Observation of the Z Mode With DE 1 and Its Analysis by Three-Dimensional Ray Tracing

KOZO HASHIMOTO
Department of Electrical Engineering, Tokyo Denki University, Tokyo, Japan

WYNNE CALVERT
Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa

Certain Z-mode wave emissions in the Earth's magnetosphere have been identified using the wave spectra and polarization measurements of the DE 1 satellite. Although such emissions accompany the aurora, and thus presumably originate from the evening-sector auroral zone, they are found to occur over much wider ranges of latitude and longitude. Since the predicted cyclotron maser emission at the cyclotron frequency could not have produced waves which travel such great distances, as we have shown by three-dimensional ray tracing, it is proposed instead that these emissions must originate from lower altitudes within the auroral zone and probably from near the plasma frequency inside the auroral plasma cavity.

INTRODUCTION

Although auroral hiss in the whistler wave mode and auroral kilometric radiation (AKR) in the ordinary and extraordinary modes have been extensively studied from satellite radio observations in the auroral magnetosphere, much less is known about the Z-mode emissions in this region. Occurring only for frequencies between a cutoff below the plasma frequency and the upper hybrid resonance (see below), such Z-mode waves are constrained to remain within the magnetosphere and cannot escape, although they can perhaps couple to the escaping ordinary mode at the plasma frequency. The Z mode thus cannot generally be excited or observed from the ground (see Eckersley [1950], as cited to by Ratcliffe [1959]), and as a result, it is considerably less familiar than the other three magnetoionic wave modes, despite its potential interaction with auroral electrons and its potential usefulness as a diagnostic of auroral activity.

As shown in Figure 1, the Z mode extends from a cutoff frequency $f_Z$, given by

$$f_Z = -f_H/2 + \sqrt{f_H^2/4 + f_N^2}$$  (1)

where $f_N$ and $f_H$ are the plasma and cyclotron frequencies, respectively, and it terminates at a resonance which occurs at or below the upper hybrid frequency ($f_{UHR}$), depending upon the wave normal direction, where

$$f_{UHR}^2 = f_N^2 + f_H^2$$  (2)

The cutoff, which is wave angle independent, corresponds to the plasma condition $L = 0$ of Stix [1962], whereas the resonance, which varies with wave direction, corresponds to the condition

$$\tan^2 \theta = -P/S$$  (3)

in the same notation. The lowest frequency of this resonance, which occurs for strictly longitudinal propagation ($\theta = 0$), is the greater of the plasma and cyclotron frequencies, whereas the lesser of these two frequencies is the corresponding upper limit for whistler-mode propagation. In a cold electron plasma, equation (3) is equivalent to

$$\tan \theta = \sqrt{(f_N^2 - f^2)(f_H^2 - f^2)}/f^2$$  (4)

which readily shows this property when the right-hand side is equated to zero.

The magnetoionic Z mode is thus characterized by a cutoff and resonance on opposite sides of the plasma frequency and no accessibility to free space. Its wave polarization is right-handed with respect to the ambient magnetic field direction above the plasma frequency and left-handed below, for waves propagating oblique or along the magnetic field, and planar perpendicular to the field for strictly orthogonal propagation [see Allis et al., 1963, chapter 4].

In the ionosphere, where the plasma frequency is generally much greater than the cyclotron frequency, the entire frequency range of the Z mode from cutoff to resonance occupies only about half the cyclotron frequency (at most 400-800 kHz at frequencies of up to 30 MHz), and consequently, such waves cannot travel very far before they encounter either the cutoff or a resonance. In the auroral magnetosphere, however, the reverse is often true [Calvert, 1981], and the frequency range accessible to the Z mode expands to occupy most of the frequencies below the cyclotron frequency, extending down to and overlapping the region of auroral hiss emissions. In the AKR source region, for example, where the plasma frequency at a cyclotron frequency of 250 kHz might be as low as 5 kHz (see Plate 1, below), the Z-mode cutoff (ignoring ion effects) becomes only about 100 Hz and virtually the entire frequency range of auroral hiss emission becomes available for Z-mode propagation. Moreover, under these same conditions the upper hybrid limit for the Z mode is only about 50 Hz above cyclotron frequency and hence quite indistinguishable from the cyclotron frequency.
which also occupies the same frequency range by their up-
ported natural Z-mode waves detected with ISIS I sounder
per cutoff at the cyclotron frequency [Anderson et al., 1981;
receiver (although some may have actually been O-mode sig-
frequency (for \( f_N < f_H \)) and distinguished from the O mode
fore, despite its insignificance to ionospheric radio propaga-
tion because of its narrow frequency range and inaccessibil-
ity from the ground, the Z mode is on a more equal footing
in most measurements. In the auroral magnetosphere, therefore,
despite its insignificance to ionospheric radio propagating
because of its narrow frequency range and inaccessibility
the Z mode is on a more equal footing with the other three magnetoionic wave modes, extending in some cases all the way from quite low frequencies up to
and just slightly above the cyclotron frequency.

Apart from their prior study as artificial echoes produced
by the Alouette and ISIS topside sounder satellites [Calvert,
1966; Hagg et al., 1969; Colin and Chan, 1969], Z-mode
waves in the auroral magnetosphere were first identified in the
Hawkeye satellite measurement by their low-frequency
wave cutoff and then applied to help define the auroral
plasma cavity [Calvert, 1980, 1981]. They have since also
been detected with the ISEE and DE 1 satellites above the
upper cutoff of the whistler-mode auroral hiss at the plasma
frequency (for \( f_N < f_H \)) and distinguished from the O mode
which also occupies the same frequency range by their upper
cutoff at the cyclotron frequency [Anderson et al., 1981;
Gurnett et al., 1983]. Benson and Wong [1987] have also re-
ported natural Z-mode waves detected with ISIS 1 sounder
receiver (although some may have actually been O-mode sig-
nals) and they attempted to identify the modes by compar-
ing the observed amplitudes with the predicted wave growth
rates of the cyclotron maser mechanism [e.g., Wu and Lee,
however, have performed two- and three-dimensional ray
tracing of the Z mode in hopes of accounting for the broad-
band nature of this radiation [Gurnett, 1983; Gurnett et al.,
1983] but found instead that the observed broad bandwidth
could not be explained by the maser mechanism producing
orthogonal emission near the cyclotron frequency.

The plasma wave instrument (PWI) on DE 1 [Shawhan et
al., 1981] can also measure polarization as well as spectra,
and the purpose of this paper is to present some of its si-
multaneous spectra and polarization measurements showing
Z-mode emissions. These observations, for the low-density
region of the magnetosphere above the polar cap and au-
oral zone where \( f_N < f_H \), will be summarized in a form of a
global occurrence distribution and compared with our own
three-dimensional ray tracing results. The other Z-mode
emissions which have also been reported, for \( f_N > f_H \) by
Oya and Morioka [1983] will not be considered, nor will the
presumably related UHR noise band at the upper hybrid
resonance frequency [Mosier et al., 1973].

**Observations**

Wave polarizations are measured by the DE 1 PWI from a
one-bit correlation of two different sensor signals, essentially
to measure the phase difference between two different wave
components. The two sensors are chosen from among (1) a
200-m tip-to-tip rotating long-wire electric antenna perpen-
dicular to the spacecraft spin axis (\( E_s \)), (2) a 9-m tip-to-
tip tubular electric antenna parallel to the spin axis (\( E_s \)),
and (3) a loop antenna for measuring the wave magnetic-
field component parallel to the long-wire antenna (\( B_s \)).
Depending on the pair of sensors used, one can thus measure
the wave electric vector rotation sense (right-handed or left-
handed, using the \( E_s \) and \( E_s \) sensors), the wave propagation
direction (up or down, using \( B_s \) and \( E_s \) ), or else a combi-
nation of these two (right-up and left-down or left-up and
right-down from the \( B_s \) and \( E_s \) sensors). The satellite is in a
polar orbit (inclination 90°) with its spin axis perpendicular
to the orbit plane and the details of these measurements are
described by Shawhan et al. [1981] (see also Calvert [1985]).

The available DE 1 wave data from September 1981 to
August 1983 were surveyed for the occurrence of Z-mode
waves in the frequency range between \( f_N \) and \( f_H \), where also,
as is typical of the polar regions at DE 1 altitudes,
\( f_N < f_H \). In this study the Z mode was identified by one
or more of the following criteria:

1. A right-handed polarization is detected with the \( E_s \)
    and \( E_s \) sensors between the plasma and cyclotron frequen-
cies.

2. A up-going right-handed polarization is detected with the
    \( B_s \) and \( E_s \) sensors in the same frequency range, some-
times also showing a reversal at the cyclotron frequency
    which can be attributed to weaker O-mode signals become
    unmasked at the upward termination of the Z-mode signals,
as discussed below.

3. There is a distinct upper cutoff at \( f_H \) in the amplitude
    spectrograms, provided it is also clear from the auroral hiss
    cutoff or other information that \( f_N \) is less than \( f_H \).
The first of these is most certain, provided \( f_N \) is clearly less than \( f_H \), since the \( E_z-E_x \) measurements indicate directly the wave electric vector rotation sense [Calvert, 1985] and only the Z mode has a right-handed sense in the pertinent frequency range. Plates 1a and 1b are an example of this, showing respectively the wave amplitude and rotation sense of the waves received by DE 1 during a south bound pass through the northern hemisphere auroral zone, with the latter showing as red a right-handed rotation sense with respect to the local magnetic field, and green, the opposite rotation sense (actually with respect to the spacecraft nadir, but for waves received in the northern hemisphere, this amounts to the same thing). In the right-hand panel, therefore, the red and green colors indicate directly the right-handed and left-handed magnetoionic wave polarizations, respectively. The white lines in both these figures, increasing from about 35 kHz on the left to 120 kHz on the right, indicate the local cyclotron frequency, \( f_H \), and the clear upper cutoff of the whistler mode auroral hiss at about 15 kHz between 0640 and 0715 UT in Plate 1a indicates the plasma frequency. The measured polarization sense in Plate 1b was thus right-handed (red) both above and below the plasma frequency, and this of course indicates whistler mode waves below the plasma frequency, as expected, and Z-mode waves above. Although matters change after about 0715 UT, as described elsewhere [Calvert and Hashimoto, this issue], it is thus quite clear that the green and light blue amplitudes in Plate 1a beforehand, between about 15 kHz and the cyclotron frequency, correspond to Z-mode waves. Also in Plate 1a, and most evident before about 0655 UT, there was a clear upper cutoff of these signals at the cyclotron frequency. This is an example of our third criterion for identifying Z-mode waves in the DE 1 observations, attributed to the cutoff of Z-mode propagation between the cyclotron frequency and the upper hybrid resonance. In this case, however, it only tends to reinforce our interpretation based more directly on the polarization sense measurements.

The transition from the whistler-mode to the Z-mode at the plasma frequency in Plate 1a presumably occurs simply because the stronger whistler-mode waves (yellow and red in the figure, versus light blue and green) cease at the plasma frequency and thus leave uncovered the weaker Z-mode signals at higher frequencies. In such cases, the intensities of the Z mode were generally about 20 dB weaker than those of the whistler mode. Obscured as they are by the whistler mode hiss, these Z-mode signals may or may not extend to lower frequencies.

It is, however, significant that there is no band of green or gap just above the whistler-mode upper cutoff in Plate 1b, since that clearly indicates that the whistler mode must have extended all the way up to the plasma frequency and hence that its upper cutoff is a reliable indicator of the local plasma frequency. Were this not the case, there would have had to have been either some left-handed Z-mode signals in this region, corresponding to a green polarization below the plasma frequency in Plate 1b, or else a gap between the Z-mode signals above the plasma frequency in Plate 1a and the whistler-mode signals below. Since neither of these occurred, it is thus quite certain that the upper hiss cutoff must have been exactly at the plasma frequency to within about 10%. Such observations, incidentally, should be quite critical to the work of Persoon et al. [1988] and others who use the whistler-mode cutoff to measure the plasma frequency, since they offer a new and unambiguous opportunity to verify that technique.

An example of the second identification method, using the \( B_z \) and \( E_z \) sensors, is shown in Plates 1c and 1d. In this case, what appears to be a more-or-less continuous pattern in the amplitude spectrogram (Plate 1c) turned out to be two different modes with opposite polarization on opposite sides of the cyclotron frequency, as indicated by the sudden change of polarization in Plate 1d. In this figure, purple indicates either upward going left-handed or downward going right-handed waves, and yellow the opposite. Above the boundary, therefore, consistent with the purple color in Plate 1d, one might thus have either upgoing O mode or downdgoing X mode; and below the boundary, either down-going O mode or upgoing Z mode. Above the boundary the choice is obvious, since there are no known sources above the cyclotron frequency to send X-mode waves downward. This means that the radiation above the cyclotron frequency in Plates 1c and 1d must have come upward from below and hence must have been in the O mode. Below the boundary, on the other hand, one might have either an O-mode source at the cyclotron level radiating downward or else a Z-mode source at some lower level radiating upward. Although an O-mode source at the cyclotron frequency might be possible, as seems to be the case in generating the O-mode by-product of the AKR [Calvert, 1982; Hashimoto, 1984; Mellott et al., 1984], this does not seem appropriate here, since there are no localized amplitude enhancements suggesting sources at this frequency, nor is it expected to have such sources so far from the auroral zone, as would have to be the case for such signals which extend all the way up to the local cyclotron frequency. This case, moreover, seems comparable to that in Plates 1a and 1b, where the right-handed polarization of these waves is quite clear. Such yellow signals, therefore, detected with the \( B_z \) and \( E_z \) sensors between the plasma and cyclotron frequencies, will be interpreted as Z-mode waves coming upward from below.

Once again, the transition across the boundary in Plate 1d seems to be caused by one mode terminating and leaving uncovered a weaker component which may or may not have also been present on the other side. The sudden polarization change in Plate 1d is thus attributed to the unmasking of weaker O-mode signals at the upper frequency limit for Z-mode propagation, and this is also consistent with the apparent decrease of intensity across this boundary in Plate 1c between about 1020 and 1035 UT. It therefore seems that there is a hierarchy of amplitudes for such auroral waves, with the whistler-mode hiss being strongest, the Z-mode waves being intermediate, and the O-mode waves just above the cyclotron frequency being weakest. These O-mode waves, incidentally, should not be confused with the O-mode AKR by-product of Mellott et al. [1984], which is often much stronger than any of these and is generally characterized by a conspicuous displacement above the local cyclotron frequency (e.g., above about 50 kHz in these figures or at 0730-0740 UT in Plates 1a and 1b).

Our third criteria, of detecting abrupt signal cutoffs at the cyclotron frequency, was the one which was actually used most to determine the occurrence of auroral Z-mode emissions. Although by itself somewhat less certain because it relies only upon the amplitude measurements, this permitted
Plate 1. DE 1 radio spectrograms showing auroral Z-mode emissions, with the amplitude spectrograms on the left (Plates 1a, 1c, and 1e) showing the wave signal strengths received by DE 1 as a function of the frequency and time, and the corresponding polarization spectrograms on the right (Plate 1b using antennas E_x and E_y; and Plate 1d and 1f using antennas E_x and B_z) showing the measured wave rotation sense. For the three cases shown (Plates 1a and 1b, 1c and 1d, and 1e and 1f), the Z mode between the plasma and cyclotron frequencies is identified by an abrupt decrease of the signal strength at the cyclotron frequency upper limit for Z-mode propagation (the white lines in Plates 1a, 1c, and 1e) and by a right-handed polarization sense (red in Plate 1b regardless of direction and yellow in Plate 1d and 1f for assumed upward propagation).
collecting significantly more cases, since the corresponding polarization measurements were not always available. An example of this, but one for which the confirming polarization measurements were also available, is shown in Plates le and lf. In the morning sector and hence presumably quite far from the auroral zone source of these emissions, Plate le clearly shows an abrupt upper cutoff at the cyclotron frequency, at about 20 kHz between 0920 and 0940 UT, along with a right-handed polarization in Plate lf for assumed upward going waves during this same period. Since in this case it was clear from the auroral hiss upper cutoff that the plasma frequency was less than about 6 kHz, these signals must have been in the Z mode. From experience with such cases, it was quickly concluded that these sharp upper cutoffs are good indicators of Z-mode waves (as also adopted by Gurnett et al. [1983]).

The positions where Z-mode emissions were detected with DE 1 using these criteria, between the plasma and cyclotron frequencies, are shown in Figure 2, based on 20-min resolution for orbit data which were used. Figure 2a shows the occurrence in invariant latitude versus local time, and Figure 2b shows it in geocentric distance versus magnetic latitude.

Z-mode emission between the plasma and cyclotron frequencies thus frequently occurs throughout the polar region, although they tend to concentrate as expected in the evening-sector auroral zone. At other times, however, as in Figure 2 for roughly one-third of the cases, they were observed quite far from this apparent evening sector auroral zone source, sometimes even as far as over the pole and into the dayside hemisphere (although, as in Plate le, separate sources at different longitudes, such as that producing the concurrent auroral hiss, cannot be ruled out). The Z mode, therefore, although presumably generated only in the evening auroral zone, must be capable of propagating over considerable distances, and this is one of the principal new results of this analysis, as will be developed further in the next section.

**RAY TRACING**

Three-dimensional ray tracing was performed in order to determine where the possible Z-mode wave source or sources might be located. This ray tracing employed the same density model as a previous AKR ray-tracing study [Hashimoto, 1984], including both an auroral plasma cavity and a plasmapause, but with no longitudinal dependence. The cavity in this model was centered on an invariant latitude of 70°, with a width and density profile chosen to fit the original Hawkeye observations [Calvert, 1981], and the plasmapause was placed at the standard position of L = 4 [see Hashimoto, 1984].

In order to represent different emission directions, the initial wave angles for the ray tracing were varied both in azimuth and in wave-normal angle with respect to the source magnetic field. Our standard values chosen to represent an azimuthally symmetric source were 0° (poleward in the magnetic meridian), 45°, 90° (east-west), 135°, and 180° (equatorward) and to represent sources approximately orthogonal to the source magnetic field, 60° and 80° (with respect to the upward field direction and hence upward relative to the magnetic horizon at the source by 30° and 10°, respectively) and 100° (10° downward). All of the ray of the paths were started on an assumed auroral source field line at 70° invariant magnetic latitude, and they were calculated until the propagation speeds became slow near the cyclotron frequency, since that is presumably where the waves would become lost to cyclotron damping. In the following figures the resulting ray paths were plotted in geocentric distance versus magnetic latitude (diagram a), and also in invariant latitude versus magnetic-longitude (diagram b).

Figure 3 shows the calculated ray paths at 100 kHz for Z-mode waves started somewhat below the local cyclotron frequency, at an altitude on the source field line where \( f = 0.9f_H \). The solid lines in this figure with second parameters of 0° and 180° represent ray paths with initial azimuths
in the source magnetic meridian (which of course must always remain in that meridian because of our magnetic-field-aligned symmetric density model); the dashed lines labeled 90° represent paths with initial azimuths perpendicular to the source meridian; and the dot-dash lines labeled 45° and 135° represent paths initially oblique to the meridian. In each case, as discussed above, the first parameter indicates the corresponding initial wave angle with respect to the upward field direction.

All of the initially upgoing ray paths in Figure 3 quickly reached the cyclotron frequency where their wave-normal angles became small and their ray directions turned away from the magnetic field (although in most cases too abruptly to be clear in the figures). The initially downgoing waves (labeled 100° in the figure) traveled farther before this occurs, with those directed equatorward (labeled with 135° and 180°) also being reflected at the plasmapause. Figure 3b shows the corresponding excursions in longitude for the ray paths directed out of the magnetic meridian, although in this case the different initial elevations caused little difference, and hence the longitude-latitude tracks are superimposed.

Figure 3 thus suggests that orthogonal generation near the cyclotron frequency cannot produce ray paths which travel very far. For example, in this case (for \( f = 0.9f_H \) at the source) the ray paths rarely reach more than about 30° of longitude or 10° in latitude from the source. Moreover, as the source moves closer to \( f_H \), the resulting propagation paths should become even smaller. The Doppler-shifted cyclotron maser instability [Hewitt et al., 1983; Omidi et al., 1984], which requires such orthogonal generation very near the cyclotron frequency, therefore, cannot produce observable Z-mode waves very far from the source. On the other hand, the Z mode in Figure 2 is observed over at least twice as large a region and generally well below 90% of the cyclotron frequency. Consequently, as was first pointed out by Menietti and Lin [1985, 1986], it is hard to explain the Z-mode observations on this basis unless either the source is more widely distributed or the initial waves are directed mostly downward.

This same conclusion also results from the observed bandwidth of the Z-mode emissions, which according to Plate 1 often extends down to well below the local cyclotron frequency. However, for this to be the case with a cyclotron source, since the cyclotron frequency decreases with altitude, one must have propagation downward from a source above the satellite, and orthogonal generation near the cyclotron frequency cannot produce such downward propagation.

On the other hand, waves which are directed downward at the cyclotron frequency can travel further and reach lower altitudes, as illustrated by Figure 4. This figure shows the corresponding ray paths for initial wave angles of 120°, 140°, and 160°, all downward with respect to the source magnetic horizon. Notice in this case that the radiation now generally fills the region poleward of the plasmapause both at longitudes quite far removed from the source and to altitudes
extending down to the Z-mode wave cutoff. Some of the waves, in fact, either directly or indirectly after reflection at the plasmapause, end up reaching the dayside hemisphere at fairly low latitudes (the apparent poleward reflection in Figure 4a actually being an artifact of the cylindrical projection used to produce that figure).

Figures 3 and 4 thus illustrate constraints on a possible cyclotron source, indicating basically that its emissions must be directed downward in order to reach the satellite at frequencies significantly below the cyclotron frequency and at the positions far from the auroral zone where Z-mode signals are observed. Since the cyclotron maser mechanism requires upward or almost orthogonal emission, it would thus seem to be ruled out as a possible source of the Z-mode signals which we observe.

However, waves started at lower normalized frequencies (or equivalently, at lower altitudes for a given frequency) can also travel farther and reach the satellite at the frequencies and positions where Z-mode signals are observed. This is illustrated by Figure 5, which shows the ray paths for a source just above the plasma frequency, at the altitude where \( f = 1.01 f_N \) at a frequency of 100 kHz. Here the ray paths also generally fill the region poleward of the plasmapause at frequencies up to the local cyclotron frequency and at longitudes extending more than 90° around the Earth from the source (although not all paths were computed here for computational reasons). Although a number of these ray paths are reflected at the plasmapause, the apparent reflections poleward of the source in Figure 5a are again artifacts of cylindrical projection. The hook at the cyclotron

---

**Figure 4.** Examples of ray paths started near the cyclotron frequency (\( f_H \)) for 100 kHz Z-mode waves and downward emission, (a) in Earth radius versus geomagnetic latitude plane, and (b) in invariant latitude versus local time (longitude).

**Figure 5.** Examples of ray paths started near the plasma frequency (\( f_N \)) for 100 kHz Z-mode waves, (a) in Earth radius versus geomagnetic latitude, and (b) in invariant latitude versus local time (longitude).
frequency which is produced as the Z-mode resonance cone opens is also evident for some of these ray paths, including that labeled (80°, 90°) where it produced what looks like a second plasmapause reflection, but which actually occurs just short of that position (see Figure 5b, recalling that our \( L = 4 \) plasmapause occurs for \( \text{INV. LAT.} = 60° \)).

This figure confirms that off-meridional propagation can extend far from the source in local time. This is consistent with the observation in Figure 2 that the Z-mode emissions are observed over a wide range of local times. Even if waves were started at \( f = 0.5f_N \), these ray paths would be essentially the same. Emission near \( f_N \) rather than \( f_H \) thus seem to explain the Z-mode observations best.

Ray paths for Z-mode waves at 20 kHz are shown in Figure 6, where all of the parameters were the same as those for Figure 5 except for the frequency. Here the waves start from a lower altitude and reach much higher altitudes before they encounter the cyclotron frequency and they readily propagate more than 90° in longitude, thus explaining the morning side observations at low frequencies in Plate 1e and Figure 2. Other essential features are similar to those of Figure 5. This figure accounts for the Z-mode observations at low frequencies, and it also shows an interesting phenomenon at 62° latitude and 4 RE where the ray paths suddenly reverse direction at the plasma frequency.

This case, moreover, is a bit more complicated because of oblique reflections at the poleward edge of the auroral cavity. For example, the two ray paths labeled 60°, 45° and 80°, 135° are in fact reflected twice at this boundary, and this peculiar phenomenon, which is comparable to whistler-mode ducting by an overdense L shell, is caused by a combination of the increased density at the cavity wall and the decreased magnetic field strength with altitude. On the other hand, some of the other apparent reflections at lower altitudes in Figure 6a are again illusions produced by cylindrical projection (e.g., for 100°, 45° and for 80°, 45°). Just outside the auroral cavity and at the lowest altitudes in Figure 6a, the waves extend to below the plasma frequency, having crossed the density step at the cavity wall without significant deflection. Although generally obscured by the stronger auroral hiss emissions in this region, such waves might extend down to the local Z-mode cutoff and thus account for the previous cutoff observations of Z-mode waves in this region [Calvert, 1981]. However, none of these waves penetrate into the plasmasphere, and so the Z-mode waves reported for this region by Oya and Morioka [1983] will require a different explanation.

**DISCUSSION**

Figure 7 shows refractive index surfaces for the Z mode, where \( f_N/f_H = 0.4 \). The elliptical and hyperbolic curves in each figure show those for \( f/f_H = 0.99 \) and \( 1.01 \), respectively. The magnetic field direction is vertical. Refractive index \( n \) in each curve for the Z mode is much larger in the magnetic field direction than that perpendicular to it. At frequencies close to \( f_H \), the ray direction (direction of the group velocity) is almost perpendicular to the magnetic field for a wide range of the wave normal angles. For meridional propagation and small electron density gradients, a component perpendicular to the magnetic field must be kept constant as the wave propagates, because the refractive index is mainly dependent on \( f_H \) and the equirefractive index plane is close to the equigeomagnetic field plane, both of which are almost perpendicular to the magnetic field. As \( f \) becomes closer to \( f_H \), the wave normal angle becomes smaller and \( n \) becomes larger. As a result the waves suffer from the cyclotron damping. For off-meridional propagation, the wave normal has a component perpendicular to the meridional plane. Therefore the wave normal angles are larger, and waves can propagate over longer distances in off-meridional directions before cyclotron damping occurs.

![Fig. 6. Examples of ray paths started near the plasma frequency \( (f_N) \) for 20 kHz Z-mode waves, (a) in Earth radius versus geomagnetic latitude, and (b) in invariant latitude versus local time (longitude).](image_url)
It is usually difficult for the Z-mode waves to pass through a point \( f = f_H \) if a boundary for Snell's law is almost perpendicular to the magnetic field direction [Gurnett et al., 1983]. According to ray tracing results, \( f \) can sometimes exceed the local \( f_H \) slightly, but the wave normal angles are small, and hence these waves are damped. This seems to be consistent with the observations although \( f_H \) and \( f_{UHR} \) are too close to be distinguished.

We have shown that waves generated near \( f_N \) rather than \( f_H \) can propagate longer distances and be observed far from the source. Although ray tracing cannot tell exactly what frequency is the best, the plasma frequency \( f_N \) is probably the best candidate, and suitable new generation mechanisms are yet to be proposed. Since strong whistler-mode auroral hiss emissions (the funnel-shaped hiss) presumably exist just below \( f_N \), they might be converted to the Z mode, although the efficiency of such conversion needs to be examined. Electric field intensities of the Z mode in the auroral region are generally blue in Plates 1a and 1c and are thus about 20 dB weaker than those of the whistler mode waves shown as green. This suggests the possibility that the Z-mode waves might be mode-converted from the stronger whistler-mode hiss at the plasma frequency.

### Conclusions

Z-mode waves were identified with the wave polarization data as well as the dynamic spectra observed with the DE 1 satellite. It was found that Z-mode waves are rather commonly observed over a wide range of frequencies and local times. Ray-tracing studies have clarified that either downward emissions at the cyclotron frequency or emissions near the plasma frequency, rather than orthogonal emissions at the cyclotron frequency, can explain these Z-mode observations, the most likely one being generation near the plasma frequency. A source region of the Z mode is assumed to be on almost the same field lines as that of the AKR. It is, however, difficult to narrow down the frequency range because the ray paths are not much dependent on the starting conditions when they are generated well below the plasma frequency. Theoretical investigations for the Z-mode generation or conversion near the plasma frequency are under way. Off-meridional propagation also seems to play an important role for a long-distance propagation of the Z mode.

### Acknowledgments

The authors thank D. A. Gurnett for access to the data and R. L. Huff for his help with data analysis. This work was supported in part by the Dynamics Explorer program under NASA contract NAG5-310, partly by NASA grant NAGW-1206, and partly by a grant-in-aid from the Japanese Ministry of Education, Project 61540309.

The Editor thanks R. G. Hewitt and I. B. Iversen for their assistance in evaluating this paper.

### References


Hashimoto, K., A reconciliation of propagation modes of...


— W. Calvert, Tokyo Denki University, Hatoyama-Machi, Saitama 350-03, Japan.
K. Hashimoto, Department of Electrical Engineering, Tokyo Denki University, Kanda, Tokyo 101, Japan.

(Received April 4, 1989; revised August 9, 1989; accepted August 10, 1989.)