FIRST MAGNETOSPHERIC ECHO TRACES FROM THE RADIO PLASMA IMAGER ON IMAGE

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The radio plasma imager (RPI) on the IMAGE satellite is a low-frequency radar system that uses orthogonal 500-m tip-to-tip dipoles to transmit RF pulses with frequencies from 3 kHz to 3 MHz. A third 20-m tip-to-tip dipole antenna along the spin axis is used for reception together with the two long antennas providing direction of arrival capability. The minimum pulse length of 3.2 ms yields a range resolution of 480 km. When the spacecraft is in the magnetospheric cavity (altitude of 5–7 RE) RPI can receive echoes associated with the plasmasphere, the magnetopause and the cusp region, at frequencies between ∼10 and 100 kHz. At high altitudes, higher frequency echoes are found reflecting from the topside ionosphere. This paper will present some of the first echo observations measured by the RPI instrument.

INTRODUCTION

The Imager for Magnetopause-to-Aurora Exploration (IMAGE) satellite was launched on March 25, 2000 into a highly elliptical polar orbit with an initial apogee geocentric radial distance of 8.22 RE and initial perigee of 1000 km. IMAGE is the first spacecraft dedicated to remote sensing of the magnetosphere (Burch, 2000). Observations from the IMAGE instruments are used to determine the global-scale structures and dynamics of the magnetosphere by imaging the aurora at several wavelengths, imaging the plasmasphere from resonance scattering He+, imaging neutral atoms from 10 eV to 500 KeV in energy, created by charge exchange with the Earth's neutral H exosphere, and by radio sounding with the Radio Plasma Imager (RPI).

The RPI instrument covers the frequency range from 3 kHz to 3 MHz with a receiver bandwidth of 300 Hz. RPI uses 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). All RPI antennas are used for reception, allowing the measurement of the angle of arrival of the signals (Reinisch *et al.*, 1999). The X axis dipole is used for transmission and is electronically tuned to enhance the transmission efficiency. The radiated RF power is limited to 10 W. A number of different waveforms can be selected to adapt to diverse environments, *e.g.*, a simple 3.2 ms pulse modulation with constant repetition rate or a complimentary phase-coded pulse consisting of 4, 8, or 16 of the 3.2 ms chips. Selective application of pulse compression and spectral integration processing enhances the signal-to-noise ratio by nominally 15 dB. The design of the RPI is described in much greater detail by Reinisch *et al.*, 2000a and is based on the design of the "Digisonde" (Reinisch, 1996) that has successfully been used for years to monitor ionospheric density from the ground.

PASSIVE OBSERVATIONS WITH RPI

Radio sounding measurements with RPI are typically interspersed with passive operations (Oya *et al.*, 1990). The result is that a complete spectrum of passive measurements is generated at least once every eight minutes

Invited paper.

Figure 1: Frequency-time spectrogram of RPI passive measurements May 11, 2000. The green trace is the expected *in-situ* gyrofrequency obtained from a model magnetic field. Local density measurements can be easily determined since plasma thermal emissions, during times when the fg $\ll$ fp, are clearly seen and provide a plasma frequency map of the polar cusp and plasmasphere as shown in this example

Figure 2: RPI echoes from the high latitude magnetosphere are shown in these plasmagram plots of apparent range versus frequency. The apparent range is determined by assuming the echoes are due to electromagnetic pulses traveling at the speed of a light in vacuum and measuring the time delay between transmission and signal reception

Figure 3: Left-hand panel shows the plasmagram of echoes from the polar cusp. The right-hand panel shows the dynamic spectrogram of plasma emissions during *in-situ* measurements as the IMAGE spacecraft passed through the polar cusp over a several hour period

Figure 4: Whistler mode echoes are observed at frequencies below about 80 kHz

and sometimes every two or four minutes. These passive wave observations are used to provide a familiar context for the RPI echo observations and to measure the characteristic cutoff frequencies in the local plasma. In the passive mode, RPI measures the electric field intensity simultaneously from each of the three axis dipole antennas with three separate receivers. Figure 1 shows a typical RPI dynamic spectrogram from 9 to 300 kHz for May 11, 2000, as measured with the X-axis dipole. Due to RPI's long antennas and very low noise receivers the spectrograms provide a very rich set of wave observations. The green trace overlaying the spectrogram in Figure 1 is the local electron gyrofrequency (fg) as determined from a typical model field. Since IMAGE's orbital period is 14.25 hours, fg can be seen to go through nearly two complete cycles in 24 hours.

On May 11, 2000 RPI observed a number of solar type III radio bursts and auroral kilometric radiation (AKR). When IMAGE enters the cusp region or the plasmasphere, the ambient emissions can no longer propagate to the spacecraft and the sudden intensity cutoffs identify the local plasma frequencies. IMAGE's orbit is such that its apogee is on the day side at about 7 hours magnetic local time (MLT) at about 45° magnetic latitude.

For May 11, 2000 shown in Figure 1, RPI measured a number of echoes and local plasma resonances throughout its orbit. Typical echo traces will be presented in the next section.

MAGNETOSPHERIC ECHOES

Echoes from RPI transmissions are observed when IMAGE is located in a low-density region between higher-density regions (which could be the ionosphere, the plasmasphere, the magnetospheric cusp and the magnetopause). The primary presentation of RPI sounding data is in the form of plasmagrams, which are the magnetospheric analogs of ionograms. Figure 2 shows a sequence of three plasmagrams on May 11, 2000, when the IMAGE spacecraft is outgoing at large radial distance over the northern polar cap in the low density region of the magnetosphere. The plasmagram is a plot of the echo amplitude as a function of frequency and echo delay τ. Instead of τ the vertical axis shows $c\tau/2$, the so-called virtual range to the reflector since it assumes that the radio pulse propagates with the speed c of light in vacuum. The true distances from the satellite to the reflecting plasma can be calculated using an inversion algorithm developed for magnetospheric sounding (see Reinisch *et al.*, 2000b).

The echo traces in Figure 2 extend to higher time delays with increasing frequencies, and have a shallow slope from 200 kHz to nearly 1000 kHz, indicating a steep density gradient in the reflecting region of the polar cap. These panels all show two traces indicating that RPI is observing the ordinary and extraordinary mode echoes. Traces such as these have been observed for times exceeding two hours, allowing an unprecedented capability of determining the high latitude density structure and dynamics.

POLAR CUSP ECHOES

One of the key IMAGE science questions is the mechanism of injection of plasma into the magnetosphere. By comparing the cusp echoes shown in the left hand panel of Figure 3 to the *in-situ* measurements, as shown in the right hand panel of Figure 3, we can determine the time history of the cusp density profile and thus determine whether the injection is steady-state or impulsive. In this case, the echo time delay shows a peak virtual range of 1.2 RE) at about 45 kHz, consistent with a shallow density gradient "shelf" at that frequency, and a shallow area from 50–90 kHz, consistent with a steep density gradient. This sweep was taken at around 0611, May 11, 2000. Comparing the estimated density profile with the *in-situ* measurements on the right shows a good agreement with the density profile observed an hour later. Thus, at least in this case, the injection mechanism is quasi-steady. However, from sweep to sweep the sounding traces show considerable variability, so that the injection mechanism is clearly not time-independent.

The cusp density profile obtained from Figure 3 can be used to determine the means of particle injection. The white line in the spectrogram represents a broad cusp density profile, which is consistent with a diffusive entry. The merging cusp entry predicts a cusp density profile that is very steep on the equatorward side and broad on the poleward side. The spectrogram on the right side of Figure 3 (see also Figure 1) shows in fact a steep equatorward gradient (at about 0730) and a broad profile on the poleward side (from 0630–0720). Thus, these profiles are consistent with entry from magnetic merging.

WHISTLER MODE ECHOES

When the RPI transmitted frequency falls below the local electron cyclotron frequency, the transmitted wave can propagate as a whistler mode wave. When IMAGE is well within the plasmasphere, whistler mode echoes are received, allowing determination of low-altitude electron density structures. Figure 4 shows whistler mode returns (falling trace from 10–40 kHz), and a plasmapause echo trace from 80–200 kHz.

CONCLUSIONS

The RPI provides a wealth of information about the electron density structures and boundary locations of many features in the Earth's magnetosphere (see Green *et al.*, 2000). Initial RPI sounding observations demonstrate that even during relatively intense natural emissions, such as solar type III radio bursts, echoes can be observed from the plasmasphere at distances of 3 RE or greater from the target. These are the first radio soundings at such large radial distances within the magnetosphere.

The RPI also operates in a passive mode in order to receive natural magnetospheric emissions. Because RPI uses the longest dipole antennas ever flown, and has ultra low noise radio receivers, as well as it is located on an electro-magnetically clean spacecraft, RPI is providing some of the most unique natural emission measurements ever made within the magnetosphere. The passive operations help to eliminate possible confusion about the reception of echoes from active RPI transmissions, and place the sounder echo measurements into a familiar context.

These types of observations provide very precise measurements of the plasma characteristics within the Earth's magnetosphere and should have a dramatic effect on improving our density models under a variety of magnetospheric conditions.

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