/N-46

Final Technical Report
For NASA Grant NAG5-3880

Design Study for a Global Magnetospheric Dynamics Mission

Principal Investigator: C. T. Russell
(03/01/97 – 02/28/99)

The study team for the Global Magnetospheric Dynamics Mission was a partnership between UCLA, NASA Lewis Research Center, NASA Goddard Space Flight Center and AeroAstro. The team included the principal investigator, C. T. Russell, C. Kluever, J. L. Burch, J. F. Fennell, K. Hack, J. E. Hanson, G. B. Hillard, W. S. Kurth, R. E. Lopez, J. G. Luhmann and J. B. Martin. The purpose of the study was to determine if the Grand Tour Cluster mission could be repackaged as a much smaller mission utilizing solar electric propulsion for maneuvering. This had the potential of saving fuel because the SEP engine is very efficient but the addition of the SEP engine adds costs and mass. Moreover, it has the potential to interfere with some of the particles and fields measurements that are needed for this mission.

The design team met four times: once at UCLA (April 10 and 11, 1997); once at Goddard (July 21-23, 1997); once at Cocoa Beach (August 25-27, 1997); and once at the Lewis Research Center (Sept. 17-19, 1997). At the Goddard meeting the design was vetted in the Integrated Mission Design Center. GMD was one of its earliest users.

A successful design was developed, one with many advantages over the original mission. The time spent in orbit was more evenly spread over the region being investigated. The radiation close was significantly lower and the mission did not rely on gravity assist at the moon and thus did not have to make measurements that far out in the tail. A spacecraft design was developed that keeps interference from the engines to a minimum. The design however was quite specific for four spacecraft. It could not be easily scaled to five spacecraft for example.

One problem was discovered that is a concern for all similar missions. Inter-spacecraft communication can determine the spacing of the vehicles easily and to the accuracy required. However, the orientation of the polyhedron with the spacecraft at its vertices is not well known for small separations. Ground station range measurements give the line of sight location well but not the angle around that vector. This is a problem any such mission needs to solve. Neither the navigation teams at Goddard nor at Lewis were willing to attempt to solve this problem.

At the completion of the study a report was made to the AGU meeting in San Francisco [1] and a paper published in the volume "Science Closure and Enabling Technologies for Constellation Class Missions" [2]. This paper is attached.

Developments at this time took some of the momentum out of the project when SEC Director George Withbroe said that no Mid Ex missions would be selected that proposed to do part of the Solar Terrestrial Probe line. Since a Grand Tour Cluster type mission was carried in the SEC Roadmap as one of the next Solar Terrestrial Probes we decided not to prepare a proposal to NASA based on this study. At that point the study funds had been largely expended and work proceeded to prepare the publication that is attached. No patents or inventions resulted from this effort.

Papers in Journals and Books

C. T. Russell, C. Kluever, J. L. Burch, J. F. Fennell, K. Hack, J. E. Hanson, G. B. Hillard, W. S. Kurth, R. E. Lopez, J. G. Luhmann, and J. B. Martin, Geospace Magnetospheric Dynamics Mission, in *Science Closure and Enabling Technologies for Constellation Class Missions*, (edited by V. Angelopoulos and P. V. Panetta) pp.58-62, UC Berkeley, Calif., 1998.

Presentations

C. A. Kluever, C. T. Russell, J. L. Burch, J. F. Fennell, K. Hack, J. E. Hanson, G. B. Hillard, W. S. Kurth, R. E. Lopez, J. G. Luhmann, J. B. Martin and S. Stevenson, The Global Magnetospheric Dynamics Mission. An optimized mission to study meso and micro physical processes in the magnetosphere, presented at Fall AGU meeting (abstract) *Eos Trans. AGU, 78*(46), Fall Meeting Suppl., F570, 1997.

Geospace Magnetospheric Dynamics Mission

C. T. Russell[1], C. Kluever[2], J. L. Burch[3], J. F. Fennell[4], K. Hack[5], J. E. Hanson[6], G. B. Hillard[5], W. S. Kurth[7], R. E. Lopez[8], J. G. Luhmann[9], and J. B. Martin[10]

Abstract. The Geospace Magnetospheric Dynamics (GMD) mission is designed to provide very closely spaced, multipoint measurements in the thin current sheets of the magnetosphere to determine the relation between small scale processes and the global dynamics of the magnetosphere. Its trajectory is specifically designed to optimize the time spent in the current layers and to minimize radiation damage to the spacecraft. Observations are concentrated in the region 8 to 40 R_E. The mission consists of three phases. After a launch into geostationary transfer orbit the orbits are circularized to probe the region between geostationary orbit and the magnetopause; next the orbit is elongated keeping perigee at the magnetopause while keeping the line of apsides down the tail. Finally, once apogee reaches 40 R_E the inclination is changed so that the orbit will match the profile of the noon-midnight meridian of the magnetosphere. This mission consists of 4 solar electrically propelled vehicles, each with a single NSTAR thruster utilizing 100 kg of Xe to tour the magnetosphere in the course of a 4.4 year mission, the same thrusters that have been successfully tested on the Deep Space-1 mission.

1. Introduction

In 1996 the Space Physics Division of NASA's Office of Space Science awarded grants for the study of new mission concepts. One of these awards was for a mission called Global Magnetospheric Dynamics (GMD) that was designed to capture the scientific objectives of the original Grand Tour Cluster mission but to accomplish this within the budget of a solar terrestrial probe class mission. At the same time an attempt was to be made to improve the science return by optimizing certain features of the mission. The award to UCLA for GMD was received in March 1997 and the study commenced. The study partners are Aero Astro, NASA's Lewis Research Center and Goddard Space Flight Center, the University of California Los Angeles and the individual scientists of the study team co-authoring this report.

2. The Critical Measurements

The purpose of this mission is to derive a complete physical understanding of the plasma processes at work, not just to identify or classify the various events encountered. Thus both the electric and magnetic fields, the low order moments of the plasma distribution and its composition, and the energetic particles that are accelerated by these processes must be measured and studied. These critical measurements require four key investigations: a magnetic fields investigation with a small accurate instrument such as the fluxgate magnetometer; a waves investigation including a search coil and dipole antenna; a 3D plasma instrument with compositional resolution; and an energetic electron and ion device with large geometric factor. Since the plasmas to be probed are tenuous and the signals to be measured are often weak, the geometric factors of these instruments cannot be sacrificed. Thus the instruments can be miniaturized only so far. In particular, booms and wire antennas need to be of the length usually found on space physics missions and the particle instrument need to have "sensors" of the usual dimensions despite the advances in electronics that make the detection circuitry much smaller. Finally we include a spacecraft interactions package to understand better the nature of the effects of the varying plasma environment on the spacecraft electric potential.

[1]Institute of Geophysics and Planetary Physics and Department of Earth and Space Science, University of California Los Angeles, CA
[2]University of Missouri, Kansas City, MO
[3]Southwest Research Institute, San Antonio, TX
[4]Aerospace Corporation, El Segundo, CA
[5]NASA/Lewis Research Center, Cleveland, OH
[6]AeroAstro, Mountain View, CA
[7]University of Iowa, Iowa City, IA
[8]University of Maryland, College Park, MD
[9]University of California, Berkeley, CA
[10]NASA/Goddard Space Flight Center, Greenbelt, MD

3. The GMD Spacecraft

The four GMD spacecraft will be launched into a Geosynchronous Transfer Orbit from a Delta II launch vehicle. Two views of the folded spacecraft are shown in Figure 1. The spacecraft consists of two sections: the main spacecraft with thruster fuel, solar panels and communication systems and an instrument panel containing the scientific instruments. Four of these folded modules fit within the Delta shroud with a deployment fixture. Upon spacecraft deployment the solar array unfolds and the booms and antennas deploy. The deployed spacecraft and antennas are shown in Figure 2. The NSTAR engine supplies a specific impulse that is ten times that of a state-of-the-art chemical bi-propellant system. Thus the GMD mission with slightly more than 100 kg of fuel can maneuver throughout the magnetosphere and perform the plane change to high inclination without a lunar gravitational assist that places the spacecraft out of the region of prime interest. The solar panels generate about 2.5 kW of power. A schematic of the thruster is shown in Figure 3. This thruster is being space-qualified on the Deep Space One mission. These thrusters generate 90 mN of thrust for 12,000 hours of operation during which time they utilize over 120 kg of Xe. At the time of this writing the thrusters have been turned on and have successfully operated in space. More data on their operation will be available over the course of the mission.

4. Trajectory Design Overview

The trajectory for the GMD mission has been designed to maximize the coverage of the important currents, regions, and boundaries of the magetospheric plasma. Four identical spacecraft are launched into a geosynchronous transfer orbit (GTO) by a single Delta 7925 launch vehicle. Solar electric propulsion (SEP) is utilized as the primary mode of propulsion for the orbital maneuvers. The four spacecraft use the SEP system to transfer from the inclined GTO to a circular equatorial orbit with a radius of 10 R_E. At this point, the tetrahedral constellation begins probing the magnetospheric regions of interest. The orbital apogee is slowly increased while the line of apses is rotated so that perigee remains near local noon and apogee remains in the geomagnetic tail. Extended coast arcs of several days are included during these maneuvers so that thrust-free measurements can be made.

Science Closure and Enabling Technologies for Constellation Class Missions, edited by V. Angelopoulos and P. V. Panetta, pp. 58-62, UC Berkeley, Calif., 1998.

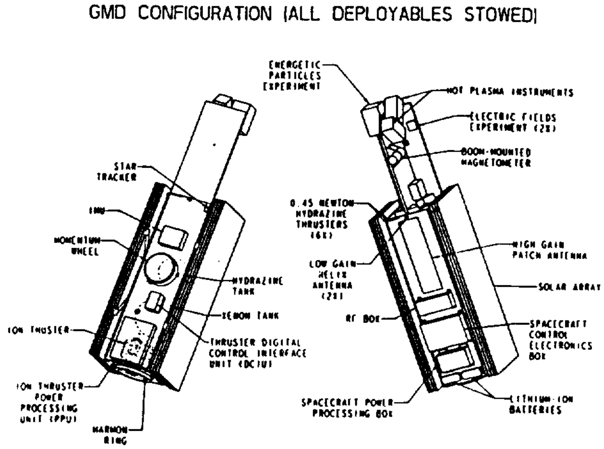

Figure 1. Two views of the GMD spacecraft in the stowed configuration.

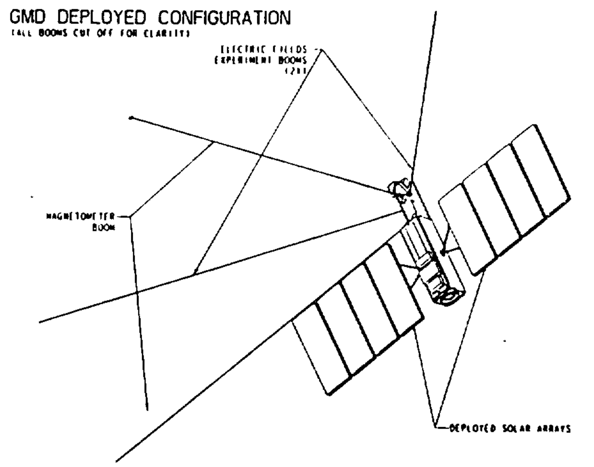

Figure 2. The GMD spacecraft in the deployed configuration.

Once an apogee of 40 R_E is reached, a plane-change maneuver to polar orbit is performed so that the high-latitude region of the magnetosphere is explored. Finally, the apogee is increased to 70 R_E at the end of the mission. The entire mission lasts 4.4 years and includes 2.8 years of thrust-free operation.

The Delta 7925 launch vehicle places a payload of 1850 kg into a standard GTO with a perigee of 185 km altitude, apogee of 35,785 km, and an inclination of 28.7 degrees. A deployment mechanism with a mass of 100 kg is used to separate the four spacecraft from the payload shroud. Therefore, the initial mass of each of the four identical spacecraft is 437.5 kg. Each spacecraft is powered by a 2.25 kW solar array of which 160 W is required for communications, guidance, navigation, and control (GN&C), instruments, and general spacecraft housekeeping functions. A single 30-cm ion thruster propels each spacecraft and 115 kg of Xenon propellant is loaded on each spacecraft. The specific impulse (Isp) of the Xenon system is set at 3300 sec, which is consistent with the SEP system for the Deep Space One Mission.

A mission that was studied earlier and called the Grand Tour Cluster (GTC) with very similar objectives to GMD had four phases each with a different orbit: 1.2 x 12 R_E, 10° inclination for 1.5 years; 1.2 x 30 R_E, 10° inclination for 0.5 years, 8 x 235 R_E, lunar swingby orbit, 1 year; and 10 x 50 R_E orbit, 90° inclination for 0.5 years. The GTC orbit plan had a number of problems. First, it encounters a high dosage of radiation because of the long lasting, low perigee. It is not until year 3 that perigee is raised to 8 R_E and out of the region of high energetic particle flux. Secondly, it only encounters the low latitude magnetopause for a short period each orbit as it moves in and out across the boundary. Third, it spends much time at a distance near 235 R_E in the tail, far beyond the average location of the distant neutral point. Fourth, the mission explores the high latitude and low latitude magnetopause but nothing in between. The GMD mission tailors its coverage closely to its objectives.

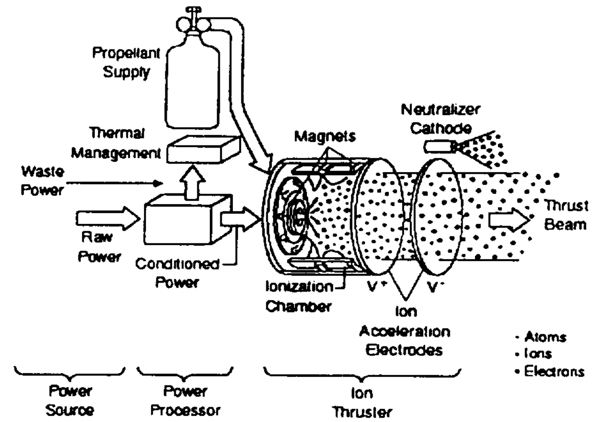

Figure 3. Schematic illustration of the operation of an ion thruster.

4.1. Phase 1 Initial Orbit and Circularization

The four spacecraft of the GMD mission would be launched into an initial orbit very much like that proposed for GTC, close to that of a Geosynchronous Transfer Orbit. A planar continuous-thrust maneuver lasting 64 days transfers the tetrahedral constellation from GTO to a 2.3 x 9.3 R_E elliptical orbit. This transfer is completed as quickly as possible so that solar array degradation caused by passage through the radiation belts is minimized. The relatively rapid orbit transfer results in a solar cell degradation of only 8%. After the four spacecraft are out of the most dangerous region of the radiation belts, the SEP thruster is used near each apogee passage so that perigee is raised to 6 R_E. After the perigee-raise maneuver, the orbit inclination is reduced to zero by using the SEP thruster at apogee so that the resulting orbit is in the equatorial plane. Finally, a series of apogee burns are performed so that perigee is raised to 10 R_E and a near-circular equatorial orbit is produced. Three mandatory 5-day coast periods were enforced during this final circularization maneuver so that the instruments could begin measuring the magnetospheric regions and boundaries. These combined orbital transfers last 394 days and require 49 kg of propellant per spacecraft. The resultant trajectory is summarized in Figure 4.

4.2. Phase 2 The Tail Current Sheet and Magnetopause

The majority of the scientific measurements are made during the next phase of the mission. The goal of this phase is to maximize coverage of the magnetopause surface, the current disruption region, and the plasma sheet. This is accomplished by using the SEP system to slowly raise the orbit apogee and rotate the line of apses of the osculating orbit so that the apses remain nearly aligned with the rotating Earth-Sun line. An innovative thrust-vector steering method is used to provide this simultaneous orbit control. Perigee burns of varying duration

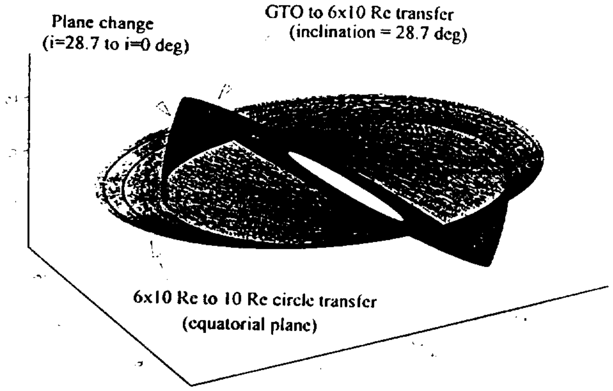

Figure 4. The GMD trajectory during the initial orbit and circularization phase.

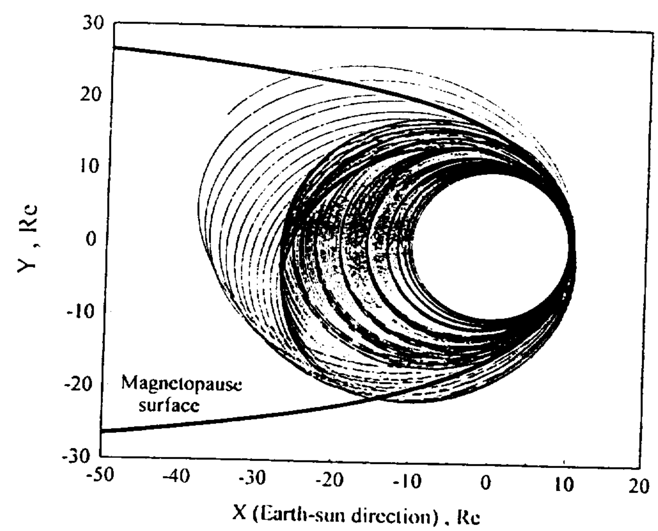

Figure 5. The GMD trajectory during the tail current sheet and magnetopause phase.

are used to maintain apogee growth. Optimal steering control for maximum apse-line rotation is utilized near the semi-minor axis crossings where this control method is most effective. Therefore, the region near apogee is free of thrusting activity so that measurements are possible. Furthermore, mandatory coasting periods of 10-20 days are enforced so that extended thrust-free measurements are possible. During the coasting period, the apses line remains essentially fixed in inertial space and begins to lag behind the rotating Earth-Sun line. At the end of the coasting period, the apogee raise/rotation maneuver is resumed so that the apses line is rotated past the Earth-Sun line while apogee is simultaneously raised. Using this technique, the growing apogee remains near the center of the geomagnetic tail for maximum coverage. The apogee raise/rotation maneuver lasts 580 days and requires 41.2 kg of propellant. The final elliptical orbit is 10.5 x 40 R_E. The orbit-plane trajectory is shown in Figure 5 in a rotating frame with the x-axis aligned with the Earth-Sun direction. To compare the time spent in the neighborhood of the regions of interest we calculate the time spent within ±0.5 R_E of the Shue et al. [1997] magnetopause with a nose at 10.3 R_E; within a plasma sheet 20 R_E wide and 10 to 40 R_E in extent down tail and 4 R_E thick; and in a current disruption region from 7 to 10 R_E, 1 R_E thick within 3 hours of midnight. During this period, the four spacecraft spend 33.8 days at the magnetopause, 3.2 days in the current disruption region, and 21.2 days at the plasma sheet. If one includes thrusting periods, the time in the current disruption region increases to 10.3 days. As a comparison, one year of the ESA Cluster mission spends 27.2 days at the magnetopause, 2.2 days in current disruption region, and only 0.8 days in the plasma sheet. One year of the first phase (1.2 x 12 R_E) of the GTC mission spends 23.5 days at the magnetopause, 14.1 days in the current disruption region, and 15.1 days in the plasma sheet.

4.3 Phase 3. The Inclination Raise to 90°

Once apogee has reached 40 R_E and the rear-Earth neutral point has been explored, the orbit inclination is raised as the line of apsides is rotated about the Earth-Sun line as the Earth orbits the Sun in its yearly motion about the Sun. During this period the 4 spacecraft explore the Earth's bow shock and the mid-latitude magnetopause. After about 9 months and the expenditure of 12 kg of xenon the orbit again enters the tail and cuts through the magnetopause at high latitudes skimming the magnetopause from the nose to about 20 R_E as the orbit plane passes through the noon-midnight meridian. At this point any unexpended fuel can be used to increase apogee to explore even more distant reaches of the tail.

4.4 How Near? How Far?

The ESA Cluster mission has chosen to operate its spacecraft a substantial distance apart, relative to typical scale lengths of the plasma. In phase 1 the separation will be about 600 km near apogee; in phase 2, 2000 to 5000 km; in phase 3, 200 to 2000 km; and in phase 4, 1-3 R_E [Escoubet et al., 1997]. However, these distances seem very much larger than ideal for studying the bow shock and magnetopause. Both these structures move rapidly and irregularly so that successful studies on ISEE 1 and 2 generally used data obtained at separations under 500 km. Certain structures such as mirror mode waves needed even shorter separations. There has not been a study of what is the shortest separation needed in such multi spacecraft studies but there is one report that indicates that 15 km separation returns very useful information [Elphic, 1989]. The key figures from Elphic's study are shown in Figure 6. In the bottom panels the two spacecraft data are simply differenced. We can already see on the right that even at 15 km separation there are large differences between the magnetic fields at the two spacecraft. On the other hand the differences are a fraction of the background field. Thus, the spacecraft at this separation are accurately acting as a curlometer.

The greatest separation distance should be chosen to provide constraints on the size and shape of the largest structure of interest. If a plasmoid of radius 5 R_E is of interest then a separation of up to 1 R_E would seem reasonable.

The greatest distance for apogee should be at the distance of the phenomenon of interest whose distance is greatest. For GMD we are interested in the near-Earth neutral point, inside of about 40 R_E. In an extended mission it would be possible to explore the distant neutral line at about 140 R_E [Nishida et al., 1996].

The size of the tetrahedron can be readily measured accurately by an interspacecraft radio link. This link can also be used to signal all four spacecraft that one of them has entered an interesting region and for all four spacecraft to begin to take higher rate data. The orientation of the tetrahedron cannot be determined with a simple radio link. The distance to each satellite along the radius vector can be determined to 300 m but not the cross-track separation. Thus the orientation of the tetrahedron around the radius vector can be determined with much less accuracy than the separation between spacecraft, and requires some further study.

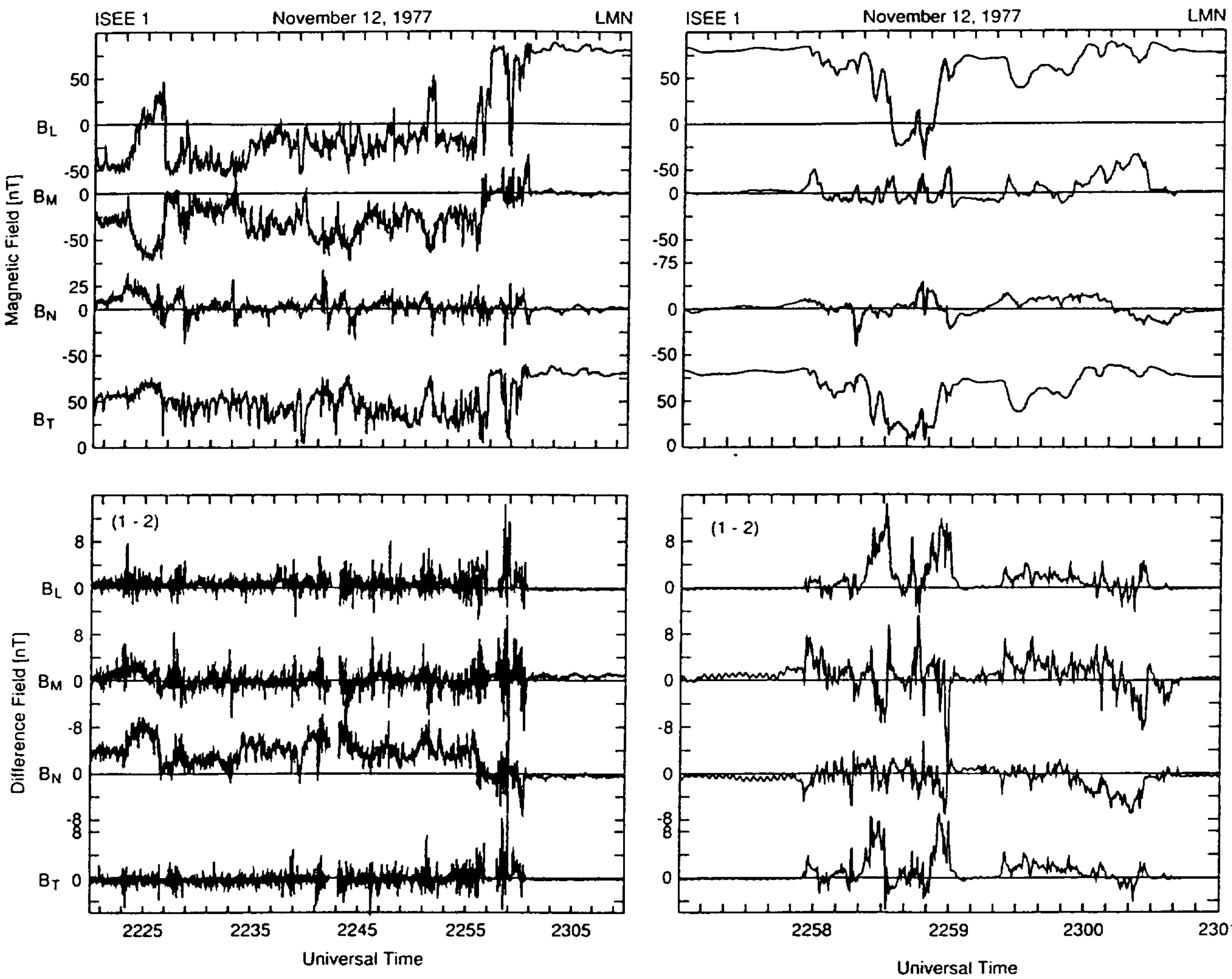

Figure 6. ISEE 1 and 2 data from November 12, 1977 near a magnetopause crossing at 2300 UT when the spacecraft were separated by only 15 km. The upper panel shows the high-resolution data from ISEE 1 and the lower panel shows the difference field, ISEE 1 minus ISEE 2. The right-hand panel shows the central four minutes of the left-hand panel. Within the current layer there is much small-scale structure. Within the magnetosphere there is no fine scale structure.

5. Summary and Conclusions

The study of the GMD mission shows that greatly increased time can be spent in the scientifically interesting regions using solar electric propulsion. The costs for such a mission lies in the range between a MIDEX and a Solar Terrestrial Probe mission. The robustness of the mission is increased by removing any reliance on gravitational assists. The solar electric propulsion system allows the trajectory to change to respond to scientific discoveries. The mission can recover from commanding and thrusting errors. It can retrace its steps if increased observing time is required of any phenomena.

There is an increased cost of about \$10M per spacecraft in using SEP but the returns on the investment are well worth the extra cost. The magnets in the thrusters create a strong field at one end of the spacecraft but a long boom enables precision measurements to be obtained. While the thrusters are in use the plasma and plasma wave environments are disturbed. Thus some measurements require non-thrusting periods. The GMD mission provides 2.8 years of such quiet operation.

We did identify a generic problem with tight clusters of vehicles in which the relative orientation of the tetrahedron is important. Interspacecraft communication allows the separation to be determined precisely but the orientation of the tetrahedron cannot be determined as well. In the limit of very small separations, the orientation of the tetrahedron around the axis to the receiving station becomes undefined. This effect occurs for separation of the order of 1 km but reduces the accuracy of tetrahedral orientations of size from 10-100 km to a lesser extent.

We conclude that solar electric propulsion is an excellent propulsion system for the Geospace Magnetospheric Dynamics mission or any mission that attempts to tour the outer regions of the magnetosphere. The mission design is robust and affordable.

Acknowledgments. This work was supported by the National Aeronautics and Space Administration under research grant NAG5-3880.

References

Elphic, R. C., Multipoint observations of the magnetopause: Results from ISEE and AMPTE. *Adv. Space Res.*, *8*, (9)223-(9)238, 1988.

Escoubet R. P., R. Schmidt, M.L. Goldstein, Cluster-science and mission overview, *Space Sci. Rev.*, *79*, 11, 1997.

Nishida, A., T. Mukai, T. Yamamoto, Y. Saito, and S. Kokubun, Magnetotail convection in geomagnetically active times 1. Distance to the neutral lines, *J. Geomag. Geoelectr.*, *48*, 489-501, 1996.

Shue, J-H., J. K. Chao, H. C. Fu, C. T. Russell, P. Song, K. K. Khurana and H. J. Singer, A new functional form to study the solar wind control of the magnetopause size and shape, *J. Geophys. Res.*, *102*, 9497-9511, 1997.

C. T. Russell, Institute of Geophysics and Planetary Physics and Department of Earth and Space Science, University of California, Los Angeles, CA 90095-1567. (e-mail: ctrussell@igpp.ucla.edu)

C. Kluever, University of Missouri, Kansas City, MO 64110. (e-mail: klueverc@umkc.edu)

J. L. Burch, Southwest Research Institute, 6620 Culebra Rd., San Antonio, TX 78228-0510.

J. F. Fennell, Aerospace Corporation, 2350 E. El Segundo Blvd., El Segundo, CA 90245-4691.

K. Hack and G. B. Hillard, NASA/Lewis Research Center, Cleveland, OH 44135-3127. (e-mail: Kurt.J.Hack@lerc.nasa.gov; Grover.B.Hillard@lerc.nasa.gov)

J. E. Hanson, AeroAstro, Mountain View, CA

W. S. Kurth, University of Iowa, Iowa City, IA 52242. (e-mail: William-Kurth@uiowa.edu)

R. E. Lopez, University of Maryland, College Park, MD 20742.

J. G. Luhmann, Space Sciences Laboratory, University of California, Berkeley, CA 94720. (e-mail: jgluhman@ssl.berkeley.edu)

J.B Martin, NASA/Goddard Space Flight Center, Greenbelt, MD 20771. (e-mail: jmartin@pop400.gsfc.nasa.gov)