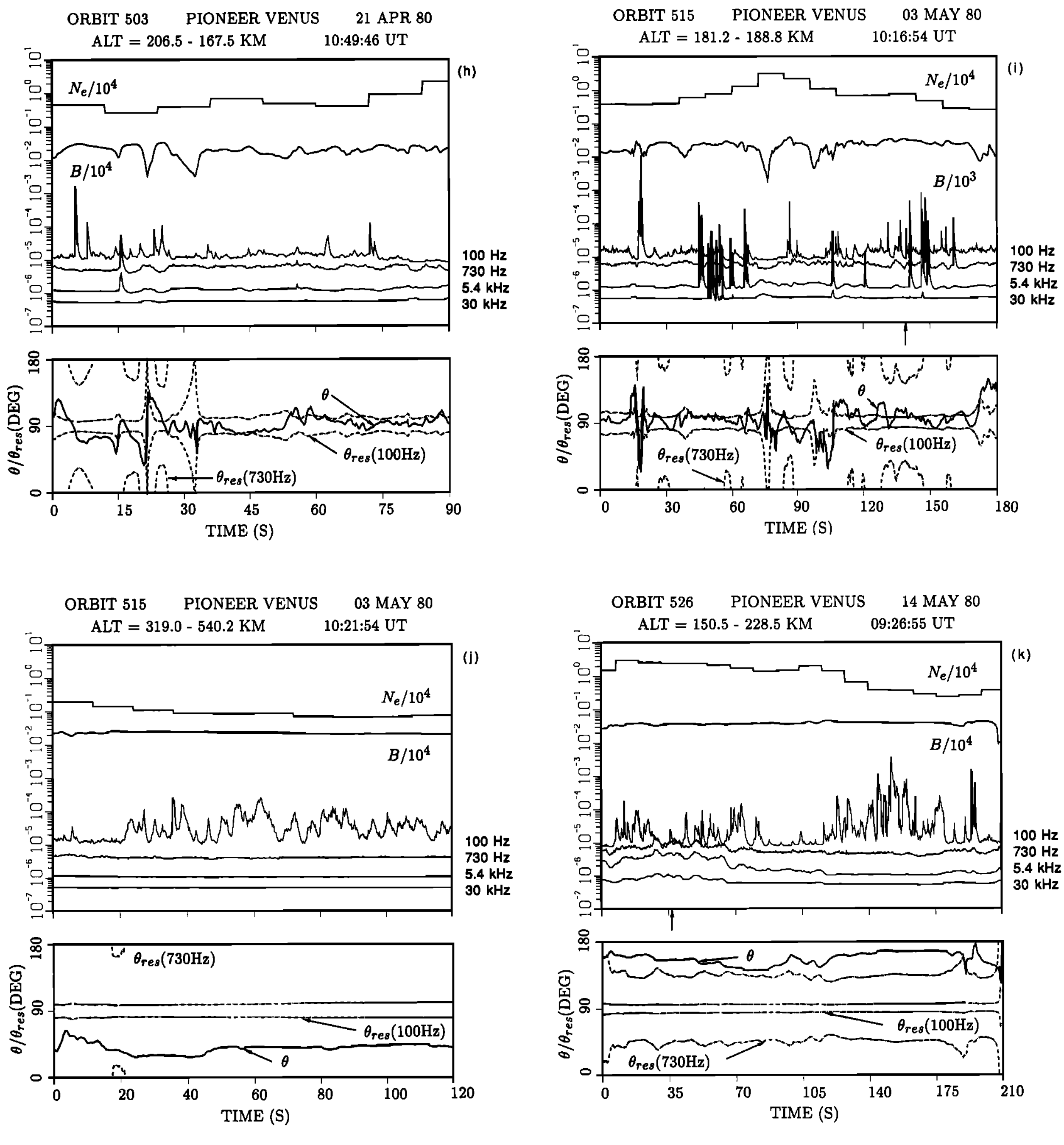


Fig. 5. (continued)

averaging over three or four cycles, as shown in Figure 7*b*, the modulation is no longer well defined, and the satisfaction of the polarization condition cannot be determined.

Comments on the Cases That Failed the Wave Normal Test for Whistler Mode Propagation

The data in category 2 above failed the wave normal test for whistler mode propagation in each of the frequency channels that were active, including that of 100 Hz. The main features of these data were:

1. The activity was generally wideband. Four out of five cases listed in category 2 exhibited burstlike signals in more than one channel. The frequencies of these signals ranged from < 100 Hz to > 30,000 Hz. The typical electron gyrofrequency (the nominal upper limit for whistler mode propagation in a dense plasma) during these observations was 1000 Hz. Thus the signals were observed over a fre-

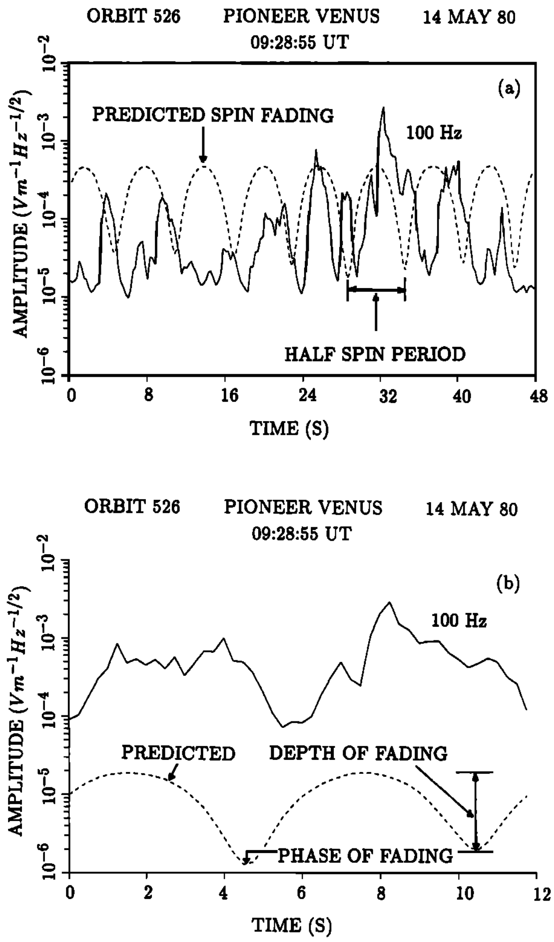


Fig. 6. (*a*) The predicted and observed spin fading for the 100-Hz signal at 0928:55 UT on orbit 526, when the wave normal direction was fairly steady (Figure 5*k*). (*b*) The predicted spin fading and data when averaged over four spin cycles. The spin period is 12 s. Well-defined spin fading at twice the spin frequency, as predicted for whistler mode propagation, is seen in the averaged data.

quency range that extended from well below to well above the local gyrofrequency (~1000 Hz) but remained below the local electron plasma frequency (>100 kHz).

2. There was no detectable evidence of dispersion in the case best suited to dispersion analysis. Orbit 501 contained many multifrequency bursts for which channel-to-channel differences in the times of amplitude peaks could be studied. Figure 8 shows some of the data in this case of apparently non whistler mode activity. The peaks in the various channels appear to be simultaneous within roughly the ~ 0.25-s time resolution of the OEFD instrument.

3. A spin-averaged polarization test of the orbit 501 data showed no preferred orientation of the polarization vector. As shown in Figure 5*e*, the 100-Hz-channel data from orbit 501 does not satisfy the wave normal test. However, if we assume that the actual wave normal angle for this case was just inside the resonance cone (such a situation could arise, for instance, if locally the plane of stratification were slightly tilted from the assumed horizontal), and then apply the polarization test, we obtain the results shown in Figures 9*a* and 9*b*. Figure 9*a* shows the predicted spin fading and the 100-Hz signal over a 30-s period. The predicted fading is deep but slightly variable as a result of small variations in the resonance cone angle along the trajectory. The spin-averaged predicted fading and the spin-averaged data are shown in Figure 9*b*. It is evident that while the predicted fading is well defined and deep, no consistent fading pattern is noticeable in the spin-averaged data.

4. DISCUSSION

In this report we have emphasized the development and initial demonstration of tests of a particular hypothesis about the origin and propagation mode of individual bursts or clusters of bursts observed by the OEFD.

We believe that the wave normal test represents an improved means of examining OEFD data for whistler mode

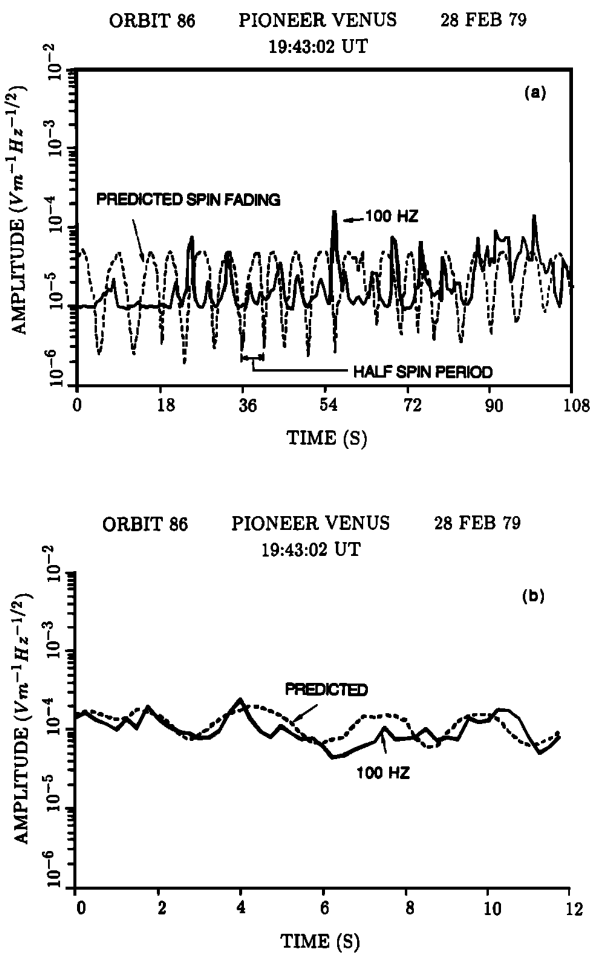


Fig. 7. (*a*) The predicted and observed spin fading for 100-Hz signals during orbit 086. (*b*) The predicted spin fading, following averaging over several spin cycles, does not show well-defined fading at twice the spin frequency, indicating that the conditions necessary for the application of the polarization test are not met.

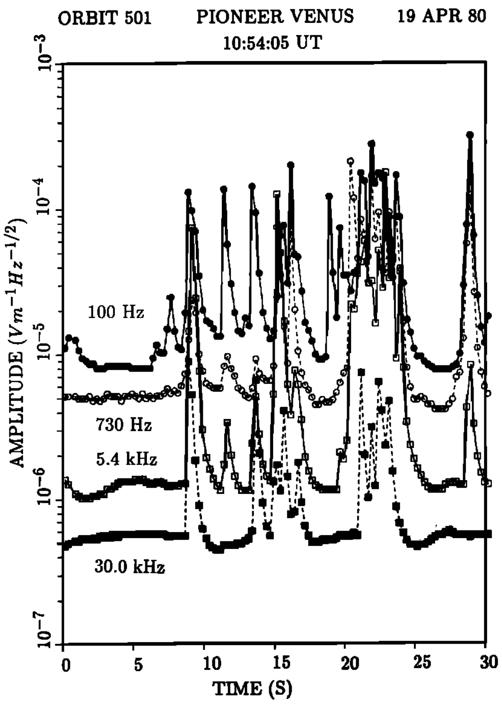


Fig. 8. Display on an expanded time scale of a close correlation among the plasma wave data in the four frequency channels for orbit 501. Based on the wave normal test (Figure 5e), these signals have not propagated in the whistler mode and therefore, within the framework of our assumptions, are not consistent with the hypothesis of a subionospheric source. Within the temporal resolution of 250 ms set by the OEFD sampling rate, the bursts show very little or no dispersion.

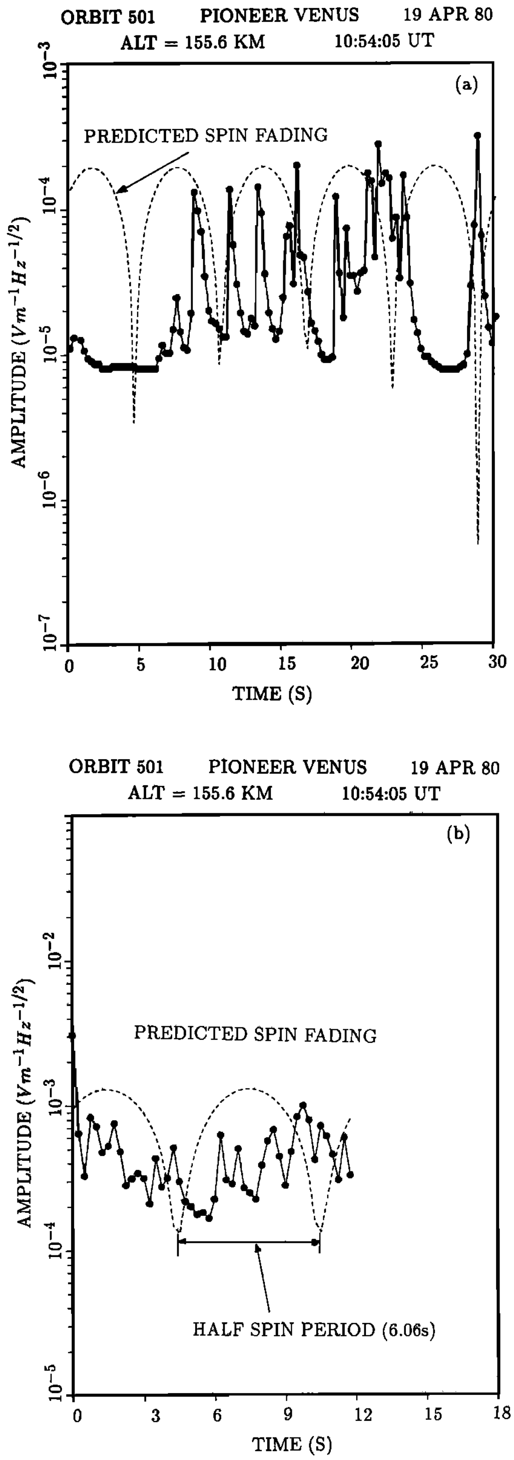


Fig. 9. (*a*) The predicted and observed spin fading for 100-Hz signals during orbit 501. It has been assumed that the 100-Hz signals have wave normal angles just inside the resonance cone. (*b*) The predicted signal envelope, following averaging over 12 spin cycles, shows well defined fading at twice the spin frequency, indicating that the conditions necessary for the application of the polarization test are met. The spin averaged data, however, do not show spin fading, indicating no preferred orientation of the polarization vector.

characteristics. In most previous work, screening of events for statistical purposes involved noting the distribution of observed activity across the four OEFD channels, and hence the ratios of observed wave frequencies to the local (or typical) electron gyrofrequency $f \sim 28B$. In two studies, only events with activity confined to the 100-Hz channel were included, such a distribution being the one that was expected under conditions of cold plasma propagation to PVO from remote broadband sources (but at 0° wave normal angle) [*Scarf and Russell*, 1983; *Scarf et al.*, 1987]. However, as we have found in the case of orbit 501 (Figure 5*f*), the 100-Hz-only criterion may include some cases that do not meet the wave normal test for whistler mode propagation. Furthermore, it excludes from consideration multifrequency cases with activity at 100 Hz and/or 730 Hz and also at 5.4 kHz or 30 kHz. In some such cases, the 100-Hz and/or 730-Hz components may have been below the local electron gyrofrequency and thus could conceivably pass the wave normal test.

In some other statistical work, cases with activity at multiple frequencies were selected, and it was recognized that at least the 5.4-kHz and 30-kHz components, if of subionospheric origin, could not be explained by conventional whistler mode theory [*Russell et al.*, 1988*a*, *c*; 1989*b*; 1990]. However, these studies did not include special whistler mode tests of the 100-Hz and 730-Hz components of the events. In all four of the multifrequency cases discussed in this paper, the wave normals were found to be outside the resonance cone for all the observed frequencies, including 100 Hz.

If the wave normal criterion for whistler mode propagation is satisfied in a given case, the dispersion and polarization tests must also be satisfied. Unlike the wave normal test, these tests are not applicable in all cases. Application of the dispersion test requires that whistler mode propagation at both 100 Hz and 730 Hz be detectable. At sufficiently low altitude one may hope to study travel time differences, while at greater altitudes the dispersive broadening effect may cause the amplitude at 730 Hz to fall below the level of detection.

We have not yet been able to study dispersion-related travel time differences between detected bursts at 100 Hz and at 730 Hz, but we have noted that in two cases in which the wave normal was inside the 730-Hz resonance cone, 100 Hz only was observed (Figures 5*g* and 5*k*). The lack of a detected signal at 730 Hz was qualitatively consistent with the attenuation expected from temporal broadening due to dispersion.

The polarization test was applied in all six cases satisfying the wave normal criterion, but in only one was the predicted spin modulation, when averaged over several spin cycles, sufficiently well defined for an assessment of its relation to the data. The polarization test was also applied to the apparently non whistler mode 100-Hz data in the multifrequency case from orbit 501 (Figure 5*e*), on the assumption that the wave normal had become tilted with respect to the local vertical so as to be just inside the resonance cone. The average predicted spin modulation was well defined, but the data showed no well-defined polarization, thus reinforcing the inference from the wave normal test that in this case the 100-Hz signal had not propagated in the whistler mode.

Possibilities for further application of the method are suggested by the distinctness with which the data thus far analyzed have been separated into categories. The wave normal test tended to provide unambiguous outcomes, and the relationship of the inferred wave normal angles to the resonance cone angle underwent few qualitative changes during the individual data intervals. Although only a small number of cases have been studied, we noted indications of what may be fundamental differences in the plasma conditions associated with the two inferred categories of data. For example, the four cases of multichannel activity that were found to be inconsistent with whistler mode propagation all occurred at altitudes below ~200 km, while the six cases found to be consistent with that hypothesis were widely distributed in altitude. It may also be significant that in all four multichannel cases the **B** field direction was far from the local vertical and that in three of these cases the field direction tended to vary rapidly.

Further assessment of the hypothesis of whistler mode propagation from lightning, including estimates of the size of the various categories identified, will require additional case studies and refinement of the method of analysis. The assumption of horizontal stratification should be more accurately satisfied at lower altitudes, and any pulse broadening should be smaller (thus increasing the peak signal intensity) at lower altitudes; thus one should look at orbits when both 100-Hz and 730-Hz signals occur at altitudes $\leq$ 200 km. This choice of data would allow application of all three tests of the subionospheric source hypothesis. The availability of electron density data from OETP makes it possible to relax the assumption of horizontal stratification. A first-order estimate of the tilt of the planes of stratification with respect to the local horizon can be obtained by comparing electron densities at the same altitude on inbound and outbound parts of an orbit. This would lead to a more precise determination of the wave normal angle θ (by Snell's law, the wave normal is perpendicular to the plane of stratification as long as $N_2 >> 1$). The polarization test could be improved by noting that even though the fading parameters M and α are functions of the medium parameters and the wave normal angle, the functional form of (5) remains the same. Thus we can statistically average data over varying medium parameters and wave normal angles (from a single orbit as well as from different orbits), provided that the data are normalized with respect to the fading parameters M and α. This kind of data averaging would increase the number of data points available to test for the sinusoidal variation expected as a consequence of the wave polarization.

There is clearly a need to investigate the origins and/or propagation mechanisms of the events that failed the wave normal test for whistler mode propagation to PVO from subionospheric lightning sources. One possible explanation of such events is that they originated in subionospheric lightning and reached the spacecraft by some as yet unknown propagation mechanism. Such propagation might involve a special condition of the ionosphere that allows it to become transparent to signals from lightning that are both above and below the gyrofrequency, as proposed by *Singh and Russell* [1986]. In support of such arguments, *Russell et al.* [1988*c*, 1989*b*, 1990] have pointed to the apparent concentration of the bursts above 100-Hz on the evening side of the planet, where lightning might be expected to be concentrated. These arguments imply the existence of two physically different ionospheric states, one that supports whistler mode propagation and one that supports a non whistler mode penetration of signals at frequencies below and above the local gyrofrequency. They also imply that the two conditions must at times coexist; on two of the orbits studied, 86 and 515 (Figures 5*c*, 5*d*, 5*i*, and 5*j*), a non whistler mode multichannel case was observed near periapsis, while 100-Hz-only events above 300 or 400 km on the same orbit passed the initial wave normal test for whistler mode propagation.

Of possible relevance to lightning as a source of the apparently non whistler mode events are recent findings in the Earth's ionosphere by *Kelley et al.* [1990], who observed signals from lightning on a rocket in the altitude range ~200-300 km. Anomalous precursor pulses to the arrival of clearly whistler mode signals were observed, and it was suggested by Kelley et al. [1990, p.2223] that an explanation could involve "a non-linear interaction of the ionosphere with the "intense whistler mode waves at the leading edge of the wave packet." However, it may be noted that the upper PVO frequencies extend well above the nominal whistler mode limit at Venus of ~1000 Hz, while the "intense whistler mode waves" referred to by *Kelley et al.* [1990] are in the whistler mode range 10–80 kHz, well below the local electron gyrofrequency at Earth of ~1 MHz.

Another possible explanation of the non whistler mode OEFD events is in situ generation by instabilities. It has been argued that 100-Hz-only OEFD cases tend to occur in regions of plasma irregularities, and in particular in ion density troughs [*Taylor et al.*, 1985; *Taylor and Cloutier*, 1986], and that such regions would be well suited to the generation of instabilities. In more general discussions, it has been pointed out that plasma transition regions abound in space and astrophysical plasmas [e.g., *Eastman*, 1991]. Called plasma boundary layers, the regions are characterized by (1) high spatial gradients Δn, $\Delta \mathbf{B}_0$, ΔT, and $\Delta \mathbf{V}$, (2) enhanced wave activity with low and high-frequency electrostatic and electromagnetic emissions, (3) changes in plasma β, high to low or low to high, and (4) multicomponent and anisotropic velocity distributions $f(\mathbf{V})$.

Strangeway [1990] has injected a cautionary note into considerations of in situ instabilities as candidate sources, pointing out that in view of the large refractive index typical of the Venusian ionosphere, it would be difficult to generate whistler mode waves locally.

In observations near other planets, wave bursts have been found to originate both in lightning and in other mechanisms. Wideband dispersionless wave bursts have been found to be a common feature of satellite observations near Earth [*Ondoh et al.*, 1989; *Sonwalkar et al.*, 1990], and bursts of this general type have also been reported near the Earth's magnetopause [*Reinleitner et al.*, 1982, 1983] and in the environments of Jupiter and Saturn [*Reinleitner et al.*, 1984]. These burst emissions have several characteristics common to the multichannel bursts observed on PVO [*Sonwalkar et al.*, 1990]. They are impulsive and show very little or no dispersion, their frequencies range from well below to well above the local gyrofrequency, but remain below the local electron plasma frequency, and there is an indication that their wave normal direction may be perpendicular to the local geomagnetic field. If these signals were sampled by a receiver similar to the one on PVO, their temporal and spectral characteristics would be similar to those observed on PVO orbits such as 501 (Figure 5e). Near Earth these signals have been observed on both electric and magnetic field antennas and have been detected in the low-density region outside the plasmapause at all local times [*Sonwalkar et al.*, 1990]. They show no association with terrestrial lightning (the spectral signature of lightning in these regions of the Earth's magnetosphere is reasonably well understood). The signals were initially interpreted as electrostatic noise generated by a resistive medium instability [*Reinleitner et al.*, 1983]. This instability is triggered by a beam of electrons of the order of several hundred eV, which could be generated by electrons trapped by the wave fields of natural chorus or hiss emissions. However, the observation of a magnetic component for these bursts has called this mechanism into question [*Sonwalkar et al.*, 1990].

5. CONCLUDING REMARKS

We have developed methods for case-by-case testing of observed bursts for evidence of whistler mode propagation from subionospheric impulsive sources. The tests are based on certain assumptions about the homogeneity and horizontal stratification of the Venusian nightside ionosphere and about the impulsive nature of lightning and its randomness in occurrence time and intensity. They allow prediction of the resonance cone angle for propagation in the whistler mode, as well as the wave normal direction, the refractive index, wave dispersion, and wave polarization. As such they are more restrictive than tests applied in previous investigations in which the data were sorted according to the distribution of activity above and below the typical electron gyrofrequency in the Venusian nightside ionosphere. The tests were applied to observations from eleven periods along seven orbits, most of which had been illustrated in the literature in support of conflicting interpretations of the data.

The key wave normal test was applied to each of the 11 cases; the dispersion and polarization tests were applied only to the limited extent that the properties of the particular data sets would permit.

The basic wave normal test for evidence of whistler mode propagation resulted in a separation into two groups, six of which passed the test and five of which did not. All six that passed involved burst activity at 100 Hz only. Of these six, two were such that activity at both 100 and 730 Hz was possible according to the wave normal test. The lack of activity at 730 Hz was generally consistent with the pulse broadening and associated attenuation with altitude predicted by the dispersion test. The polarization test, although applied to all six cases, produced usable results in one only, in which the data showed agreement with the predictions for whistler mode propagation.

Of the five cases that did not pass the basic wave normal test for evidence of whistler mode propagation, one involved 100 Hz only, while in the four others there was activity both at 100 Hz and at one or more other frequencies.

On the basis of these results we conclude that subionospheric lightning is a candidate source to explain at least some of the OEFD bursts. We caution that in terms of our own program of analysis, a persuasive case for such a source can be made only after completion of additional studies in which the more stringent whistler mode dispersion and polarization tests are applied to other cases that pass the wave normal test, and in which a larger body of data can be tested for wave normal behavior.

A logical question for future study is the extent to which all cases of activity at 100 Hz only pass the wave normal test for whistler mode propagation. To the extent that most do, support would be provided for the decision of previous investigators to regard 100-Hz-only cases as a homogeneous population for statistical purposes. Although six of the seven 100-Hz-only cases in our study passed the wave normal test, it would be premature for us to draw any conclusions on this point at the present time.

Note also that we have thus far considered only subionospheric sources of signals; tests should be developed and applied assuming source locations within the ionosphere, both local to and distant from PVO. For distant impulsive sources, we would still expect propagation to take place in the whistler mode, while for local waves, we would not expect the data to obey whistler mode relations.

One of the more fascinating and controversial aspects of the OEFD data is the occasional occurrence of multichannel bursts, with activity at frequencies clearly above the range to be expected for whistler mode propagation. In our present study of four such cases, none of the events in the various channels, including 100 Hz in each case, passed the wave normal test. The essentially different nature of some multifrequency cases in comparison to 100-Hz-only events was illustrated in one case in which our assumptions about horizontal stratification of the Venusian ionosphere were changed sufficiently to allow the wave normal test to be passed. The group delay and dispersion and polarization tests were then applied, but in neither case were whistler mode characteristics evident.

A question for future study will be the extent to which the 100-Hz signal in multichannel bursts fails the wave normal test for whistler mode propagation. The outcome of such studies should help in assessing the plausibility of explanations for such events in terms of non whistler mode penetration of the ionosphere from subionospheric lightning sources and in terms of plasma mechanisms local to the spacecraft. Investigations at Earth by other experimenters have revealed both anomalous ionospheric radio phenomena associated with nearby lightning [e.g., *Kelley et al.*, 1990] and dispersionless radio impulses in the middle magnetosphere that are clearly not lightning related [*Sonwalkar et al.*, 1990]. Further analysis of these effects may help in the interpretation of the OEFD data.

In the present work we have had occasion to reference previous work representing both sides of the OEFD controversy, but we have done so primarily for the purpose of mentioning particular previous assumptions and claims and not for the purpose of judging the broader merits of these works. As our studies continue, we expect to make more substantial contributions to resolution of the ongoing debate than are possible at this initial stage of our work.

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D. L. Carpenter and V. S. Sonwalkar, Space Telecommunications and Radioscience Laboratory, Stanford University, Stanford, CA 94305-4055.

R. J. Strangeway, Institute for Geophysics and Planetary Physics, University of California, Los Angeles, CA 90024-1567.

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