Final Report
Magnetospheric Seismology: A Pilot Study
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Project Objectives

One of the last frontiers of magnetospheric exploration is its mass density structure. The only location in which it is regularly monitored is at synchronous orbit (with LANL plasma analyzers). However, even here there may be hidden populations of plasma that are missed. Recently a technique has been perfected to sound the mass density of the magnetospheric plasma using pairs of neighboring magnetometers to detect the resonant frequencies of the magnetosphere. This technique is similar to helioseismology on the sun that also detects resonant oscillations triggered by natural sources. A second possible seismologic probing of the magnetosphere is more analogous to terrestrial seismology and depends on the propagation of waves through the magnetosphere induced by interplanetary shock waves rapidly compressing the magnetosphere. In contrast to the former technique that provides a local measurement this new approach is capable of providing global constraints on the density in the magnetosphere. We have perfected this latter magnetospheric seismological tool and have compared its inferences with both the resonance technique and in situ measurements with Los Alamos satellites. Two new magnetometers were installed in key regions of the US to optimize the accuracy of these inversions. The inversion study was led by graduate student Z. J. Yu. He received his PhD this year 2004. We also were able to obtain a grant from NSF to extend the array to provide an even better correlation with the LANL data at geosynchronous orbit. It contributes to the LANL Space Physics focus and to the understanding of the coupling of the ionosphere and magnetosphere.

Summary of Research Results

We can monitor the behavior of the plasma in the Earth's magnetosphere first by using the frequency of oscillation of magnetic field lines with periods of from 10s to 100s of seconds. The physics behind this monitoring is described below. The waves, carrying the information about the magnetospheric plasma, travel along the dipolar magnetic field lines from the equatorial regions, where they are furthest from the Earth, to the ionosphere where they drive currents whose signatures are seen in ground based magnetometers. We can also examine the time of arrival of step-like increases in the field, or sudden impulses as they are called.

A particularly difficult region for spacecraft to study but one of increasing importance to the communication industry is the region from 1000 km to 4 Earth radii where there are few scientific research spacecraft but many communication relay satellites. We can monitor this region from the ground by monitoring magnetic pulsations and sudden impulses. We refer to these measurements as magnetospheric seismology. The first technique is very similar to helioseismology that has been used to determine the structure of the Sun and the latter to terrestrial seismology that uses the impulses launched by earthquakes to study the interior of the Earth.

The University of California with the assistance of the Los Alamos National Laboratory through their minigrant program in earlier years established a chain of high-resolution high sampling rate magnetometers in the western US to specifically study the region between 40^o and 55^o magnetic latitude or $1.7 \leq L \leq 3$. Four magnetometers are in a north-south chain along the eastern side of the Rocky Mountains at Teoloyucan near Mexico City at Los Alamos, Colorado Springs and Boulder, Colorado. Three additional sites have been established as part of this activity in El Paso, Minneapolis and in Rapid City, SD. This year we installed one more in northern Minnesota. In addition the US National Science Foundation has funded UCLA to establish a similar magnetometer facility in Jicamarca, Peru, on the magnetic equator. This latter magnetometer was installed in late 1997 and has been running continuously since January 1998. Further UCLA has established a chain of stations along the East Coast of the US, the MEASURE array under Mark Moldwin and a 2D array of stations in China under Peter Chi's oversight. These data were all available to this study. In our studies we compared the results of two ground-based techniques: resonating waves and traveling waves. We also compared with satellite data. Below we first review the two techniques.

a). Resonating ULF Waves

The shape of the Earth's magnetic field is similar to that of a dipole in low-latitude regions. The field lines are set into oscillation like a violin string either by the solar wind or by internal excitation mechanisms [Dungey 1954; Waters, 1999]. Since the end points of the field lines are fixed in the Earth's ionosphere, field line resonances occur very much like the resonance when one perturbs that violin string. Figure 1 shows schematically this variation for two modes of vibration of the field lines. The theory of field line resonance predicts a sudden phase change across the resonant point as one moves in latitude. This feature is well known by ground observers. However, only recently has this property been used to find resonances by comparing the phase of signals of a pair of stations on the same meridian [Waters et al., 1991]. Once the resonant frequency is identified it can be used to remotely sense to the plasma density in near-Earth space [Waters et al., 1994].

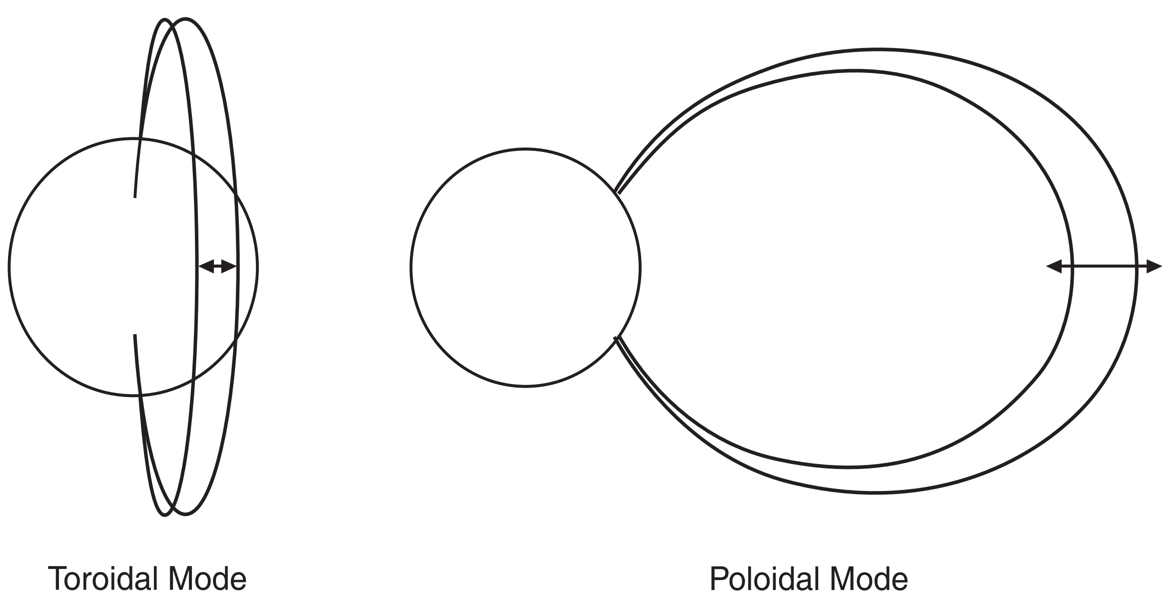


Figure 1. The two modes of resonant vibration.

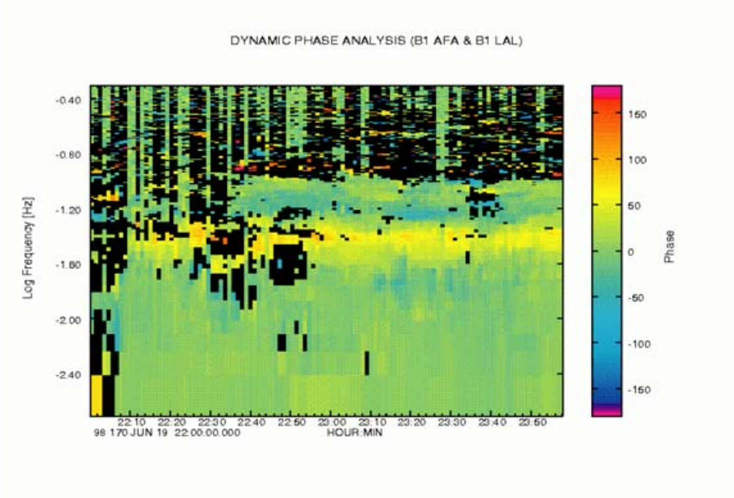
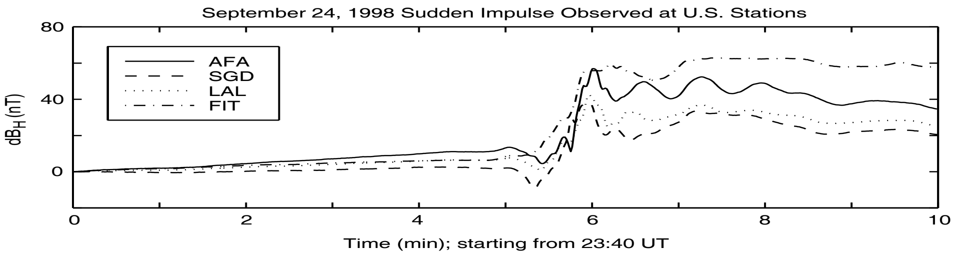


Figure 2. An example of cross-phase spectrograms made from the data of the Air Force Academy station (lat. 47.5º) and the Los Alamos station (lat. 44.4 º).

Figure 2 shows an example of cross-phase spectrograms made from the data of the Air Force Academy station (lat. 47.5 deg) and the Los Alamos station (lat. 44.4 deg). The wave frequency with the large phase difference is roughly 40 mHz. From the resonant frequency the plasma density on the equator for the field line passing through the midpoint of the above two stations must be 2800 protons per cc. Since the cross-phase spectrum can be obtained every 10-20 minutes throughout the day, the near-Earth plasma density can be estimated in real time. This technique provides a local measure of the mass density on a particular magnetic flux tube.

b). The Time of Arrival of Sudden Impulses

Sudden impulses are step changes in the magnetic field on the surface of the Earth, produced when an interplanetary shock strikes the Earth's magnetosphere (e.g. Wilken et al., 1982). The energy propagates through the magnetosphere in a matter of minutes producing a complex response that can differ greatly from the causative pressure pulse (Araki, 1977). By using these pressure pulses in combination with numerical models we can learn much about the behavior and structure of the magnetosphere. Only now with the advent of GPS-derived precision timing and high resolution (20 bit in our magnetometers) measurements can the full potential of this technique be attained. Figure 3 shows data obtained during the 1998 Sept. 24 sudden impulse together with data obtained on the other side of the Pacific by K. Yumoto's Circum Pan Pacific Magnetometer Network. These data reveal many interesting features, some never before realized. First some stations see a very small but immediate change beginning when the interplanetary shock first hits the magnetosphere. We believe this rapid response may be due to compressional waves traveling through the polar magnetosphere that is nearly devoid of plasma (Lee and Kim, 1999). A second disturbance quite evident in these records is the preliminary decrease preceding the compression. This has been observed before (Araki, 1977) but is here revealed in detail never before possible. This signature marks the twist experienced by magnetospheric field lines when the shock wave passing through the equatorial magnetosphere first reaches that field line. Then the field strength begins to increase as the compressional wave reaches the ionosphere above the station.



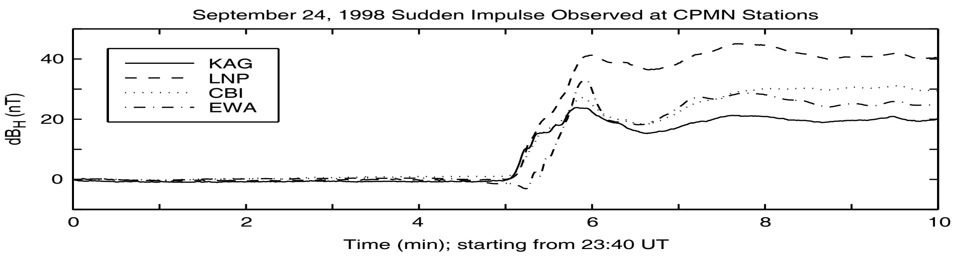


Figure 3. Deviations in the horizontal component of the Earth's magnetic field as the sudden impulse propagates through the magnetosphere on Sept. 24, 1998. US station on top. Asian stations (courtesy of K. Yukoto) on the bottom.

Figure 4 shows the arrival time of the preliminary reverse impulse of a sudden commencement seen on September 24, 1998. The shock responsible for this sudden commencement was accurately timed using multiple solar wind spacecraft [Russell et al., 2000]. If we take a very simple model in which the compressional wave moves across the magnetic field line in the equatorial plane and an Alfven wave moves along the field in response to the arrival of the compression, and if we take a power law density profile, we can predict the arrival time at each of our stations. This propagation model can be checked using a MHD model to simulate the wave propagation. Figure 5 shows that our predictions agree quite well with observations. Nevertheless we need to improve the inversion model, examine more events and verify the results with ground truth from ULF resonant frequencies and synchronous orbit data.

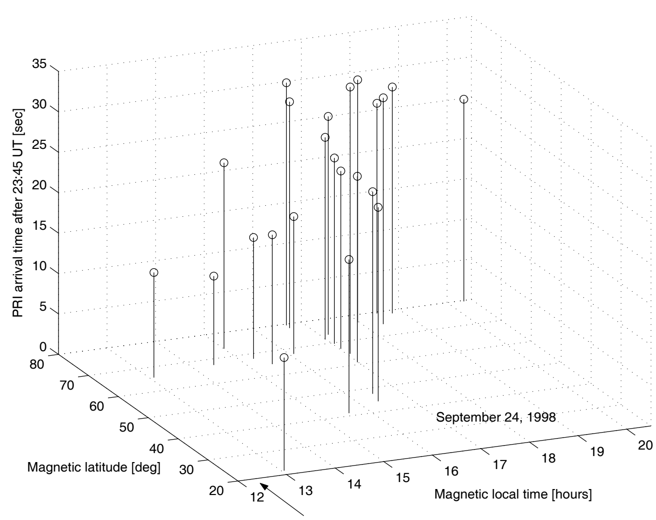


Figure 4. Arrival times of PRI observed at twenty-three magnetometer stations for the SC event on Sept. 24, 1998. The sudden compression started at 12.3 magnetic local time.

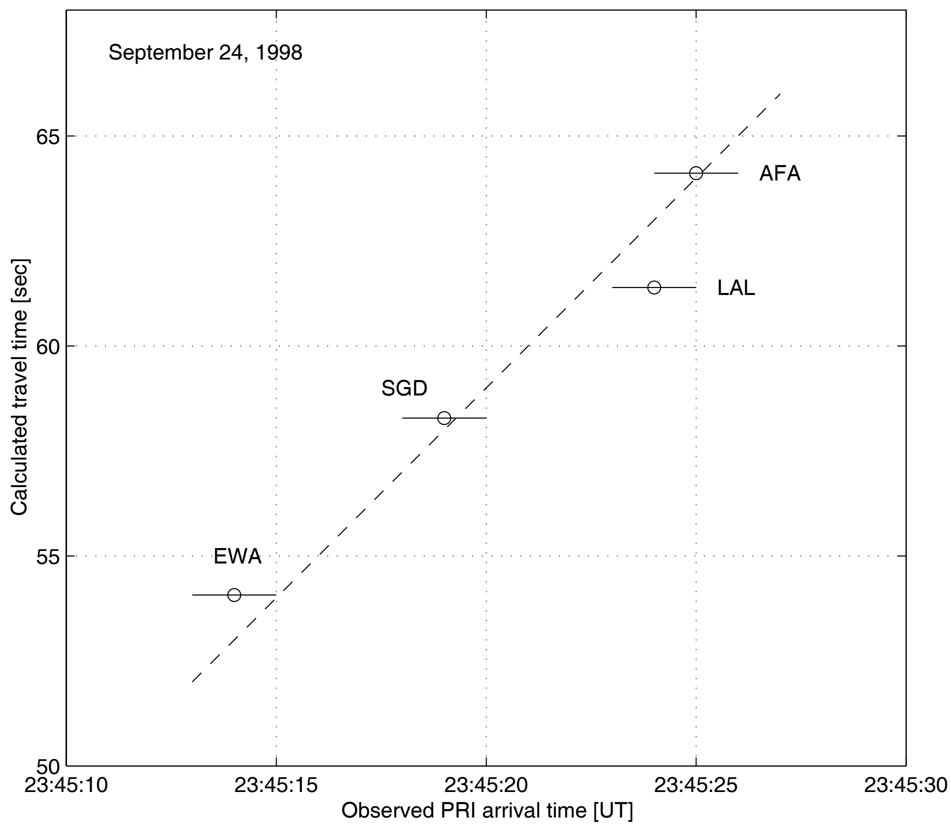


Figure 5. A comparison between the observed PRI arrival time and the calculated arrival time based on MHD wave propagation. The dashed line has a slope equal 1. The error bars are ± 1 sec, indicating the uncertainty in determining the PRI arrival time due to the 1-sec time resolution of the magnetometer data.

Key Personnel, Facilities and Future Project

The key personnel on this project in addition to the Principal Investigators were graduate students Z. J. Yu and D. Berube, undergraduate B. Kuo Tiong, researcher P. J. Chi and Prof. M. B. Moldwin. Peter Chi, Dave Berube and Mark Moldwin were funded separately. Studies of the transient propagation were carried out mainly by P. J. Chi, inversion work done by Z. J. Yu, studies of resonance by D. Berube, (under the guidance of M. Moldwin) and data retrieval and archiving by B. Kuo Tiong. Other collaborators included D. H. Lee and J. Raeder. During this grant period both B. Kuo Tiong and Z. J. Yu received degrees (BS and PhD respectively) and D. Berube made significant progress toward his Ph.D.

LANL provided a site for one of the magnetometers and collected data from that site. The PI visited LANL twice each year counting IGPP and science only related visits.

A proposal was submitted to NSF and funded to extend the IGPP chain from Mexico to Canada through the LANL site along roughly the front range of the Rockies. These data will be available for determination of the plasma mass density out to synchronous orbit and thus support the LANL measurements there.

In Summary the IGPP-LANL magnetometer data have been used to study two types of magnetoseismology, namely the travel-time method and the eigenmode method. Combining the IGPP-LANL data with the data from CANOPUS and CPMN arrays, we studied the arrival time of the preliminary reverse impulses (PRI) for the September 24, 1998 sudden commencement (SC) to infer the plasma mass density of the magnetosphere [Chi and Russell, 2001]. It is found that the profile of estimated density qualitatively agrees with empirical density models. We have also examined the PRI arrival time for several other SC events that were observed at different local times [Fleishman et al., 2002]. We find that the differentiation of arrival time is larger as the local time is further away from the local noon. This result is again consistent with the MHD wave model of PRI propagation but is against the Earth-ionosphere waveguide model. The eigenmode method is also applied to IGPP-LANL data in conjunction with the data of MEASURE array to compare the plasma densities at different local times [Berube et al., 2001]. It is found that the density can be very different even though the separation in local time is merely two hours. This result is consistent with recent findings by the IMAGE satellite that observed longitudinal structure of the plasmasphere.

We should also note some serendipitous science achieved by the array. C-C. Cheng from Taiwan visited UCLA and became very interested in the array data and used it to study the internally generated Pi2 waves and their associated substorms. He found good evidence for the control of substorm onset by IMF variations.

In short, we have perfected two techniques of determining the mass density of the equatorial plasma. We have installed sufficient stations to test our inversion methods and to check the robustness of our techniques. We now need to collect more data and to add at least one more station. We believe that our initial results have been very influential on the direction and recommendations of the Sun Earth Connections Decadal Study as well.

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(a) Refereed Journal Articles Published

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