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DE 1 Observations of Harmonic Auroral Kilometric Radiation

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The plasma wave instrument on board the DE 1 spacecraft has observed several intervals of auroral kilometric radiation during which harmonic structure is clearly present. We present evidence, some of which is based on unique capabilities of the DE instrument, which argues strongly that the harmonic structures are natural rather than instrumental in origin. The harmonic emissions occur infrequently, but when present may persist for intervals of up to an hour. The emissions are relatively narrow band and consist of a relatively weak fundamental (10^{-14}–10^{-11} V^2/m^2 Hz) accompanied by an even weaker second harmonic. The ratio of power in the fundamental band to the power in the harmonic ranges from 10 to 100. In all cases, polarization data indicate that the fundamental is a left-hand ordinary (*L-O*) mode emission while the harmonic is right-hand extraordinary (*R-X*) mode. These observations are consistent with predictions based on the cyclotron maser mechanism.

INTRODUCTION

Auroral kilometric radiation (AKR) is an intense impulsive radio emission, with frequencies between 50 and 700 kHz, which originates on nightside auroral zone field lines in association with discrete auroral arcs [*Gurnett*, 1974]. Its general properties are well established, but questions have been raised by reports of harmonic structure in AKR records. The plasma wave instrument (PWI) on board the DE 1 satellite has unique measurement capabilities which provide important new information about harmonic AKR, which we present in this paper.

Harmonic structure in the auroral kilometric radiation was first observed on ISIS 1 ionograms by *Benson and Calvert* [1979], who tentatively ascribed it to nonlinearities in the instrumental response. However, further work produced evidence for a natural origin [*Benson*, 1982], and detailed studies of the properties of the harmonic structure observed in the ISIS 1 data have since appeared [*Benson*, 1984, 1985]. The origin of the signals has, however, remained controversial [*Calvert*, 1983; *Benson*, 1985]. One of the primary difficulties is that the ISIS 1 orbit, which is restricted to relatively low altitudes, often placed the spacecraft directly in the AKR source region. In this region the emissions are strong enough that the ISIS 1 receiver was often saturated. Therefore one has good reason to suspect nonlinearities in the instrument response. DE 1's higher altitude, in contrast, places it far from the source region, where emissions are generally weaker and nonlinear instrumental responses are much less likely.

Several mechanisms for producing the harmonic structure have been suggested. Most of them involve some variation on the *Wu and Lee* [1979] cyclotron maser instability [*Lee et al.*, 1980; *Wu and Qiu*, 1983; *Melrose et al.*, 1984], although entirely different mechanisms have also been invoked [*Oya and Morioka*, 1983]. *Lee et al.* [1980] presented the first discussion of the generation of harmonics by this mechanism. Their calculations predicted the presence of second harmonic radiation, but with small growth rates in the usual AKR source region, and with relatively high growth rates only in regions of high plasma density. This general result has been confirmed by succeeding calculations [*Hewitt et al.*, 1982; *Wu and Qiu*, 1983; *Melrose et al.*, 1984; *Winglee*, 1985]. This approach accounted reasonably well for the presence of the second harmonic emissions, but not for the higher harmonics observed by Benson.

Measurements made by the DE 1 plasma wave instrument can clarify several of the questions which have been raised by observations of harmonic AKR. The ability of this instrument to determine wave polarizations has proven particularly helpful in this regard, showing that the harmonic AKR propagates in two modes: the fundamental in the left-hand polarized ordinary mode, and the harmonic in the right-hand polarized extraordinary mode. The DE measurements provide evidence for the natural origin of the harmonic structure and are in good agreement with predictions based on the cyclotron maser mechanism.

INSTRUMENTATION AND OBSERVATIONS

The DE 1 satellite is in a polar orbit with a 90° inclination, an apogee of 4.65 R_E geocentric, a perigee altitude of 675 km, and an orbital period of 7 hours. The satellite spins in a "reverse cartwheel" mode, with its spin axis perpendicular to the orbital plane (see *Hoffman et al.* [1981] for details of the spacecraft and orbital characteristics). This paper reports on data from the DE 1 plasma wave instrument and includes measurements dating from launch (August 3, 1981) through the end of 1982. The plasma wave instrument makes spectral and polarization measurements over a frequency range of 2 Hz to 400 kHz [*Shawhan et al.*, 1981]. The instrument uses two dipole antennas for electric field measurements, one oriented along the spin axis (EZ) and the other perpendicular to the spin axis (EX). Magnetic field measurements are made using a rotating loop antenna (B).

We have used data from the sweep frequency correlator (SFC) of the plasma wave instrument, which provides a record of the phase difference between signals from various pairs of antennas. Wave polarizations and directions of arrival can be determined from these records when the correlator is connected to the two electric antennas, and wave polarizations can be inferred when the EX and loop antennas are used [*Shawhan and Gurnett*, 1982; *Calvert*, 1985].

Plate 1 presents examples of second harmonic auroral kilometric radiation observed by DE 1 during two different

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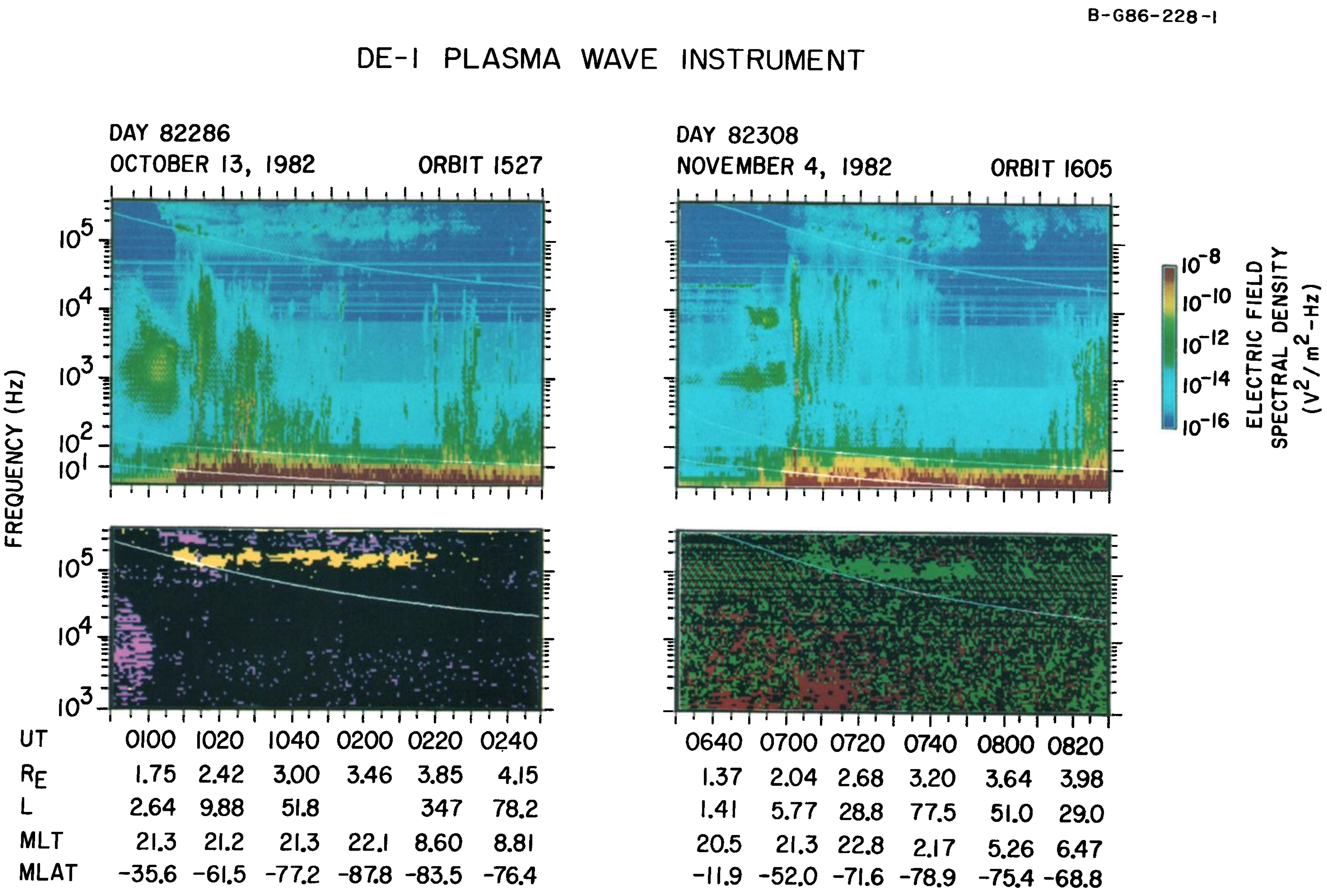

Plate 1. Electric field (top) and polarization (bottom) spectrograms. The curved white lines represent the local electron (upper) and proton (lower) gyrofrequencies, and the emissions adjacent to and above the electron gyrofrequency are AKR. In the first case the instrument was in the EX-B mode, and left-handed radiation is shown in yellow and right-handed in purple. In the second case the instrument was in the EX-EZ mode, and green represents left-hand polarized radiation, and red represents right-handed.

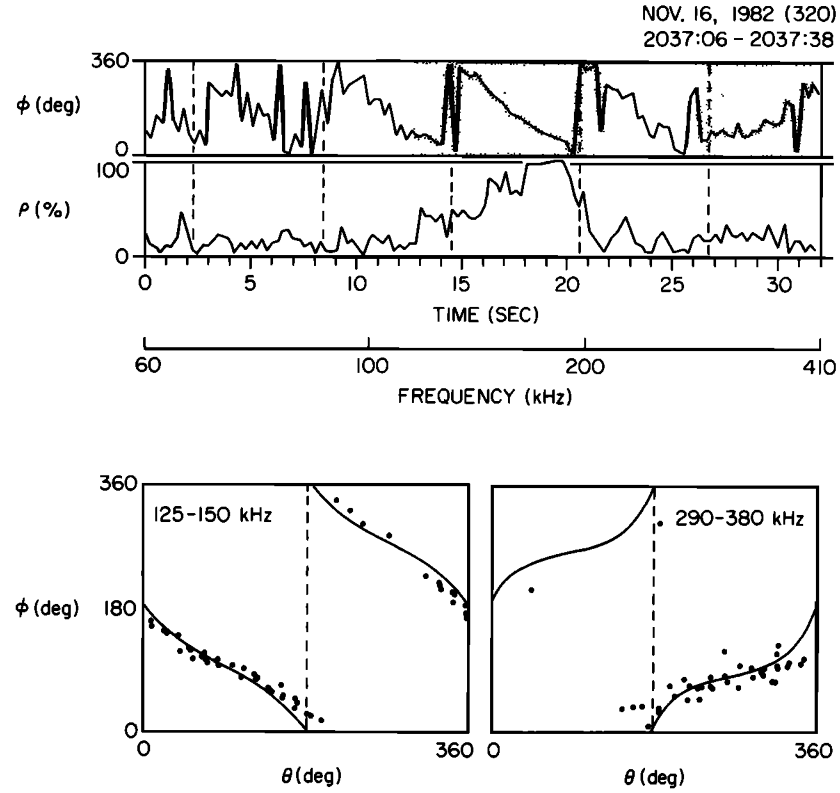

Fig. 1. Phase plots and fits for November 16, 1982. The top panels display the relative phase between signals from the two orthogonal electric field antennas, and the correlation between those signals, as a function of time (or, equivalently, frequency). The single-frequency sweep is taken in a little over five rotations of the spacecraft, as can be seen from the nadir crossings, which are marked with dotted vertical lines. Fits to these functions over the bandwidths of the fundamental and harmonic signal are shown in the bottom panels.

intervals. Electric field intensities are shown in the top panels, and the associated wave polarizations are presented in the bottom panels. The high-frequency emission appearing adjacent to and above the gyrofrequency is AKR. In these examples, as in all other cases, the fundamental is left-hand polarized (*O* mode), and the harmonic is right-hand (*X* mode) polarized.

Origin of the Harmonic Structure

Specific features of the harmonic AKR and of the response characteristics of the plasma wave instrument argue strongly that the DE harmonics are natural rather than instrumental in origin. Of particular interest in this connection are the preflight calibration data on the instrument response to strong input signals. From these data we can characterize the behavior of the instrument fairly completely. The calibrations show that nonlinearities cause a response at integral fractions of the passband frequencies, and at twice the passband frequencies. Some response can be seen at a much lower level at other frequencies. This effect diminishes rapidly with decreasing input signal level, effectively vanishing at an input level of ~0.03 V. As we outline below, the characteristics of the harmonic signals discussed in this paper differ in significant ways from those which would result from instrumental nonlinearities, and we argue that the weight of the evidence points to a natural origin.

1. According to calibration data, the amplitude of the signals associated with harmonic AKR is much too weak to produce instrumental harmonics.

Calibration data indicate that detectable spurious second harmonic signals should appear when the receiver input signal exceeds ~1 mV/m (assuming use of the more sensitive spin plane antenna). This distortion threshold is 3 orders of magnitude higher than the peak amplitudes of the fundamental signals associated with the DE 1 harmonic AKR, which can reach amplitudes of 10^{-3} mV/m. We also note that the harmonic signals persist throughout long intervals, during which time the intensity of the fundamental has an average value an order of magnitude lower than these peak amplitudes (of the order of 10^{-4} mV/m). That is, the amplitude of the fundamental associated with the harmonic AKR is much too low for one to expect it to produce instrumental harmonics.

This inference is of course subject to the argument that peak intensities within a given measurement period may be significantly higher than the values measured if intensities change more quickly than the instrument can respond. There is evidence, however, outlined in point 2, which suggests that this is not the case for the DE 1 harmonic AKR.

2. Instrumentally generated second harmonics should be accompanied by other observable spurious effects, which are not seen.

AKR is generally detected in the uppermost channel of the SFC, which sweeps through the frequency range from 50 to 410 kHz. There is a useful symmetry in the nonlinear response pattern of this channel of the SFC: the level of the spurious response at one half of a passband frequency is approximately the same as that of the signal at twice the passband frequency. Thus a monochromatic input signal, at a power level great enough to generate a spurious second

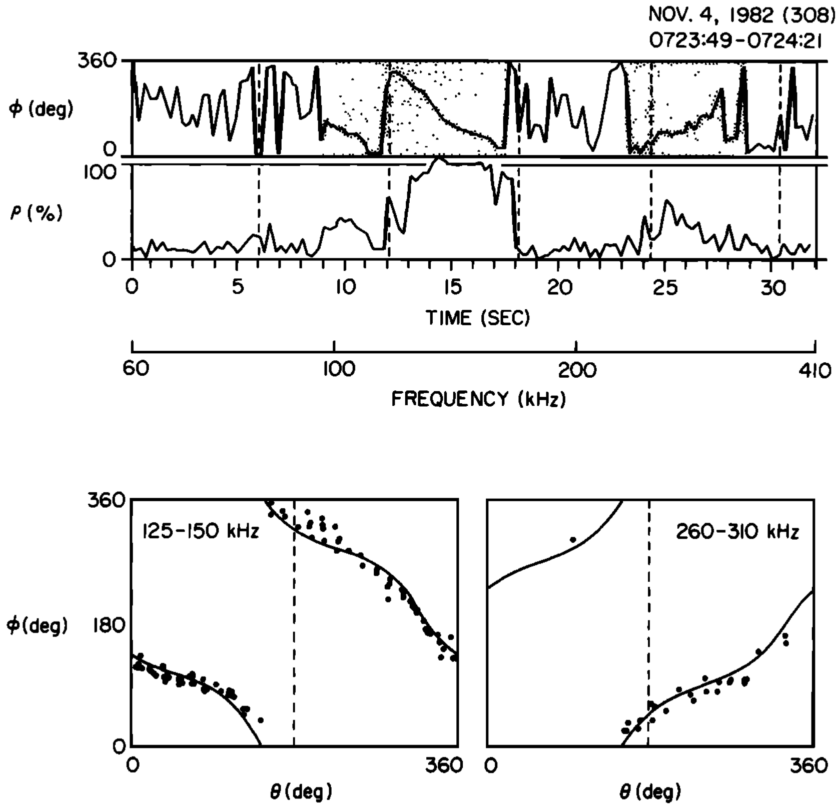

Fig. 2. Same as Figure 1 except November 4, 1982.

harmonic, will also generate equal amplitude spurious emissions at one-half the passband frequency. This effect would appear in the frequency/time spectrograms as "ghost" emissions at one-half and integral multiples of the actual signal frequency. Auroral kilometric radiation is, on the other hand, a relatively broadband signal, and even in the case of the relatively narrow band emissions studied here, extends over four to five frequency steps. In such cases the spurious emissions may extend to the upper and/or lower frequency boundaries of the SFC channel. This effect, which is termed "channel saturation," produces a sharp amplitude discontinuity at the lower edge of the channel and can in fact be observed during intervals of intense AKR emission. Such discontinuities are not seen during any of the intervals of harmonic AKR, however, indicating that signal levels are below threshold for observable nonlinear effects.

3. The EX and much weaker EZ signals are in phase and well correlated for both fundamental and harmonic.

The EZ antenna is relatively insensitive, and much of the time, second harmonic AKR signals are at or below the background noise level for the EZ antenna. The very weakness of the EZ signal adds weight to the argument that the fundamental signal in our events is too weak to produce instrumental harmonics. Additionally, however, when the harmonic signal is detected by the EZ antenna, the correlator confirms that its signals are in phase with those from the EX antenna, and correlation coefficients between the two signals are reasonable.

4. Phase measurements of the observed second harmonic vary periodically at the spacecraft spin rate, whereas one expects the phase of instrument-generated second harmonics to vary at twice the spin rate.

Because of the rotation of the EX antenna, the phase/time signature of natural signals is periodic at the spacecraft spin period. On the other hand, for instrument-generated harmonics, when the phase of the fundamental changes by an amount ϕ, the phase of the second harmonic changes correspondingly, but by an amount 2ϕ. The measured phase for a second harmonic due to distortion should thus vary in time at twice the spin rate of the spacecraft. Although the phase signatures of the DE 1 AKR harmonics are noisy (see the top panels of Figures 1 and 2), the patterns are clearly periodic at the spin rate. No doubling of the pattern is indicated.

5. Variations in frequency/time structure between the fundamental and harmonic are difficult to explain in terms of purely instrumental response.

A fixed relationship is expected between fundamental and instrument-generated harmonic amplitudes unless signal variations occur during single-frequency sweeps (32 s in the case of the DE 1 PWI). The DE 1 harmonic AKR often exhibits frequency/time structure which does not show the precise correspondence between the fundamental and harmonic which one would expect from instrumentally generated signals. Examples of such structure can be seen, for instance, on day 286 of 1982 (Plate 1). In this case the fundamental emission first appears at 0107, is fairly strong, and shows a low-frequency cutoff near the local electron gyrofrequency. The second harmonic appears at 0103, 4 min before the fundamental, and has a low-frequency cutoff that tracks $2f_g$. The two emissions are quite similar in bandwidth and intensity. Later, during the same pass the two emissions behave differently. During the interval 0132–0138, for instance, the character of the two emissions differs; the fundamental is a relatively narrow band signal centered at

TABLE 1. DE Observations of Harmonic AKR

Year	Day of Year	UT	MLT	MLAT	Mode	*Kp*
1981	268	1710–1730	2300	50 to 60	EX, EZ	4
1981	295	1255–1325	2100	57 to 65	EX, B	7
1982	286	0100–0220	2100–0800	−35 to pole	EX, B	4
1982	308	0700–0800	2100–0400	−60 to −78	EX, EZ	2+
1982	320	2020–2120	1800	−53 to −77	EX, EZ	2

140 kHz, while the second harmonic is a significantly weaker emission distributed over a wider range of frequencies.

Observations

We have thus far found five examples of second harmonic AKR in the DE 1 data. (Note that because of the upper frequency cutoff of the instrument we could not see higher harmonics even if they were present.) These five cases and the general conditions under which they occurred are outlined in Table 1. All of the harmonic AKR occurred in the evening sector, where it was generally seen poleward of and coincident with auroral zone crossings. *Kp* ranged from 2 to 7 during the various intervals, with the long-lasting narrowband emissions tending to occur during the more quiet intervals. Satellite positions at the time of the observations corresponded to radial distances ranging from 2 to 4 R_E.

We have surveyed several hundreds of hours of DE data in our search for harmonic events, and we have found only a few cases of harmonic AKR in that time, indicating occurrence rates of at best a few percent. On the other hand, AKR is typically a much broader band emission than the signals studied here. It is possible that in some cases, harmonic structure is present but is masked by the broad bandwidth of the fundamental.

In the three most striking cases both the fundamental and the harmonic were relatively narrow in frequency (50–100 kHz), but two cases broader in frequency have also been found. Characteristics of the radiation in each case are presented in Table 2. Individual intensity and frequency measurements were obtained from printouts of the electric field amplitudes for instrument sweeps covering the intervals during which the harmonic emissions occurred. The intensities are well determined, and the standard deviation for the intensity ratio represents variation in the ratio itself rather than measurement error. The error in the frequency ratio is primarily a function of the frequency resolution of the PWI. As is shown, the events can be relatively long lived, typically lasting of the order of an hour or so. The intensity of the fundamental (10^{-13} V^2/m^2 Hz) is of the order of or a little less than that of the *O* mode examples which were studied in our earlier paper on AKR propagation modes [*Mellott et al.*, 1984]. The ratio of the intensity of the harmonic to that of the fundamental ranges from 0.01 to 0.1, with 0.1 being the more typical value. In some cases the correlation between the intensities of the two signals is quite high (0.96), and in other cases quite low (0.05). The ratios of the frequencies of the strongest emissions in each of the two bands are consistent with a value of 2.0 given the frequency resolution of the instrument.

When the PWI correlator is connected to the EX and EZ antennas, as it was for three of the harmonic AKR observations, direction-finding measurements are possible in addition to the polarization determinations [*Calvert*, 1985]. Determinations of the direction of arrival of the radiation are made from fits of the plot of the phase difference between the EX and EZ antennas such as those shown in Figures 1 and 2. The top panel in each case shows a plot of this phase difference as a function of time (or equivalently, frequency) as well as a plot of the correlation coefficient between the signals from the two antennas. Significant correlation between signals from the two antennas is seen only over the two relatively narrow frequency bands (shaded area) which represent the fundamental ($f \sim 150$ kHz) and the harmonic ($f > 250$ kHz) radiation. The shape of the phase plot in the two bands is determined by various features of the radiation. The polarization of the two emissions is reflected in the phase values of the plots at the nadir crossings (~270° implying a left-handed fundamental and ~90° implying a right-handed harmonic).

The actual direction of arrival measurements are made using routines which fit the data points within a given frequency range for a specified time interval. Such fits have been attempted for both the fundamental and harmonic in each of the cases where the spacecraft was in the EX-EZ mode, and examples of the resulting fits are shown in the lower panels of Figures 1 and 2. Reasonable characterization of the fundamental was possible in all cases. However, because of the relative weakness of the signal, description of the harmonic proved more difficult and was possible only for two short intervals, one each on November 4, 1982 (82 308), and November 20, 1982 (82 320).

Results of measurements for the two cases where direction-finding was possible on the harmonic are shown in Figure 3.

On November 4, 1982 (82 308), direction finding for the fundamental (bottom panel) was consistent with a source at the local gyrofrequency on the 70° field line. Measurements on the harmonic (top panel) indicated roughly equivalent directions of propagation.

On November 16, 1982 (82 320), the fundamental (bottom panel) again appeared to originate from field lines slightly higher in latitude than 70°. The direction of arrival of the harmonic (top) was essentially the same as that of the fundamental.

In an additional case (not shown) from September 25, 1981 (81 268), the fundamental appears to originate on the 75° invariant field line at an altitude consistent with generation at the local electron gyrofrequency. No measurements were possible on the harmonic in this case because of the weak-

TABLE 2. Characteristics of the AKR Harmonic Emissions

Year	Day of Year	I_0	I_1/I_0	f_1/f_0	r
1981	268	1.1×10^{-13}	0.11 ± 0.08	1.9 ± 0.2	0.96
1981	295	8.4×10^{-12}	0.58 ± 0.74	1.9 ± 0.2	0.07
1982	286	3.9×10^{-13}	0.12 ± 0.16	1.9 ± 0.3	0.18
1982	308	4.0×10^{-13}	0.14 ± 0.19	1.9 ± 0.2	0.05
1982	320	3.1×10^{-13}	0.01 ± 0.02	1.9 ± 0.2	0.44

I_0 is intensity of fundamental (V^2/m^2 Hz); I_1/I_0 is ratio of intensity of harmonic to intensity of fundamental; f_1/f_0 is ratio of frequencies of harmonic and fundamental; and r is correlation between intensities of harmonic and fundamental.

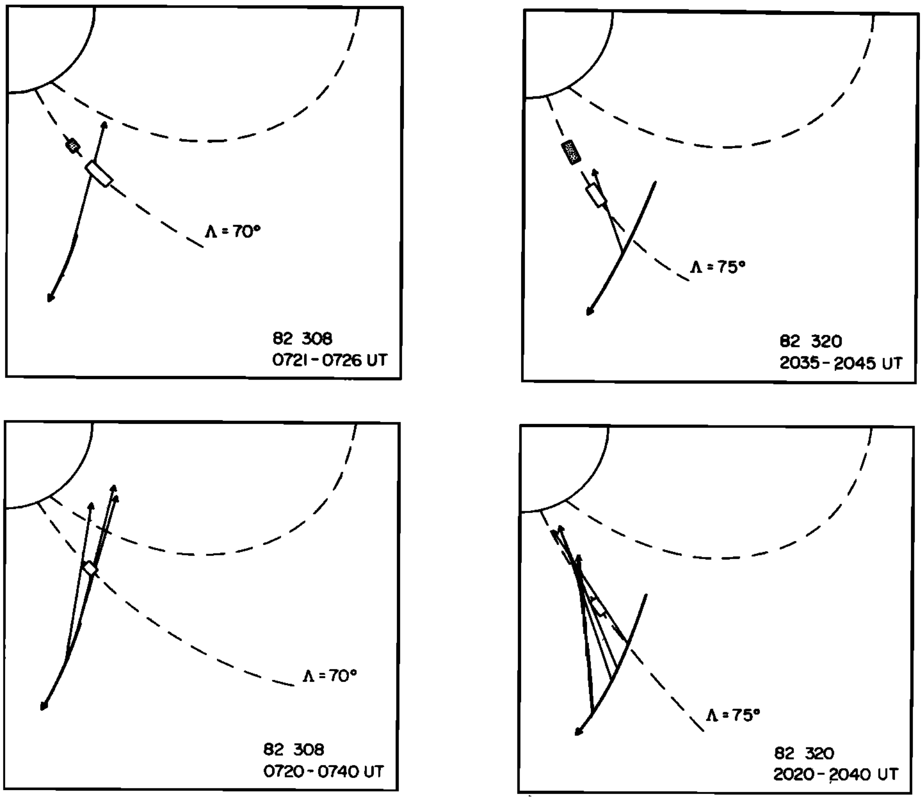

Fig. 3. Direction-finding studies. The bottom panels show direction-finding results for fundamental AKR. Results for second harmonic AKR are shown in the top panels. The satellite orbit is indicated by a bold line. A nominal plasmapause ($L = 4$) and a representative invariant latitude line are indicated by dashed lines, and the direction of arrival determinations are indicated by the arrows. The boxed regions represent altitudes at which the local electron gyrofrequency would be equivalent to the frequency of the fundamental AKR. Shaded boxes indicate the second harmonic.

ness of its signal. The sources suggested in Figure 3 are based only on line-of-sight extrapolation of the direction of arrival, and future effort should include ray-tracing studies of these emissions. Differences in the propagation characteristics of the O and X mode may, for instance, affect our conclusions about the similarity of their sources. We know relatively little about the plasma environment in which these emissions are propagating, and it is not clear what model of plasma densities would be appropriate for such calculations.

Summary and Discussion

As discussed above, a number of specific features of the observed radiation, in combination with our knowledge of the response characteristics of the DE 1 plasma wave instrument, argue strongly that the DE 1 harmonics are natural rather than instrumental in origin, and we proceed on this hypothesis.

We first summarize the DE 1 observations of harmonic auroral kilometric radiation and then discuss their implications.

1. The events are quite rare, with preferential occurrence during magnetically quiet times.

2. Second harmonics are observed. Higher harmonics would be outside the instrument's frequency range.

3. Harmonic emissions are very narrow band and relatively weak in comparison with typical auroral kilometric radiation.

4. The ratio between the frequencies of the harmonic and the fundamental is typically 1.9 ± 0.2.

5. The ratio between the intensity of the fundamental and that of the harmonic is typically of the order of 0.1 to 10.

6. When harmonic AKR is observed, the fundamental and harmonic are found to propagate in different modes: the fundamental in the ordinary mode, and the harmonic in the extraordinary mode.

7. The fundamental and harmonic appear to originate from similar positions on high-latitude nightside auroral field lines.

These observations are not consistent with harmonic generation mechanisms suggested by *Oya and Morioka* [1983], who postulated the existence of an electrostatic harmonic emission, or with that of *Melrose et al.* [1984], who require the presence of a fundamental Z mode radiation. They are, on the other hand, consistent with predictions based on the cyclotron maser mechanism [*Wu and Lee,* 1979], as discussed by *Lee et al.* [1980], *Hewitt et al.* [1982], *Wu and Qiu* [1983], *Melrose et al.* [1984] and *Winglee* [1985]. Calculations based on this mechanism predict that when the maser is driven in regions of relatively high plasma density ($0.3 < fp/fg < 1.0$), it should produce an O mode fundamental and, at a lesser intensity, an X mode second harmonic. The DE 1 observations are characterized by this combination of O mode fundamental and X mode harmonic.

The DE 1 observations thus suggest that the harmonic auroral kilometric radiation is generated in regions of relatively high plasma density, on field lines directly within or neighboring the auroral zone. It is not yet clear whether they occur along auroral field lines on occasions when the auroral plasma cavity has disappeared or are generated off auroral field lines, where higher densities are typical.

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