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OBSERVATIONS OF MAGNETOSPHERIC PLASMAS BY THE RADIO PLASMA IMAGER (RPI) ON THE IMAGE MISSION

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ABSTRACT

The Imager for Magnetopause-to-Aurora Global Exploration satellite (IMAGE, see http://image.gsfc.nasa.gov), launched on March 25, 2000, is the first mission dedicated to observing the global-scale structure and dynamics of the magnetosphere. Remote-sensing instruments on IMAGE are designed to observe the magnetopause, ring current, plasmasphere, polar cusp, and the auroral region, in order to reveal the morphologies and interactions among these inter-connected regions. In particular, the RPI, a digital radio sounder with direction-finding capabilities, can transmit radio pulses from 3 kHz to 3 MHz (corresponding to plasma densities of 0.1-10^5 cm^{-3}) to probe different magnetospheric plasmas. Using two 500-m tip-to-tip orthogonal dipole antennas in the spin plane and a 20-m tip-to-tip spin-axis dipole antenna, signals reflected at remote plasma regions are received as echoes. The RPI measures the echo amplitude, phase, range, polarization, Doppler shift, and angle of arrival as a function of sounding frequency. Advanced digital techniques allow echoes of low-power transmitted signals to be detected over magnetospheric distances. With a nominal 2-minute IMAGE spin period in a highly inclined (90°) elliptical orbit (apogee of 8 R_E), the RPI (with a nominal 1-min resolution) situated in the magnetospheric cavity observes the inner and outer magnetospheric boundaries. Its observations can reveal the electron density profiles and dynamics of key magnetospheric plasma regions. This paper highlights the science objectives of the RPI on IMAGE and presents some early RPI observations. Published by Elsevier Science Ltd on behalf of COSPAR.

INTRODUCTION

The IMAGE satellite, launched into a polar orbit from Vandenberg Air Force Base, California, on March 25, 2000, carries a suite of remote-sensing instruments (HENA, MENA, LENA, FUV, EUV, and RPI) to perform magnetospheric observations. These observations can be used to determine the global-scale structures and dynamics of the magnetosphere. Unlike past space physics missions, the IMAGE mission is the first mission dedicated to performing remote-sensing observations of the magnetosphere (Burch, 2000 and articles therein). Because of the diversity in the Radio Plasma Imager (RPI) observations, this paper introduces various basic RPI observations, which can be analyzed independently or in conjunction with other IMAGE instrument data. We will first provide a brief summary of the RPI instrument characteristics, then show some early observations.

THE RADIO PLASMA IMAGER (RPI)

The RPI is basically a digital radio sounder (Reinisch *et al.*, 2000). It is designed to receive mirror-like (specular) reflections and coherent scatter returns (e.g., see Sales *et al.*, 1996) from distant magnetospheric plasmas. Operating like a radar, the RPI transmits coded electromagnetic pulses with a minimal pulse length of 3.2 ms, corresponding to a range resolution of 480 km. Transmission is accomplished by using a dipole wire antenna in the satellite spin (x-y) plane. The two long crossed dipoles (500-m tip-to-tip) and a 20-m dipole antenna along the satellite spin (z) axis are then used for echo reception. Using three 300-Hz-bandwidth receivers, the RPI measures the amplitude, phase, echo direction of arrival, time delay, polarization and Doppler shift for each echo at frequency *f* (Reinisch *et al.*, 1999; 2000). The angular resolution of direction finding is about 1°, limited primarily by the z-antenna noise level. A detailed description of the RPI instrument and analysis of the received echoes is given in Reinisch *et al.* (1999, 2000).

Analysis of the RPI range data is based on the assumption that the sounder waves are specularly reflected, *i.e.*, that geometric optics holds (Green *et al.*, 2000). As a result, the echo power falls off as the inverse-square of the round-trip distance traveled by the sounder signal (see Flock, 1970; Calvert *et al.*, 1995). Some consideration of the effects of plasma irregularities on the RPI measured echoes is discussed in Fung *et al.* (2000). More information on the feasibility of detecting magnetospheric echoes by a radio sounder instrument can be found in Franklin and Maclean (1969) and Calvert *et al.* (1995, 1997). In this paper, we introduce the variety of RPI observations of magnetospheric plasmas and indicate how they may be used in conjunction with other IMAGE data to determine the global-scale magnetospheric structures and dynamics.

FIRST OBSERVATIONS BY RPI

The basic RPI range data display is the plasmagram (Oya *et al.*, 1990; Benson *et al.*, 1998) which is obtained by transmitting and receiving signals from low to high frequencies. Assuming free-space light-speed propagation, the virtual range ($c\tau/2$, where τ is the echo time delay) of the echo can be plotted against sounder wave frequency (see Figure 1), analogous to ionograms in ionospheric sounding. Inversion of plasmagrams will yield "line-of-sight" density profiles of remote plasma structures (Huang and Reinisch, 1982). The model plasmagram shown in Figure 1 contains many model echo traces, representing the expected echoes in both ordinary and extraordinary modes returning from different magnetospheric plasma structures. Although the echo traces from different magnetospheric regions can appear simultaneously in a plasmagram, they can be distinguished by their tendency and locations, dependent on the spacecraft location relative to the different plasma regions. This figure can be used as a guide for identifying echoes from key magnetospheric features.

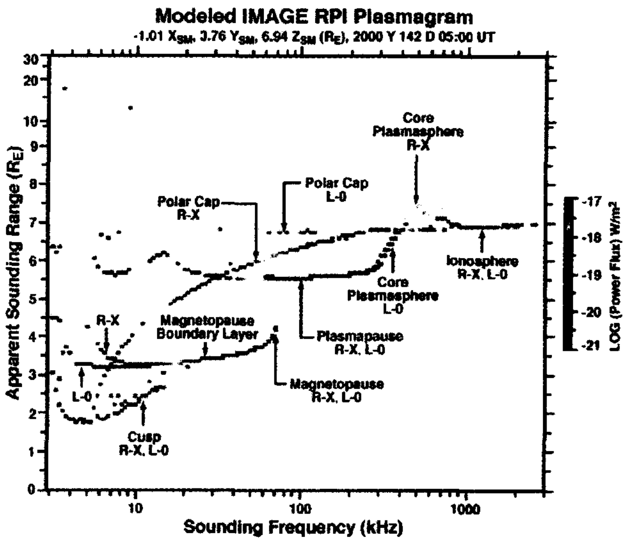

Figure 1. Model plasmagram with multiple echo traces from various magnetospheric plasmas (from Green *et al.*, 2000).

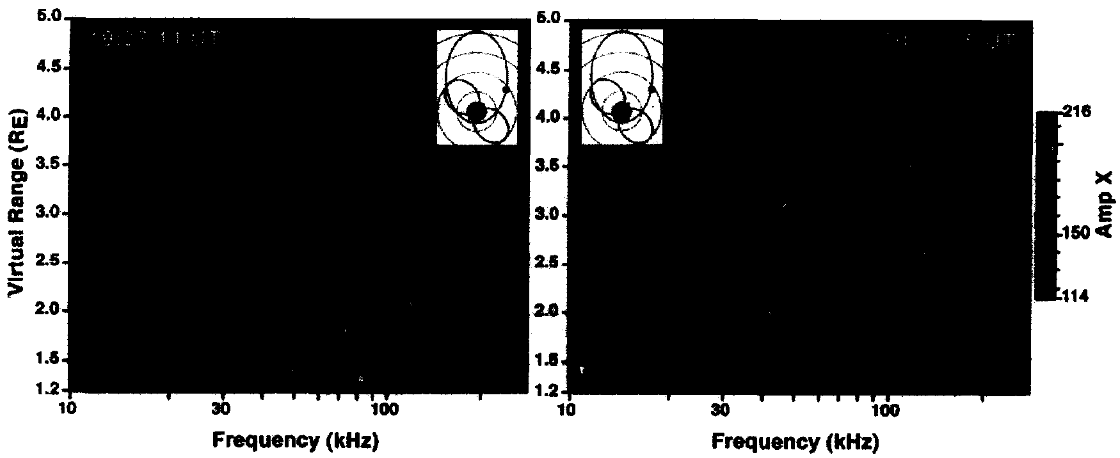

Figure 2. Plasmagrams of raw X-antenna amplitudes of polar cap echoes observed on June 12, 2000 as a function of virtual range and sounder frequency. The insets show IMAGE positions (left panel: 22.82MLT, 82.9 ILAT; right panel: 5.64 MLT, 83.1 ILAT) relative to the Earth and the L=4 dipole field lines. The small white arrows on the horizontal scale indicate the approximate lower frequency cutoff of the polar cap traces. Background most-probable noise levels have been subtracted to bring out echo features indicated in both panels.

Polar Cap Echoes

Figure 2 shows two examples of the echo traces observed by RPI on June 12, 2000, 19:07-22:27UT (for almost 3.5 hrs) when IMAGE was climbing over the polar cap toward apogee. During this time, the low-frequency cutoff of the echo traces migrates toward lower frequencies as IMAGE moves to higher altitude, indicating the decreasing density and magnetic field encountered by IMAGE. The echo traces shown in Figure 2 are remarkably similar to the extraordinary-mode model polar cap trace shown in Figure 1. The echo relative amplitude display shown in Figure 2 clearly indicates that the long-range echoes can readily be observed despite the presence of low-frequency (< 100 kHz) natural noise background.

Plasma Wave Observations

In addition to active sounding measurements, RPI also makes passive observations of thermal noise and natural plasma emissions with its highly sensitive radio receivers. These measurements are made in between active soundings such that local plasma conditions can be sampled and analyzed (Meyer-Vernet *et al.*, 1998). They thus provide the context upon which the sounding observations can be interpreted. Figure 3 shows an example of a dynamic spectrogram obtained early in the mission by the RPI on May 11, 2000.

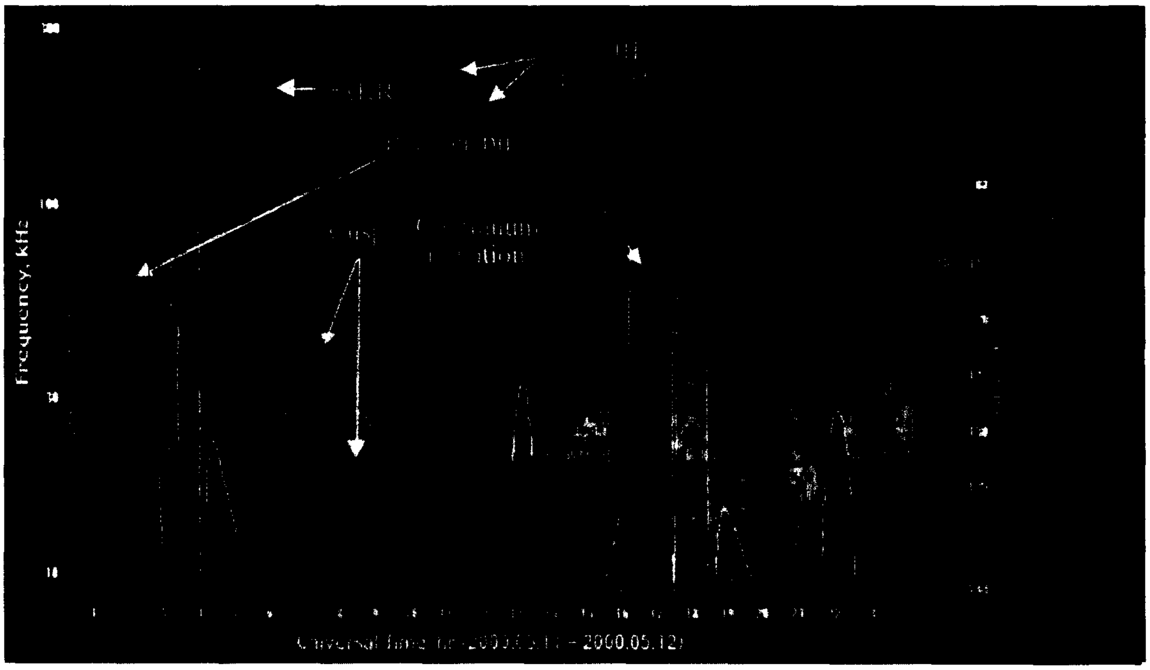

Figure 3. A 24-hr dynamic spectrogram taken by the RPI x-antenna on May 11, 2000, showing the presence of key natural emissions (AKR, type III bursts and continuum radiation). The darkened regions outline the relatively high-density cusp and plasmasphere. The red and white curves are model electron gyro and plasma frequencies, respectively. The red crossed-broken lines mark the time and local plasma frequency where the cusp echoes shown in Figure 4 were observed.

Owing to the highly sensitive RPI receivers at low frequencies (Reinisch *et al.*, 2000), the dynamic spectrogram shown in Figure 3 exhibits remarkable details of the cusp and plasmapause boundaries. Blockage of the trapped nonthermal continuum radiation by the relatively high electron plasma density in the cusp and plasmasphere yields the darkened appearance of these plasma regions in the spectrogram. Minima (maxima) of the model electron gyro and plasma frequencies indicate roughly the times of apogee (perigee) of the IMAGE orbit. Within the interval 06:00-09:00, the IMAGE satellite was climbing toward apogee at radial distances 5-7 R_E with magnetic local time (MLT) becoming more dawnward and decreasing invariant latitudes [see Figure 4(a)]. Two consecutive cusp crossings by IMAGE separated by about 1 hour are observed during this time interval. While the fine structure seen in the cusp crossings may be associated with processes internal to the cusp boundary plasma region, the overall lower density and narrower extent of the second crossing may indicate a peripheral crossing of the cusp [nominally centered at local noon with an average invariant latitude of 81° (see e.g., Fung *et al.*, 1997)] at the earlier MLT and lower invariant latitude. More detailed analyses are needed to determine the occurrence of multiple cusp crossings by IMAGE under only moderate changes in solar wind paramenters, as suggested by Wind Key Parameter observations during this interval (not shown; see *http://cdaweb.gsfc.nasa.gov/cdaweb/istp_public/*).

Assuming ordinary mode propagation for the nonthermal continuum radiation, the low frequency cutoff of the radiation is thus the local electron plasma frequency (see e.g., Fung and Green, 1996). During the descending portion of the IMAGE orbit, e.g., 12:00–16:00 UT [see Figure 4(a)], RPI passive measurements show that the dayside plasmasphere is quite distended, as indicated by the elevated plasma frequency (density) compared to the plasma model (white curve) used in ray-tracing calculations shown in Figure 1 (Green *et al.*, 2000).

Cusp Echoes

The red crossed-broken lines in Figure 3 mark the time (07:26 UT) at which a set of cusp echoes were observed by RPI. The IMAGE spacecraft at this time was located just outside the cusp boundary [see Figure 4(a)] where the local plasma or upper hybrid frequency is *nearly* 50 kHz. As shown in Figure 4(b), the cusp echo trace starts at about 47.1 kHz at a virtual range of 1.15 R_E and ends at about 74.5 kHz at a virtual range of 0.6 R_E. The negative slope of the echo trace is apparently caused by the slower propagation speeds of the lower frequency waves that were propagating near their respective cutoff, resulting in longer delay times. Conversely, the higher frequency sounder waves have higher group speeds and thus have shorter delay times, despite having traveled to and reflected from within the cusp. The slow propagation speeds and short virtual range of the echoes strongly suggest that IMAGE was located very close (within 1 R_E) to the cusp boundary when the sounding observations were made. Except for the difference in frequencies, this is analogous to the low-frequency portion of the model cusp trace shown in Figure 1.

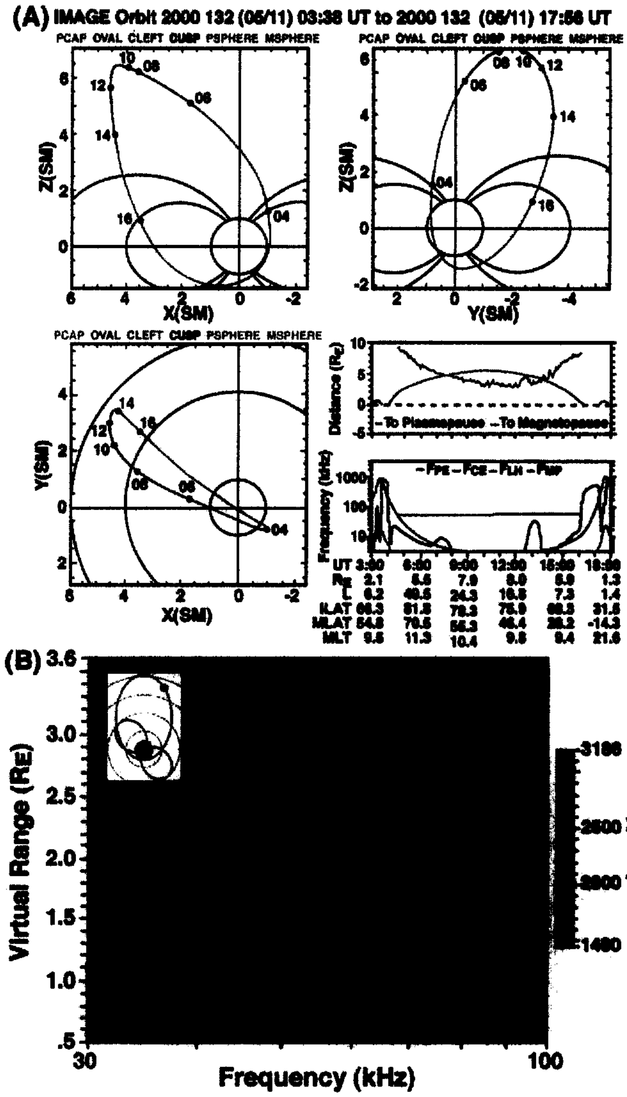

Figure 4. (A) IMAGE orbit on May 11, 2000; (B) Cusp echoes observed between 47.1 and 74.5 kHz at 7:26 UT.

Ducted Echoes

Sounding of plasmaspheric density irregularities and ducts have been investigated for over two decades (Oya and Ono, 1987; Ondoh *et al.*, 1978; Calvert, 1981). Early indication of presence of plasmaspheric ducts was found in the sounding observations by the Japanese Akebono spacecraft at about 0.9 R_E altitude near the equator (Oya *et al.*, 1990). With RPI, ducted echoes are observed for the first time at radial distances greater than 2 R_E. Figure 5 shows an example of ducted echoes occurring over two consecutive frames taken by RPI on June 12, 2000, when IMAGE was traversing the outer equatorial plasmasphere. Although the raw data shown in Figure 5 are not calibrated, ducted echo signatures similar to those observed in the ionosphere are clearly visible. In analogy to the interpretation of ionospheric ducts in the ionosphere by Muldrew (1963), the trace with an "upside-down hook" is believed to be formed by the echoes returning along a magnetic field-aligned duct extending from the vicinity of the spacecraft into the ionosphere in the local hemisphere. In addition, the multiple traces with downward sweeps starting at different virtual distances are echoes that have gone through multiple bounces and returned from the conjugate hemisphere along the same field-aligned duct.

The IMAGE ephemeris data shown in Figure 5 indicate that the ducted echoes were observed when IMAGE was located at 10-17 degrees south of the equator. Based on the ionospheric analogy mentioned above, the ducted echoes were results of sounder signals guided by a morning side plasmaspheric duct having a transverse scale of about 0.5 R_E.

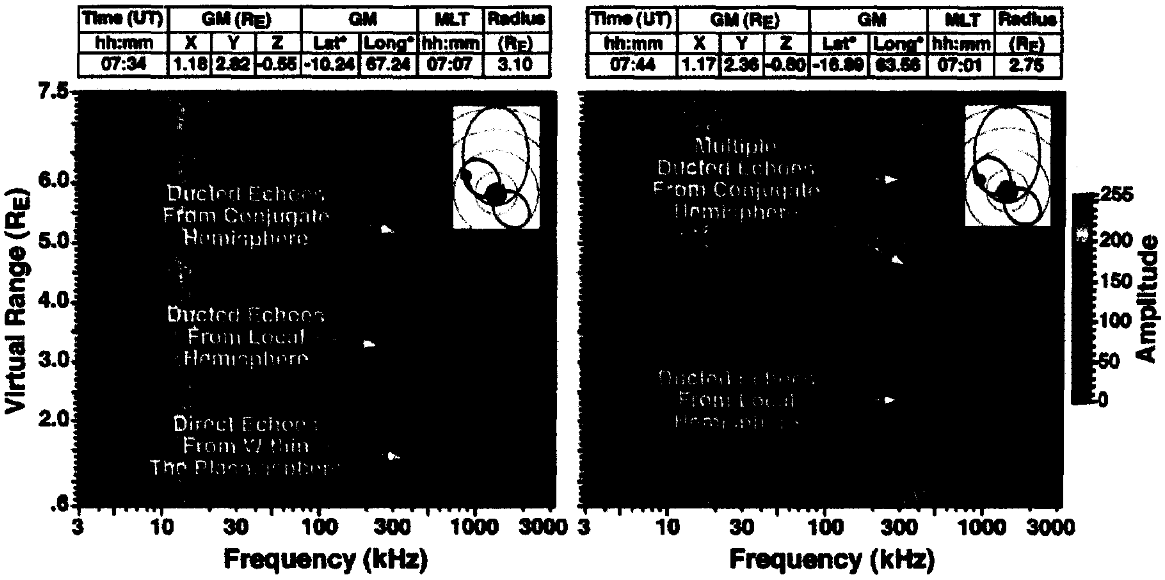

Figure 5. Ducted echoes seen in two consecutive frames of RPI data taken ten minutes apart on June 13, 2000. The "scattered" echoes (just above the 300 kHz mark and below virtual rage of 1.6 R_E) are direct echoes from the vicinity below the spacecraft.

Gyroharmonic Emission

While plasma cutoffs observed by RPI can yield information on magnetospheric electron density (Figure 3), gyroharmonic resonances excited by the RPI transmissions can produce valuable information on the magnetic field strength at the vicinity of the satellite location. Figure 6 shows an example of the multiple gyroharmonic resonances observed by RPI during a near-equatorial pass of IMAGE at 21:27:59 UT on June 29, 2000. The multiple harmonics observed allow accurate determination of the local magnetic field strength, which can then be used to validate magnetic field models (e.g., see the corresponding model f_{ce} based on the T96 model field) that are used to analyze active sounding measurements. This is useful because IMAGE carries no research-quality magnetometer aboard. We note that the reason for not observing all the intermediate harmonics is due to the finite (4% logarithmic) spacing of the receiver frequency channels with only 300-Hz bandwidth.

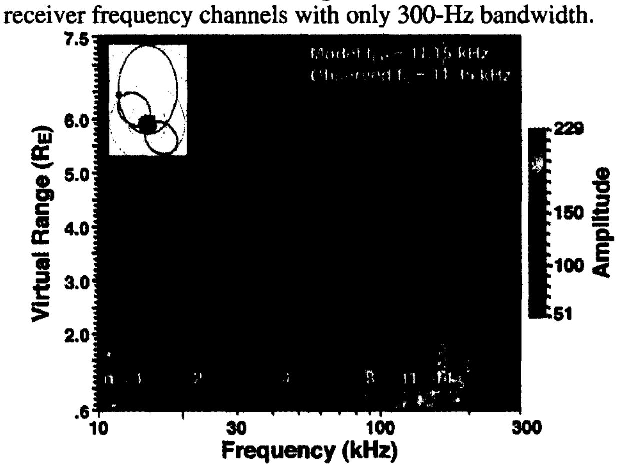

Figure 6. Gyroharmonic resonances observed by RPI on June 29, 2000 when IMAGE was located at (R, MLAT, MLT) = (4.2 R_E, -5.77°, 6.58 hr).

Whistler Mode Echoes

During southern perigee passes of IMAGE, transmission by RPI often excites whistler mode echoes at frequencies below the local electron cyclotron frequency. Figure 7 shows the raw Y-antenna measurements of a typical example of the whistler mode echoes detected by RPI. The inset indicates the IMAGE satellite location at this time. The T96 model magnetic field yields a model electron cyclotron frequency of about 731 kHz, while the echo frequencies are less than 100 kHz. The negative slope of the echo trace is characteristic of whistler mode wave propagation. As higher frequency whistler waves travel with higher propagation speeds (Stix, 1992), the corresponding echoes thus have shorter time delays and shorter virtual ranges. The relatively uniform background observed at all virtual ranges below 100 kHz is likely due to whistler-mode auroral hiss emissions in the southern ionosphere (Gurnett, 1966; Helliwell, 1969). Based on the upper frequency limit of the whistler trace and hiss emission, the local electron plasma frequency is estimated to be ~ 100 kHz. The plasma model used by Green *et al* (2000) indicates a lower f_{pe} value (42.8 kHz), but f_{pe} is much more difficult to model than f_{ce} and the RPI often detects such discrepancies (see Figure 3 and associated text).

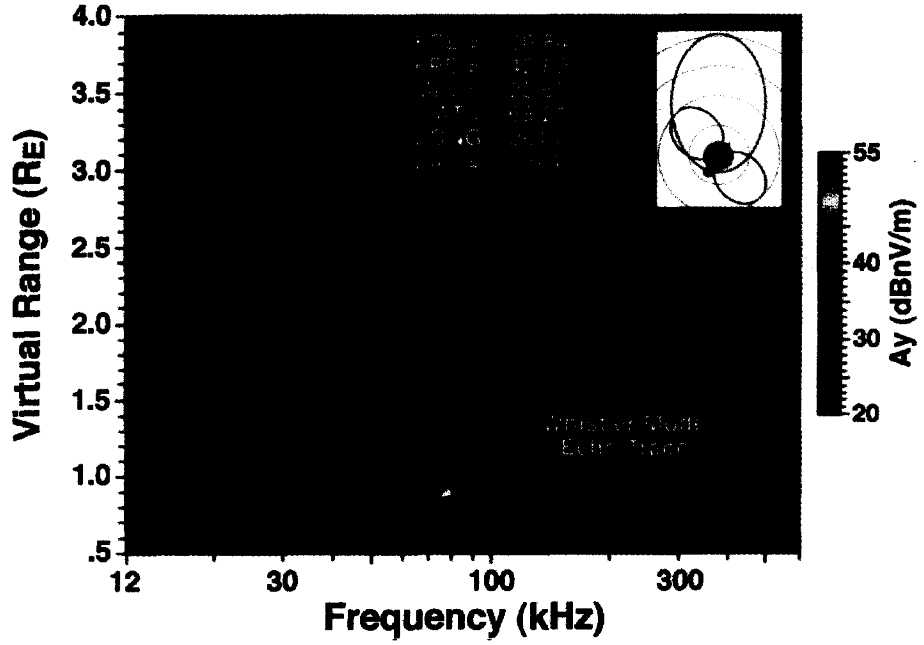

Figure 7. Whistler mode echoes detected by RPI near perigee passage in the Southern Hemisphere at 04:16 UT on May 8, 2000.

Potential Boundary Layer and Magnetopause Echoes

With IMAGE situated near apogee in the magnetospheric cavity, it can be relatively close (within a few R_E) to the outer magnetospheric boundary. It is then possible to probe the boundary layer and magnetospause by using the RPI-transmitted signals (Reiff *et al.*, 1994; Calvert et al., 1995; 1997; Fung *et al.*, 2000). Being surrounded by the magnetospheric boundary, the dipolar radiation transmitted by RPI can be reflected upon encountering a plasma cutoff (Stix, 1992). Since echoes are received when the reflected ray directions are approximately parallel to the density gradient at the reflection point, signals reflected at different locations in the magnetospheric boundary can be detected. This is in contrast to the relative uniformity in direction of echoes from other regions as shown above. Well-defined echo traces from the boundary layer and magnetospause region are likely to be observed only during relatively static magnetospheric conditions.

Figure 8(a) shows a plasmagram containing some echoes detected by RPI near IMAGE apogee on August 23, 2000. The indicated echo trace with limited frequency range (54-73 kHz) might be results of echoes reflected at the magnetopause boundary layer. Shown in their raw x-antenna amplitudes as a function of virtual range and frequency, the echo trace is visible above a relatively uniform background, perhaps due to trapped nonthermal continuum radiation. This background has been subtracted to provide clarity of the trace shown. Unlike the model boundary layer trace shown in Figure 1, the observed echo trace has only limited frequency range, suggesting that only a partial frequency sweep of the RPI sounder pulses was reflected by the remote boundary layer. Although the discrete appearance of the trace may suggests that it could be the result of field-aligned guided echoes (Fung *et al.*, 2001), the lack of near-range signals argues against such possibility. It is also an unlikely result of direct echoes from the plasmapause because plasmapause direct echoes tend to appear scattered due to presence of field-aligned irregularities (Fung *et al.*, 2001).

Echo reflection points can in principle be determined from echo directions of arrival (Reinisch, *et al.*, 1999; 2000) and virtual ranges. However, due to the lack of definitive calibration of different RPI antenna signals at the present time, uncertainties remain in the echo arrival directions. Nevertheless, the inset in Figure 8(a) shows a plot in the IMAGE orbit plane the virtual ranges (5.7 to 5.9 R_E) of the observed echo trace from the magnetopause general direction and an orbit-plane profile of the Roelof-Sibeck (1993) model magnetopause. Since the orbit-plane model profile (near MLT=2.25) is located just beyond the virtual ranges of the echo trace, while the closest distance to the model magnetopause from IMAGE for this time is DMP = 5.0 R_E (see legend), the actual reflection point must have been located on the dayside/dawnside magnetopause [see lower left panel in Figure 8(b)]. The narrow range (0.2 R_E) in virtual range of the echo trace implies that all the echoes in the trace must have been reflected from a relatively sharp boundary layer. Figure 8(b) shows the IMAGE orbit configuration when the observations shown in Figure 8(a) were taken. Unlike the configuration that favors cusp observations [*cf.*, Figure 3(b)], the cusp would not be a likely target region reflecting the echoes observed at MLT = 2.25 hr. At time of apogee, the boundary layer and magnetopause are the most likely targets visible by RPI at low frequencies.

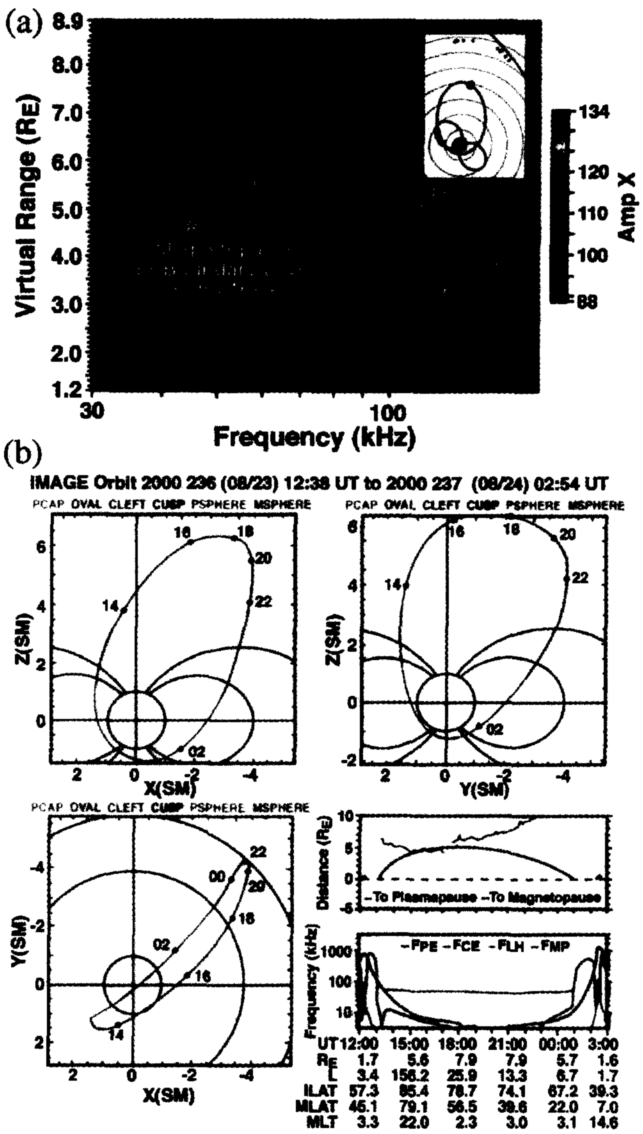

Figure 8. (a) Plasmagram of possible boundary layer and magnetopause echoes observed by RPI at 17:57 UT on August 23, 2000; and (b) IMAGE orbit

CONCLUSIONS

With the longest spinning dipole antenna system flown in space to date, the Radio Plasma Imager on IMAGE (Reinisch *et al.*, 2000) has positively demonstrated the feasibility of magnetospheric radio sounding as a fruitful technique for making magnetospheric observations. Early RPI data have shown many echo signatures characteristic of the polar cap, cusp, plasmaspheric ducts, whistler mode waves, plasma resonances, and the magnetopause boundary layer. Passive measurements of natural emissions have shown detailed plasma structures and irregularities in the plasmasphere and cusp. Significant differences between *in situ* measurements and magnetospheric plasma models are indicated.

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