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doi: 10.1016/S0273-1177(03)00270-9

ADVANCES IN MAGNETOSPHERIC RADIO WAVE ANALYSIS AND TOMOGRAPHY

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ABSTRACT

Initial theoretical studies of multi-spacecraft radio tomographic imaging of the magnetosphere have shown the potential scientific value of the technique. We report a series of multistatic radio propagation experiments with the goal of testing and verifying the capabilities of radio tomography. These experiments focused specifically on measuring the plasma-induced rotation of the wave polarization (Faraday rotation), from which the path integrated product of magnetospheric electron density and magnetic field can be directly inferred. These experiments used the Radio Plasma Imager (RPI) on the IMAGE satellite as the transmitter. The receiving instruments were the WAVES instrument on WIND and the WBD instrument on CLUSTER. These experiments showed that Faraday rotation can be measured on relatively long (>10 R_E) magnetospheric propagation paths with existing transmitter and receiver technology. We conclude that radio tomographic imaging of magnetospheric electron density and magnetic field is a powerful technique with unique, large-scale measurement capabilities that can effectively address important questions in magnetospheric physics.

INTRODUCTION

Modern experimental space physics is pursuing an approach of imaging rather than point measurements. Measurements of large scale regions of space plasma are acknowledged as necessary to solve many outstanding problems in space physics. Large volumes of connected plasma must be probed during relatively short periods of time, which cannot be done with single spacecraft in situ measurements. There are two approaches to achieving this kind of measurement: simultaneously measure in situ parameters on multiple spacecraft, or employ imaging techniques to remotely probe a large volume of space. One promising remote imaging technique is tomography, in which multiple line-of-sight or spatially integrated measurements are processed into a complete multidimensional image of the probed volume. In its most general form, tomographic imaging is used routinely in many fields, including seismology, medical imaging, and non-destructive testing.

In radio tomography, multiple receivers and transmitters are used to measure a path-integrated quantity on multiple line-of-sight propagation paths. Mathematical reconstruction techniques are then used to assemble the information from these paths into an image. This technique is now commonly used to probe the electron density structure in the ionosphere (*Bernhardt et al.*, 1998), as the radio group delay and phase advance are linearly related to the path-integrated electron density (*Davies*, 1990).

Two different radio tomography techniques have been proposed for probing the magnetosphere. *Ergun*

Adv. Space Res. Vol. 32, No. 3, pp. 329–336, 2003

Printed in Great Britain
0273-1177/$30.00 + 0.00

et al. (2000) have analyzed magnetospheric electron density tomography using 16 spacecraft constellation based on interspacecraft phase difference and group delay measurements. Measurements from multiple satellite-to-satellite magnetospheric propagation paths can be tomographically reconstructed into images of electron density. The concept of magnetospheric electron density remote sensing with this technique was proven with a single propagation path experiment with ISEE 1 and 2, which contained a transmitter-receiver pair designed to measure the total phase shift on a 683 kHz signal propagating between the two spacecraft (*Harvey et al.*, 1978).

Ganguly et al. (2000) have shown how interspacecraft Faraday rotation measurements also enable tomographic reconstructions of large-scale magnetospheric structures. Faraday rotation is the rotation of the polarization of a linearly polarized wave as it travels through an anisotropic medium like magnetospheric plasma. For frequencies higher than the electron plasma and gyrofrequencies, Faraday rotation θ_F is proportional to the path-integrated product of the electron density N_e and the magnetic field $\mathbf{B}$ parallel to the wave vector k, or

$$\theta_F = K(f) \int_p N_e \mathbf{k} \cdot \mathbf{B}/|k| dl, \tag{1}$$

where $K(f)$ is a known frequency dependent constant of proportionality. Thus, a single path Faraday rotation measurement contains information about the electron density and magnetic field along that path. Faraday rotation measurements on multiple paths through the same volume of space thus gives information about the whole volume that can be assimilated into an image using tomographic reconstruction techniques.

Faraday rotation and phase difference measurements have been combined to separate the ionospheric and plasmaspheric contributions to the total column-integrated electron content in spacecraft-ground propagation experiments (*Garriott et al.*, 1970; *Davies et al.*, 1976). Extending this concept to the magnetosphere, simultaneous phase difference and Faraday rotation measurements on multiple magnetospheric propagation paths enables independent imaging of electron density and magnetic field (*Ganguly et al.*, 2000). However, there are limits on where Faraday rotation tomography is feasible due to the frequencies required (*Ganguly et al.*, 2000), and Faraday rotation on satellite-to-satellite propagation paths had not been reported before the experiments described by *Cummer et al.* (2001) and herein.

Below we first examine theoretically the capabilities of magnetospheric radio tomography to demonstrate its considerable potential in making novel magnetospheric measurements. This is followed by a description of a series of successful multi-satellite radio propagation experiments designed to measure Faraday rotation and thereby test and validate a key component of magnetospheric radio tomography. These experiments used the versatile Radio Plasma Imager (RPI) on the IMAGE satellite as the transmitter, and the receiving instruments were the WAVES instrument on WIND and the WBD instrument on CLUSTER.

THEORETICAL CAPABILITIES OF MAGNETOSPHERIC TOMOGRAPHY

We first demonstrate theoretically the capabilites of magnetospheric tomography, using a simulated seven satellite constellation. It is assumed that a multi-frequency transmission scheme is used that enables each satellite to measure unambiguously the frequency dependent phase difference and Faraday rotation on each of the 21 independent propagation paths between satellites in the constellation. We treat each measurement as noiseless to explore the maximum potential of tomographic imaging.

Figure 1 demonstrates this combined measurement with a tomography simulation that we performed using realistic electron density and magnetic field results from an MHD simulation (*DeZeeuw et al.*, 2000) available through the Community Coordinated Modeling Center (CCMC) at NASA Goddard Space Flight Center. The left panel shows the positions of the 7 satellites in the X-Y (GSE) plane, which span a significant fraction of the mid- to near-earth plasma sheet. Each of the individual radio propagation paths is plotted over a background of the electron density (derived from the MHD ion density assuming quasi-neutrality) and the vector magnetic field in the satellite plane.

The middle two panels show the signal phase difference (between 910 kHz and 1 MHz) and the Faraday rotation difference (between 150 and 600 kHz) that would be observed in an ideal situation. From these raw measurements, the path integrated electron density and electron density/magnetic field product can be determined on each path. The path integrated measurements can then be tomographically reconstructed

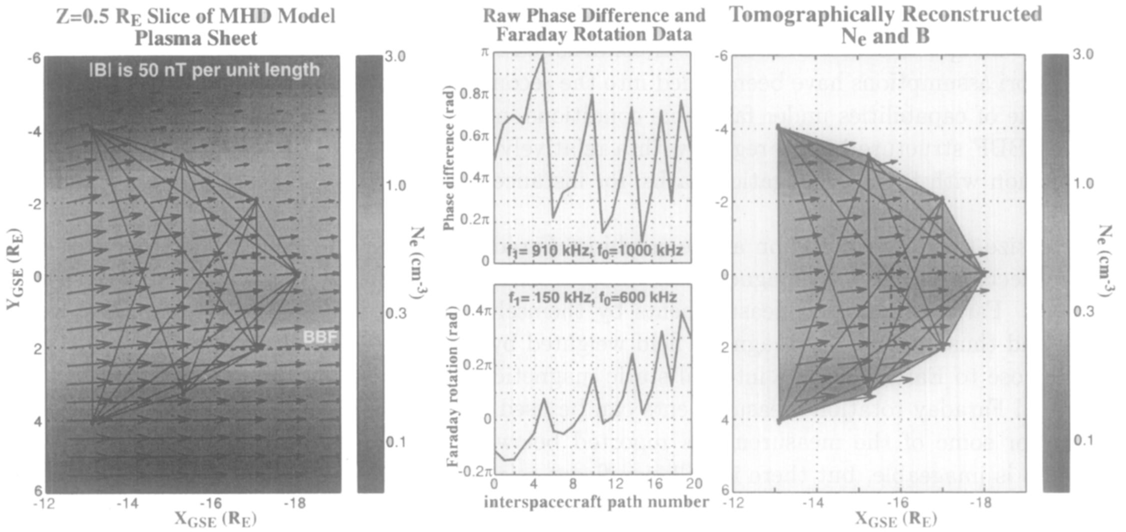

Fig. 1. Seven satellite simulation of magnetospheric radio tomography in the nightside plasmasheet. The electron density and X_{GSE} and Y_{GSE} components of the magnetic field computed from an MHD simulation are shown in the left panel. A constellation of spacecraft transmit and receive radio signals, measuring the phase difference and Faraday rotation between two frequencies, giving the measurements shown in the middle panel. Using the algorithm described here, these measurements are then tomographically reconstructed into the measured electron density and magnetic field shown in the right panel.

into a 2D image of the magnetic field and electron density, as has been shown previously (*Ergun et al.*, 2000; *Ganguly et al.*, 2000). For these simulations, we use (and achieve good results with) a reconstruction technique based on deterministic regularization of the discretized least squares inverse problem (*Press et al.*, 1992). To briefly summarize, the forward problem of expressing the path integrated measurements in terms of the probed quantity can be written as $\mathbf{y}_{\text{obs}} = \mathbf{A}\mathbf{x}$, where $\mathbf{y}_{\text{obs}}$ is a vector containing the path-integrated measurements, $\mathbf{x}$ is a vector containing the electron density and magnetic field at every point sampled by the radio propagation paths, and $\mathbf{A}$ is a sparse matrix that maps these two quantities. The magnetospheric parameters $\mathbf{x}$ that minimize the mean square error of the observations, is given by the matrix equation

$$\mathbf{x} = (\mathbf{A}^{\mathrm{T}}\mathbf{A} + \lambda\mathbf{H}^{\mathrm{T}}\mathbf{H})^{-1}(\mathbf{A}^{\mathrm{T}}\mathbf{y}) \tag{2}$$

which can be solved either directly or iteratively. $\mathbf{H}$ is a deterministic regularization matrix that enforces smoothness on the solution, and λ is an adjustable parameter that controls the relative weighting of the path-integrated measurements and smoothness-enforcing regularization in the reconstruction. We have had good success with this reconstruction approach, especially for relatively sparse satellite constellations. This reconstruction method is also flexible enough to account for any additional information that might be available about the probed quantities, such as in situ measurements from these or other satellites. *Frey et al.* (1998) analyzed a number of tomographic reconstruction algorithms and found that many do not produce good reconstructions when the measurements become sparser. Further work is needed to find optimal approaches to this problem for the specific application of magnetospheric tomography.

Applying this method to the simulated measurements gives the reconstructed electron density and magnetic field in the right panel of Figure 1. The reconstruction is a quantitatively correct image of the original, with all of the main features visible. The spatial resolution of the reconstruction is roughly 1–2 R_E, comparable to the spacing between adjacent propagation paths. Resolution is hard to define precisely in this context because it varies with spatial position relative to the constellation. More satellites are required for finer spatial resolution, but even a modest constellation of 7 satellites could resolve magnetospheric structure on scientifically important scales. The ability of radio tomography to image the large scale structure of the magnetosphere, including sharp boundaries, promises to advance magnetospheric science substantially should it be implemented in a multi-satellite mission.

This image reconstruction method, like most, imposes smoothness on the resulting electron density and magnetic field images in order to make the ill-conditioned reconstruction problem solvable. But other than this, no a priori assumptions have been folded into the reconstruction. The simulation presented is meant to be an example of capabilities under favorable conditions, not necessarily average conditions. For example, the resolved BBF structure is in a region with a relatively high density of propagation paths. If the BBF were in a region with fewer propagation paths, for instance farther from apogee, it probably would not be resolvable.

We emphasize that the simulation above combines Faraday rotation and phase difference measurements to separate electron density and magnetic field measurements in the manner first demonstrated by *Ganguly et al.* (2000). Faraday rotation measurements by themselves, which we report here, are only capable of measuring and thus imaging the magnetic field weighted by the local electron density. However, in regions sufficiently close to Earth that the internal static magnetic field component dominates, the magnetic field is known, and Faraday rotation measurements can be used to image electron density unambiguously. This is the case for some of the measurements reported below. In more distant regions, only the combined $N_e\mathbf{B}$ product is imageable, but there is still significant scientific value to the combined measurement. The unique large-scale measurement capabilities of this technique could be used to determine whether or not hypothesized or conjectured plasma structure and dynamics are present.

EXPERIMENTAL TESTS

Since August 2000, a series of two satellite radio transmission experiments have been executed to test some of the concepts behind magnetospheric radio tomography. The transmitter in all of these experiments has been the Radio Plasma Imager (RPI) on the IMAGE satellite. This instrument is a versatile, frequency-agile radio transmitter designed primarily for radio sounding of the magnetosphere and associated boundaries (*Reinisch et al.*, 2000). RPI also has the capability of transmitting nearly CW single and alternating multiple frequency signals of the kind that would be used in a dedicated magnetospheric tomography mission, and is thus uniquely capable of acting as a space-based transmitter in these experiments.

Two different satellites have been used as the radio receiver in these experiments. The WAVES instrument on the WIND satellite (*Bougeret et al.*, 1995) has a sensitive and broadband radio receiver that spans the optimal frequencies (roughly 100 kHz to 1 MHz) for magnetospheric tomography. WAVES has been used in multiple experiments. The WBD instrument on the four CLUSTER satellites (*Gurnett et al.*, 1997) has also been successfully used in these experiments. WBD is designed primarily for waveform sampling and consequently has a narrow frequency range. Below we describe and summarize the results from each of these experiments.

In all of these cases, the data are of sufficient quality that the $N_e\mathbf{B}$ product can be quantitatively measured. Although none of these experiments contained additional phase difference measurements to separate electron density and magnetic field, we anticipate that there will be scientific value in our ongoing analysis to generate large scale measurements of the combined product, particularly in identifying regions containing spatial structure and temporal variability.

RPI-WAVES, August 2000

A series of WIND petal orbits brought the spacecraft within 4 R_E of the Earth during August 2000. More importantly, WIND passed within 6 R_E of IMAGE during these periods. On August 3–4, 2000 between 2250 and 0050 UT, and on August 15–16 2000 between 1950 and 0000 UT, RPI transmitted a ~6 W linearly polarized signal on one of its spinning dipole antennas. The 828 kHz single frequency transmission repeated a 2 minute cycle of 64 seconds of 0.5 seconds on/0.5 seconds off modulation, followed by 56 seconds of silence. The frequency was chosen to maximize the transmitted power and to be significantly higher than auroral kilometric radiation AKR to maximize the signal to noise ratio (SNR) at WIND. WAVES received the RPI signal on both days, but it sampled the 828 kHz signal much faster (every 358 ms on the non-rotating Z antenna) on August 15.

The data from August 15, 2000 were discussed and analyzed in detail by *Cummer et al.* (2001). The 6 W transmitted signal, after over 6–8 R_E distances, produced an average received signal power of 2–3$\times$10^{-16}

W/m^2, consistent with expectations based on the relative orientation of the transnmitting and receiving antennas, dipole antenna gain, and other instrumental factors. For comparison, the cosmic background power in the 3 kHz WAVES bandwidth at 828 kHz is approximately 10^{-16} W/m^2. Despite the quantitatively poor signal to noise ratio (SNR), the key qualities of the signal were quantitatively analyzable with good precision. The WAVES receiver bandwidth is intentionally broad, and in future implementations of radio tomography, the power SNR could easily be improved by a factor of 30 or more with a narrower bandwidth receiver. Occasionally, during the 5 hour experimental period, solar radio bursts drastically increased the noise level and swamped the signal, but for more than 60% of the period the noise was near the cosmic background lower limit, and the RPI signal was detectable.

The original goal of this experiment was to measure the signal polarization directly using this capability of WAVES and thereby Faraday rotation. But this proved difficult because of the complicated interplay between the 358 ms WAVES integration time and the 0.5 second on/off modulation of the transmitted RPI signal. However, it was realized that time-varying Faraday rotation influenced the apparent spin modulation of the received signal, and from this the time-integrated Faraday rotation could be measured (*Cummer et al.*, 2001). Specifically, time-varying Faraday rotation would make a fixed source appear as though it were spinning because the wave polarization rotates in time as it would for a spinning source. When time-varying Faraday rotation is combined with a spinning source, the apparent spin rate of the source is altered by the Faraday rotation. Thus the time rate of change of Faraday rotation can be measured by the discrepancy between the apparent source spin rate detected at the receiver and the true source spin rate, which is known. Using this method, the path-integrated electron density/magnetic field product was measured subject to an unknown constant. For further details of the experiment, analysis, and conclusions, the reader is referred to *Cummer et al.* (2001). The known relative orientations of the transmitting and receiving antennas can be included in the analysis to further reduce the measurement ambiguity. We are currently implementing such analysis.

This experiment showed that Faraday rotation, a key quantity for magnetospheric radio tomography, can be measured over significant magnetospheric distances with existing transmitter technology. It also led to the continuous polarization measurement based on spin modulation, which only requires a single receiving antenna.

RPI-WAVES, Oct.-Dec. 2001

A second RPI-WAVES radio propagation campaign was executed during a later series of WIND petal orbits with low perigee. The goal of this experiment was to eliminate some or all of the ambiguities in the Faraday rotation measurement in the first experiment by alternating between two transmitted frequencies. In this case, the two frequencies chosen were 508 kHz and 828 kHz, which are sufficiently separated to yield a significant Faraday rotation difference under many magnetospheric conditions.

This two frequency experiment was implemented successfully on October 23, 2001 and December 2, 2001. Higher quality data was recorded on December 2 and we focus on that day herein. Figure 2 shows a plot of the IMAGE and WIND orbits during the experimental period (0200–1600 UT). The 6 W RPI signal at both frequencies was recorded by WAVES on propagation paths longer than 15 R_E in this experiment, about double the propagation distance in the previous experiment.

Figure 3 shows a two hour section of the recorded 508 and 828 kHz signals during the experiment. The signals appear as short spikes due to the 64 seconds on/176 seconds off transmitter modulation at each frequency. The instantaneous voltage SNR is approximately two times worse than in the August 15, 2000 experiment, consistent with the doubled propagation distance (signal voltage is proportional to electric field strength, which falls as r^{-1} with distance). Nevertheless, both signals still exhibit spin modulation of the RPI signal of the type used to measure Faraday rotation in the earlier single frequency experiment (*Cummer et al.*, 2001). If the relative orientation of the transmitting and receiving antennas is known, then Faraday rotation measurements at two frequencies can yield the path integrated electron density/magentic field product with no ambiguity. Analysis of these data is ongoing to produce this unambiguous measurement.

In addition to showing that Faraday rotation can be measured indirectly through measured spin modulation, these RPI-WAVES experiments have demonstrated and that spin modulation can be measured

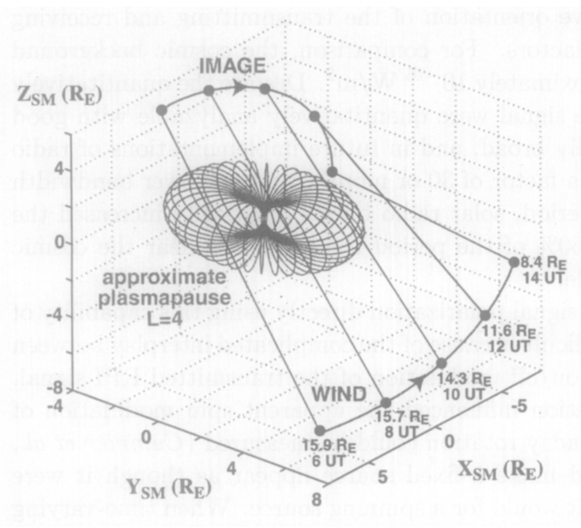

Fig. 2. The positions of IMAGE and WIND during the radio propagation experiment on December 2, 2001.

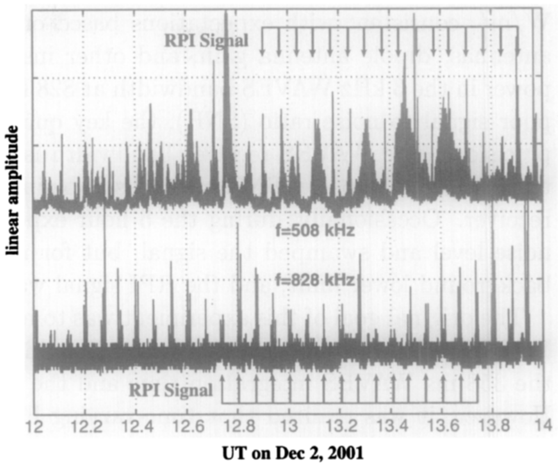

Fig. 3. RPI signal at both transmitted frequencies (508 and 828 kHz) seen in two hours of WAVES data. The narrow peaks at 508 and 828 kHz are the RPI signal, while the broader peaks at 508 kHz are natural radio emissions.

accurately even in a very low SNR situation. Quantitative analysis of the data from these experiments in terms of remote sensing observables is continuing and will be addressed in future publications.

RPI-WBD, April 2002

A third RPI propagation experiment used the WBD instrument on the four CLUSTER satellites as the receiver (*Gurnett et al.*, 1997). The primary motivation for this experiment was testing the interferometric capabilities of the four receivers, but the experiment proved useful for Faraday rotation meaurements. This experiment took place on April 23, 2002, between 0420 and 0445 UT. Figure 4 shows the relative IMAGE and CLUSTER positions during this period. CLUSTER was in a tightly spaced formation and the 4 satellites were effectively collocated for our purposes. The IMAGE-CLUSTER propagation distance was approximately 3 R_E but varied significantly during the measurement period.

The WBD instrument is effectively a narrow-band waveform sampler and thus required a different RPI transmission scheme. RPI transmitted a series of 32 second signals with a 1 kHz frequency step between each signal. These signals spanned the WBD frequency ranges centered near 250 and 500 kHz. Figure 5 shows the received signal spectrogram between 500 and 510 kHz for one of these periods. The stepped frequency RPI signal was clearly received on all four CLUSTER spacecraft. Initial analysis of the spin modulation of these signals clearly shows a spin modulation frequency shift of the kind used to measure Faraday rotation from the RPI-WAVES experiment of August 2000 (*Cummer et al.*, 2001). The small frequency steps may not be enough to detect the frequency dependence of Faraday rotation, and thereby measure Faraday rotation unambiguously. But the waveform sampling capabilities of WBD yielded high quality RPI signals, and further analysis is expected to yield valuable measurements of the intervening magnetospheric medium.

THE SCIENTIFIC POTENTIAL OF MAGNETOSPHERIC TOMOGRAPHY

In addition to unique scientific measurements of large scale magnetospheric parameters, this series of experiments has achieved, at a minimum, the important goal of demonstrating that Faraday rotation measurements can be made on long (>10 Re) propagation paths using existing transmitter and receiver technology. Given that phase difference measurements have already been demonstrated in satellite experiments (*Harvey et al.*, 1978), full-fledged magnetospheric radio tomographic imaging of electron density and magnetic field is feasible. The value of such measurements has been considered by others (*Ergun et al.*, 2000; *Ganguly et al.*,

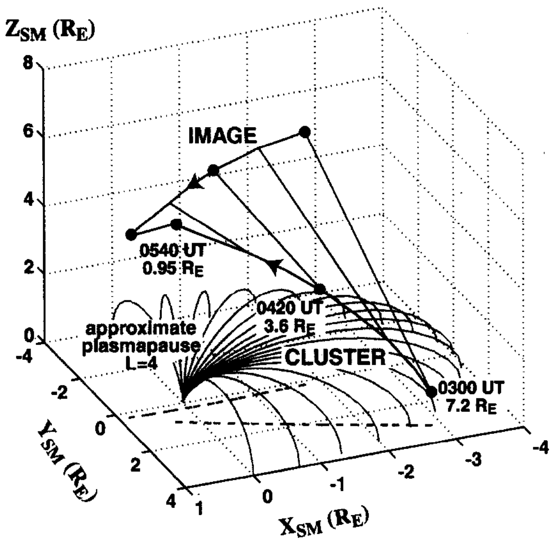

Fig. 4. The positions of IMAGE and CLUSTER during the radio propagation experiment on April 23, 2002.

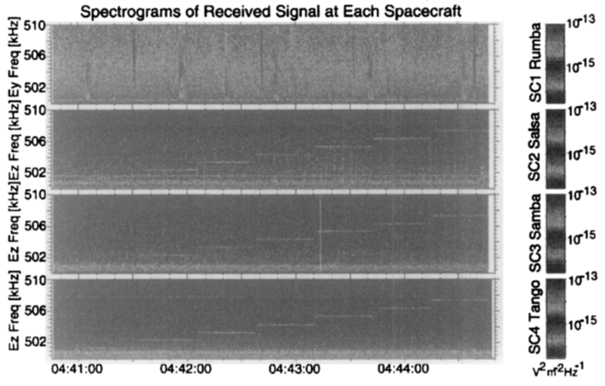

Fig. 5. Spectrogram of received signal on each CLUSTER spacecraft, showing the stepped frequency RPI signal. The interference seen as a broadband every 52 seconds in panel 1 (spacecraft 1) is due to the Whisper sounder pulses. Also note the overall higher noise floor observed on this same spacecraft.

2000) and is substantial. The inherently large-scale, temporally simultaneous measurements (in contrast to local and temporally spread measurements from single satellites) is ideal for addressing many of the most important questions in magnetospheric physics. A dedicated magnetospheric radio tomography mission could achieve a number of scientific "firsts", including

- large scale images of the interaction of earthward flow bursts and the inner magnetosphere
- large scale images of the dipolarization (restructuring) of the magnetic fields in the near-tail region
- large scale measurements of substorm injections of energetic particles into the inner magnetosphere
- large scale images of the response at magnetospheric boundaries to varying solar wind input

SUMMARY AND CONCLUSIONS

Magnetospheric radio tomography is a technique in which path integrated measurements of magnetospheric quantities are determined from multistatic radio propagation measurements. These path integrated measurements can then be tomographically assembled into images of electron density (*Ergun et al.*, 2000) and 2D magnetic field (*Ganguly et al.*, 2000). Simulations of this technique presented above demonstrate the potential value of magnetospheric tomography, which is inherently a large scale, temporally unambiguous measurement technique well-suited to addressing many remaining questions of magnetospheric physics.

A series of magnetospheric radio transmission experiments designed to test key concepts in magnetospheric radio tomography, using IMAGE/RPI as the transmitter and WIND/WAVES and CLUSTER/WBD as the receivers, have been implemented between August 2000 and April 2002. The experiments have increased in complexity, moving from single to multiple frequencies and receiving spacecraft. The first single frequency experiment showed that Faraday rotation can be measured accurately (though with some ambiguity) by measuring the apparent spin modulation of the received signal (*Cummer et al.*, 2001). The subsequent, multiple frequency experiments have the potential to measure the path integrated electron density/magnetic field product without ambiguity, and analysis of these data is ongoing. These experiments have shown that Faraday rotation magnetospheric radio tomography is feasible with existing transmitter and receiver technology. By itself, Faraday rotation can only measure the $N_e\mathbf{B}$ product. But in near Earth regions the known magnetic field enables electron density imaging, and we believe that there is significant scientific value in large scale measurements of the $N_e\mathbf{B}$ product (particularly in evaluating the consistency of measurements and theoretical predictions of plasma structure and dynamics) that currently only radio tomography can produce. Interpretable signals have been received on propagation paths longer than 15 R_E, which is sufficiently long that a dedicated magnetospheric tomography satellite constellation could image a large section of the plasma sheet, magnetopause, or any other magnetospheric structure. Magnetospheric tomography is a feasible imaging technology that can provide results not easily obtainable using more conventional space physics instrumentation.

ACKNOWLEDGMENTS

The authors thank the many people involved in planning and executing the multi-satellite radio propagation measurements described in this work, including R. Benson and M. Reiner (NASA GSFC), K. Goetz (Univ. of Minnesota), R. Manning (late of Observatoire de Paris, Meudon), I. Galkin (UMass Lowell), C. Abramo (CSOC/DSN), J. Volpp (ESA/ESOC), and M. Hapgood (RAL). Work at Duke University was supported under NASA grant NAG5-12072. BWR was supported by NASA subcontract 83822 from SwRI. Work at the University of Iowa was supported under NASA/GSFC Grant NAG5-9974.

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Manuscript received 4 December 2002; revised 14 May 2003, accepted 16 May 2003.