Small-scale field-aligned plasmaspheric density structures inferred from the Radio Plasma Imager on IMAGE

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[1] Among the objectives of the Radio Plasma Imager (RPI) on IMAGE is the observation of the Earth’s plasmasphere from the satellite’s polar orbit, with apogee ≈8 RE geocentric distance and perigee near 1200 km altitude. This objective is here pursued by (1) remote sounding from high-altitude regions outside the main plasmasphere, (2) sounding within the plasmasphere, and (3) in situ passive measurements of natural wave activity. During sounding of the plasmasphere from both outside and inside the plasmapause, RPI echoes that follow non-field-aligned ray paths are usually not the discrete traces on range-versus-frequency records (plasmagrams) that are predicted by ray-tracing simulations in smooth magnetospheric density models. Instead, such RPI echoes exhibit various amounts of spreading, from ≈0.5 RE to ≈2 RE in virtual range (range assuming free-space speed of light propagation). The range spreading is attributed to scattering from, partial reflection from, and propagation along geomagnetic field-aligned electron density irregularities. There exists a substantial body of theoretical work on mechanisms that might explain the appearance of such irregularities both within and beyond the plasmasphere. That the spread-producing irregularities are field-aligned is suggested by the efficiency with which RPI excites discrete echoes that propagate along the geomagnetic field, sometimes into both hemispheres. The spatial distributions and scale sizes of the spread-producing irregularities remain to be investigated. The RPI echo data, however, coupled with earlier evidence from topside sounders and whistler mode instruments, suggest that they can have cross-field scale sizes within a range from ≈200 m to over 10 km and electron densities within ≈10% of background. RPI is found capable of detecting plasmapause locations from distances of ≈3 RE or more. When minimal signal integration is used, the location and range of density values of a steep plasmapause can be determined from distances of order 1 RE, and echoes can at times be returned from points extending inward from the plasmapause to locations where the electron density reaches ≈3000 cm⁻³, which is usually at L < 3.

INDEX TERMS: 6964 Radio Science: Radio wave propagation; 0659 Electromagnetics: Random media and rough surfaces; 2403 Ionosphere: Active experiments; 6969 Radio Science: Remote sensing; 2768 Magnetospheric Physics: Plasmasphere; KEYWORDS: plasmasphere, plasmapause, radio sounding, spread echoes, field-aligned irregularities

1. Introduction

1.1. Radio Sounding and the Earth’s Plasmasphere

[2] Sounding of the Earth’s plasmasphere by the Radio Plasma Imager (RPI) instrument [Reinisch et al., 2000] was among the original objectives of the IMAGE satellite mission [Burch, 2000]. The density structure of the plasmasphere has been investigated via measurements on previous satellites [e.g., Lemaire and Gringauz, 1998], but much about it remains poorly known, especially its behavior on various spatial scales during cycles of erosion and recovery [e.g., Carpenter and Lemaire, 1997].

[3] The ways in which RPI “sees” the plasmasphere depend upon the special properties of the IMAGE polar orbit, with apogee at ≈8 Earth radii (RE) geocentric distance, perigee ≈1200 km altitude, inclination 90°, and initial line of apsides at a latitude of 40°. Figures 1a and 1b show partial plots of IMAGE orbits on 18 and 19...
January 2001, when apogee was at high northern polar latitudes. In each case the orbit has been projected onto a plane in SM coordinates that is approximately aligned in MLT with the MLT at the satellite. As a consequence, apparent distances from point to point along the plotted orbit differ slightly from the real distances, but the amounts involved are not large enough to affect the conclusions of our paper. The plasmasphere boundary, or plasmapause, is shown in idealized fashion as a dipole field line, in Figure 1a at L = 4.1 and in Figure 1b at L = 5.6. From such a 14-hr orbit one might expect to receive echoes from the plasmasphere over intervals of several hours. Reflections should occur not only in the outer, plasmapause “layer,” but deeper within the plasmasphere, as dictated by the spatial distribution of cutoff frequencies for the ordinary (O) and extraordinary (X) free-space wave modes.

Figure 2 shows a simulated “plasmagram,” or display of echo intensity in coordinates of virtual range versus frequency (propagation at velocity c along ray paths to reflection points assumed). The figure is based on ray tracing calculations from a satellite position indicated by the arrow along the orbit in Figure 1a. As described by Green et al. [2000], simulations of this type employ a “smooth” electron density (n_e) model that combines a diffusive equilibrium distribution [Angerami and Thomas, 1964] with an ionosphere and plasmasphere profile from Kimura [1966] and a model of the plasmapause by Aikyo and Ondoh [1971].

In Figure 2, the frequency range is divided into four parts, corresponding to (see Figure 1a): (1) that part of the plasma trough between RPI and the plasmapause, (2) the plasmapause region of steep gradients, (3) the plasmasphere region from inside the plasmapause to the ionosphere, (4) the ionosphere. In region (1), the apparent range increases with sounding frequency above the X and O mode cutoff frequencies at the spacecraft (in the range ≈15–20 kHz for the particular density model used). Maxima in range develop below 40 kHz, due to the low group velocities in portions of the plasma trough where the
wave frequencies are not far above the local X and O mode cutoff frequencies. The ranges then decrease with frequency as the effects of increasing group velocity more than compensate for further increases in the true range to reflection points. The traces then level off at \( \frac{C^2}{0.8 R_E} \), corresponding to the apparent distance to region (2), the plasmapause, where density gradients are large and thus the reflection points for a series of frequencies are closely spaced. As frequency increases further (beyond \( \frac{C^2}{300 \text{ kHz}} \) for this particular density model), reflections occur progressively deeper within region (3), the plasmasphere, and the echo ranges increase accordingly. Near and above 1 MHz the ranges exceed 3 \( R_E \), corresponding to reflections in region (4) at ionospheric heights. There the O and X mode signals once again encounter steep density gradients and exhibit maxima in range, much as they did below 50 kHz in the approach to the plasmapause region of steep gradients. At frequencies above \( \approx 500 \text{ kHz} \) the traces resemble those traditionally displayed on topside ionograms [e.g., Hagg et al., 1969], except that virtual range is plotted upward in this case.

[6] In a prelaunch feasibility study by Calvert et al. [1995], it was estimated that RPI would receive detectable echoes from the plasmasphere when as far away as \( \approx 4–5 R_E \). This estimate was based upon specular reflection of echoes from the convex plasmapause “surface” and the use of coherent integration to increase the signal to noise ratio for detection of the echoes. In other prelaunch work, ray tracings from points along sample orbits were performed, leading to plasmagrams of the type shown in Figure 2 [Green et al., 2000]. Within the \( \approx 500 \text{ km} \) range resolution imposed by the minimum transmitter pulse length of 3.2 ms, the predicted ordinary and extraordinary mode echo traces were discrete, i.e., single valued in time delay as a function of frequency.

[7] Prior to IMAGE launch, irregular density structure in and near the plasmapause had been reported both from ground whistlers and in situ satellite measurements [e.g., LeDocq et al., 1994; Moldwin et al., 1995; Carpenter and Lemaire, 1997, and references therein; Carpenter et al., 2000]. Various amounts of range spreading or degradation of sounding pulses from RPI were therefore to be expected.

Figure 2. Simulated plasmagram, or display of echo intensity versus frequency and range, based upon ray tracing calculations that employ the electron density model described by Green et al. [2000]. The sounder was taken to be at location \( z \) in Figures 1a and Figure 3 (arrows). The plasmapause was assumed to be at \( L = 4.1 \). The four frequency bands shown correspond to echoes from: (1) the plasma trough, (2) the plasmapause, (3) the main plasmasphere, and (4) the ionosphere, as illustrated in Figure 1a.
under certain geophysical conditions \[e.g., \text{Fung et al.}, 2000\]. Expectations of discrete echoes were strengthened by knowledge that on spatial scales of \(\approx 200\) km or more the radial plasmapause density profile can at times be free of embedded irregularities \[Carpenter and Anderson, 1992\]. The possibility that RPI echoes from the region of steep plasmapause gradients would at least on occasion be discrete was suggested by a rare result obtained from the Alouette 2 topside sounder when it received a discrete echo from a density “wall” located just equatorward of the satellite at \(2000\) km altitude \[\text{Clark et al.}, 1969\] and at the location of a middle-latitude \((L \approx 2.5)\) red arc reported by \textit{Norton and Marovich} \[1969\].

\subsection*{1.2. Instrument Description}

\[\text{RPI}\] is a multimode instrument \[\text{Reinisch et al.}, 2000\] in which sounding and listening frequencies, range detection, pulse characteristics and repetition rate are adjustable parameters over a wide range of values. The instrument covers the frequency range from \(3\) kHz to \(3\) MHz with a receiver bandwidth of \(300\) Hz. There are three orthogonal thin-wire antennas, two \(500\)-m tip-to-tip dipoles in the spin plane \((X\ and\ Y)\) and a \(20\)-m tip-to-tip dipole along the spin axis \((Z)\). The long dipoles are used for transmission, and all three antennas are used for reception. The nominal radiated power from RPI, variable \(\text{(in terms of free-space mode excitation)}\) from \(0.1\) mW at low frequencies to \(\approx 10\) W per dipole at \(200\) kHz, was reduced by \(3\) dB on \(\text{May 8, 2000}\) when the power supply for the \(Y\) axis transmitter failed. A further \(3\) dB reduction occurred on \(\text{October 3, 2000}\), when one of the \(X\) axis monopoles was partially severed, apparently by a micrometeorite. In spite of these difficulties, excellent data have been, and continue to be, acquired as described below.

\subsection*{1.3. Early Results From Sounding}

\[\text{Early RPI results obtained as IMAGE approached the plasmapause within 30 degrees of the magnetic equator showed a number of unexpected features} \text{[e.g., Reinisch et al.}, \text{2001a]}.\] During swept frequency sounding programs, each lasting from tens to hundreds of seconds and involving various pulse formats and signal processing methods, the most frequently observed echoes were found to come from two widely different directions, one being the direction of the local geomagnetic field and the other generally inward toward the plasmapause. The echoes coming from the field line direction were discrete, occupying from one to three \(480\)-km range bins at a given frequency, while the “direct” echoes, returning along non-field-aligned ray paths, consistently showed spread in range, occupying from \(\approx 5\) to \(20\) or more range bins at a given frequency. Furthermore, on many orbits direct echoes were identifiable only when \(\text{IMAGE}\) was within \(\approx 1\ \text{RE}\) of the plasmapause.

\[\text{The observation of field-aligned echoes was not in itself surprising, in the light of topside sounder observations of echoes propagating between opposite hemispheres along field-aligned paths at invariant latitudes below \(\approx 40^\circ\)} \text{[e.g., Muldrew, 1963, 1969; Loftus et al., 1966]}.\] What was surprising with RPI, however, was the occurrence of field-aligned echoes under a wide range of geomagnetic conditions and along field lines both inside and well outside the plasmapause \[\text{[e.g., Fung et al.}, 2002\].}

\[\text{Our purpose in this paper is to discuss the response of the plasmapause to soundings from various \text{IMAGE}\ orbital locations. We will summarize the main aspects of the response as determined thus far and suggest that the persistent range spreading of the echoes may be interpreted in terms of interactions of RPI waves with correspondingly persistent geomagnetic field-aligned electron density structure in the region of steep plasmapause density gradients and throughout much of the main plasmasphere.}

\section*{2. Plasmasphere Echoes: Experimental Results}

\subsection*{2.1. General Conditions of Echo Observation}

\[\text{Several trends have emerged in regard to direct (non field-aligned) echoes observed from \text{IMAGE locations outside the plasmasphere:}

\[\text{1. Echoes from region (3), interior to the plasmapause, are the most common echo form, and in terms of recognition on plasmagrams do not seem strongly dependent upon the amount of signal integration used. They have been detected at ranges up to \(\approx 4\ \text{RE}\) both by means of short pulses and minimal integration and by means of longer pulses and coherent integration.}

\[\text{2. In contrast, the appearance on plasmagrams of well defined echoes from the region of steep plasmapause gradients (region (2)) appears to be range dependent. At ranges from \(\approx 1\ \text{RE}\) to \(\approx 4\ \text{RE}\), such echoes have primarily been detected by means of long pulses and use of coherent integration. Within \(\approx 1\ \text{RE}\) of the boundary, at ranges too short for use of the longer pulses, plasmapause echoes from short pulses are regularly detected.}

\[\text{3. Echoes from points in the density trough region between \text{IMAGE}\ and the plasmapause are not generally observed, although echoes from various points elsewhere in the plasma trough are seen when echoing occurs along field-aligned paths \text{[e.g., Fung et al.}, 2002].}

\[\text{At \text{IMAGE} locations within the plasmasphere, short pulse transmissions are regularly used and direct echoes from region 3 are nearly always observed, with returns from region 4 appearing at the lower altitudes.}

\subsection*{2.2. Examples of Echoes From the Plasmasphere: Short (3.2 ms) Pulses}

\[\text{Case 1 of 18 January 2001: Wave and Plasma Density Environment}

\[\text{Figure 1a shows an \text{IMAGE} orbit on 18 January 2001, while Figure 3 shows a dynamic spectrogram (3 kHz–1 MHz) from the period 0120 UT to 0400 UT on 18 January as \text{IMAGE} approached and then entered one lobe of the plasmasphere at \(\approx 0252\) UT (\(\approx 1600\) MLT). The record was obtained by moving the 300-Hz bandwidth RPI receiver through 243 frequency steps between 3 kHz and 1 MHz. The interval 3 kHz–20 kHz was covered by 44 steps of \(400\) Hz, while another \(199\) frequency steps (2\% increments) covered the \(20\) kHz–1 MHz interval. At each frequency step, RPI sampled the receiver amplitude 36 times at \(3.2\) ms intervals and calculated a series of eight 25.6 ms running averages. In this way, transient signals tend to be suppressed and relatively steady signals such as local resonances and continuum radiation emphasized. A frequency sweep is run every 2 to 6 min, each sweep taking about 1 min to complete. The data gaps between}
successive sweeps are filled for the display by continuing the value from the preceding measurement. In case of a data dropout, the value from the most recent measurement is further extended. The beginnings of such extensions (in the density regions relevant to our discussion) are indicated by downward pointing arrows along the top of the record. One such dropout is indicated in Figure 3 between \( L = 3 \) and 4.

In Figure 3, the dipole L value at the satellite is marked along the upper edge of the record, while in Figure 1a, asterisks mark the IMAGE positions at 0120 and 0400 UT, the time limits of Figure 3. The spectrogram of Figure 3 exhibits a number of radio phenomena already familiar from the sweep frequency receiver (SFR) records of satellites such as ISEE 1 [e.g., Gurnett et al., 1979] and CRRES [e.g., Anderson et al., 1992; Carpenter et al., 2000] and from reports on RPI by Reinisch et al. [2001a] and Fung et al. [2002] such as continuum radiation, auroral kilometric radiation (AKR), and whistler mode emissions at the lower frequencies. Following Mosier et al. [1973] and Gurnett et al. [1979], we here interpret the intense discrete values that move upward from \( \approx 40 \) kHz at 0200 UT as the upper hybrid resonance frequency (UHR), which can be used to provide a good estimate of the plasma frequency \( f_p \) and hence the local electron density \( n_e \). The right-hand scale shows the values of \( n_e \) that correspond to the left scale when the latter is interpreted as a measure of the electron plasma frequency. The smooth curve shows the electron gyrofrequency \( f_g \) along the orbit, based upon a combination of IGRF and Tsyganenko models. There is no onboard magnetometer for scientific measurements.

At \( \approx 0200 \) UT, \( n_e \) rose sharply from \( \approx 2–4 \, \text{cm}^{-3} \) to \( \approx 16 \, \text{cm}^{-3} \) as IMAGE reached \( L \approx 9 \). Since the magnetic local time was \( \approx 1600 \) hours, this abrupt increase is tentatively attributed to the crossing of a separatrix between magnetospheric plasma flow regimes, i.e., from a low density region associated with either the nightside plasma trough or plasma sheet to the higher-density dayside plasma trough. Examples of such density jumps in the duskside magnetosphere were reported by Carpenter et al. [1993].

In the dayside trough, detected between \( L \approx 8 \) and \( L \approx 4.2 \) (see upper scale in Figure 3), \( n_e \) rose at first irregularly and then quite smoothly from \( \approx 20 \, \text{cm}^{-3} \) \( (f_p \approx 40 \, \text{kHz}) \) to \( \approx 100 \, \text{cm}^{-3} \) \( (f_p \approx 90 \, \text{kHz}) \). Such high values, approaching levels that under some conditions could be considered characteristic of the plasmasphere, may be expected in the late afternoon sector (\( \approx 1630 \) MLT in this case) as a consequence of prolonged dayside refilling from the ionosphere [e.g., Carpenter and Anderson, 1992]. Geomagnetic conditions were quiet, with a maximum Kp...
value of 2– in the preceding 24 hours. Then, beginning at L ≈ 4.2, $n_e$ rose steeply to ≈800 cm⁻³ ($f_p$ ≈ 250 kHz) to form what appears to be a narrow peak. This peak was then followed by a more gradual, “plasmasphere-like,” increase to densities of 4000 cm⁻³ at lower altitudes.

Figure 4. (a)–(f). Series of 6 plasmagrams, obtained in sequence at the approximate locations of dots a through f in Figure 1a and the corresponding arrows in Figure 3, showing a series of echoes from the plasmasphere. (a) corresponds in time to the simulation of Figure 2. A field-aligned echo propagating outside the plasmasphere appears in (a) while in (e) and (f) there are echoes from field-aligned paths that extended to the local (northern) hemisphere and were embedded in the region of plasmapause density gradients.

[18] In Figure 1a, dots along the orbit indicate locations 4 min apart as the satellite approached and then penetrated the plasmasphere while receiving the echoes illustrated below. The dipole field line in the figure represents the approximate location of the plasmapause determined in situ by RPI's
encounter with steep plasmapause density gradients at ≈0252 UT (Figure 3).

2.2.2. Case 1 of 18 January 2001: Plasmapagram Sequence

[19] Figure 4 shows a series of six gray scale RPI plasmagrams, obtained in sequence at the locations marked in Figure 1a and at the times marked a through f in Figure 3 (the dot locations in Figure 1a are approximate, since each sounding required 46 s to complete). In each panel of Figure 4, virtual range to 4.5 \( R_E \) is displayed versus sounding frequency from 40 kHz to 600 kHz. For RPI, detectable virtual ranges begin at 0.3 \( R_E \), since the round trip propagation delay must exceed the length of the transmitted pulse, which in this case was the minimum value of 3.2 ms.

[20] The data of Figure 4, and other cases shown below, have been processed using a noise suppression algorithm commonly employed with ground-based Digisondes [Reinisch, 1996] and made available in special software that we have used for review and display of the RPI data presented in this paper [Galkin et al., 2001]. At each sounding frequency the signals in all of the range bins are surveyed and the most probable amplitude (MPA) value found. This value is then treated as the noise level for that frequency. For a given record, one may choose to display only those received signal levels that are a specified number of dB above the noise level at each frequency. In the cases illustrated in Figure 4, the display is from the long X axis dipole antenna and represents signals that were at 9 dB or more above the noise level.

[21] There are two distinct echo groups in Figure 4a. The discrete echo that appears at a virtual range of ≈3.5 \( R_E \) is interpreted as having propagated toward the northern hemisphere ionosphere along a geomagnetic field-aligned path outside the plasmasphere, as in a case shown by Reinisch et al. [2001], rather than to the relatively close (≈1 \( R_E \)) plasmapause (see Figure 1a). Field-aligned paths leading to reflections of ≈150 kHz waves at apparent distances of ≈3–3.5 \( R_E \) are consistent with the orbit plot of Figure 1a. Although not visible on the record below ≈90 kHz, the discrete echoes are inferred to have begun at zero range at a wave cutoff near 60–75 kHz (as indicated by the UHR data of Figure 3 and the plasma resonance at 66 kHz on the plasmagram of Figure 4a). Virtual range then increased with echo frequency such that near 100 kHz the apparent distance to reflection was ≈3 \( R_E \). The nearly constant virtual ranges for frequencies above ≈130 kHz suggest propagation along a fixed path followed by reflection from a region of relatively steep density gradients where the reflection altitudes vary only gradually with frequency.

[22] The diffuse echoes with shorter ranges in Figure 4 are interpreted as direct echoes from the plasmasphere. At most of their detected frequencies they are spread in range by ≈0.5 \( R_E \) or more. In Figures 4a and 4b the nearly constant value of the minimum virtual range between ≈100 kHz and 200 kHz suggests reflection at or near the region of steep plasmapause density gradients indicated in Figure 3 at ≈0252 UT. Overall, the variations with frequency of the echo delays in Figure 4a agree well with those of the calculated plasmagram in Figure 2, which was obtained by ray tracing for the same time, satellite position, and estimated plasmapause location, but using the smooth plasma density model mentioned above.

[23] In Figure 4 the minimum virtual range of the direct echoes decreased from plasmagram to plasmagram in apparent agreement with the movement of the satellite toward the nearest point of reflection from the plasmasphere. At 0239 UT (Figure 4a) the minimum virtual range near 150 kHz was ≈0.7 \( R_E \). From the orbit plot of Figure 1a, this satellite location (dot with arrow) was ≈0.6 \( R_E \) from the nearest point on the dipole field line used to represent the plasmapause. Although in need of a more refined demonstration and study of more cases, this suggests that the distance to the plasmapause can be remotely measured to within ≈0.1 \( R_E \) without a process of numerically calculating the true range.

[24] By the time of the third sounding at 0247 UT (Figure 4c) the minimum range of the plasmapause echoes (i.e., those below ≈200 kHz) had fallen below the 0.3 \( R_E \) range limit of the record, a position also suggested by the 3rd dot in Figure 1a. At 0251 UT (Figure 4d and 4th dot in Figure 1a), the spacecraft appears to have been at the outer limit of the region of steep density gradients, near the 100 kHz level of Figure 3. At 0255 UT (Figure 4e and 5th dot in Figure 1a) local densities had reached the ≈180 kHz level and echoes were received only from above that frequency. At 0259 UT (4f ), the minimum echo frequency had risen to ≈240 kHz.

[25] It is evident from Figure 4 that the amount of range spreading generally increased as IMAGE approached and then entered the plasmasphere. This increase may be associated both with a reduction in path length to reflection points and with the occurrence in the outer plasmasphere of “zero range” echoes, i.e., echoes with the minimum observable range of ≈0.3 \( R_E \) in a band above the local cutoff frequency. The effect appears similar to the type of zero range backscatter reported from topside sounding at high latitudes [e.g., James, 1989], in which echoes are observed with ranges substantially shorter than those to be expected in a “smooth” medium. While IMAGE was outside the plasmasphere, for example in Figures 4a and 4b, there was a relatively clear range gap at each sounder frequency between the transmitted pulse and the first returning echo, implying a spatial gap between IMAGE and the location of the nearest reflection point. However, after plasmasphere entry, say in Figures 4e and 4f, there was no range gap for a limited band of frequencies above the local cutoff frequency. For example, at the time of Figure 4f the local wave cutoff was at ≈240 kHz. Pulses from ≈240 kHz to ≈350 kHz produced echoes at the lowest detectable range (≈0.3 \( R_E \)) as well as at longer ranges extending to 1.5–2 \( R_E \). Above 400 kHz, the zero range effect was not evident.

[26] This case illustrates a point that is now clear from study of other RPI data: range spreading occurs not only in echoes from the plasmapause region, but also in returns from well inside the plasmasphere.

2.2.3. Case 1 of 18 January 2001: Comments on Field-Aligned Echoes

[27] Above the plasmasphere echoes in Figures 4e and 4f, at virtual ranges between 3.5 and 4.0 \( R_E \), are echoes that are believed to have followed geomagnetic field-aligned, or ducted, paths to reflection points in the northern, or local hemisphere. Such paths are suggested by the hook-like
connection of the echoes to the zero-range level. The near-vertical rise in the trace to a maximum virtual range near cutoff is attributed to a large scale height along the propagation path and to the low group velocity near cutoff. Such sounder-reflection traces are observed in the high-latitude topside ionosphere under conditions of low $n_e$ [e.g., see Benson and Grebowsky, 2001, Figure 3] where nearly 3000 km of apparent range near the X mode cutoff can correspond to only 50 km of real range from the satellite (e.g., see the discussion with Figures 12 and 13 of Hagg et al. [1969]). The ducts appear to have been “embedded” at two different density levels in the region of steep plasmapause density gradients. These different local density levels are indicated not only by a shift from $\approx 180$ kHz to $\approx 240$ kHz in the low frequency limits of the direct echoes, but also by differences in the low frequency extent of the field aligned echoes themselves. The downward slope of these echoes is the result of increases in group velocity with increasing frequency, which (as noted above in connection with Figure 2) more than compensate for the increased distance to the reflection points. Reinisch et al. [2001b] have calculated the field-aligned $n_e$ distribution for a case in which propagation to both hemispheres was observed. They showed that the calculated echo traces using the derived $n_e$ profiles reproduced the observed traces.

2.2.4. Case 2 of 18 January 2001

On the next inbound pass on 18 January 2001, RPI detected the plasmasphere profile shown in Figure 5. It was similar to that of the previous pass (Figure 3) except that instead of a peak at the outer edge of the plasmasphere there was a region spanning four measurement intervals near 1720 UT in which the UHR remained near 200 kHz. Figure 6a shows a simulated RPI plasmagram for the time indicated by an upward arrow on the timescale in Figure 5. The frequency and range scales have been matched to those of the data in Figure 6b. A smoothed version of the electron density profile scaled from the in situ data of Figure 5 was used in place of the corresponding profile in the standard density model noted above. There is a cusp-like feature at $\approx 200$ kHz, which is analogous to the type of cusp found in bottomside ionograms and attributed to a ledge in the altitude profile of electron density in the transition from the F1 to the F2 region. [e.g., Ratcliffe, 1956; Rishbeth and Garriott, 1969]. The RPI echoes taken at the same time exhibited such an effect, as shown by Figure 6b. There was a jump in minimum echo range from $\approx 0.8$ $R_E$ to $\approx 1.6$ $R_E$ between the echoes below $\approx 200$ kHz and those near 300 kHz. These observations are consistent with those shown in Figure 5, which indicate that the $\approx 200$ kHz plasma frequency was first encountered by IMAGE at an L value of $\approx 4$, while the $\approx 300$ kHz level was only reached at an L value of $\approx 3.1$.

Note that range spreading was not confined to echoes from the region of the density ledge, but was also present in echoes returning from deeper in the plasmasphere.
2.2.5. Case of 19 January 2001: An Outbound Plasmapause Crossing

[30] Good examples of echoes from the plasmasphere were also observed during outbound crossings in January, 2001, a particularly good case having appeared on 19 January at \(700\) MLT along the orbit illustrated in Figure 1b. Figure 7 shows a portion of the dynamic spectrogram for this region, indicating essentially plasmaspheric \(n_e\) levels (at or above \(700\) cm\(^{-3}\)) out to \(L \approx 5\). The \(n_e\) profile between \(L = 4\) and \(L = 5\) is poorly defined because of data dropouts (arrows at the top). However, there are clear indications of a decrease from \(\approx 300\) cm\(^{-3}\) to \(\approx 80\) cm\(^{-3}\) between \(L \approx 5\) and \(L \approx 7\). The plasmapause is represented in Figure 1b by a dipole field line at \(L = 5.6\) where, as discussed below, the electron density was found to exhibit an increased rate of falloff on the basis of changes in the X mode cutoff frequency observed at 4-min intervals. The increase in plasmapause radius over that observed on the previous day in the afternoon sector (Figures 3 and 5) is consistent with the deep quieting trend in geomagnetic activity at the time.

[31] Figures 8a through 8f show plasmagrams recorded 4 min apart as IMAGE moved from the plasmasphere into the plasma trough region. The corresponding locations of IMAGE are shown by dots in Figure 1b and the times are marked \(a\) through \(f\) in Figure 7. At 0915 UT (Figure 8a), plasmasphere echoes with range spreading of \(\approx 1\) \(R_E\) appeared above 400 kHz. To the left of these echoes,

![Figure 6. Comparison of simulated (a) and actual (b) plasmagrams for the sounding at 1651:20 UT on 18 January 2001 showing substantial agreement on overall echo form, especially on the occurrence of a cusp effect near the density “ledge” at \(\approx 200\) kHz. The time of the sounding is marked on Figure 5 by the upward pointing arrow on the UT scale at the bottom of the figure.](image-url)
centered at \( \approx 370 \) kHz, is a vertical line representing a resonance response at the level of the closely spaced plasma and UHR frequencies. On records 8b, 8c, and 8d, spread plasmasphere echoes continued to appear and were centered at progressively lower frequencies. The changes in their lower frequency, inferred to be near the X mode cutoff, are consistent with the changes in the density environment shown (coarsely) in Figure 7. The plasmasphere echoes in this case exhibited \( \approx 20\% \) to \( \approx 50\% \) less range spreading than was present on the previous day on inbound passes (Figures 4 and 6). The reason for this is not clear, possible factors being differences from those cases in MLT, in magnetic conditions, and in the geomagnetic coordinates of sounding locations (cf. Figures 1a and 1b).

As in the case of Figure 4, range spreading observed from IMAGE locations within the plasmasphere included zero range (\( \approx 0.3 \) \( R_E \)) echoes in a band above the local cutoff frequency. Those echoes are evident in Figure 8a and are best defined in Figure 8c. In Figures 8d, 8e and 8f, in what appears to have been the plasmapause region and the region just beyond, the wave cutoff frequency was not sharply defined. Zero range effects may have been present, but appear to have been less important than during the preceding soundings when IMAGE was in the main plasmasphere.

2.2.6. Case of 19 January 2001: Comments on Field-Aligned Echoes

At 0927 (Figure 8d), there are indications of a weak X mode field-aligned echo with cutoff near 195 kHz, accompanying the plasmasphere echo. Four min later, at 0931 (Figure 8e), with IMAGE at L \( \approx 6 \), a much stronger field-aligned echo appeared with cutoff at \( \approx 120 \) kHz (local \( n_e \approx 180 \) \( cm^{-3} \)). As usual, the field-aligned echo exhibited less range spreading than did the plasmasphere echo. Then, at 0935 UT (Figure 8f) near L = 7 the echo pair was again present but with an apparent lower cutoff frequency, near 80 kHz, indicative of satellite motion into a region with \( n_e \approx 80 \) \( cm^{-3} \). In both records the two types of echoes extended in frequency to 500 kHz or more at a maximum virtual range of \( \approx 2 \) \( R_E \). The field-aligned echo, which may have been detectable above the record limit of 600 kHz, is inferred to have penetrated to moderately low altitudes of order 1000 km outside the plasmapause where \( n_e \) reached at least \( \approx 4500 \) \( cm^{-3} \). The direct echo must have reached a point inside the plasmasphere where \( n_e \) was at least \( \approx 3000 \) \( cm^{-3} \), probably at an altitude of several thousand km. Possible ray paths, of order 2 \( R_E \) in maximum length, can be visualized with the aid of Figure 1b.

2.3. Notes on Echoes From the Plasmasphere:

Long (51.2 ms) Pulses

Data records show that RPI can obtain echoes from the plasmapause and main plasmasphere at ranges of 3 \( R_E \) and more. The best examples of such echoes noted thus far were acquired using 51.2-ms-long transmit pulses consisting of a sequence of sixteen phase-coded pulses that were repeated four times at each frequency (see Reinisch et al. [2000] for details). In one case, on July 8, 2000, the plasmapause was near L = 5 and geomagnetic conditions
were quiet, with Kp = 2 or less over the preceding 48 hours. Over a period of \( \approx 1 \) hour, or 6 soundings 10 min apart, the detected virtual range of the echoes corresponding to region 2 in Figures 1 and 2 decreased from \( \approx 2.8 \) \( R_E \) to \( \approx 1.2 \) \( R_E \), the latter being the minimum range detectable with 51.2 ms pulses. At 2.8 \( R_E \) this distance was comparable to the real distance from the IMAGE position to the nearest point on a dipole field line at \( L = 5 \). Range spreading reached as much as \( \approx 2 \) \( R_E \) as IMAGE moved to within \( \approx 1 \) \( R_E \) of the plasmapause and then further inward, exceeding the amount of spreading observed during soundings with 3.2 ms pulses that alternated with the 51.2 ms pulse program.

2.4. Examples of Echoes on an Exceptionally Quiet Day: Short (3.2 ms) Pulses

On June 29, 2001, magnetic conditions were unusually quiet and sounding programs were in use that covered
Figure 9. Dynamic spectrogram showing wave data from the outbound plasmasphere lobe on June 29, 2001 between 0130 UT and 0400 UT. Arrows a through f show the times of the plasmagrams in Figure 11.

Figure 10. IMAGE orbit plot for June 29, 2001. Asterisks delimit the interval 0130 UT to 0400 UT as IMAGE moved from perigee through the plasmasphere at 2030 MLT. Dots a through f mark the approximate positions of IMAGE during the 6 RPI soundings identified in Figure 10 and documented in Figure 11.
the frequency bands 180 kHz–245 kHz, 350 kHz–480 kHz, and 600 kHz–860 kHz. Frequency resolution was a factor of \( \frac{\gamma}{C^{2.5}} \) better than the 4% steps often used. Figure 9 shows a dynamic spectrogram for the period 0130 UT to 0400 UT as IMAGE moved outbound through and beyond the plasmasphere at \( L = 1800 \) MLT. The plasmapause was not sharply defined, but we interpret it as having been crossed at \( \approx 0230 \) UT, at \( L = 4.3 \), where the slope of the UHR profile in Figure 9 became more gradual. The Kp index was zero during this interval and had been near zero for the preceding 36 hours. The \( n_e \) profile was very smooth, with the exception of a local peak at \( L \approx 3.2 \).

[36] Figure 10 is an orbital plot showing the locations of the six soundings illustrated in Figure 11. Panels 11a and 11b show consecutive soundings 2.5 min apart in the frequency range 600 kHz to 860 kHz, when IMAGE was at \( L \approx 1.9 \). The O and X mode traces from the ionosphere below IMAGE are well defined, showing the forms predicted for region 4 in Figure 2 (but from a different sounder location). They converge at the high-frequency end of the record at virtual ranges of \( 1.765 \) RE, ranges that are in rough agreement with the distance to the northern hemisphere ionosphere of the dipole field line drawn at \( L = 2.7 \) in Figure 10. Direct echoes extended over the entire frequency range of the record in Figure 11c a strong X mode field-aligned trace rises from a cutoff at about 365 kHz, leveling off at a virtual range of \( 2.2 \) R\(_E\), which is consistent with the distance to the northern hemisphere ionosphere of the dipole field line drawn at \( L = 2.7 \) in Figure 10. Direct echoes extended over the entire frequency range of the record in Figure 11c, being particularly strong at zero range (or 0.3 R\(_E\)) and appearing in many of the range bins short of those occupied by the strong field-aligned trace, especially just above the X mode cutoff. These echoes exhibit the same zero range effect shown earlier (with poorer frequency resolution) in Figures 4e, 4f, and 8a, 8b, and 8c. This general configuration, including a field-aligned trace, diffuse echoes spread widely inside the field-aligned “envelope”, and strong zero range effects, was well defined between \( L \approx \)
2.5 and \( L \approx 3.2 \), during 5 successive soundings spaced 2.5 min apart.

[39] Figure 11d shows a continuation of the types of echo activity displayed 5 min earlier in Figure 11c. Only the constant-range part of the field-aligned trace is seen, since the X mode cutoff was now below the 350 kHz start of the sounding range. The zero range type of scattering continued, although there is indication of an increase with frequency in the range to the strongest returns, as well as a falloff with frequency in returns from the longer ranges.

[40] To the upper right in both Figures 11c and 11d are echoes at virtual ranges near \( 4 R_E \). Each is believed to have followed a field-aligned path to the conjugate hemisphere, presumably the same path excited in the local hemisphere. The corresponding real length of the dipole field line at \( L = 2.7 \) in Figure 9 is consistent with this result. During the two soundings after that of 11d, only local-hemisphere field-aligned echoes were detected. If conjugate hemisphere echoes had been detectable, they would probably have arrived outside the \( 4 R_E \) receiving range of the plasmapause because of their longer path lengths.

[41] Differences between the echoes observed near points \( a \) and \( b \) and those near points \( c \) and \( d \) are worthy of note. The frequencies in 11c and 11d were lower due largely to the drop in the local plasma frequency at IMAGE from \( \approx 640 \) kHz in \( 11a \) to \( \approx 350 \) kHz in 11d. The traces at lower altitude and lower L (Figures 11a and 11b) showed minimal range spreading, but contained evidence of branching. There was even some indication of branching on the X mode trace in Figure 11b, beginning around 760 kHz. Wide range spreading only began as IMAGE reached \( L \approx 2.5 \). A tendency for range spreading effects to peak in the outer and middle plasmasphere and to fall off at the lower altitudes has been found in other RPI records.

[42] Figures 11e and 11f represent data acquired in the 350 kHz–480 kHz band at two well separated locations, one in an area of rapidly falling density in what may be called the plasmapause region and the other at a point \( \approx 2.7 R_E \) further along the orbit, when IMAGE appeared to have encountered the plasma sheet (see Figures 9 and 10). Figure 11e shows a spread X mode trace, rising with frequency in the manner of the data in Figure 8d. This is a continuation of the activity of Figures 11c and 11d, but without clear evidence of field-aligned propagation. Data taken a few seconds earlier in the 180 kHz to 245 kHz band show spread echoes extending from minimum range to \( \approx 0.8 R_E \) throughout the band.

[43] Figure 11f shows echo activity that increased more or less steadily in range over the 70 min after the data of 11e, and disappeared out of range after another \( \approx 20 \) min. These echoes are believed to have come from inside the plasmasphere (region 3 in Figure 2), in that they continued to exhibit range spreading of \( \approx 0.5 R_E \) or more.

### 2.5. Brief Summary of Plasmasphere Echo Properties

1. Range spreading on RPI direct echoes from the plasmasphere is observed on essentially all IMAGE orbits, irrespective of the level of geomagnetic activity.

2. RPI short-pulse echoes from the region of steep plasmapause density gradients are spread so as to appear at ranges longer than those expected from a smooth plasmapause density model.

3. Echoes from the interior of the plasmasphere received outside the plasmapause exhibit spreading of \( \approx 0.5 R_E \) or more. When received inside the plasmasphere, beyond \( L \approx 2 \), such echoes exhibit spreading by at least \( 0.5 R_E \) and may appear at ranges both longer and shorter than those expected in a smooth medium.

4. On occasions when the ranges are substantially shorter than those expected and begin at zero range or the minimum observable range of \( \approx 0.3 R_E \), they typically occur in a band of frequencies extending \( \approx 100 \) kHz or more above the local X mode cutoff, as illustrated in Figures 11c and 11d. At higher altitudes such bands are seen in the \( \approx 200–400 \) kHz range, while at lower altitudes they appear between \( \approx 400 \) kHz and \( 800 \) kHz.

5. Range spreading of echoes returning from locations in the plasmasphere tends to occur over the entire detected frequency range of the echo.

### 3. Discussion

#### 3.1. Irregular Density Structure and the Range Spreading

[44] It is clear from the RPI data that the plasmasphere presents a “rough” target to a radio sounder at frequencies below \( \approx 800 \) kHz. We do not yet know how to describe or model that roughness. However, on the basis of the data described above as well as earlier studies of topside sounder data and of whistler mode propagation, we suggest that the observed range spreading is caused by a combination of aspect sensitive scattering from, partial reflection from, and propagation along field-aligned electron density irregularities.

[45] Strong scattering from irregularities with cross field scale sizes comparable to one half the probing wavelength is probably involved in the zero range echoes reported here. As noted, such scattering has been found in topside records from the auroral zone [e.g., James, 1989]. In the RPI data, the frequencies exhibiting this effect range from \( \approx 200 \) kHz to \( \approx 800 \) kHz, which for a half-wavelength dependence corresponds to irregularities in the \( \approx 200–800 \) m range, with the larger scales being observed at the higher altitudes. The high-frequency limit to which zero frequency echoes extend in a particular case may be controlled by the manner in which the irregularity scale sizes and the receiving antenna aperture depend on the probing wavelength.

[46] Echoes excited within the plasmasphere and observed at substantially longer ranges than those expected in a smooth medium may be partly due to the process of combination mode ducting [e.g., Calvert and Warnock, 1969], noted above in connection with Figures 11a and 11b. In such cases the ducting effects would be expected to involve field-aligned density depletions with scale sizes several times the probing wavelength and hence widths of \( \approx 1 \) to 10 km.

[47] As noted, the spreading of echoes from the plasmapause region itself does not seem to be the result of returns from the region between IMAGE and the region of steep gradients, and thus must involve ray paths longer than those expected for an idealized profile. One might attribute them to aspect sensitive reflections from irregularities spaced in longitude along the plasmapause or to multiple scattering from a distribution of irregularities embedded in the plas-
3.2. Density Irregularities: Theoretical Work

[45] Theorists have discussed a number of mechanisms which may underlie the formation of field-aligned irregularities in the plasmasphere. We mention several examples, a notable one being the pioneering work of Gold [1959], who introduced the idea of convective MHD instability, in which flux tubes are interchanged in a manner that preserves the form of the magnetic field. An MHD “quasi-interchange” instability, in which the k vector of the wave mode has a non zero component in the direction of the magnetic field and hence does not preserve the shape of the geomagnetic field, was discussed by Newcomb [1961] and recently has been the subject of extensive analysis and review by Ferrière et al. [1999, 2001].

[46] Particular attention has been paid to instabilities in the plasmapause region. Hasegawa [1971] was among the first to consider the drift wave instability at the plasmapause. Using a kinetic approach as opposed to MHD, Richmond [1973] showed how small-scale field-aligned irregularities can form in the plasmapause region due to the presence of electron pressure gradients. He discussed how interchange instability can act to modify the plasmapause profile and pointed out that “self-induced convective motions may also be important in the production and/or redistribution of small-scale irregularities of thermal plasma observed both inside and outside the plasmapause.” Lemaire [1974, 1975] discussed the gravitational interchange instability and how it would affect the plasma distribution interior to and beyond a radius at which the gravitational and centrifugal forces balance one another. It is noteworthy that Neil Brice, in the process of revising some of his earlier ideas about the plasmapause/plasmasphere [e.g., Brice, 1967] initiated a study of interchange instabilities prior to his untimely death in 1974. The study has been published as Brice [2001].

[49] As noted by Lemaire and Gringauz [1998], candidate mechanisms for the formation of field-aligned whistler mode wave ducts include irregular electric fields, which give rise to flux tube interchange [Cole, 1971; Thomson, 1978] and thundercloud electric fields, which cause a stirring effect on flux tubes with differing electron content [Park and Helliwell, 1971]. Bell and Ngo [1988] suggested that ducts could form as a consequence of the conversion of whistler mode waves into lower hybrid waves in the ionosphere at the location of existing ionospheric irregularities. The short-wavelength lower hybrid waves could then cause pitch angle scattering and precipitation of radiation belt particles, leading to ionospheric plasma density enhancements. Upward diffusion of cold plasma from the enhancements could then produce magnetic field-aligned density irregularities.

3.3. Density Irregularities: Experimental Evidence

[51] Is there evidence that irregularities with scale sizes \( \approx 200 \text{ m} \) to over \( 10 \text{ km} \) appear in the plasmasphere on a regular basis? As noted above, during periods of enhanced magnetic activity, or in the aftermath of such periods, various types of density structure have been found to appear in the outer plasmasphere and plasmapause region, including MHD turbulence, quasiperiodic density variations with peak-to-valley density ratios of 2 or more, and deep, factor-of-5-or-more, density cavities [e.g., LeDocq et al., 1994; Moldwin et al., 1995; Carpenter and Lemaire, 1997, and references therein; Carpenter et al., 2000]. As time passes during quieting, some of the larger scale features may decay into the smaller scale ones at issue here. Sales et al. [1996] investigated cases in which irregularities formed on the “walls” of a field-aligned density depletion in the equatorial ionosphere.

[53] The plasmapause region has been found to be particularly active in terms of the formation of density structure [e.g., Horwitz et al., 1990; Carpenter et al., 1993; LeDocq et al., 1994; Moldwin et al., 1995]. Kintner and Gurnett [1978] reported that drift wave activity at the plasmapause had produced doppler shifted electrostatic waves observed on a satellite. The findings of Southwood [2000] during the 1999 Cassini spacecraft Earth swing-by are noteworthy. A fluxgate magnetometer detected isolated dips in the background magnetic field in the plasmapause region, which the author proposed were due to interchange instability of the plasmaspheric plasma and hence indicative of processes outlined much earlier by Richmond [1973] and Lemaire [1974, 1975], in which bubbles of high-density thermal plasma break away from their locations and drift outward.

[55] Using a Very Large Array radio interferometer, Jacobson and Erickson [1993] identified a type of irregularity extending 30 to 40 km transverse to the magnetic field with amplitude of order \( 100 \text{ cm}^{-3} \), or approximately 5–10% of the background level. Such irregularities were detected most frequently near \( L = 2 \) and were found to be approximately rotating with the Earth. Jacobson et al. [1995] later used radio beacons from nearly geostationary satellites to detect the drift of plasmaspheric irregularities past the radio lines-of-sight. Most of the drift events were found to occur at \( L > 2.5 \).

[57] That the irregularities discussed here may be small scale and also geomagnetic field-aligned is supported by RPI data showing field aligned propagation during quiet periods [e.g., Fung et al., 2002]. Field-aligned echoes are usually detected at one or more points along each IMAGE pass through the plasmasphere, and on some passes such echoes have been received every 2 or 4 min during 10 or 15 successive soundings from altitudes above \( \approx 4000 \text{ km} \). In topside sounder work, as noted earlier, clear evidence was found in support of the existence of field-aligned irregularities with cross field dimensions of a few kilometers that can guide free-space-mode waves along paths at invariant latitudes below \( 40^\circ \) [e.g., Muldrew, 1963, 1969; Loftus et al., 1966]. From theoretical considerations of the enhancement factors required for guidance by Booker [1962], and in view of the latitudes and wave frequencies of observation, Loftus et al. [1966] concluded that the density irregularities involved deviated in most cases no more than 1% from the background level and in all cases by less than 8%. Platt and Dyson [1989] extended earlier work on ducting by modeling the effects of the duct density profile on the reception of both direct and conjugate ducted echoes at low latitudes. They found...
that the percentage depletion needed for guiding was higher than had been found in previous calculations using simplified theory, but was still in the 2%–5% range.

[55] Muldrew and Hagg [1969] found evidence of echoes propagating back and forth along high-latitude field lines between a sounder and reflection points at lower altitudes, and James [2000], reporting on the Oedipus-C dual payload radio sounder, described strong ducted echoes that were observed along subpayload paths in the auroral E region.

[56] Evidence was found that most ionospheric irregularities are elongated in the direction of the geomagnetic field [e.g., Calvert and Warnock, 1969]. Calvert [1981] later discussed the need for a duct sounder operating in the magnetosphere, and concluded that AKR detected while ISEE 1 was in the plasmasphere shadow zone had propagated to ISEE along ducts of slightly depleted plasma density outside the plasmasphere [Calvert, 1982].

[57] Whistler mode signals are known to propagate in both a “ducted” and “nondocted” mode, having been observed for years by a combination of ground and satellite recordings [e.g., Hayakawa, 1995; Sonwalkar, 1995]. Although the wave mode involved is a trapped, rather than a free-space mode, the associated findings seem quite relevant to the issue of field aligned irregularities. There is clear evidence that at invariant latitudes extending from L < 2 beyond the plasmasphere, whistler mode ducted signals follow discrete, field aligned paths [e.g., Hayakawa, 1995; Carpenter and Šulíč, 1888], which according to theory involve either localized density enhancements by a few percent, analogous in action to light fibers, or step-like changes in density (one sided ducts) [e.g., Smith, 1961; Helliwell, 1965; Inan and Bell, 1977; Strangeways and Rycroft, 1980; Strangeways, 1991]. Studies show that whistler paths, or paths on which man-made transmitter signals propagate, can undergo bulk, noncorotational motions under the influence of convection electric fields [e.g., Carpenter et al., 1972; Carpenter and Smith, 2001]. Ducted whistler signals can be observed over a wide range of geophysical conditions and at all magnetic local times. They have in some periods been observed on the ground at rates of 1 or more per minute over successive 24-hr periods [e.g., Carpenter, 1966]. On magnetically quiet days, the output of 10 to 20 ducts can be collected by a ground station receiver, and various analyses suggest that the density enhancement factors involved in such cases are less than 30% [e.g., Smith, 1961; Helliwell, 1965; Carpenter et al., 1981].

[58] Propagation within, and leakage from, a group of whistler ducts was detected in situ near the equator by Angerami [1970], who found that the ducts were several hundred km in radial extent near the equator at L ≈ 4. On the other hand, analysis of ground and satellite whistler data reveals that a single whistler can contain several hyperfine elements [e.g., Beghin and Stirelay, 1964; Hamar et al., 1990], which could be interpreted either in terms of electron density fluctuations of the order of 1% and spatial scale sizes of the order of 50 km, or possibly in terms of the excitation of multiple propagating modes within a duct [e.g., Hamar et al., 1992]. Overall, it seems reasonable to suppose that the physical conditions that give rise to discrete whistler mode paths can also produce the conditions necessary for ducting of the free space modes.

[59] The existence of irregularities with transverse dimensions of ≈5–100 m in the plasmasphere at L < 2 and in the ionosphere from middle to subauroral latitudes poleward of the plasmapause has been indicated through doppler shifts of narrow band whistler mode transmitter signals injected into the magnetosphere from ground based transmitters. Spectral broadening of ≈1 Hz bandwidth whistler mode waves was interpreted as evidence of conversion of part of the incident wave into lower hybrid waves at the boundaries of density irregularities with enhancement factors as low as 5% [Bell and Ngo, 1988, 1990]. The effect was observed on 60 satellite orbits which penetrated the inner radiation belts (L ≤ 2), and in many cases the effect was observed continuously from the magnetic equator at L ≈ 2 down to perigee at ≈1000 to 3000 km [Bell and Ngo, 1988].

3.4. Use of RPI Soundings for Large-Scale Diagnostics of the Plasmasphere

[60] Prior to the IMAGE launch it was expected that RPI echoes from the plasmasphere would allow the study of the larger scale (>0.1 Re) structure of the plasmasphere. Observed range-versus-frequency echo forms indicate that such studies are indeed feasible. Echoes received when IMAGE is outside the plasmapause can be used to: (1) locate the plasmapause position to within ≈0.1–0.2 Re, (2) determine the approximate density level at the inner limit of the steep plasmapause density gradients, (3) infer the general form of the density profile inside the plasmasphere (in spite of the occurrence of range spreading).

[61] That part of a plasmasphere echo for which the minimum range is roughly constant with frequency can be used for locating the plasmapause position, as noted above in connection with Figure 4. Of particular interest is the possibility of detecting cross-L inward or outward motions of the boundary with respect to the IMAGE orbit plane. Such motions could easily reach ≈0.5 Re hr⁻¹ or more during substorms, and are known to last from tens of minutes to more than an hour [e.g., Carpenter et al., 1972, 1979]. The motions could be tracked by RPI during a 30 min period of observation; a plasmapause displacement of ≈0.5 Re per hour (equatorially) would at the end appear as a departure by 3 range gates from the delay expected on the basis of a fixed plasmapause L value (provided RPI enters or exits the plasmasphere within ≈30 degrees of the equator). When additional signal integration is used, and the plasmapause can be detected at ranges of 3 Re or more, as in the case noted above in which longer pulses were used, there will be longer observing times (up to 2 hours or more). This longer observing time will provide opportunities to investigate longitudinal variations in the plasmapause radius as well as its radial motions.

[62] In plasmasphere echoes from relatively sharp boundaries, such as those illustrated in Figures 3 and 5, the sounding frequency of transition from region 2 to region 3 (in Figure 2) can provide a coarse measure of ne at the inner limit of the plasmapause gradients, as noted in the discussions of Figure 4 and Figure 6.

[63] General properties of the profile inside the plasmasphere can be obtained in some cases from the general shape of the plasmasphere echoes, as in the case of Figure 6. When the echoes extend to frequencies of 500 kHz or more.
and range spreading is small compared to the overall change in range, as in the case of Figure 8, the echo form can provide information on the large scale distribution of \( n_e \) extending to relatively low altitudes in the plasmasphere. Individual echo forms may be simulated by ray tracing in a density model based on the RPI dynamic spectral profile for the pass in question, after which the model may be refined until the calculated echoes are consistent with those observed during two or more successive soundings. This approach is not unlike that employed by Inan et al. (1977) who used whistler mode signals from the experimental transmitter at Siple Station, Antarctica and received on IMP 6 to study the plasma distribution near the plasmaopause, and by Kimura et al. (1997) who used whistler mode signals from ground transmitters received on AKEBONO at multiple points in the plasmasphere to study the large scale electron density distribution. The approach is complementary to that of Reinisch et al. (2001b), who used ducted RPI echoes observed at multiple points along an IMAGE orbit to study plasmaspheric density.

[64] It is not yet clear why short range direct echoes from the plasma trough (region 1 in Figure 2) have not been detected by RPI, since field aligned echoes from various points in region 1 have been observed. It is possible that the trough region is “smoother” than the nearby plasmasphere, in terms of the presence of irregularities that might produce scattering of RPI signals. LeDucq et al. (1994) found the trough profile to be less irregular than the plasmapause region. An important factor may be the predicted steep falloff in radiated power from RPI at frequencies below 50 kHz [Reinisch et al., 2000], a range within which most direct echoes from region 1 might be expected.

4. Conclusions

[65] Persistent range spreading is observed on RPI echoes that follow non-field-aligned ray paths within and near the plasmasphere. The range spreading is believed to be caused by interactions with geomagnetic field-aligned electron density structures. Such interactions appear to include scattering from irregularities with cross-field dimensions roughly one half the signal wavelength as well as refraction into and partial propagation along ducts with cross-field scales of several signal wavelengths. There are indications that the spreading effects are a maximum in the plasmapause region and outer plasmasphere, and that they diminish below altitudes of several thousand km. The RPI data, supported by evidence from other radio experiments such as topside sounders and whistler mode instruments, suggest that the plasmasphere is regularly permeated by field-aligned irregularities with electron density within <10% of background. The cross field scale sizes of the irregularities are inferred to fall within the range \( \approx 200 \) m to >10 km. Some such structures may develop as the result of instabilities at the edges of known large scale density features such as the plasmapause and density cavities in the plasmasphere. Efforts to understand the origins of the irregularities should give new impetus to an already well established and growing body of theoretical work on plasmaspheric instabilities.

[66] Further study of the RPI data should lead to better understanding of the spatial distributions and scale sizes of range spreading irregularities, and of how they may act to produce the range spreading effects. Those effects are not predicted by conventional 2D ray tracing calculations, even when smoothed versions of measured density profiles are used. We suggest that full-wave electromagnetic models will be needed to analyze and gain understanding of the factors involved, as well as ray tracing in density models permeated by ducts.

[67] We find that RPI echoes can regularly be returned from points extending inward from the plasmapause to locations where \( n_e \) reaches \( \approx 3000 \) cm\(^{-3}\) which is usually at \( L < 3 \). Because of this depth of echo penetration it appears possible to detect certain major structural features of the outer plasmaspheric \( n_e \) profile, such as the ledge indicated in Figure 6.

[68] In spite of range spreading, the leading or low-delay edge of a given echo has been found to provide a useful measure of distance inward to points in the plasma trough and especially to the region of steep plasmapause density gradients. With the distance to the plasmapause known to within \( \approx 480 \) km (or the size of one range bin), it should be possible to investigate changes with time in that range associated with erosion effects, outward drifts, or longitudinal structure.

[69] In further work it is hoped to gain understanding of the particular forms of density irregularity to which the RPI signals are sensitive, and in so doing provide support for interpretive work on the physical mechanisms underlying those forms. The irregularities are part of the coupled magnetosphere-ionosphere system, and it is possible that subsets of the irregularities that give rise to range spreading and to the field aligned echoes noted above may be of importance in controlling the propagation and distribution in space of the naturally occurring and man made whistler mode waves that are known to interact strongly with electrons in the Earth’s radiation belts.

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