PROPOSAL SUMMARY

DESCRIPTIVE TITLE OF INVESTIGATION
The Magnetospheric Mapping Mission

PRINCIPAL INVESTIGATOR / INSTITUTION:
Dr. Harlan Spence, Assistant Professor of Astronomy
Boston University Center for Space Physics (BUCSP)

CO-INVESTIGATOR(S) / INSTITUTION(S):
* Dr. Robert Sheldon, Research Associate, BUCSP (Lead Investigator)
Dr. Harry Petschek, Research Fellow, BUCSP
Dr. George Siscoe, Research Professor, BUCSP

Magnetospheric physics has reached a threshold from which a new leap can be launched that will solve major, long-standing problems and open up major new areas of research. The leap will be achieved with a new tool for magnetospheric research that will give the ability to obtain continuous sequences of magnetospheric images simultaneously in 3-D with spatial coverage broad enough to encompass the main magnetospheric process and with resolution great enough to see the associated movements and transformations of the relevant magnetospheric structures. The new tool comprises a constellation of autonomous micro-satellites with advanced detectors that provide pixels out of which magnetospheric images are rendered with tailored software. Our goal is to launch >100 satellites into the magnetosphere to measure the magnetic field configuration with nearly 1 R_E resolution between 5-10 R_E in the northern hemisphere, and correlate it with the plasma environment, particularly as recorded on the Earth's ionosphere.

Two related problems have to be solved: 1) Although instrumentation can be scaled down, telemetry cannot. Several tens of watts would be needed to communicate with a reasonably sized radio dish on the ground, multiplied by the >100 satellites and the gigabyte/day of data; 2) Tracking the satellite remains important and scales inversely with size of satellite. We believe we can solve both of these problems with the developing technology used in laser communication with satellites and lunar ranging. We locate the power on the ground, where it is cheaper, and modulate the signal in space accomplishing this with a corner reflector and a laser system, which uses none of the completely saturated DSN resources. Thus the satellites themselves can be built smaller, cheaper and lighter and communicate faster. We propose to use current astronomical observatories as sites for these ground-based facilities, but operate 24 hours/day.

The enabling technology is a reliable method of modulating the corner reflectors in space so as to maximize signal/noise and telemetry rate while minimizing power consumption, weight and size. We believe that a front surface mirror with a piezoelectric backing will satisfy the necessary light weight, durability, telemetry rate and power constraints. This proposal will fund the prototyping and reliability testing for the top 5 piezo-mirror contenders. We will also construct several prototype corner reflectors made from Invar or light-weight composites for thermal and stress testing, in order to determine the thermal and mechanical design constraints on the mirrors. Although we expect improved satellite electronics to be available as communication satellite constellations drive the market, we breadboard the electronics of a mirror controller, magnetometer and DPU with the goal of obtaining a working system in ~1 watt as proof-of-principle. Again we expect the solid propellant boosters to be made under contract, but we will study the launch system stabilization and decoupling mechanism so as to obtain maximum accuracy for orbit insertion. Finally, we will make use of powerful orbital mechanics software tools to design a constellation of elliptical orbits that have the properties of 1 R_E volume spacing even under time-evolution and estimate the DV requirements on rocket design.

TABLE OF CONTENTS

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I. INTRODUCTION

We are at an important threshold in the study of the magnetosphere, one that many other disciplines have already crossed. We have passed the age of exploration—new regions, new boundaries—and are approaching the age of synthesis. Rather than studying an isolated "event", such as a major magnetic storm, we are attempting to synthesize the global picture, the relationship of magnetospheric "events" with the entire geospace environment. In analogy with meteorology or seismology, this synthesis stage requires a great deal of standardized data (far beyond what can be analyzed by human scrutiny alone) as input into supercomputer simulations. Several large MHD simulations of the magnetosphere exist, but are starved for data, so that solutions remain dependent on arbitrary assumptions. So the next critical step in our understanding of the magnetosphere, is to sample the magnetosphere sufficiently densely to constrain the computer models currently in existence. This step implies two conditions: the measurements must be global in the sense that the models are global; and the measurements must be sufficient—they must actually determine the model solutions. If only one type of measurement were possible, then the data that most closely constrains the MHD models would have to be the vector magnetic field (see the white paper from the April '96 "New Missions" JHU/APL meeting). Since magnetic fields must be measured *in situ,* we are led by this logic to propose a multisatellite magnetic field measurement of the magnetosphere.

II. SPECIFIC SCIENTIFIC OBJECTIVES

The prime scientific objective of this mission is to provide global, simultaneous 3-vector measurements of the magnetospheric magnetic field with approximately 1 R_E volume spacing from 5 - 10 R_E over the entire northern hemisphere. In crucial regions, such as the plasmasheet, higher resolution is necessary to resolve the very narrow current systems. In these regions we would employ "clusters" of 2-4 satellites with spacings of 1-1000 km. The data should have a better than 1 sec time resolution though in practice the sampling frequency is limited not by the instrument but by the telemetry. The data should be downloaded from the entire constellation at least once per day, and perhaps more frequently depending on the quantity and time-resolution required. The entire constellation should be operational and data available for at least one year, in order to sample a full cycle of dipole tilt angles. A secondary objective is to monitor the plasma and energetic particle environment of each satellite, so as to determine the region of the magnetosphere being sampled. A tertiary objective, though not essential to the success of the mission, is to have the data from a selected subset of satellites available in near real-time, with delays of no more than 10 minutes so as to provide predictive capability of the constellation. This implies not only a fast downlink, but powerful data processing capabilities.

III. EXPERIMENTS

A. Magnetometer

The primary instrument is a 3-vector fluxgate magnetometer. Although absolute accuracy is desirable, 1 nT precision is sufficient for our purposes, particularly if the offset error can be corrected by other means. The crucial requirements for the magnetometer are the power and size constraints: it must draw less than 1 watt and fit within the satellite launch tube, preferably between or at the corners of the piezo-mirrors of the satellite. Several candidate designs have been advertised, none of which meet all the above criteria. JPL has designed a low-power, small-sized magnetometer, though they have not demonstrated the 1 nT sensitivity. Space proven fluxgates have been built within the power and sensitivity constraints (e.g. Explorer 41), but not all the packaging constraints. We expect that given the resources, a suitable instrument can be easily implemented using these proven, simple designs but with modern integrated components.

B. Plasma and Energetic Particles

In the spirit of synergy, we can make the attitude determination subsystem double as a plasma and energetic ion detector. We use a pinhole camera with a light (and particle sensing) CCD sensor behind to achieve better than 1 degree pixels. We expect to have more than enough photons to discover the sun, and indeed, will need to suppress the sun response with appropriate coatings. These same coatings enable us to set the threshold for energetic particles, so that we can obtain a crude integral energy spectrum for each pixel. We do not need more than 3 or 4 energy thresholds to characterize the regions of the magnetosphere: 1-10 eV for plasmasphere, 100-1000 eV for plasmasheet or magnetosheath, and 10-100 keV for ring current. We can use the high voltage from the piezo-mirror controller to accelerate ions with a grid behind the pinhole, so that the lowest energy ions have sufficient energy to trigger the CCD detector.

C. More Energetic Particles

Because the observed particle spectra in the magnetosphere decrease in intensity with increasing energy, the geometric factor of the above pinhole arrangement is not suitable for 100keV - MeV range particles. Again in the spirit of synergy, the tethers used to maintain a cluster of satellites at 1 km spacing can be modified from a suitably doped and coated optical fiber so as to produce a scintillation detector with a significant geometrical factor, as is done in the high energy physics community. Photodiodes on the spacecraft would then continuously monitor the light intensity and frequency from the scintillator. Integrated flux of MeV penetrating particles could be calibrated to the Gbyte memory bit flips corrected by the CRC algorithm.

IV. ENABLING TECHNOLOGY: PHILOSOPHY

The crucial enabling technology that makes this entire venture practical is the method of reducing the telemetry power requirements, and, depending critically on the telemetry needs, the launcher for such a large constellation. The instrumentation, while requiring a novel packaging for this satellite, is not the driver for this mission. Let us restate that. This satellite can be easily modified, both in size and weight, to permit even off-the-shelf magnetometers to be flown, provided that the telemetry problem is solved. Therefore we do not dwell on details of the instrumentation so much as the satellite telemetry design and implications for the launcher.

A. The Radio Telemetry Problem

The problem is quite simple: to communicate to geosynchronous orbits and beyond with a standard radio telemetry requires a nearly linear tradeoff between data rate, transmitter power, transmitter antenna size, receiver antenna size and satellite attitude control. Thus to make a smaller satellite, one has to reduce the antenna size which reduces the data rate unless the power is increased or the pointing accuracy increased. One can perform an optimization of these tradeoffs, but the net result is that a microsatellite at 15 R_E has a very low data rate mitigated only by very large (DSN) receivers on the earth. However the DSN is saturated at the moment (*Space News*, 1996), nor is it clear whether enough frequency channels will be available to track the >100 satellites nearly continuously, as such a low data rate requires.

A simple example will suffice. For our purposes, a 1 Mbps link is desired with 1 watt transmitter. From geosynchronous altitude, with a transmitting antenna that focusses the beam on the entire earth (using an energy-per-bit / noise density ratio of 12.6 dB and a noise figure of 3dB with no atmospheric losses), we need a 10 meter receiver dish (reference). At 15 R_E, the receiver dish would have to be 20 meters. This size dish is already competing with the 26 meter dishes used for GGS, and we have >100 satellites. Nor is such a solution compatible with our microsatellites because merely the attitude control needed adds extensively to the complexity and size of the spacecraft. But if we use an omnidirectional antenna and keep the 20 meter dish, then the data rate drops to 4 kbps. Thus the telemetry needs alone set a lower threshold on the size of the satellite, and hence the launcher and overall expense of the >100 constellation.

B. The Laser Telemetry Solution

To break through this size barrier, some other means of telemetry is needed. And in fact, LEO constellations based on interconnected satellites have already addressed this problem. The solution they arrive at, from purely economic constraints, is a laser based inter-satellite link. We propose exactly the same solution for our microsatellites. However, unlike the LEO constellations, our power budget is limited, and our attitude control cannot approach the stringent requirements of laser pointing. The solution to this problem was solved by the lunar ranging community 20 years ago when they used corner reflectors on the moon to reflect a laser beam back to the Earth. Thus we can put the laser (and laser power source) on the ground and modulate the signal in space, returning the signal passively with a corner reflector whose reflection coefficient can somehow be modulated by the satellite (see Figure 1).

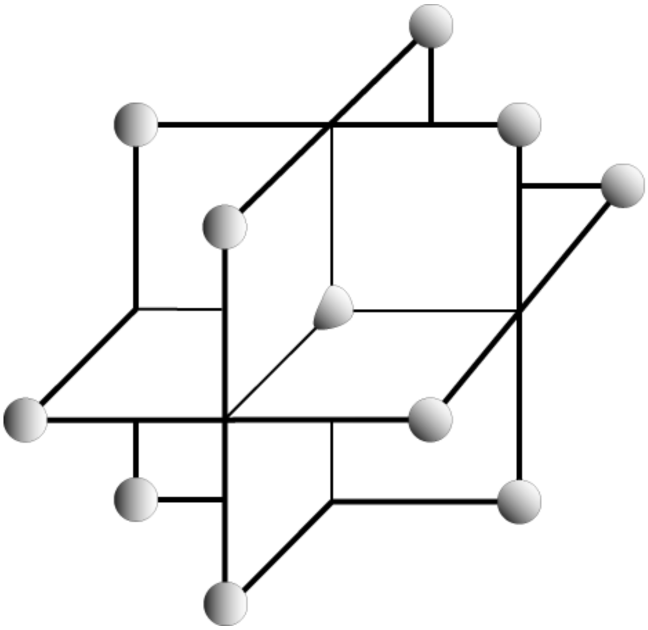


Figure 1. Microsatellite Structure

Net Weight: 1 kg
Length:Height:Width: 10cm
Power: 1 watt solar
Battery: Flat pack, NiCd
DPU: 603 class
Memory: 1 Gbyte RAM
Telemetry: 1 MHz
Instruments: 300 g

- One 3-axis magnetometer
- 12 pinhole diodes / sunsensors
- Scintillation detector / tether

1. Advantages

This is by no means an exhaustive list, but due notice should be taken of the real advantages of this system. It does not (yet) require a FCC license since the bandwidth of most lasers is not regulated. This alone should make it a prime contender in the commercial market. It has unlimited broadcast capability to all line-of-sight receivers. It has inherently large bandwidth. It requires very little satellite power, independent of radial distance from the earth. It has a very small footprint, so that, for example, satellites can be packed closer together than the 2 degree geosynchronous slots currently used. It does not require any attitude control. It is nearly unjammable from a distance making it attractive for military applications. Finally, technological advances in lasers, pulse shaping, receivers and power can only improve the telemetry rate of the system; we are not locked into an out-of-date system on the day that we launch.

2. Disadvantages

The most glaringly obvious disadvantage is that lasers cannot penetrate clouds, and are limited to the frequency spectrum over which the atmosphere is transparent. Let us point out that astronomers have exactly the same limitations, and their solutions are directly applicable to our case. We therefore will assume that current astronomical observatories are the optimal places to locate such a laser telemetry system; and indeed the more locations around the globe in operation, the greater the probability of 100% data recovery.

C. Implications for Launchers

The three constraints on any launch system are generally size, weight and accuracy. If we include the deployment, then a launch system must also be capable of attitude and spin-rate control. By reducing the size and weight, and relaxing the accuracy constraints, we can greatly simplify the launch system. But the real winner is relaxing the attitude constraints, which means that “dumb” solid propellant rockets can be used for deployment. It would be a meaningless triumph to reduce the satellite dimensions and then to have the deployment motors become 90% of the complexity and cost. This is another advantage of laser telemetry: it requires no pointing at all. With no attitude control needed and low weight and size, we have capitalized on the extreme simplicity of launchers to design a launch system capable of launching >100 satellites into highly eccentric orbits from a single platform in as little time as a day. Thus the launch cost for the entire constellation is a single GTO launch for the mother satellite, which then launches the microsatellites using solid propellant kick motors. The deployment of the entire constellation requires only a “point-and-shoot” capability of the mother satellite.

V. ENABLING TECHNOLOGY: DETAILS

A. Corner Reflectors

In order to create a reliable telemetry link, the corner reflectors must return enough (modulated) photons back to the ground station to transmit 1 Mbps. This puts constraints on the minimum size and tolerances allowed in the design of the corner reflector. The launcher puts additional constraints on the maximum size of the corner reflectors, >100 of them must fit in the shroud of a Delta II. There is no particular advantage to making the mirrors smaller than 10cm, whereas 20 cm is an upper limit based on the fairing diameter. Thus purely for illustrative purposes, and without any other optimization, we calculate the expected photons/bit using 2 different frequency 1 watt lasers and a 10 cm cube corner reflector.

1. CO_2 Laser at 10000 nm

Using the rule-of-thumb that a 6" mirror gives diffraction limited images in the visible equal to the atmospheric distortion, we calculate the angular distortion of the originally parallel laser beam caused by atmospheric distortion,

$$l/d = 500 \text{ nm} / 15 \text{ cm} = 3\text{x}10^{-6} \text{ radians}$$

At geosynchronous orbit, 40,000 km from the earth, the spot size enlarges to,

$$3\text{x}10^{-6} \text{ radians x } 40{,}000 \text{ km} = 130 \text{ meters}$$

since the intensity drops as the square of the spot size, we intercept about,

$$(10\text{cm} / 120 \text{ m})^2 = 7.5\text{x}10^{-7} \text{ of the outbound signal}$$

The return intensity depends on the diffraction limitation of the mirror and the wavelength chosen. Using 10,000 nm for CO_2 laser with a ground station mirror of 2 meters gives the following estimate of signal decay on the return bounce:

$$10{,}000 \text{ nm} / 10 \text{ cm} = 1\text{x}10^{-4} \text{ radians diffraction limiting}$$

$$1\text{x}10^{-4} \text{ x } 40{,}000 \text{ km} = 4 \text{ km spot size}$$

$$(2 \text{ m} / 4000 \text{ m})^2 = 2.5\text{x}10^{-7} \text{ of the inbound signal}$$

The total decrease in signal strength is the product of the outbound and inbound legs,

$$2.5\text{x}10^{-7} \text{ x } 7\text{x}10^{-7} = 1.9 \text{ x } 10^{-13} \text{ net reduction.}$$

Then the photons in a single bit are,

$$1 \text{ Watt x } 1.6\text{x}10^{19} \text{ eV/J x 8 photons/eV x 1 ms/bit x } 1.9 \text{ x } 10^{-13} = \quad 16 \text{ photons/bit/Watt}$$

Of course, kilowatt CO_2 lasers are possible, raising this photons/bit to a more respectable number. But the long wavelength on the small mirrors is a drawback that suggests we might do better with a shorter wavelength laser.

2. Green Laser at 500nm

If instead we choose a doubled-YAG or He-Ar laser at 500 nm wavelength, we get the same numbers for the outbound leg, since the atmospheric distortion is relatively insensitive to wavelength. We calculate the inbound leg to be,

$500 \text{ nm} / 10 \text{ cm} = 5\text{x}10^{-6}$ radians diffraction limiting

$5\text{x}10^{-6} \text{ x } 40{,}000 \text{ km} = 200 \text{ m}$ spot size

$(2\text{m} / 200 \text{ m})^2 = 1\text{x}10^{-4}$ signal reduction on inbound leg

Then the overall signal reduction is the product of the outbound and inbound leg,

$7.5\text{x}10^{-7} \text{ x } 1\text{x}10^{-4} = 7.5\text{x}10^{-11}$ net reduction in signal

Then the photons per bit are,

$1 \text{ Watt x } 1.6\text{x}10^{19} \text{ eV/J x } 0.4 \text{ photons/eV x } 1 \text{ ms/bit x } 7.5 \text{ x } 10^{-11} = 480$ photons/bit/Watt

which is about a 30-fold improvement in the efficiency. Again, kilowatt lasers would be employed to compensate for atmospheric absorption, mirror losses and improve signal-to-noise.

3. Lunar Ranging

Of course in any theoretical discussion of this nature, it helps to have a concrete example. Ever since the Apollo program placed corner reflectors on the Moon, scientists have been reflecting laser pulses from the moon to determine its distance. The numbers from their experiment are instructive. They have a 1000 cm^2 reflector on the Moon's surface, 60 R_E from the Earth and are viewing the return pulse with a 76cm telescope. By our calculations the attenuation on the total trip is:

$3\text{x}10^{-6}$ radians x 400,000 km = 1200 meters spot size on the Moon

$0.1 \text{ m}^2 / (1200\text{m})^2 = 7\text{x}10^{-8}$ outbound reduction

500 nm / 30 cm x 400,000 km = 667 meter spot size on the Earth

$(0.76\text{m}/667\text{m})^2 = 1.3\text{x}10^{-6}$ reduction on inbound leg

$1.3\text{x}10^{-6} \text{ x } 7\text{x}10^{-8} = 9\text{x}10^{-14}$ net reduction in signal

Factoring in all the detector efficiencies and filters, the claim is that they detect 1 photon per $3\text{x}10^{18}$ photons transmitted. This means that there is another factor of 1/30,000 in their detection efficiency that reflects "state-of-the-art" at this time. Using this factor, we would need a kilowatt green laser, or a 20 kilowatt CO_2 laser to obtain a reliable link. These numbers are not unreasonable, and improved detection assemblies (e.g. cooled CCD cameras) would only improve these numbers. As we discuss later, we have a number of advantages over the lunar-ranging lasers that permit even more sensitive detectors.

B. Piezoelectric Modulation of Reflected Laser Beam

In order to modulate the corner reflectors, we have to change the reflecting property of the mirrors. Although this can be done with electro-optical properties, (Kerr, Pockels cells) we prefer a simpler approach based on the piezo-electric effect. The concept is simple—a piezo material is used for the substrate of a front-surface mirror so that a voltage applied across the piezo causes the mirrors to distort and reduce the reflected beam. Several approaches are being followed: varying the thickness of the piezo material so that differential contraction causes the mirrors to distort; using a poly-crystalline thin film of piezo material that contracts randomly due to the random orientation of the crystal axes with the mirror normal; or employing deformable mirrors with cantilevered actuators.

The voltages needed for these distortions depend on the thickness as well as the properties of the piezo material. We estimate that modern piezo ceramics (e.g. $BaTiO_3$) have strains of about $1\text{x}10^{-9}$ for applied electric fields of 1 V/m. The minimum contraction we need is about a wavelength. If we assume a 1mm thick layer and a wavelength of 500nm, then we need a strain of $5\mathrm{x}10^{-4}$, which requires about 500 V across the ceramic. Solutions requiring less voltage would involve cantilever arms to deformable mirrors, but perhaps with a lower frequency response.

The most compact approach for fabricating these mirrors would be to combine the solar panels and the mirrors into a sandwiched construction, accepting some reduction in either laser intensity or solar panel efficiency. In Figure 2 below, layer 1 is a front surface mirror, layer 2 the piezo material, 3 is a transparent conductor, 4 is the solar panel and 5 the collector. Or the order can be reversed with 1 the transparent conductor, 2 the solar panel, 3 the front surface mirror, 4 the piezo material and 5 the rear anode. Alternatively we can separate the mirrors and the solar panels using a nested construction, where the solar panels extend beyond the corner reflector at the center (see Figure 2). These issues and tradeoffs would be analyzed in the phase A study.

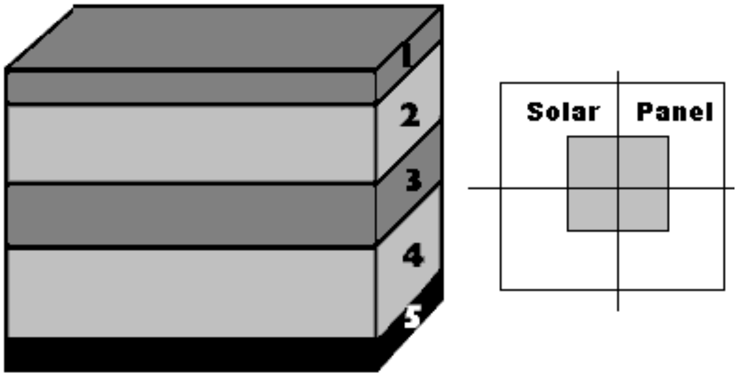


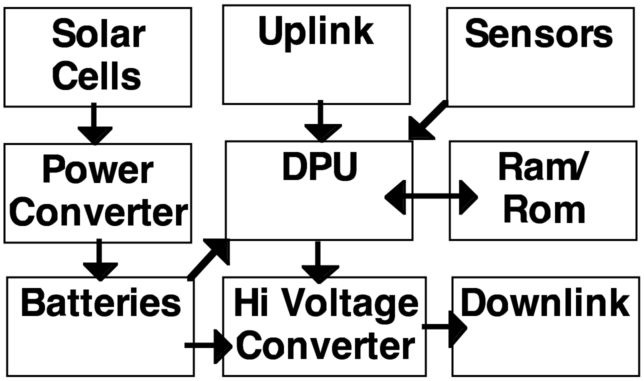
Fig. 2. Piezo Mirror Schematic

Multiple-layered solar panel and piezo electric mirror telemetry concept. Solar panel and telemetry system may be colocated (left) or be separately located (as on right).

C. Satellite Subsystems

The satellite subsystems are shown in a functional schematic in Figure 3. Details of these systems are outlined below:

Figure 3. Satellite Functional Schematic



1. Solar Cells:

   High quality Silicon solar panels with 15% efficiency are cheaper though not as efficient as GaAs solar cells.

2. Batteries:

   These can be commercial flatpack NiCd batteries which can be screened for high quality. Note that sophisticated charging algorithms can greatly prolong the life of NiCd batteries.

3. Power Converter:

A DC-DC power converter cleaned up to eliminate RF noise that can be picked up by the magnetometer sensor.

4. Uplink:

   A sensitive photodiode tuned to the frequency range of the laser used for the uplink. Under some circumstances this may be a different frequency than the downlink. If possible, light-pipes or lenses may be employed to increase the gathering power of the photodiode.

5. DPU:

   A commercial low-voltage, low-current chip similar to those used in laptop computers. It is envisioned that this would be a Power PC class chip, which has the best Mflops per watt ratio of the current generation of CPU, running at 100 MHz or less depending on power constraints. Loral is advertising a 100kRad hardened 603 clone for this application.

6. High Voltage Converter:

   This high frequency (MHz) power supply would drive the piezo material of the mirrors at an appropriate voltage. It is expected that less than a kV would be required, depending on the material used.

7. RAM/ROM:

   Again, commercial static RAM (if it exists in sufficient size ~1Gbyte) and programmable ROMs would be used to store the programs and the data. With sufficient storage, error correction code can be extensively used to correct for radiation upsets. Likewise, the components should have sufficient radiation hardness to survive the expected exposure in earth orbit. Should static RAM not be available, the more power intensive dynamic RAM could be used with little loss in functionality. The crucial factors are size (sufficient to store a days worth of data) and speed (sufficient to dump a days worth of data at 1 MHz).

8. Downlink:

   This is the critical component of the entire spacecraft. It has been described in detail above, and clearly requires the most attention of any part of the spacecraft. It consists of a sandwich of solar-cells and piezo material which can change its reflectivity at a frequency of 1MHz.

9. Sensor:

   The actual sensor package may vary, with the suggestion of a magnetometer and CCD particle detectors with a scintillation detector as well. The only requirements are that it have light weight and low power and small size.

D. Launch System Design

The launch system, as described above, can use “dumb” solid-propellant boosters to achieve the ~3 km/s = DV needed for orbit insertion from GTO. If the satellite mass, m_S, is 1 kg then the mass of the propellant, m_P, from the rocket equation is,

$$m_P = m_S\,[\exp(DV / I_p\, g) - 1]$$

where I_P is the specific impulse for solid propellants (~300 s) and g is the acceleration due to gravity. Then we achieve a propellant mass of about 2kg. With typical solid propellant densities of 1.8 g/cm^3, we obtain a cylinder 10cm in diameter and 14 cm tall. Allowing for packaging and the nozzle and we have a launch system with satellite about 30 cm long. We can launch this satellite using spin stabilization, which is easily managed by adding rifling grooves and teflon guides to the rocket motor. In the DeltaII shroud, we can extend the launch tube nearly 5 meters, if necessary, to obtain the angular accuracy needed for the launch system (see Figure 4).

The mother satellite consists of a collection of these launch tubes, so that the maximum number of microsatellites is determined by the area of the rocket fairing. Allowing 2 cm for the launch tube and 10 cm for the diameter of the satellite, we get a rough number of 114 cm^2 for the area of a single launcher. The area of a Pegasus shroud is about 11,300 cm^2, allowing only 99 launchers which fill the entire shroud. This does not meet our requirement for >100 launchers (nor leave space for the attitude control of the mother satellite), so we assume a DeltaII shroud would be required. A DeltaII has about 53100 cm^2 area, allowing up to 465 microsatellites launchers to be deployed. Since the mother satellite must have precise attitude and orbit control, we would use some of the volume for a kick motor and attitude control as well as a star-sensor.

The intention is to put the mother satellite into geosynchronous transfer orbit at 6.6 R_E or higher, so that microsatellites can be placed into both high (10 R_E) and low (5 R_E) orbits needed to achieve the 1 R_E spacing. The kick motor can be used to change the orbital inclination of the mother satellite so as to cover the entire volume of the northern hemisphere.

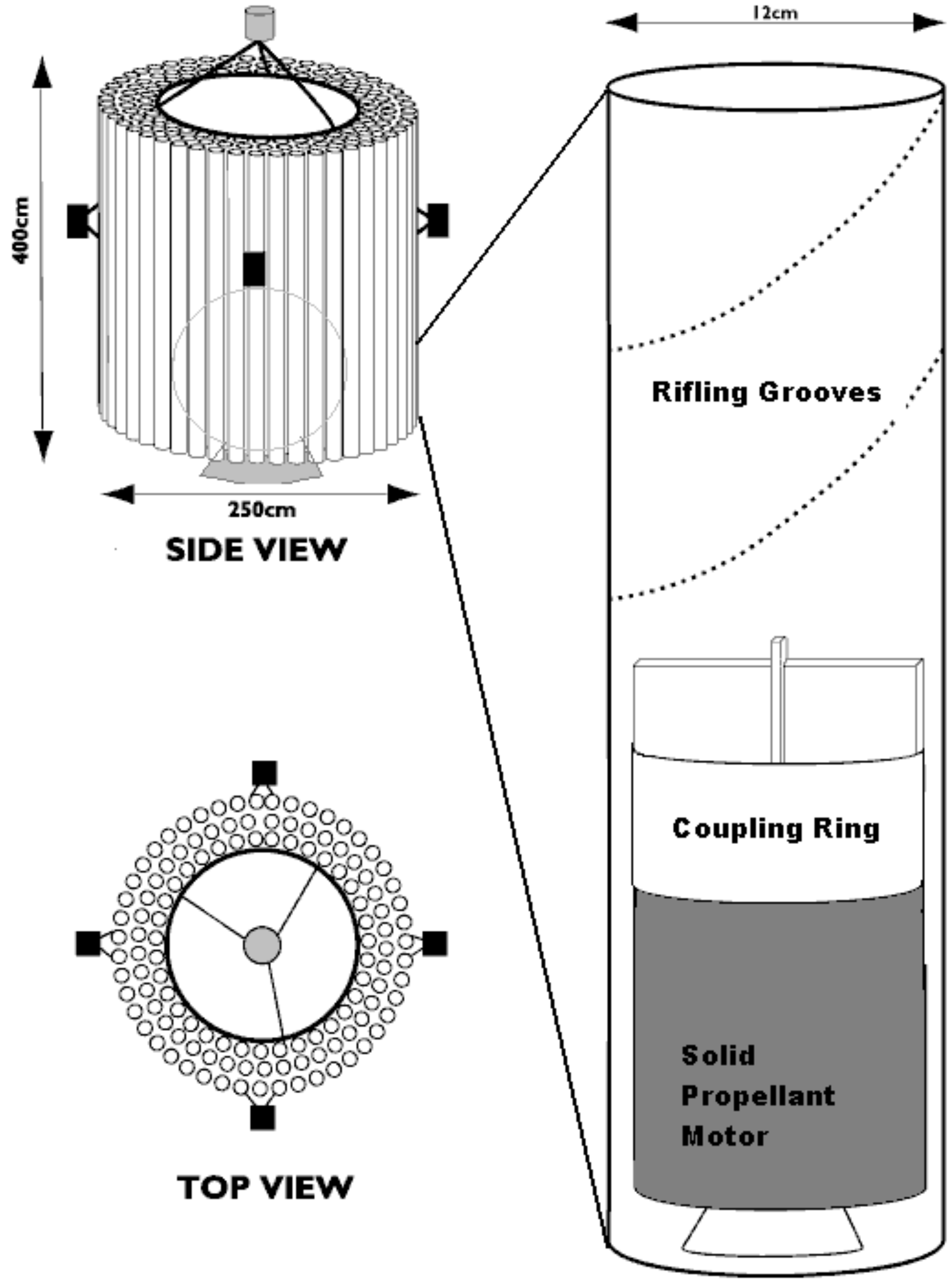


Figure 4: Launcher Configuration

E. Ground System Constraints

1. Gathering Power

We have done the calculation above showing that the technology of lunar ranging combined with a 2 meter dish, requires a 1 kilowatt green laser to achieve a reasonable telemetry rate. Unlike the lunar ranging experiment, however, we do not need to know the distance to our satellites to a centimeter. This means that the phase delays can be much longer, approximately the speed of light divided by the modulation frequency,

$$3x10^8 \text{ m/s} / 1 \text{ MHz} = 300 \text{ meters}$$

Thus we can collect light, without imaging it, from a 300 meter plane if necessary. Of course, for tracking and acquiring the satellite, we need some rudimentary resolution, but far less stringent than astronomical constraints. A possible receiving station may look like a heliostat, a solar-furnace installation with many small adjustable mirrors focussing their light on a central CCD collector. Additional collecting capacity can then be added incrementally, increasing the telemetry rate with every upgrade.

2. Tracking and Acquisition

Acquiring the satellites will be somewhat difficult initially. From our earlier analysis, we estimate that the laser will illuminate a 200m spot at geosynchronous altitude. Thus the laser can either be raster scanned, or the laser can be defocussed so as to cover the expected region of the sky. In either case, the important criteria is signal/noise for the return. This can be greatly improved by putting the downlink into a standby mode, say, a 1 kHz modulation, so that a narrow bandpass filter at 1 kHz could be used. Then the algorithm for satellite acquisition will consist of an optimization of raster scanning and defocussing, depending on current seeing conditions. After the orbital elements are calculated, it is expected that the acquisition will be much faster, requiring a much smaller region of space to be raster-scanned.

The laser and receiver then, should be designed for fast raster scanning. This can be accomplished by small mirrors with high slew rates. Alternatively, solid state devices with refractive indices that depend on electric field could be used to scan the laser. The receiver, as mentioned above, would consist of many small mirrors with inherently fast slew rates.

3. Signal / Noise Criteria

All the above discussion hinges on the signal/noise ratio (SNR) of the receivers. This can be greatly improved, even with turbulent atmospheric seeing conditions by using a ratio of two laser wavelengths transmitted simultaneously. If the satellite mirror modulation is wavelength dependent (the roughness has an intermediate scale length) then the ratio of the reflected beam changes when the mirrors are in a “1” or a “0” state. Thus this ratio would encode a bit, making the bit immune to random attenuations due to passing clouds or turbulence. It should be possible, with a powerful enough filter, to operate the instrument under daylight conditions, thus allowing 24 hour accessibility for the downlink.

4. Global Coverage

The constellation will spend most of its time in the northern hemisphere, so we position 3 ground stations roughly equidistant on the globe. Although high latitude stations may have better angular views, the crucial requirement is a high percentage of good “seeing” days.

VI. MISSION ARCHITECTURE AND OPERATIONS

A. Ground Stations

Three ground stations would be placed at existing astronomical observatories, after evaluation of all available sites. Depending on existing facilities, the laser and 2m mirror would be the initial design for the downlink. Construction of needed facilities could begin as soon as possible after selection, with the expectation that they would come on line in 2 years—the expected development time of the microsatellites. The sheer number of satellites and their complex orbital evolution preclude manual operation of the downlink, so the tracking and data recovery would be automated as much as possible with great reliance on numerical algorithms for optimizing the data recovery from the constellation. Continuous contact would be maintained with other tracking stations so as to optimize the resources and the data recovery.

B. Orbital Constellation

Clearly our goal of sampling the magnetosphere sufficiently densely to constrain the models is limited by the sheer volume of the enterprise. A simple calculation shows that the volume of a 5-10 R_E shell is about $4 \times (10^3 - 5^3) = 3500\ R_E^3$ which implies the same number of satellites are needed for 1 R_E spacing. We are also constrained by the asymmetry of the magnetosphere, since a satellite at 15 R_E will be in the magnetosphere perhaps 20% of the time and in the solar wind the remaining 80%. Therefore we use 10 R_E as the maximum radius because it is the nominal standoff distance of the magnetopause, meaning that circular orbits at this radius will remain inside the magnetosphere under nominal conditions. Because of the presumed N-S symmetry of the magnetosphere, we can reduce our volume in half by sampling only the northern hemisphere. Therefore we use 2 basic orbits for the constellation: circular orbits in the equatorial plane, and elliptical orbits with apogee above the northern hemisphere.

Circular orbits have the advantage that the orbit does not evolve appreciably with time, so that simplifies the constellation design. The crucial region to monitor for the magnetosphere is the equatorial plane, which is ideally suited for these orbits. However they have the disadvantage that they sample both hemispheres equally, which we have argued is redundant. Thus for most of the constellation we use elliptical orbits.

We have designed a launch system that can place these satellites into elliptical orbits around the earth from 5-10 R_E. Circular orbits are only possible with a single burn motor if the mother satellite orbit intersects the circular orbit desired. With sufficient fuel, the mother satellite could be put into a 1 x 10 R_E elliptical orbit and launch a single orbital plane (consisting of 6 x [5+…+10] = 270 microsatellites) into circular orbits with 1 R_E spacing. Then a DV maneuver can rotate the orbital plane of the mother satellite and launch the elliptical orbits.

Although conceptually a 1 R_E grid spacing is easy to visualize, the crucial requirement is the constraint on the models. Thus the placement of the remaining elliptical satellites will depend on knowing where the current theoretical models show the most variability, where a measurement provides the maximum constraint. This will be one area for further study. But for illustrative purposes only, we propose a "pincushion" of elliptical satellites with apogee at 10 R_E spaced 1 R_E apart requiring 6 x (1 + 2 + …+ 10) = 330 satellites. The total constellation would then be 600 microsatellites.

VII. DATA REDUCTION PLAN

A. Processing

The data would be downloaded from the microsatellites at about 1 Mbps. It is expected that the data rate on board the satellite would be about 50 kbps, and that advanced compression techniques could achieve at least 10:1 ratio giving a 200:1 data:telemetry ratio, so that 24 hours of data could be downloaded in about 8 minutes or less. For 600 satellites, this requires a minimum of 3 stations to process all the satellites during the 24 hour period.

The data would be made available nearly hourly (direct links to supercomputing centers?), in a successively updated form, for use in real-time modelling. In addition, the data would be interpolated to a grid for comparison and mapping.

B. Archiving

The data would naturally be archived in both its "raw" and "processed" form on archival material. At the moment this would be on 650Mbyte CD-ROMs, though clearly a higher density medium would have to be sought for the ~60Gbytes of data expected each day. For the moment, high capacity tapes would be sufficient, but a more permanent solution is desired.

C. Analyzing

It would no doubt be cost-effective to have several man-years of dedicated analysis time budgetted, particularly in the early part of the mission. But it is expected that the magnetospheric community would do the majority of the analysis on this data set. Thus the major effort of the initial project would be making the data accessible to the wider community. This means standardizing protocols and file formats as well as algorithms for removing noise, data dropouts and other extraneous information with the goal of providing a standard, high-quality data set with no qualifications.

VIII. MISSION COST

All of the mission costs will depend critically on economies of scale. The cost of materials in a single satellite contract is typically <10% of the cost. With 600 satellites, the materials are expected to be 80% of the cost, reducing the cost of individual components. Much of these calculations depends on the availability of space-proven parts, which we expect will become much easier to obtain with the advent of LEO communication constellations (several of which propose a similar number of spacecraft as discussed herein). This is a rough calculation then of how we expect the construction costs to proceed.

A. Microsatellite
5K CNC produced Invar/composites skeleton
5K piezo-front surface mirrors and installation to specs
5K IC fluxgate magnetometers
5K CCD sun sensors and pinhole optics
1K 603 chipset
1K 1 Gbyte static RAM
5K Solar cells, battery and DC-DC converters
3K photodiodes, custom logic gates, high voltage mirror controllers

30K Total x 600 = 18 M

B. Microsatellite Launcher
5K solid propellant motor
5K separator/avionics

10K Total x 600 = 6 M

C. Mother Satellite Launcher
7M for 3-axis stabilized platform with kickmotor

D. Ground Station
100K laser
100K mirror, receiver
800K buildings and overhead

1 M Total x 3 = 3 M

E. Data Reduction
100Kx 3 networked DEC Alphas
100K for 1 years worth of archival media
600K for 6 man-years of data analysis

1 M Total

Grand Total = 35M

IX. PHASE A STUDY

A. Management Approach/Critical Tasks

The critical factor for the success of this mission is the feasibility of the laser telemetry system. Therefore we will concentrate our efforts on proving this technology. We will study the piezo materials available and focus on the 5 that show the most promise, testing them in our Center for Space Physics laboratories at Boston University. We will study the manufacturing of thin films of this material and come to a manufacturing process that shows the best likelihood of success for mass production. We will study the temperature stability of the corner reflectors, and decide on a skeleton substrate material and manufacturing process. For example, a cast Invar block may be finished with a CNC mill to 1 mil tolerances. This work will be done by a qualified mechanical engineer in collaboration with the Engineering school at BU to apply the best of modern manufacturing techniques.

The second factor is the power budget. For this we will run the proposed 603 processor at a slower clock speed to collect and process the data within the 1 watt budget expected. Shielding, SEU and latchup recovery, fault tolerance all need to be built into the system. The design of the power system and mirror controller will need careful attention to detail to operate in the 1 MHz range, both on low power and to avoid interference with the magnetometer. This work will be done by a qualified electrical engineer with spacecraft experience.

Third, the science and grand overview have to be kept always in mind. When there are tradeoffs, they must be done in a way that minimally impacts the scientific purpose of the mission. We will use the expertise of our Co-Investigator's to assess the scientific return of the mission, and its interface with the scientific community.

B. Milestones/Schedules

Year 1 Tasks - Modulate laser beam @ 1 Mhz with piezo mirror telemetry subsystem
Construct corner reflector at the diffraction limit
Breadboard subsystem electronics with 1 Watt
Assess scientific sensor technologies
Year 2 Tasks - Optimize orbit constellation
Investigate mother satellite launchers
Breadboard magnetometer and CCD sensors
Test proof-of-principle for autonomous power subsystem
Package, integrate, and test at microsatellite system level

C. Personnel

The Magnetospheric Mapping Mission design team is located in adjacent offices within the Center for Space Physics at Boston University, thus facilitating and promoting creativity. The Center for Space Physics [CSP] was formed during the 1987/1988 academic year to provide a focus for research and graduate training in space physics at Boston University. It is a multidisciplinary center within the Graduate School that includes faculty from the College of Engineering and the College of Arts and Sciences. The PI and Co-I's will draw upon both the internal scientific and engineering expertise within the Center for Space Physics and the external resources of Boston University at large, for electrical, mechanical, environmental design and analysis, and fabrication capabilities.

The mission definition team will consist of the following key personnel: Dr. Robert Sheldon who will be the lead mission architect; Professor Harlan Spence who will be the mission definition manager; Dr. Harry Petschek who will be the science and technology consultant; and Professor George Siscoe who will be the mission definition scientist. Only Dr. Sheldon is seeking financial support for these efforts. In addition to the physicist personnel, the proposed Phase A study will require funds for a mission definition lead engineer.

D. Facilities and Equipment

1. Spaceflight Hardware Development Facility

The Center for Space Physics is located on the fourth and fifth floor of the College of Arts and Sciences [CAS] Building on the campus of Boston University. Laboratory facilities in Rooms 406 and 408 will be used for the development, breadboarding, and testing of the satellite subsystems and the instruments as required. These laboratories are equipped with electrostatic charge dissipating flooring and work benches, a Tenney Jr. thermal chamber for temperature testing subsystems, two high-vacuum chambers with oil-free pumping capabilities, adequate power, and clean bench facilities. Office space for the project personnel is also co-located.

2. Optical Calibration and Test Facility

Boston University Center for Space Physics has constructed a vacuum Ultra-Violet calibration facility. This laboratory includes a 200 sq ft dark room and 800 sq ft calibration area which includes an approximately 300 sq ft., class 10,000 clean room. Two high-vacuum calibration tanks fed by normal and grazing incidence vacuum monochromators feed light from hollow cathode ultraviolet and Manson soft x-ray light sources into the tanks, or from sources at other wavelenghts. A separate area has optical benches and lasers for optics design. This laboratory will be available for mirror design, development, and testing, of the proposed corner reflector system.

3. Hardware Fabrication Facility/Machine Shop

The Scientific Instrument Facility [SIF] at Boston University is a modern four million dollar, five thousand square foot machine shop, containing all necessary machines and tools for this project. The SIF is located in the basement of the Physics Building and is administered by Physics Department personnel. This facility has a staff of eight machinists and an assembly team of three technicians. The shop is a climate controlled work space with truck access, crane coverage, and high bay area. The shop has a full complement of machines including a complete set of high-capacity, high-precision, conventional and CNC lathes, vertical and horizontal end mills, a CNC boring mill and grinder, and CAD controlled systems. These machines give this facility a production capability both for quality and quantity that is among the best at any university. All of the CNC machines are connected to an Anvil 5000 CAD/CAE with the software running on a Sun platform. The SIF staff are equipped with workstations at which the CNC programs are prepared and then downloaded to the machines on the shop floor. The shop also has all the machinery needed for stock preparation, including a large shear, an automatic cutoff saw, and a large bending brake, as well as a complete welding and leak-checking capabilities. The shop has years of experience in scientific instrument design and fabrication.

4. Electronics Design Facility

The Electronics Design Facility [EDF] is located on the fourth floor of the Physics Research Building. It has a staff of three engineers and three technicians and regularly employs students as additional workers as required. The EDF offers advanced electronics design, prototyping, and testing capability in support of the BU research program. A major design tool is an electronics CAD package from Mentor, running on Apollo workstations. With this resource, circuits are not only designed but can also be simulated before any actual prototyping is done. Advanced analog and digital circuits have been designed and produced. The EDF has high-speed test equipment and operates a data acquisition system to be able to test experimental equipment.

5. Computational Facilities

The computers at BU are more than sufficient to do the orbital modelling and systems design required. In addition to BUCSP workstations (up to Sparc 20 class), we also have access to a computer that has set a record as the world's fastest: the CM-5 massively parallel computer, made by Thinking Machines Corporation of Cambridge. This so-called "Connection Machine" is part of a large integrated computing environment at BU which includes 20 Gbyte DataVault parallel disk storage units, high speed links to the Graphics Laboratory, and many departmental computers.

6. Administrative and Office Support

Other support includes administrative and grant management services. Ms. Kathryn A. Nottingham has been the administrative coordinator of the CSP since its inception and provides extensive capabilities in cost accounting and cost tracking that supplement and complement the University's cost and grant accounting procedures.