Magnetospheric Tomography

Suman Ganguly and Andrew Brown
Center for Remote Sensing, Inc.
11350 Random Hills Road
Fairfax, VA 22030

ABSTRACT

A novel remote-sensing technique for simultaneous imaging of plasma density N and magnetic field vector B using group delay and Faraday Rotation data was proposed by Ganguly, et al. (1999). The potential for this tomographic mission is huge. It renders possible the monitoring of the entire magnetosphere, in which spatial and temporal evolutions between varying regions are linked. The scientific issues involve: Plasma sheet, fast earthward flows in the inner magnetosphere, substorm current wedge, plasmoid tracking, BBF (bursty bulk flow), magnetopause and boundary layers, polar cusp dynamics, etc. Major mission elements include: orbits, number of satellites, transmit-and-receive systems, communication, etc.

INTRODUCTION

Ganguly et al (1999,2000) presented a novel concept of simultaneous imaging of the electron density and magnetic field distributions in the magnetosphere using multiple satellites carrying simple radio beacons and receivers. The concept is further expanded in terms of scientific requirements as well as experimental design. The important feature of this work is the ability to simultaneously image the plasma density (N) and the magnetic field vector (B). It will have a broad impact upon the geospace community, because our method can provide a large-scale picture of magnetospheric structure through the remote sensing of the plasma and magnetic field.

Faraday rotation and group delay measurements are well established techniques in ionospheric physics. Although the Faraday rotation has been used since the days of Sputnik, the first demonstration of the Faraday Rotation data for reconstruction of 3- D elctron density distribution in the ionosphere using tomographic techniques was performed by Ganguly et. al (1999b). This laid the foundation of tomographic reconstruction using Farady Rotation data and the feasibility of the simultaneous imaging of electron density and magnetic field distributions in the magnetosphere has been demonstrated by Ganguly et al. [1999a, 2000]. With suitable choice of experimental parameters both large-scale as well as localized features can be imaged. In this paper, we focus towards some of the pertinent issues relevant to magnetospheric physics, derive approximate images under different conditions, simulate these conditions and then determine the experimental configurations necessary for reconstruction. These will provide answers to some key questions such as:

- How small and detailed structures can be observed.
- What are the satellite configurations and other experimental parameters under which these can be performed?
- What are the spatial and temporal resolutions in different regions?
- What are the limitations?

Answers to these questions will allow us to design and plan worthwhile experiments.
Proposed techniques can be effective in obtaining both large scale as well as small-scale structures. Using a large number of satellites, one can obtain instantaneous global images. With fewer satellites, one can trade time resolution and covered area with cost. It is appropriate to address the scale of the experiment in the light of magnetospheric physics.
The large-scale structure of the magnetosphere is of immediate interest because there are so many open questions pertinent to the global nature of the magnetosphere. The boundaries between the characteristic regions of the magnetospheric change with solar wind and interplanetary magnetic field (IMF) conditions. The global reaction of the magnetosphere to the passage of an interplanetary disturbance, such as a coronal mass ejection (CME) or interplanetary shock, has not been observed. The coupling processes between the solar wind and magnetosphere influence the flow of plasma and energy into geospace, and, hence, the configuration of the magnetoplasma. A quantitative understanding of the relevant physics requires the large-scale mapping of the N and B distributions over extended periods of time (~10hrs.). These observations could allow for the validation of magnetospheric models-both static and dynamic
During the course of a magnetospheric substorm, the configuration of the magnetosphere can change significantly. Local measurements indicate that the magnetosphere becomes more dipolar after the substorm onset. It is currently thought that a substorm is activated in the tail, but the large-scale physical processes in the magnetosphere remain unobserved. It is realized that the magnetotail is intimately connected with the storm/substorm processes. Dramatic changes in the tail are coupled during various phases of the storm and the energy stored in the magnetotail is one of the strong internal drivers of the substorm. Understanding the connection between the inner magnetosphere, the ionosphere and the magnetotail during the substorm is one of the goals of ISTP. The proposed technique will allow simultaneous imaging of different regions and will allow valuable inferences to be drawn regarding the coupling and interrelationships

between these regions and associated processes. We propose to design an experiment that continuously monitors the near-Earth magnetotail; this would provide an observational record of substorm evolution through a time series of N and B images.

Single point, or in situ, observations cannot resolve space-time ambiguities. That is, the data from a single spacecraft is affected by temporal variations in the environment and the motion of the spacecraft through a spatially varying medium. Multi-point observations could clear up this ambiguity, but practical imitations, such as cost and operational complexity, are serious obstacles facing experiments that require a large number (~100) of spacecraft. Our remote sensing technique can use as few as three satellites to provide simultaneous images of N and B over a 1 RE x 2 RE (RE =Earth radius) region of the inner magnetosphere. Constellations with 20 to 30 satellites would allow larger areas (~10 RE) of the magnetosphere, such as the tail, to be monitored constantly and yield an unbroken time record of the N and B distributions in the region of interest.

RESEARCH PLAN

We have performed numerical simulations of multi-satellite tomography in the magnetosphere. Some of the results have been presented in Ganguly (2000). The results are extremely promising. In order to develop a multi-satellite magnetospheric imaging system we must address various magnetospheric conditions and the relevant physics. We then investigate the issues associated with radio tomography under these different conditions. Finally, we design experimental plans for optimized experimental campaigns under different conditions.

For this our methodology consists of:

Investigate different magnetospherically interesting situations. The proposed technique has the potential for simultaneous imaging of the electron density and magnetic field distributions with various spatial and temporal resolutions. It can be applied in various regions of the magnetosphere, both locally as well as over a global scale. A wealth of physical situations can be encountered. Some of the interesting situations include:

Tail reconnection processes in the overall magnetosphere as well as in localized regions. Density controls in the plasma sheet.
Fast earthward flows in the inner magnetosphere.
Substorm Current Wedge (SCW)
Plasmoid tracking
Plasma sheet observations;
Correlation between substorm and BBF, size-scale of BBF's, effects of ionospheric conditions
Observations in Magnetopause and Boundary layers
Polar Cusp Dynamics

At this time only the Near-Earth Neutral Line (NENL) model of substorms is sufficiently well developed to make self-consistent, non-ad-hoc predictions regarding how substorm effects rapidly appear throughout the magnetosphere in a reproducible and coherent fashion. This model forms the basis for our rapidly maturing ability to simulate magnetospheric substorms using MHD and kinetic numerical computer codes. We propose to use some of these codes and/or other approximations in order to simulate situations, which would appear appropriate under these and other magnetospherically interesting situations.

2. Investigate Experimental Parameters Under Different Magnetospheric Conditions:

We first describe the magnetospheric conditions to the best we can, using simulations and/or empirical data- bases. We generate synthetic data (group delay, Faraday rotation, attenuation etc.) for a chosen experimental conditions (satellite positions, number of satellites, orbits, frequency of operation, power etc.). We then use these synthetic data for reconstructing the magnetospheric electron density and Magnetic Field distributions. Finally, we compare the initial model with the reconstructed image and estimate the uncertainties and reliabilities. We next repeat the processes using different experimental conditions. Of course, the choice of the experimental conditions etc. will be guided through our experiences in tomographic reconstruction and radio propagation conditions. Examples of a cluster using 18 satellites are given by Ganguly et al (2000). Simulations with 7 satellites are shown in Figure 1.a, and 1.b. The reconstruction is not too useful in resolving plasmoid like structures shown in Fig. 1.b.

3. Design Experimental Plan for Magnetospheric Imaging of both electron Density and Magnetic Fields:

Based on these investigations we plan experiments for magnetospheric imaging under different conditions. The experiments should be planned with the objectives of solving magnetospherically interesting questions. They should be optimized in terms of objectives, accuracies, cost etc. The plans should include system level descriptions of various experimental modules including: Transmitter, Waveform, Antenna, Power, Polarization, Control Architecture, Receiver, Required accuracies and stabilities, Telemetry etc. The design will be based upon established practice and would specify the following:

- Satellite configuration: number, attitude, orbits, etc.
- Radio frequencies: range of values for different magnetospheric regions, satellite configurations, etc.
- Transmitter and receiver characteristics, waveform, timing, power
- Antenna type
- Telemetry
- Pertinent satellite related issues; power, size, launch, life, cost

Results of simulations with different geometrics, frequencies, etc., allow us to design the experimental plan. Expected resolutions (N and B variations in spatial and temporal scales) are derived for each experimental configuration. The transmit-receive system is capable of multiple frequency operation. The different frequencies are sequenced in quick succession. The sequence and timing issues, the waveform and bandwidth requirements, the Doppler shift, receiver tracking requirements etc., are derived under different S/N conditions. Power control of the transmitter, antenna requirements, storage and telemetry of data etc. have been evaluated. Finally, some preliminary cost estimate will be performed for each of the configurations. Optimization of the power is one of the major objectives for the design. For about 20 watts of ERP, most of the magnetosphere can be imaged. Degradation is S/N will happen during AKR. Effective S/N improvements can be made by increasing the integration time and by using sophisticated processing (coding and beam forming). Power budget may be improved by using low duty cycle waveform. Depending on the desired temporal resolution, the frequencies may be polled one after the other.

Design of suitable antenna is another critical area and will affect the cost and complexity of the system. Both loop and dipole like antennas are being considered and the relevant issues associated with matching the electronics, radiation efficiency and total power budget etc. will be evaluated.

The most important design issues involve the antenna and the power budget. Optimization on these two items are crucial in the total budget. Every attempt is being made to reduce the power requirements commensurate with the S/N consideration. All digital electronics using software radio concept used by us in several other projects is used for the most efficient design of the system. The digital system allows sophisticated signal processing to improve S/N and at the same time reduces the weight and power requirements.

5 **CONCLUSION**:

The ability to map magnetospheric N and B using some practical and realistic experiment, is a logical next step to current efforts. Interrelationships between large and small-scale processes and between different regions of the magnetosphere, their spatial and temporal evolutions are necessary. These are needed for:

Understanding the various processes
Validating existing concepts
Validating models
Development of new models

Several somewhat limited efforts are underway to attain these objectives. GEOTAIL, Image, Cluster Satellite project etc. provide somewhat limited views of the magnetosphere. The proposed technique is perhaps the only way to simultaneously monitor the electron density and magnetic field evolutions throughout the magnetosphere. This is necessary to understand the complex process throughout the magnetosphere.

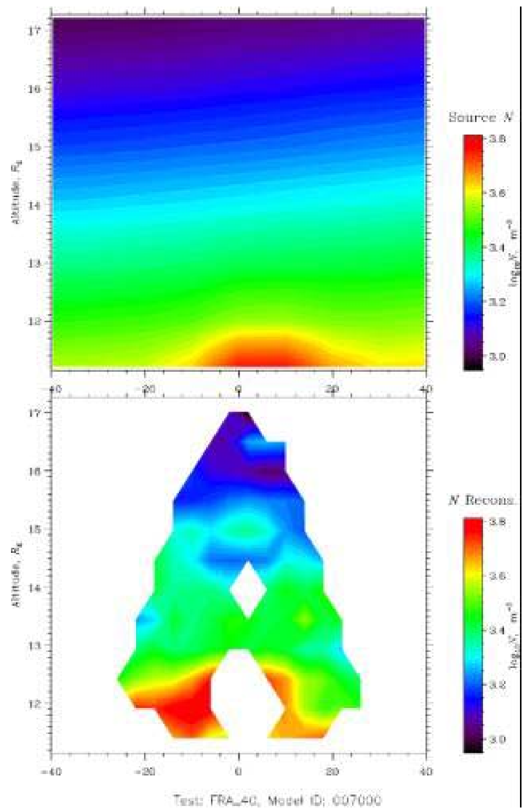

Fig. 1.a. Simulated magnetospheric densities (top figure) and reconstructed densities using only 7 satellites.

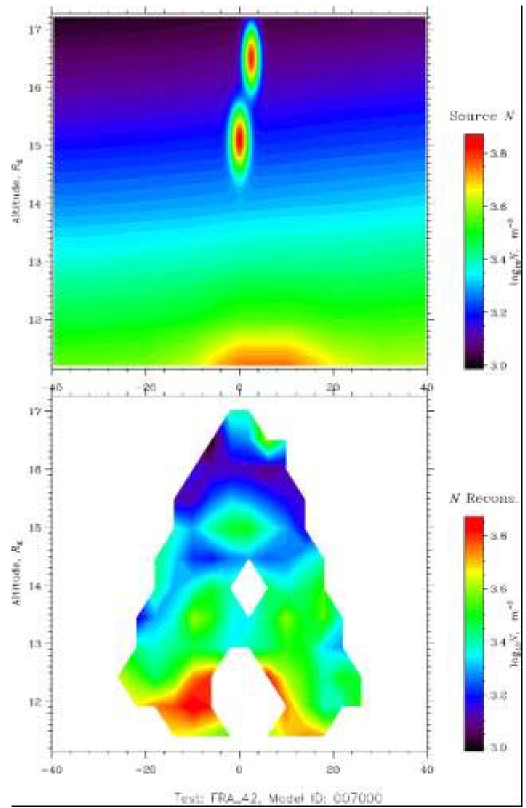

Fig. 1.b. Similar to 1.a., except two plasmoids are added

REFERENCES

Birn, J., and M. Hesse, The substorm current wedge and field-aligned currents in MHD simulations of magnetic reconnection, J. Geophys. Res., 96, 1611, 1991.

Brown, A., and S. Ganguly Ionospheric tomography, issues, sensitivities and uniqueness, Radio Sci,, 2000.

Ganguly S. and A. Brown, Real time characterization of the ionosphere, Radio Science, 2000.

Ganguly, S. G.H. Van Bevel and A. Brown, J. Geophys. Res., 2000a.

Ganguly S., G.H. Van Bevel, A. Brown, and A. Desgupte, Ionsospheric Reconstruction using Faraday Rotation Data; Ionosphere Effects Symposium, Alexandria, VA, Conf. Proc. pp. 1999b.

Hesse, M., and J. Birn, On dipolarization and its relation to the substorm current wedge,
J. Geophys. Res, 96, 19,41, 1991.

Ieda, A., D.H. Fairfield, T. Mukai, Y. Saito, S. Kokubun, K. Liou, C.-I. Meng, G.K. Parks, and M.J. Brittnacher, Plasmoid ejection and auroral brightenings, J. Geophys. Res., 105, 2000.

Kepko, L., and M. Kivelson, Generation of Pi2 pulsations by bursty bulk flows, J. Geophys. Res., 86, 25,021, 1999.

Kokubun, S., and R.L. McPherron, Substorm signatures at synchronous altitude, J. Geophys. Res., 86, 11,265, 1981.
reconfiguration: Explosive growth phase, J. Geophys. Res., 97, 19,311, 1992.

Slavin, J.A., D.N. Baker, J.D. Craven, R.C. Elphic, D.H. Fairfield, L.A. Frank,
A.B. Galvin, W.J. Hughes, R.H. Manka, D.G. Mitchell, I.G. Richardson, T.R. Sanderson,
D.J. Sibeck, H.J. Singer, E.J. Smith, and R.D. Zwickl, CDAW 8 observations of
plasmoid signatures in the geomagnetic tail: An assessment, J. Geophys. Res., 94,
15,153, 1989.

Slavin, J.A., M. F. Smith, E. L. Mazur, D. N. Baker, T. Iyemori, H. J. Singer, and
E. W. Greenstadt, ISEE 3 plasmoid and TCR observations during an extended interval
of substorm activity, Geophys. Res. Lett., 19, 825, 1992.

Taguchi, S., J.A. Slavin, and R.P. Lepping, IMP 8 observations of traveling compression
regions in the mid-tail near substorm expansion phase onset, Geophys. Res. Lett, 24, 353, 1997.