Final Report for NASA Grant NAG5-12072 Magnetospheric Radio Tomography: Observables, Algorithms, and Experimental Analysis Grant Period: May 1, 2002 to April 30, 2005

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1 Summary of Research

This grant supported research towards developing magnetospheric electron density and magnetic field remote sensing techniques via multistatic radio propagation and tomographic image reconstruction. This work was motivated by the need to better develop the basic technique of magnetospheric radio tomography, which holds substantial promise as a technology uniquely capable of imaging magnetic field and electron density in the magnetosphere on large scales with rapid cadence. Such images would provide an unprecedented and needed view into magnetospheric processes. By highlighting the systems-level interconnectedness of different regions, our understanding of space weather processes and ability to predict them would be dramatically enhanced. Three peer-reviewed publications and 5 conference presentations have resulted from this work, which supported 1 PhD student and 1 postdoctoral researcher. One more paper is in progress and will be submitted shortly. Because the main results of this research have been published or are soon to be published in refereed journal articles listed in the reference section of this document, we provide here an overview of the research and accomplishments without describing all of the details that are contained in the articles.

Our research was divided into two primary components: experiments of opportunity and reconstruction theory. A series of successful radio propagation experiments with IMAGE, WIND, and CLUSTER spacecraft clearly showed that multiple satellites could effectively receive signals from a single transmitter, as would be needed in a dedicated radio tomography satellite mission. These experiments were used, in conjunction with our theoretical studies, to implement tomographic imaging in the data analysis. On the theory side, we developed two new tomographic image reconstruction approaches that are robust with relatively few individual path-integrated measurements, as is likely to be the case for any magnetospheric radio tomography mission. These approaches were shown to perform better than standard algorithms that have been previously applied to the magnetospheric problem.

Below we describe the significant technical accomplishments resulting from this research.

2 Accomplishments

Our main research accomplishments are as follows:

- Successful implementation of multispacecraft radio transmission experiments with CLUSTER/WBD that demonstrate the fundamental feasibility of simultaneous, multipath Faraday rotation measurements that form the basis for an implementation of magnetospheric radio tomography [*Cummer et al.*, 2003].
- Unambiguous analysis of previous WIND/WAVES propagation experiments that have produced novel line-integrated electron density measurements in the magnetosphere and that also are the basis of a limited form of experimental tomographic imaging [*Cummer et al.*, 2005].
- Development and demonstration of a tomographic reconstruction technique that is numerically efficient, robust for a relatively small number of propagation paths, and performs better than other algorithms that have been applied to this problem [*Zhai and Cummer*, 2005a].
- Development and demonstration of a tomographic reconstruction technique that incorporates snapshots of the targeted region from MHD simulations in order to produce realistic and correct reconstructions from as few as 6 line-integrated measurements [*Zhai and Cummer*, 2005b].

Each of these is described more fully below.

2.1 Experiments of Opportunity

Under this grant, a series of successful multi-spacecraft radio transmission experiments have been executed in collaboration with IMAGE/RPI, WIND/WAVES, and CLUSTER/WBD teams, to probe the intervening magnetospheric medium through Faraday rotation measurements and to test and verify 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 have steadily increased in complexity as our research has progressed, moving from single to multiple frequencies and receiving spacecraft.

The first RPI-WAVES experiment took place in August 2000 before this project began and showed that Faraday rotation can be measured accurately by measuring the apparent spin modulation of the received signal. A series of follow-on multifrequency experiments with WAVES in 2001 and 2002 were completed with the support of this grant. These experiments showed that the RPI signal could be reliably received more than 14 R_E from

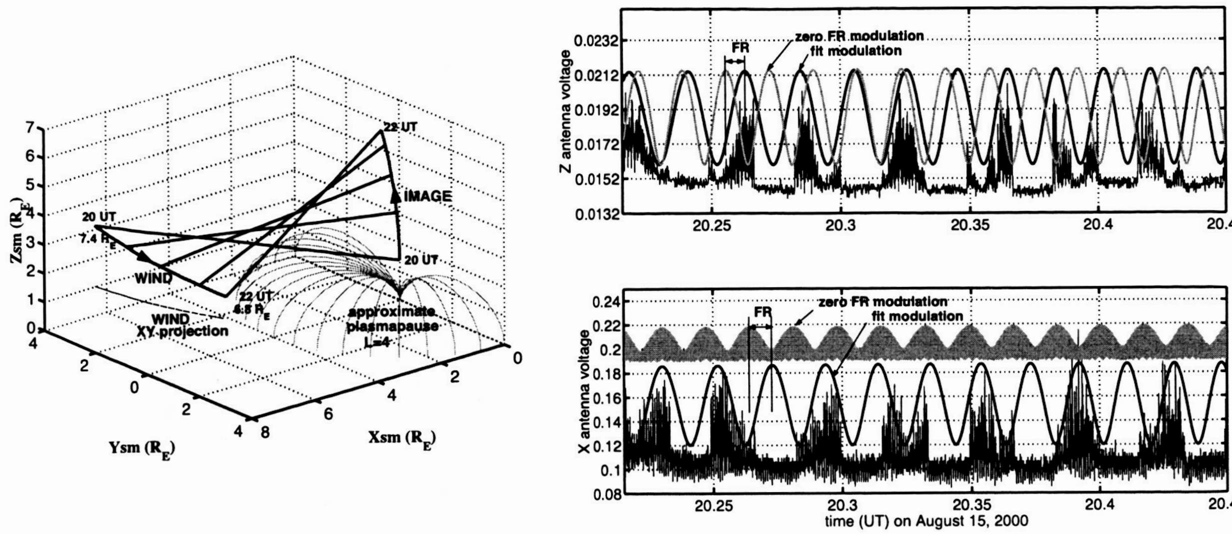

Figure 1: Left Panel: The relative orbits of IMAGE and WIND during the August 15, 2000, radio transmission experiment. Right panel: The modeled 828 kHz RPI signal with zero Faraday rotation and the WAVES X and Z antenna received signals with non-zero Faraday rotation. The perceived time-varying signal polarization spin rate was analyzed for probing variabilities of magnetospheric parameters.

the transmitter at signal levels very close to the cosmic background limit. Further analyzing the data from the August 2000 experiment under this grant, we were able to measure the absolute Faraday rotation from the phase difference between IMAGE spin-phase modeled signal and the WIND received signal. Figure 1 shows the IMAGE and WIND trajectories during the experiment on August 15, 2000 and the WAVES antenna received signals with time-varying Faraday rotation. The average electron density along signal propagation path extracted using the Tsyganenko magnetic field model agrees well with empirical models of the northern polar region. We were able to demonstrate basic magnetospheric tomographic imaging by reconstructing a 2-D image with an assumption of electron density distribution along signal propagation paths. The result of this analysis is described in a journal paper currently in preparation for submission [*Cummer et al.*, 2005].

Beginning in 2002 a unique opportunity arose for radio propagation experiments between RPI and CLUSTER/WBD, and we pursued this vigorously with experiments in 2002 and 2003 that still continue. The RPI signals of multiple frequency bands (~250 kHz and ~500 kHz) were received by 3 CLUSTER spacecraft on April 23, 2002, and all 4 CLUSTER spacecraft on May 27 and May 30, 2003. The truly unique capability of IMAGE/CLUSTER operations is the instantaneous multi-path measurements due to the four CLUSTER spacecraft. The larger spacecraft separations provide opportunities of maybe limited (i.e., currently two-dimensional) but genuine multi-path tomographic reconstruction of electron density in large volume of Earth's magnetosphere. The WBD multi-frequency capability can provide multi-scale Faraday rotation measurements due to the sensitivity of Faraday rotation to signal frequency.

Figure 2 shows the perceived time-varying signal modulation and the phase difference between the received signal and the modeled signal. The perceived signal polarization spin rate varied with time, indicating time-varying Faraday rotation that can be analyzed to probe

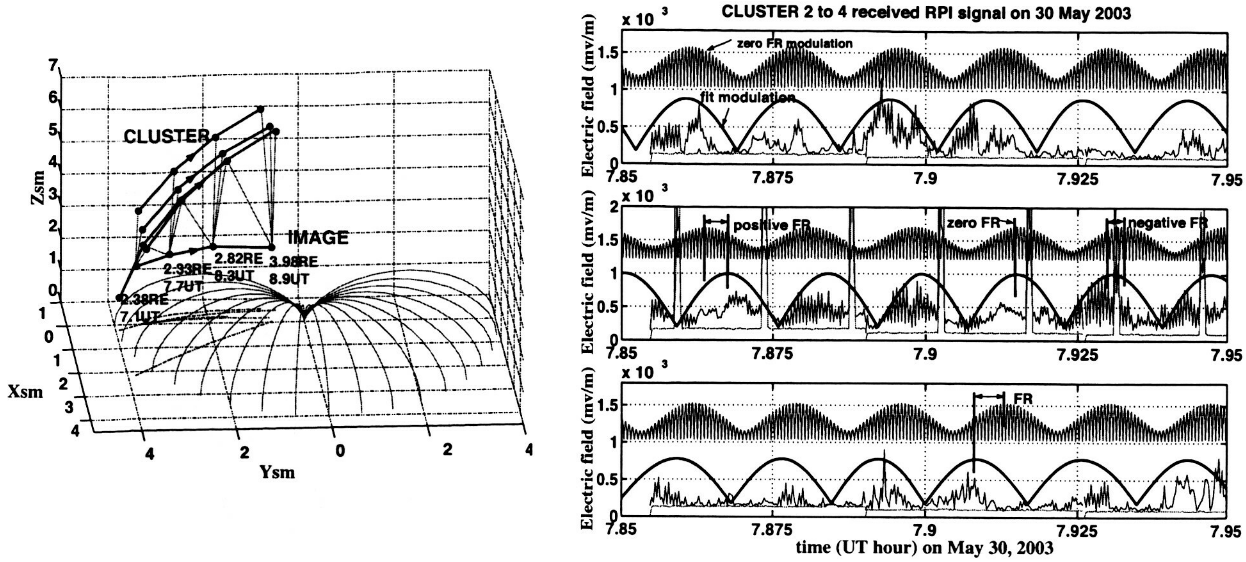

Figure 2: Left panel: The relative orbits of IMAGE and CLUSTER during the May 30, 2003, radio transmission experiment. Right panel: The modeled 250 kHz RPI signal with zero Faraday rotation and the CLUSTER/WBD received signal with time-varying Faraday rotation, which was analyzed to probe the plasma density between the satellites.

the plasma density and magnetic field between the satellites. These experiments have shown that Faraday rotation magnetospheric radio tomography is feasible with existing transmitter and receiver technology. The initial results from the CLUSTER experiments are described in a published journal paper ([*Cummer et al.*, 2003]) and have been described in a number of conference presentations listed at the end of this report.

2.2 Reconstruction Theory

In our theoretical analysis of realistic magnetospheric radio tomography, we developed a flexible and robust direct reconstruction method and found that for a combined reconstruction of plasma density and magnetic field the direct reconstruction method performs as well as popular iterative methods such as Algebraic Reconstruction Technique (ART) and Multiplicative Algebraic Reconstruction Technique (MART) for large number of satellites, but it performs significantly better when the number of satellites is small. The main advantages of this method are that extra information, such as in situ measurements, can be easily and flexibly incorporated into the reconstruction; it is relatively robust in the presence of noise; and it is less sensitive than other methods to numerical reconstruction parameters like assumed grid size. We demonstrate (see Figure 3) good performance of this method in reconstructing electron density and magnetic field using constellations of relatively few satellites (11 and fewer) in a single orbit in a variety of magnetospheric regions. Although this method is relatively robust to noisy measurements, local measurements can significantly increase the reconstruction accuracy.

Our simulations 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. The detailed algorithm

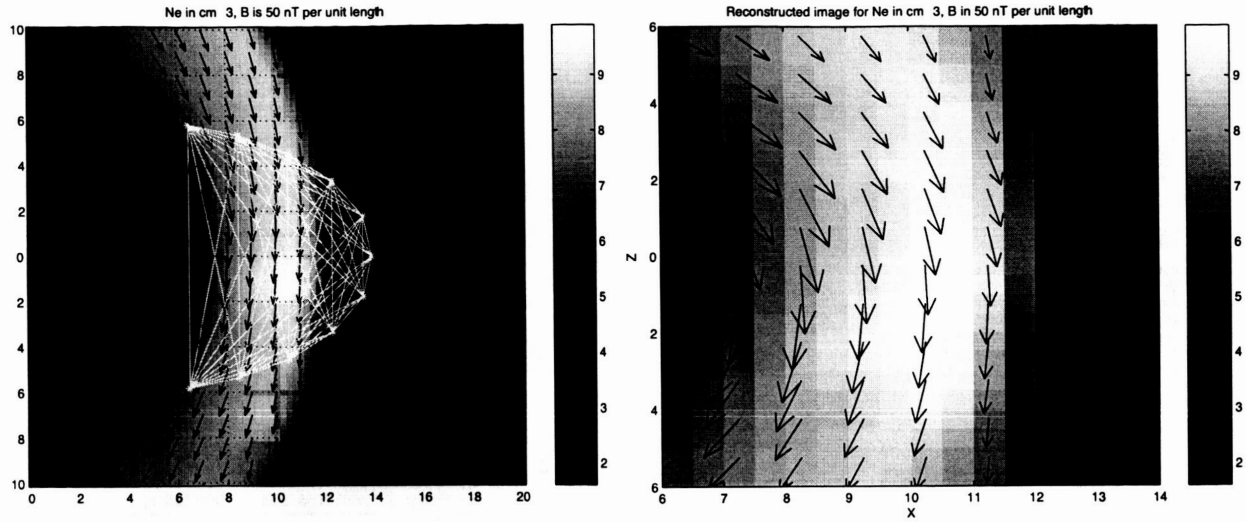

Figure 3: Left panel: MHD simulated electron density and magnetic field for an 11-satellite radio tomography mission with frequencies 200kHz and 400kHz. Right panel: Reconstructed electron density (with 3% mean square error) and magnetic field (with 3% mean square error in y-component) in the probed region.

formulation and simulation results are described in a paper published in Radio Science ([*Zhai and Cummer*, 2005a]).

A challenging problem in ill-posed inverse problems is incorporating prior knowledge of the solution into reconstruction techniques. This problem is particularly important in magnetospheric radio tomography where the path integrated measurements of the target region may be sparse. Under this grant, we developed an orthogonal projection and regularization (OPR) technique that incorporates prior knowledge of magnetospheric parameters from existing models or past measurements into a direct reconstruction algorithm. The OPR scheme extracts first an optimal orthonormal basis containing the main features of the unknowns from an ensemble of modeled or measured snapshots through the proper orthogonal decomposition (POD), then projects the line-of-sight equations onto the subspace spanned by the empirical orthonormal basis. The resulting low-dimensional model is well-conditioned, its coordinates are uncorrelated, and it contains prior knowledge of the solution. The magnetospheric parameters in the transformed coordinate are reconstructed from the low-dimensional model and quantities in the physical coordinate are easily recovered from the POD transformation. We demonstrate that the POD-based method may perform significantly better than the regularized direct method with sparse path-integrated measurements, combined with a few (5-10) model snapshots (see Figure 4 for a POD-based reconstruction of the tail region with six snapshots). These results were described in a paper currently in review at the Journal of Geophysical Research ([*Zhai and Cummer*, 2005b]).

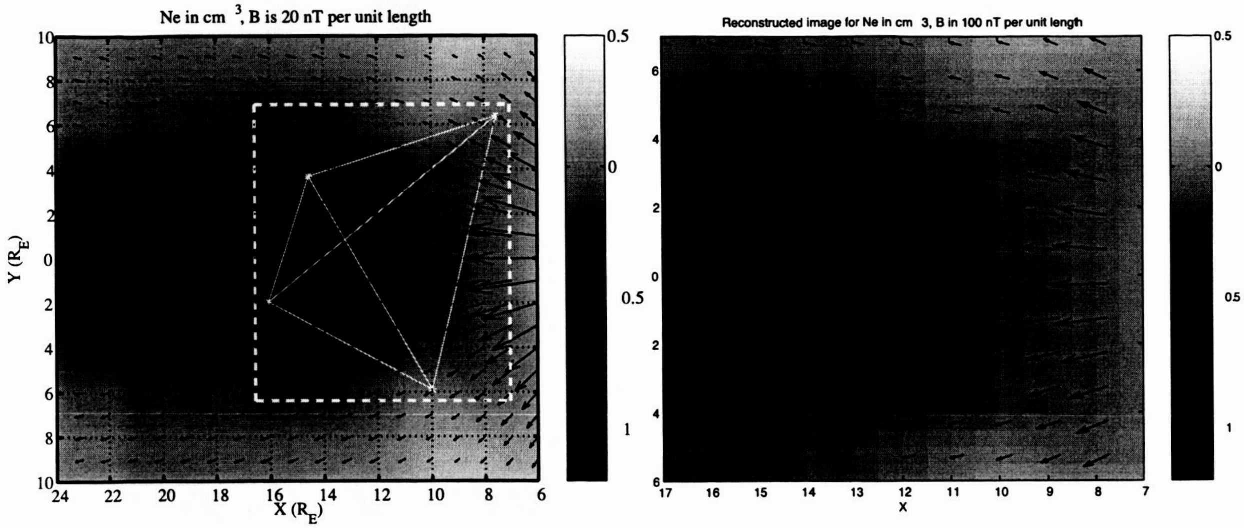

Figure 4: Left panel: MHD simulated electron density (logarithm) and magnetic field of the X-Y plane plasma sheet. Right panel: Reconstruction with OPR-technique with 2.9%, 14.9% and 16.0% mean square errors in electron density, the x and y-components of magnetic field respectively.

3 Papers and presentations supported by this grant

3.1 Refereed Journal Papers

1. Cummer, S. A., J. L. Green, B. W. Reinisch, S. F. Fung, M. L. Kaiser, J. S. Pickett, I. Christopher, R. Mutel, D. A. Gurnett, C. P. Escoubet, Advances in magnetospheric radio wave analysis and tomography, Advances in Space Research, v.32, p. 329, 2003.

2. Zhai, Y., and S. A. Cummer, A flexible and robust direct reconstruction method for magnetospheric radio tomography, Radio Science, vol. 40, no. 3, RS3004, doi: 10.1029/2004RS003100, 2005a.

3. Zhai, Y., and S. A. Cummer, An orthogonal projection and regularization technique for magnetospheric radio tomography, Journal of Geophysical Research, in review, 2005b.

4. Cummer, S. A., Y. Zhai, J. L. Green, B. W. Reinisch, M. L. Kaiser, M. J. Reiner, K. Goetz, Electron density measurements and imaging from IMAGE-WIND magnetospheric radio transmission experiments, Journal of Geophysical Research, in preparation, 2005.

3.2 Conference Presentations

1. Green, J., S. Cummer, B. Reinisch, W. Fund, M. Kaiser, R. Mutel, J. Pickett, I. Christopher, D. Gurnett, Advances in magnetospheric radio wave analysis and tomography, 34th COSPAR Scientific Assembly, October 10-19, 2002, Houston, TX.

2. Cummer, S., J. Green, B. Reinisch, M. Kaiser, R. Manning, K. Goetz, I. Christopher, R. Mutel, J. Pickett, D. Gurnett, C. Escoubet, Magnetospheric Radio Tomography

Experiments using IMAGE, WIND, and Cluster, American Geophysical Union Fall meeting, December 6-10, 2002, San Francisco, CA.

3. Cummer, S. A., J. Green, B. Reinisch, R. Mutel, J. Pickett, D. Gurnett, C. Escoubet, M. Kaiser, M. Reiner, Magnetospheric radio tomography experiments using Cluster and IMAGE, Spatio-Temporal Analysis and Multipoint Measurements in Space Conference, May 12-16, 2003, Orleans, France.

4. Cummer, S. A., J. Green, B. Reinisch, M. Reiner, R. Manning, K. Goetz, I. Christopher, R. Mutel, J. Pickett, D. Gurnett, Magnetospheric radio tomography experiments using IMAGE, WIND, and Cluster, IEEE International Symposium on Antennas and Propagation and URSI North American Radio Science Meeting, June 22-27, 2003, Columbus, OH.

5. Zhai, Y., S. Cummer, J. Green, B. Reinisch, I. Christopher, R. Mutel, J. Pickett, D. Gurnett, C. P. Escoubet, Magnetospheric Radio Tomography: Theory and CLUSTER Experiments, American Geophysical Union Fall meeting, December 13-17, 2004, San Francisco, CA.