Magnetospheric Sounding by IMAGE

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The Radio Plasma Imager (RPI) on the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) spacecraft was designed as a long-range magnetospheric radio sounder, relaxation sounder, and a passive plasma wave instrument. The RPI is a highly flexible instrument that can be programmed to perform these types of measurements at times when IMAGE is located in key regions of the magnetosphere. The echoes observed by RPI are analyzed to obtain electron densities profiles all along the sounder ray paths allowing a comprehensive picture of the structure and dynamics of the inner magnetosphere to be created.

1. Introduction
The IMAGE spacecraft was launched on March 25, 2000 into a highly elliptical polar orbit with initial geocentric apogee of 8.22 Earth radii (R_E) and perigee altitude of 1000 km. The RPI instrument transmits coded electromagnetic waves over a selectable frequency range from 3 kHz to 3 MHz from a long dipole antenna. RPI utilizes three orthogonal dipole antennas of 325 m (X-axis), 500 m (Y-axis), and 20 m (Z-axis). The X-axis dipole is used for transmission while all antennas are used for the reception of the return echoes and for making passive radio measurements. For more details on the RPI instrument, see Reinisch et al. [2000]. The far-field radiation pattern of the RPI transmissions cover nearly all directions. From a sweep over a series of sounding frequencies RPI observes a wide variety of magnetospheric echoes. This short paper provides a brief overview of the type of RPI echoes observed and some of the results from their analysis.

2. Types of Echoes Observed
Figure 1A is an RPI plasma gram (signal strength as a function of virtual range and frequency) when the IMAGE spacecraft was just inside the plasmasphere. The virtual range is given by ct/2 where c is the free-space speed of light and t is the echo delay time. The echo intensity is color-coded. Three basic types of RPI echoes (field-aligned, diffuse, and resonance) are shown in Figure 1A.

Fig 1. RPI plasma gram with field-aligned and diffuse echoes labeled (panel A). The directions of the observed echoes relative to the spacecraft position (panel B). The diffuse echoes are spread in range and are therefore reflecting from a series of irregularities (panel C).

Figure 1B shows the directions of the observed echoes relative to the spacecraft position. The diffuse echoes typically show range or frequency spreading whereas field-aligned (guided) echoes tend to appear as discrete traces in plasmasgrams and often in multiple traces over the same frequency range. The diffuse resonances are spread in range due to reflections from a series of irregularities as shown in panel C. Plasma resonances observed by RPI appear as vertical emissions in plasmasgrams (see section 7).

3. Diffuse Echoes
Based on direction analysis and the observed virtual ranges for the spacecraft observation location, the ray paths of the diffuse and field-aligned echoes of Figure 1A are shown schematically in Figure 1B. Carpenter et al. [2002] and Fung et al. [2003] attributed the range spreading of the diffuse echoes to coherent (aspect-sensitive) scattering from field-aligned electron density (N_e) irregularities (FAI) having < 10% variations of the background N_e that range in size from 200 m to a few km as illustrated in Figure 1C. Carpenter et al. [2002] also pointed out the possibility of refraction into and partial propagation along ducts having cross-field scales of several signal wavelengths.

4. Field-Aligned Echoes
From ray tracing calculations, Fung and Green [2005] have demonstrated that multiple traces of RPI discrete echoes of the type shown in Figure 1A are most likely due to ducted signals from conjugate hemispheres along closed field-aligned paths, analogous to the mechanism generally invoked to explain similar ionospheric observations. Figure 2 shows that ducting of nearly field-aligned propagating waves (ψ ~ 0°) occurring within N_e depletions as small as 1% and less than 10 wavelengths wide. Conjugate field-aligned echoes observed by RPI are most likely due to waveguide ducting with relatively smooth ducts, maintained along the plasmaspheric field lines.

In the case of ducting, EAI can act like a waveguide that traps and channels wave energy along the background magnetic field. For high-frequency electromagnetic waves (f >> f_ahu, where f_ahu is the upper hybrid resonance frequency), a region of N_e depletion extending some distance along the magnetic field may be able to trap wave energy by total internal reflections along a field-aligned N_e duct. The questions of generation and
maintenance of field-aligned $N_e$ ducts remain outstanding and require further investigation.

Echoes at different frequencies that propagate in the same mode and direction form a distinct trace on a plasmagram. Figure 3A shows five such traces; indicating that only a limited number of modes and propagation directions can produce strong echo traces. The five traces in Figure 3A were actually produced by three modes, labeled X and Z in the figure (the Z involves coupling to the O mode), each propagating parallel (toward the northern hemisphere, labeled N) and anti-parallel (toward the southern hemisphere, labeled S) to the magnetic field direction [Reinisch et al., 2001].

Fig. 2. Ray tracing calculations in a plasmaspheric density duct of free escaping R-X mode waves at 120 kHz. Rays launched within a few degrees of the magnetic field are ducted while other are refracted away.

The field-aligned $N_e$ profiles in the two hemispheres, derived from the echo inversion technique are shown in Figure 3B as one curve, as a function of latitude. Multiple field-aligned $N_e$ profiles obtained successively along the spacecraft track by RPI can be combined to produce a 2-dimensional $N_e$ distribution along the field and along the IMAGE spacecraft track [Huang et al., 2004]. When the spacecraft revisits the same region periodically in different orbits, plasma depletion and refilling and other dynamic processes can be investigated [Reinisch et al., 2004].

Fig. 3. The RPI plasmagram (panel A) shows field-aligned echoes, which allow inversion of the data into a field-aligned plasma electron density profile (panel B).

5. Plasmasphere Refilling

The time it takes for the plasmasphere to refill after the March 31, 2001 storm period can be determined by comparing those field-aligned $N_e$ profiles with the profiles obtained during a quiet day with very low Kp. The March 31, 2001 storm was so strong that the enhanced cross tail electric field reduced the L value of the plasmapause to about 2.3 thereby emptying plasmaspheric flux tubes all the way out to the pre-storm plasmapause at $L = 5$. Typical RPI observations of guided echoes after this very large geomagnetic storm are shown in Figure 4A (as an example of one out of a succession of plasmagrams). Inverting the guided echoes gives a $N_e$ profile shown in Figure 4B. The $N_e$ along the same L value from the quiet day empirical model is also shown.

Fig. 4. Panel B compares the results of the inversion of the measured ducted echoes in panel A with the quiet day model of the plasmasphere. The quiet day model was constructed from observed ducted echoes during a time of low Kp.

A large difference in $N_e$ is found in this comparison indicating the extensive loss of plasma that occurred during the geomagnetic storm period. Since plasmasphere filling is a process that can take a day or more, successive IMAGE passes through the plasmasphere can be used to monitor the filling process. The IMAGE/EUV observations clearly shows that the plasmasphere was stripped of cold plasma down to very low L values at all local times during this geomagnetic storm. A plasma convection tail was also observed by EUV in the late evening local time sector; however, the RPI observations were made along the orbit plane, which was primarily in the noon-midnight meridian avoiding any region of enhanced plasmaspheric material that would adversely effect the determination of the filling rate.

Figure 5 shows the RPI derived equatorial $N_e$, normalized by the quiet day equatorial $N_e$, from four consecutive passes of IMAGE through the plasmasphere. Since the IMAGE orbital period is approximately 14 hours, "snapshots" of plasmaspheric filling can be obtained every 14 hours. The inner plasmasphere, below about L of 2.3, shows no depletion from the storm while the equatorial densities at higher L values undergo extensive depletion. The refilling process at $L = 2.8$ started at approximately 1600 UT on April 1 and, as shown in Figure 5, is complete by about 2000 UT on April 2. The refilling of plasma in the plasmasphere at an L value of 2.8 is therefore completed in less than about 28 hours. These observations are consistent with those of Park [1974], who determined refilling times from whistler observations.

The RPI observations of guided echoes also provide a unique capability to compare RPI derived field-line $N_e$ distributions with plasmasphere transport models. Comparisons by Tu et al.,
of RPI derived field-line $N_e$ distributions with the field-line inter-hemispheric plasma (FLIP) model shows good agreement only for the equatorial region and that higher densities are found at higher latitudes. The agreement can be improved by invoking direct heating of ions in the plasmaphere at the equator during the time of plasmaphere refilling. Ion heating at the equator, and therefore enhanced ion pressure, will impede ionospheric flow into the plasmaphere giving rise to an increase in the $N_e$ gradient along at the mid-latitudes.

**6. Polar Cap Electron Densities**

During IMAGE apogee passages over the northern polar region, polar cap echo traces have been observed to last up to three hours [Nsumei et al., 2003]. In this high latitude region, the geomagnetic field lines are nearly radial, so that direct echoes from the polar cap and field-aligned guided echoes are not easily distinguishable. Inversion of polar cap traces (either from direct or guided echoes) will yield the nearly radial $N_e$ profiles of the polar cap. Nsumei et al. [2003] created an empirical model as a function of $K_p$ by appropriately binning and averaging the RPI $N_e$ data. The result of this analysis is shown in Figure 6 along with a comparison of the Persoon et al. [1983] and Gallagher et al. [2000] polar cap models.

The Persoon, Gallagher, and Nsumei $K_p = 1$ models agree relatively well. However, the RPI polar cap model clearly shows the dependence of the polar cap densities with increasing geomagnetic index $K_p$. The analysis in the Persoon and Gallagher models primarily involve interpretation of wave propagation cutoffs and particle measurements under low densities and spacecraft charging conditions, all of which typically underestimates polar cap $N_e$. The RPI echo observations have no such limitations and provide a much more realistic determination of the polar cap densities.

It is important to note that the RPI measurements were taken near solar maximum while the Persoon and Gallagher models were derived from observations that range over the entire solar cycle. This may account for some of the difference in the models. RPI's ability to obtain the polar cap $N_e$ structure during individual passes will shed new light on the processes that governs polar wind outflow and the contributions of plasmas from auroral or polar cusp sources under different geomagnetic conditions. These studies are underway.

**Polar Cap Density Models**

Fig. 6. RPI polar cap density models for three separate $K_p$ ranges derived from 108 plasmagrams. The average polar cap densities for low $K_p$ compares reasonably well with the previously published model results of Gallagher and Persoon, however, the RPI model densities for large $K_p$ indices are significantly higher (by a factor of ~10).

**7. Local Sounding**

The RPI is also a relaxation sounder that generates and detects short-range electrostatic wave echoes at the various resonance frequencies or normal modes of a plasma. Like many other missions that have preceded IMAGE (e.g. GEOS 1, ISEE 1) a relaxation-sounder permits accurate determination of the local $N_e$ and magnitude of the magnetic field ($B$) at the spacecraft when the resonances have been properly identified. The advantage of the RPI over other magnetospheric relaxation sounders is that it has enough power to generate the long-range electromagnetic echoes (as described in the previous sections) that can uniquely identify the X and O mode cutoff frequencies and thereby allow for the proper identification of all the natural plasma resonances observed.

The local $N_e$ and $B$ are determined mainly from the measured frequencies of the sounder-stimulated plasma resonances at $f_p$, $f_x$, and $f_n$ (where $n = 2$, $3$, and larger values). Other resonances, such as the Q and D resonances, can also be used to determine these parameters but only when care is taken to properly identify the resonances at frequencies both above the upper hybrid resonance frequency ($f_{uhb}$) and below the plasma frequency. Use of the resonance measurements can allow for the determination of the $f_p$ to within ~1% and $f_x$ to within ~0.1%.

Figure 7 shows two plasmagrams with plasma resonances taken near apogee one orbit apart just before (panel A) and during (panel B) a geomagnetic storm using the Z axis antenna. Figure 7 is the result of an extensive resonance analysis process that begins by resorting the RPI data with respect to the gyrofrequency harmonics (see Benson, et al., 2003 for more details on this technique). Since all the Q and D resonances have a gyrofrequency dependency then they too can be identified in this new coordinate system. D resonances appear below the plasma frequency ($f_p$) and Q resonances appear above the plasma.
frequency. The resulting identified resonances are then plotted onto the plasmagram to create Figure 7.

Fig. 7. Two RPI plasmagrams showing the local plasma resonances conditions near apogee on consecutive orbits prior (panel A) and during (panel B) a large geomagnetic storm.

The only resonances measured in Figure 7A are from the harmonics of the gyrofrequencies \( f_g \) whose value has been determined to be 2.375 kHz. The local \( f_p \) must be below 6 kHz since that is the frequency at the start of the sounding sequence. The observed resonances in Figure 7B, one orbit later, are significantly different and show \( f_p, n f_g, Q, \) and D resonances. These storm time observations show that \( f_p \) is now over 8 kHz and the observed \( f_g \) is ~17.4 kHz. The observed Q resonances, or Bernstein mode waves, have group velocities nearly matched to the spacecraft, and have been observed in the ionosphere and magnetosphere [Benson et al., 2003] at frequencies between the \( f_g \) harmonics and above \( f_{uhc} \). Prior to the launch of IMAGE, the D resonances had only been reported in the topside ionosphere at frequencies between the \( f_g \) harmonics and below \( f_{uhc} \). There has been an on-going controversy as to the existence in planetary magnetosphere of the D resonances but it is now clear from the RPI resonance observations that these D resonances are similar to those stimulated by topside sounders in spite of the large differences in the electron temperatures. In light of the intense D resonances easily observed by RPI, previously published results from other magnetospheric relaxation sounders may need to be re-examined for the D resonances.

8. Conclusions

The long-range sounder echoes from RPI allow remote sensing of a variety of plasma structures and boundaries in the magnetosphere. A profile inversion technique for RPI echo traces has been developed and provides a method for determining the \( N_e \) distribution of the plasma from either direct or field-aligned echoes. This technique has enabled the determination of the evolving \( N_e \) structure of the polar cap and the plasmasphere under a variety of geomagnetic conditions.

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References