NASA Technical Memorandum 87796

Observations of the Earth's Magnetic Field From the Shuttle: Using the Spartan Carrier as a Magnetic Survey Tool

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Observations of the Earth's Magnetic Field From the Shuttle: Using the Spartan Carrier as a Magnetic Survey Tool

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National Aeronautics
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OBSERVATIONS OF THE EARTH'S MAGNETIC FIELD FROM THE SHUTTLE: USING THE SPARTAN CARRIER AS A MAGNETIC SURVEY TOOL

W. J. Webster, Jr.

ABSTRACT

The shuttle deployed and recovered Spartan shows promise as an inexpensive and simple support module for potential field measurements. The results of a preliminary engineering study on the applications of the Spartan carrier to magnetic measurements show:

(1) Extension of the mission duration to as long as 7 days is feasible but requires reconfiguration of the internal systems.

(2) On-board recording of Global Positioning System signals will provide position determination with an accuracy consistent with the most severe requirements.

(3) Making Spartan a magnetically clean spacecraft is straight forward but requires labor-intensive modifications to both the data and power systems.

As a magnetic survey tool, Spartan would allow surveys at regularly spaced intervals and could make quick-reaction surveys at times of instability in the secular variation.

INTRODUCTION

Observations of the earth's magnetic field by spacecraft require a wide range of mission parameters in order to cover the total range of spatial frequencies inherent in the three sources (core, crust and magnetosphere) which make up the total field (Webster et al 1985). Because no one set of mission parameters can measure all of the spatial frequencies with equal accuracy, a number of different mission profiles are necessary to obtain a complete description of the field. In a sense, a given mission profile is usually "tuned" to be sensitive to a particular field source. Therefore, several satellite missions are under study. These range from high-altitude, long lived satellites primarily sensitive to the low-order spatial frequencies of the core field to very low altitude (120km or less) satellites sensitive to the high order spatial frequencies of the crustal field.

In this study, we have examined the practicability of repetitive, single-epoch surveys of the core field using an existing system capable of multiple deployments and recoveries from the shuttle. Although originally designed as support system for astrophysics experiments, we have found that this system, called Spartan, can be adapted to repetitive magnetic field measurements with only a modest amount of difficulty.

THE SPARTAN SYSTEM

Spartan is a complete service module which operates independent of Shuttle systems after deployment. Spartan was conceived as a means of extending sounding rocket technology and the ease of use characteristic of sounding rocket to the shuttle. The keys to the success of this effort are (1) the retention of the mode of operation typical of sounding rockets (i.e. simple interfaces, low cost and minimum documentation) and (2) providing a high level of technical capability in a small and easily reconfigured package.

The Spartan carrier is capable of supporting a wide variety of sensors as it currently exists. Spartan is best though as a service module to which a given instrument is attached. Except for the duration of operation, the standard services provided are very similar to those of a fine-pointed sounding rocket. Table 1 reproduces the standard support services provided to an experiment (See Appendix 1 for additional details). This level of support is more than sufficient for a 40 hour duration magnetic mission.

Table 1. Spartan Capabilities Available to the Instruments.

Experiment Chargeable Weight:	up to 500 pounds
Power:	28V ±5 VDC (silver zinc batt's) up to 8 Kwhrs
Data Storage:	tape recorder with 10^{10} bit capacity of which approximately 5×10^8 is available to the instrument
Data Encoding:	Pulse Code Modulation (PCM) System digital or analog inputs – 9 bit binary word (+ one parity) – 0-5 VDC signal 80 samples/sec to 1 sample per 13 seconds data rates

The Spartan is attached to a docking fixture in the shuttle cargo bay. In operation, it is lifted out of the bay by the cargo arm and detached in a stable altitude. Spartan power up and initializes its on-board clock and computer system at detach thus beginning operation. As it currently exists, Spartan has no translation capability. However, it does have a precision altitude control system managed by the on-board computer.

Spartan has a sophisticated control computer which manages the data acquisition system and the use of expendable resources such as control gas and battery power. When the expendables reach a low enough level or when the programmed end of mission arrives, the control system powers down everything except the acquisition aids (if any) and places the Spartan in a stable attitude for pickup.

While performing its mission, Spartan is completely independent of the shuttle. As currently configured, Spartan has no provisions for telemetry or beacon transmission. The data is recorded on magnetic tape for playback after the recovery of Spartan and the return to earth. The nearly complete independence of Spartan from crew activities represents nearly the minimum cost to the user for payloads to be deployed and retrieved from a manned spacecraft.

The tape containing the data acquired by the Spartan data system is removed after return to the ground and is provided to the experimenter. At the time the tape is removed, the experiment is also removed. It is then possible to "recycle" the Spartan for another mission.

A typical magnetometer suitable for spaceflight makes a very modest demand on most of the support systems. The vector fluxgate magnetometer flown on Magsat (Acuna et al 1978), for example, requires only about two watts, weighs 0.6 kg and is contained within a rectangular solid 11.4 x 5.7 x 5.8 cm. Data rates tend to be relatively slow (<5 kbs) and, depending on the field accuracy requirements, can be 1 kbs or less.

The principal demands that magnetic observations place on Spartan are threefold. First, the inertial attitude must be well known so that the components of the magnetic field vector can be derived in a consistent way and so that the magnitude of the vector is not biased by directional variations. Second, the position at which each measurement is taken must, at least after the fact, be known to high accuracy so that geographic aliasing can be avoided. Finally, the magnetic signature of the Spartan carrier must be small and must attenuate very quickly with distance so that the magnetometer sensor head need not be on an excessively long boom. Table 2 summarizes the requirements for the highest quality measurements. These requirements are abstracted from the report of a review committee which examined the next generation of magnetic field measurement satellites (Hertzler et al. 1983).

Table 2. Field Survey Requirements

Launch Date:	1st launch in 1987-88 (near solar minimum)
Mission Duration:	40 hour minimum science mission
Reflights:	2 per year for 10 years
Orbital Requirements:	28.5 deg. minimum inclination (the higher the better, polar orbit preferred) 300 km altitude separation of at least 1 km forward of the orbiter
Attitude Determination:	±15 arc-sec
Tracking Requirement:	±50 meter positional determination
Instrument Thermal Constraint:	30 ±20 deg. Centigrade with less than 1/2 degree gradient across sensor
Data Rates:	2-3 Kbps
Power Required:	20 Watts (maximum science requirement)
Magnetic Cleanliness:	Spartan carrier to contribute less than one nanotesla at the magnetometers

Many of the requirements in Table 2 are within the capabilities of Spartan as it currently exists. To reach some of the goals of Table 2, modifications to the basic Spartan system will be required. For example, current tracking planned for Spartan will not reach 50 meter accuracy. In what follows, we will review the results of an engineering study on the required modifications to Spartan.

ENGINEERING STUDY

As it currently exists, Spartan is not capable of satisfying all the requirements in Table 2. In order to assess the kinds of modifications required to meet these requirements, an engineering study was conducted. The study addressed three basic questions:

1. How can the Spartan be made sufficiently magnetically clean so that the sensor can be close to the spacecraft main structure?
2. How can the operational lifetime be extended to more closely approach the duration of a typical shuttle mission?
3. How can the tracking accuracy be improved to the 50 meter level? In Appendix 2, we reproduce the summary of the engineering study. In the remainder of this section, we will review the results with emphasis on mission planning inputs. The three questions will be treated in reverse order.

The need for positional accuracy can be understood by noting that the rate of change of the magnetic field in three dimensions sets the accuracy with which the position must be determined. If one has a specific accuracy for the field components in mind, it is straightforward to determine the required positional accuracy. Using the technique described in Webster et al., (1985), a typical field gradient vector at shuttle altitude yields the errors in Table 3. Note that the errors are different in the three vector components. The error in the scalar field (norm of the vector) for a 50 meter position error in each component is 1.6 nt. As is almost always the case, instrument measurement performance is far better than this.

Table 3. Scalar Field Error at STS Altitude (200 km)

	Vertical	Along Track	Cross Track
Maximum Gradient (nT/km)	-30.3	-10.0	+13.3
Tracking Error (m)	60	100	100
Component Error	3.0	1.0	1.33
		Scalar Field Error 1.85 nT	

Achieving a 50 meter tracking accuracy at 200 km altitude has been a prohibitively expensive task until recently. Traditional high precision tracking methods include doppler, range and range rate, laser ranging and radar tracking. Due to the variations in atmosphere drag and other perturbations, continuous tracking by any of these methods is mandatory to achieve 50 meter accuracy at 200 km. The variations is so rapid and unpredictable that extrapolation over a period larger than an hour or so is not possible.

With the advent of the Global Positioning System (GPS, Denaro, 1984), it is now possible for an autonomous payload such as Spartan to at least record the necessary signals for 50 meter navigation and simultaneously obtain a very precise time code. The accuracy of the time code is far in excess of any that could be provided by the present Spartan system with reasonable-cost updates. Accordingly, the use of a GPS receiver with the recording of the output on the Spartan data tape effectively eliminates the timing accuracy as a consideration and makes possible 50 meter accuracy positioning.

Postflight processing would therefore have to be expanded beyond calibrating the magnetometer data. Normal processing of satellite observations includes the reduction of the raw values to apparent magnetic field strengths for each component, correction for axis perpendicularity errors and other instrumental effects (such as the precise value of each digitization step), and the temporal registration of each measurement with respect to the on-board timing system. The time tags generated by the temporal registration are then used to merge the data with geographic locations extracted from an ephemeris. This ephemeris is usually derived independent of the magnetic data. Since the necessary GPS signals would be recorded along with the data and since these signals include the GPS timecode, the position solution can be obtained for the exact time of the magnetic observations with no need to interpolate.

At present, the operating lifetime of Spartan is limited by two major factors: attitude control gas and battery power. A lesser limiting factor is the amount of storage space available on the standard Spartan tape recorder: This last limit is easily overcome.

The current recording system records a time code and the data on multiple tracks. In order to satisfy the position location requirement, it will be necessary to record the output from the GPS receiver and its associated time code with the data. Compared to other measurements, the required data rate for a vector magnetometer at 200 km altitude is extremely low. A maximum data rate of 3 kb/s for a 3 axis instrument (Acuna et al., 1978) would, for several possible applications, be decimated to about 1.5 kb/s. In any case, the magnetometer will not be the limiting factor. Changing the number of tracks to double the present value would accomodate about 190 hours of operating time. This can be done by changing the record head to a double density version.

At present, the attitude control system used on Spartan is a cold-gas, pulse frequency system. Extension of the operating time for this system is, up to a point, a matter of adding additional gas. For the greatest extension, a combination of additional gas and a change from pulse frequency to pulse width would yield a comfortable safety margin at the end of the mission.

Magnetic cleanliness is a very difficult problem for any spacecraft measurements. Most frequently spacecraft are specifically designed for magnetic observations and are manufactured to a high degree of magnetic cleanliness. Even with the most stringent precautions, extensive work is usually required to supress the carrier magnetic field after assembly. In the case of Spartan, which was not designed for magnetic measurements, the supression measures will be extensive but are very well understood.

Since the magnetic moment of the Spartan carrier has not (as of this writing) been measured, the analysis of the required supression measures can not be definitive. However, it is clear that the basic requirements for magnetic cleanliness can be achieved by rigorous attention to conventional supression measures. Even so, it will undoubtedly be essential to place the magnetometer sensor head on a non-magnetic boom. This supression mesure will assure that the spacecraft field will be less than the measurement accuracy.

The study examined previous experience with the required boom length needed on spacecraft which were not specifically designed for magnetic measurements. The size of these spacecraft ranged from Spartan size and mass to commercial communications satellite size and mass. The record indicates that, with proper care, a one meter boom will yield a spacecraft field at the sensor under 0.5 nt.

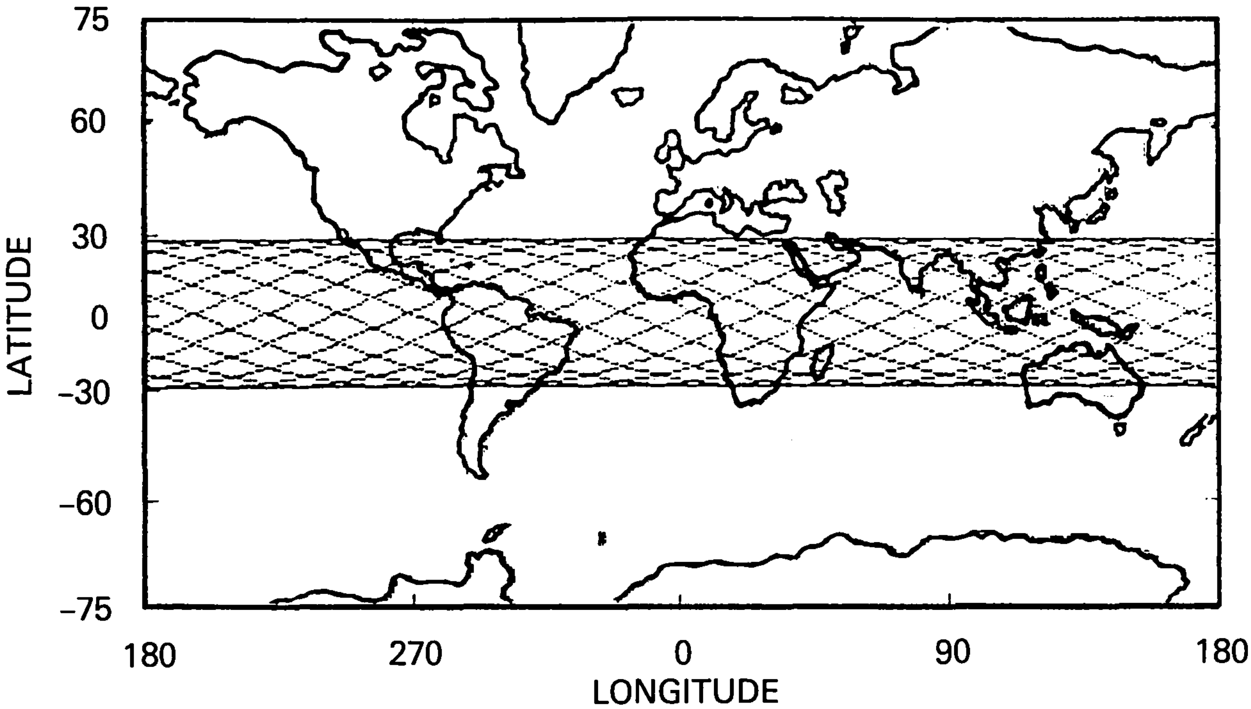
MEASUREMENT PERFORMANCE

The current ground-based magnetometer network does not sample the global field distribution very well. The value of spacecraft observation in establishing the global field at least at a single epoch was demonstrated by Magsat (Langel et al., 1982). In view of the known time variations in the field and randomness of a major portion of these variations, frequent remeasurement is required to accurately define the spectrum of variations.

In examining the measurement performance, we will investigate the ability to determine the field as a function of the inclination of the measuring orbit. Although we will include a model secular variation in the analysis, it should be noted that this analysis will be concerned with the representation at a single epoch. Also, we will treat the case where the measuring orbit is circular and the duration of the measurement is 7 days. The orbital parameters are thus typical of an average shuttle orbit while the duration is typical of a shuttle-spacelab mission.

Ground coverage diagrams of the type used in STS mission planning are useful in understanding the data coverage to be expected in a seven day mission. In Figures 1, 2 and 3, we reproduce the coverage diagrams for a sun-synchronous polar orbit, a 57 degree inclination orbit and a 28.5 degree inclination orbit. Once an orbital inclination is selected, the data density is determined by the orbital altitude. Selecting the orbital altitude also selects the repeat cycle, i.e., how long between geographically coincident ground tracks. Fine tuning the repeat cycle can maximize the chances of obtaining data with the minimum possible contamination from the external field.

Webster (1983) has shown that in a given 7 day period, it is highly likely (probability between 50 and 70 percent) that enough usable data will be obtained to fill all 0.5 degree x 0.5 degree cells with latitude less than the orbital inclination with at least one data point. This conclusion holds true even at the peak of the solar cycle. In what follows, we will assume that the totality of half degree cells accessable at a given inclination are filled. The analysis will consider the comparison of the recovered scalar field with the global field used as input. We will not consider the errors introduced by orbital position and sensor orientation. The interested reader should consult Webster et al. (1985) for further details.



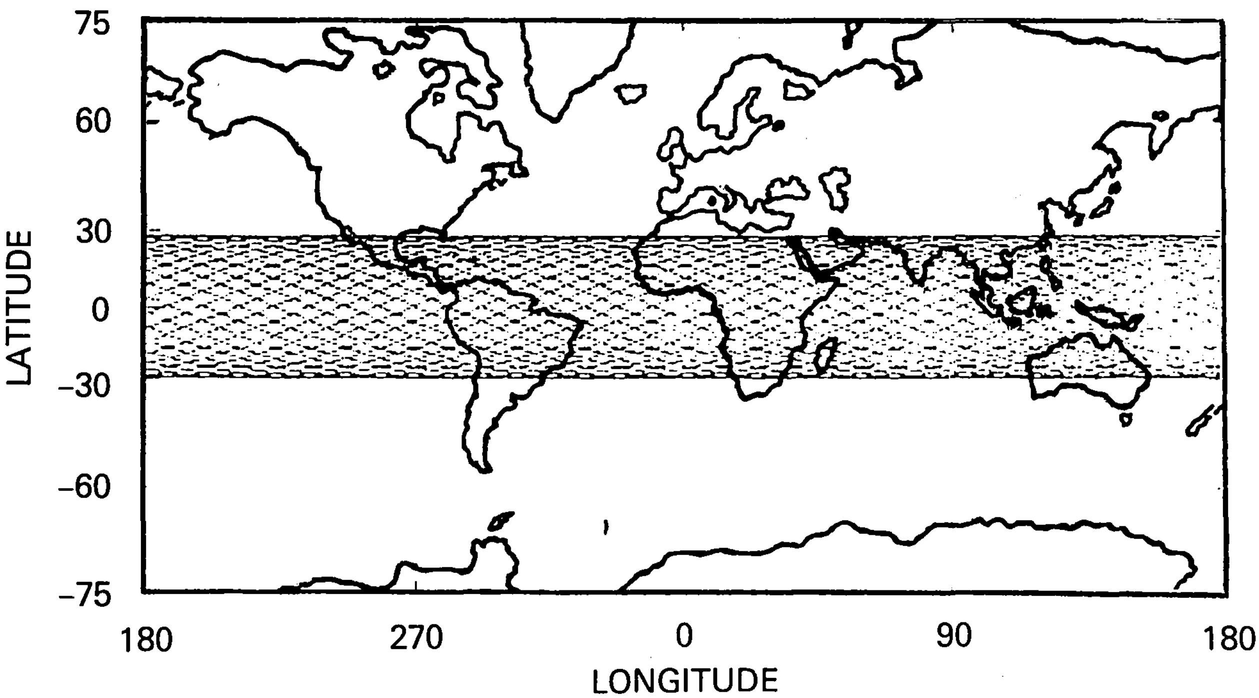


Figure 1. Ground tracks for 28.5° orbital inclination:

a. Altitude 180km: This altitude results in a ground track separation at the equator of 22.5 degrees of longitude and gives 1-day repeat cycle.

b. Altitude 323km: This altitude results in a ground track separation at the equator of 11.25 degrees of longitude and gives 2-day repeat cycle.

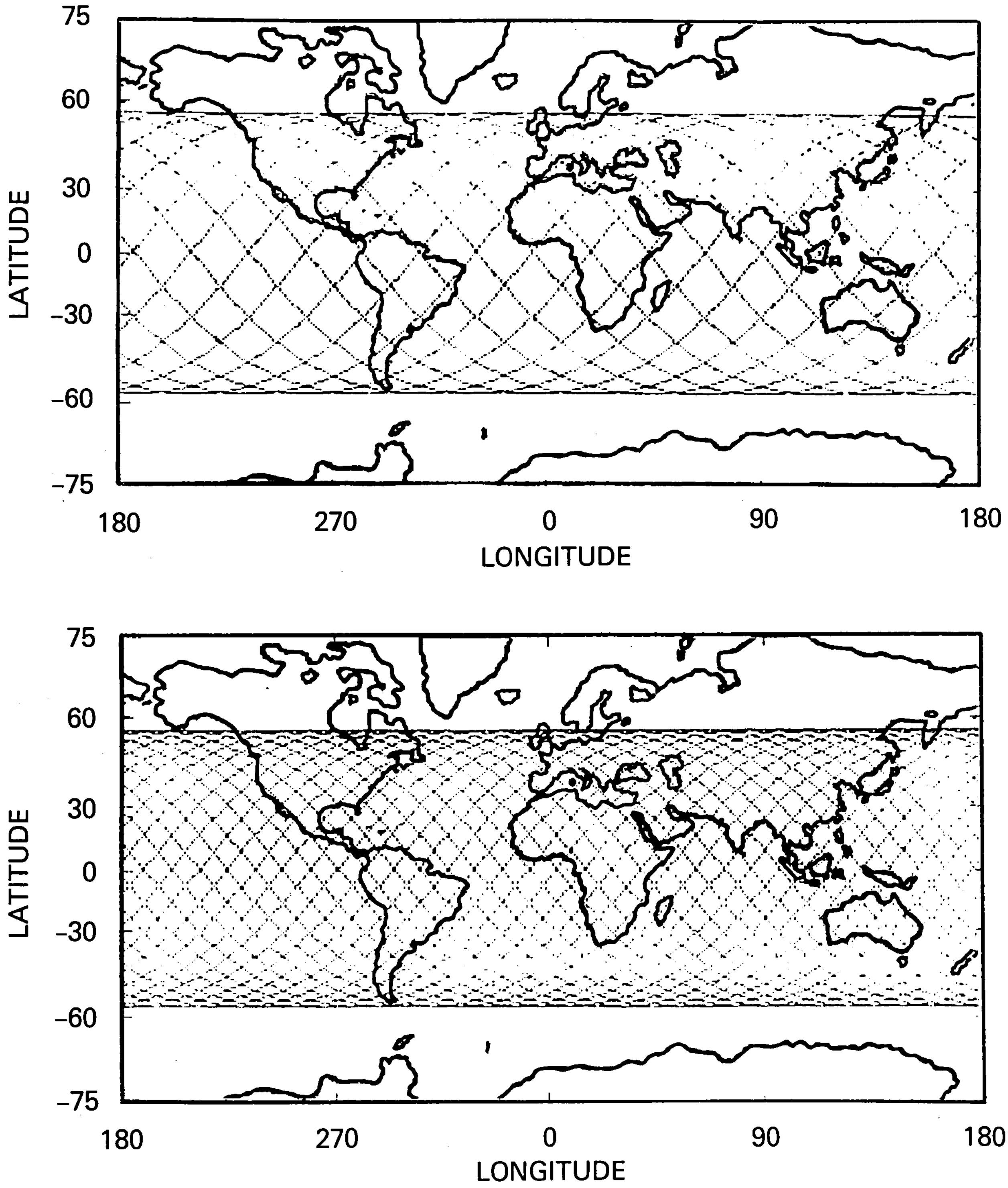


Figure 2. Ground tracks for 57° orbital inclination:

a. Altitude 204km: 22.5° track separations, 1-day repeat cycle.

b. Altitude 345km: 11.25° track separation, 1-day repeat cycle.

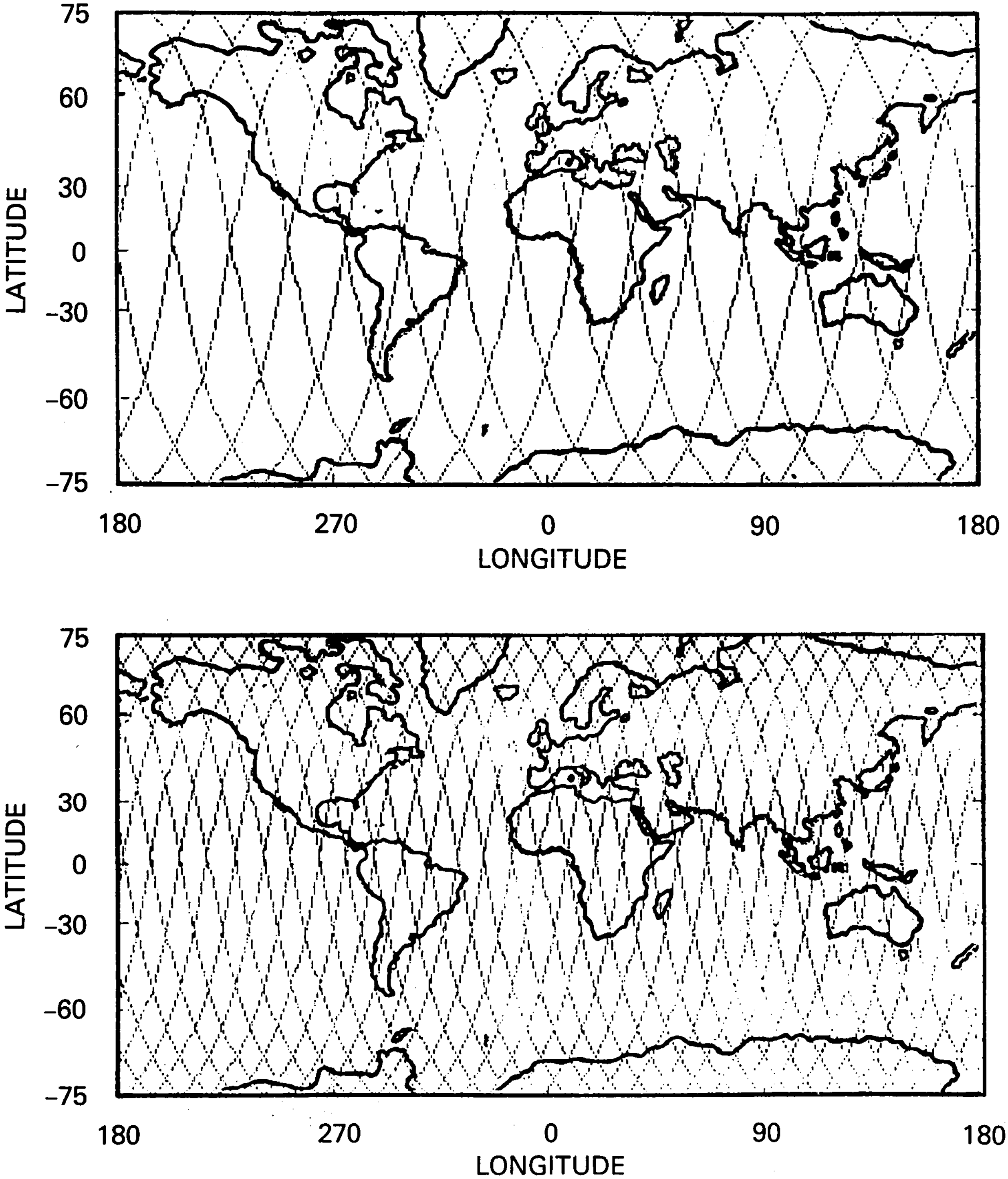


Figure 3. Ground tracks for 96.6° orbital inclination (sunsynchronous):

a. Altitude 268km: 22.5° track separation, 1-day repeat cycle.

b. Altitude 406km: 11.25 track separation, 2-day repeat cycle.

The analysis process (Webster et al., 1985) consists of the following steps:

1. Generate a vector model field covering the entire planet at altitude in half degree cells. The model field used is derived in large measure from Magsat measurements (Langel and Estes, 1985) and includes 4 years of secular variation.
2. Slice the grid so that the remaining cells are between latitudes equal to ± inclination.
3. Solve for the static and dynamic Gauss coefficients using the grid resulting in step 2.

In the interest of simplicity, the coefficients of the scalar (norm of the vector) field are solved for. Noise can be introduced in the analysis before step 3. The Gauss coefficients that result are compared to those used to generate the original model field. The comparison of these coefficients and the rms deviation of the two representation is an objective assessment of the performance.

Although we have performed such an assessment, it should be clear that a real operation would be far more complex than this simple senario. If one must be satisfied with non-global satellite coverage, the satellite data would be combined with the existing observatory data to improve the global coverage. The resulting model is likely to be superior to the satellite data by itself.

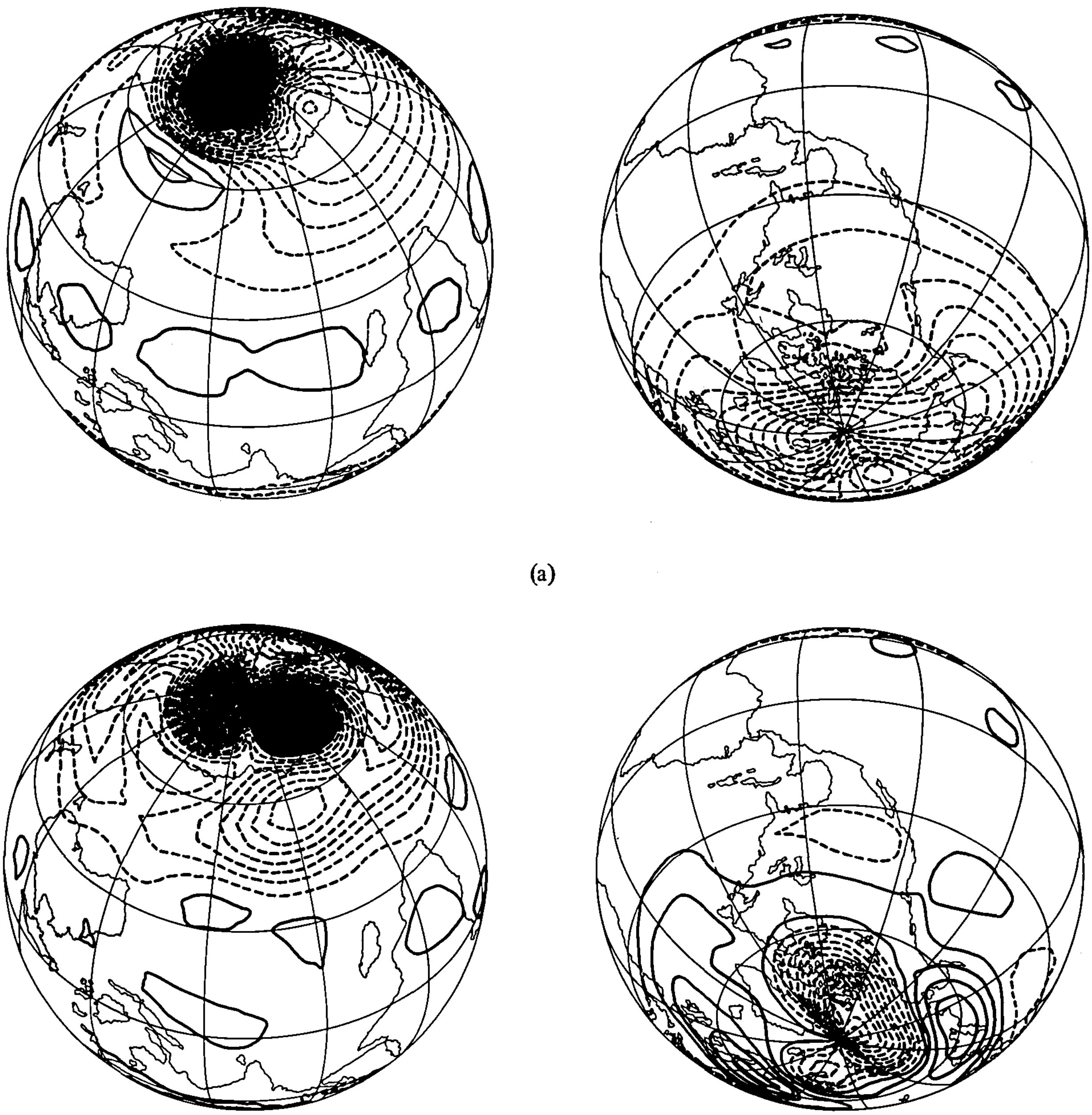
In Table 4, we give the differences between the Gauss coefficients for orbital inclinations between 30° and 60° and

Table 4. Deviations of Individual Moments (Gauss Coefficients) and Their Time Deviations from Full Latitude Coverage.

20 km altitude, 6 nT/axis noise

	60°	50°	45°	30°	Inclination
Static Terms					
G_{21}	13.6	27.8	37.0	69.7	
G_{22}	0.9	1.9	2.5	3.5	
H_{22}	0.3	0.6	0.8	1.4	
G_{31}	8.4	19.9	25.7	30.4	
G_{32}	0.0	0.0	0.5	0.1	
H_{32}	0.1	0.3	0.6	0.6	
G_{33}	0.0	0.0	0.1	0.0	
H_{33}	0.1	0.1	0.2	0.3	
		Units nT			
Dynamic Terms					
G_{21}	0.3	0.5	0.6	0.7	
G_{22}	0.6	1.1	1.4	1.7	
H_{22}	0.2	0.3	0.4	0.6	
G_{31}	0.0	0.0	0.0	0.0	
G_{32}	0.0	0.0	0.2	0.0	
H_{32}	0.0	0.0	0.1	0.0	
G_{33}	0.0	0.0	0.0	0.0	
H_{33}	0.1	0.1	0.1	0.1	
		Units nT/yr			

those of the global model. In Figure 4, we show the world maps of the difference between the two fields. Clearly, the global representation of the scalar field is poorest in the regions not covered at a given inclination. Also, the smaller the region not covered, the better the global representation.



(a)

(b)

Figure 4. Global projection of the difference between the input Magsat model's scalar field and the scalar field which results from measurements at (a) 30° orbital inclination N and S hemispheres and (b) 60° orbital inclination N and S hemispheres. Dashed contours are negative values; solid contours are zero or positive contours. In 7a, contours over the south pole below -1300 nT are filled in while in 7b, contours over the south pole below -140 nT are stippled in and contours above 20 nT are filled in.

The improvement in model quality with increasing orbital inclination is nonlinear (In Figure 5, we show the rms difference between the original model and the output model.) The nonlinearity is caused by the field geometry. The field is nearly cylindrical until the inclination of the measuring orbit is high enough that the convergence to the magnetic poles becomes apparent. Clearly, once the inclination rises from 28° to 35°, a large further change is required to obtain a significant improvement.

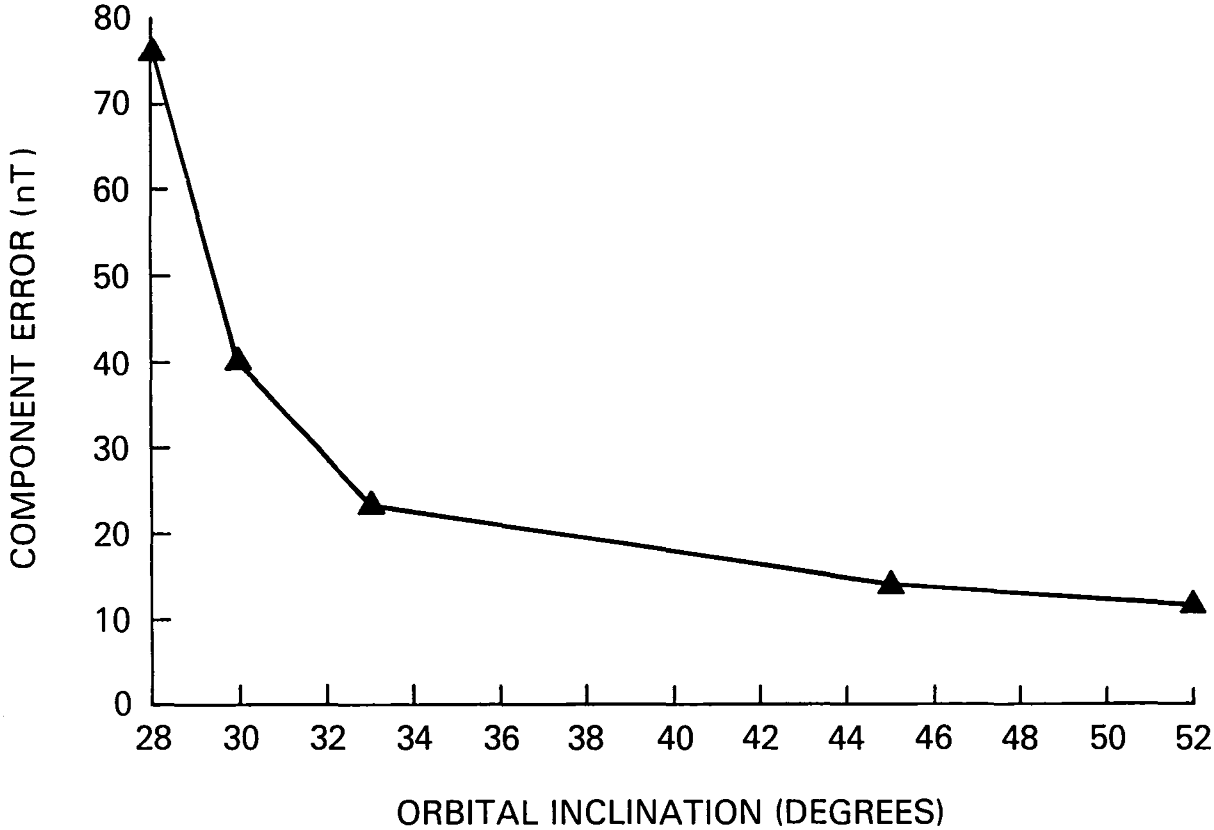


Figure 5. RMS Error in the Total Fit as a function or orbital inclination for the data in Table 4.

SUMMARY

Although not designed as a carrier for magnetometry, Spartan can be adapted to support high quality field measuresurements. The adapting of Spartan requires no new technology. However, the work would require the rigorous principles of magnetic "cleanliness". The extension of Spartan's operating lifetime beyond the present 40 hours is straightforward and would allow on-board recording of GPS receiver output for precise positioning.

Used as a magnetic survey tool, Spartan would permit observations of the field at regular epochs to define the low-order secular variation. Spartan could also be employed as a quick-reaction tool for defining the field at critical epochs, i.e., at or near suspected inflection points in the temporal distribution.

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APPENDIX 1

May 30, 1984

TO: 740/Associate Chief, Special Payloads Division

FROM: 742.1/Advanced Projects Section

SUBJECT: Spartan Field Survey Mission Definition

Reference: (a) A Satellite Mission To Measure the Geomagnetic Field and its Secular Change," A report of the Magnetic Fields Survey Working Group, January 1984

(b) Spartan Capability Statement, February 1984

INTRODUCTION:

The Magnetic Field Survey Working Group issued a report in January 1984 (reference a) which concluded that a contemporary description of the Earth's magnetic field and its secular variation is urgently needed. Dr. William Webster (Code 922) approached the Special Payloads Division in order to determine if a Spartan carrier could satisfactorily perform a field survey mission which would provide a considerable savings in cost over that of a satellite mission. In addition, it would provide a multiple refly capability. This memorandum represents a first cut at defining a Spartan Field Survey Mission.

MISSION REQUIREMENTS

The Working Group defined the mission as having a launch during the next solar minimum in 1987 or 1988 and near either a June or December solstice when irregular magnetic activity is at a minimum. A polar orbit with an altitude of 600 km and launched near the dawn-dusk meridians is recommended. The desired mission duration is for 3 years. Additional requirements call for a tracking accuracy of ± 50 meters in all three directions and an attitude determination accuracy of ± 15 arc-seconds.

The duration requirement obviously reflects a satellite mission. Dr. Webster's goals are to determine whether Spartan represents an affordable alternative to a satellite mission. Spartan would trade the altitude and duration recommended by the Working Group *for multiple reflights and a substantial cost savings. Dr. Webster would like to fly twice a year for 10 years starting in the 1987-88 time frame. Spartan would typically be manifested aboard the next available Shuttle flight and accept whatever orbit and altitude were scheduled. Once in orbit, the Shuttle would deploy Spartan for a 40-50 hour free flyer mission. Spartan would then be retrieved and returned for refurbishment. Planned enhancements in the Spartan program could eventually provide longer mission durations. Program enhancements are discussed later in this memorandum.*

The science requirements as applied to the Spartan mission are summarized in table 1.

SPARTAN GENERAL DESCRIPTION

The following is a brief description of the Spartan carrier. A more complete description can be found in reference b.

The Spartan carrier provides a standardized service module which houses the various support systems (power, data handling, Attitude Control System (ACS) and thermal) and provides the mounting surfaces and space for all experiment hardware. The structure is built of milled aluminum plates which are bolted together. The basic service module is shown in figure 1 which also includes an estimated weight summary of the service module.

Batteries supply all of Spartan's power. Up to 8 KW hours of power are available to the experiment for a 40 hour science mission. A pulse code modulation (PCM) encoding system is used for the handling of all payload data. The data is stored (continuously recorded) on a tape recorder. The recorder is a Bell & Howell Mars 1400 with multitrack, multispeed capability and 10^{10} bits maximum storage capacity. Spartan has no RF links to the shuttle or to the ground. However, while stowed in the shuttle bay, the crew can communicate with Spartan through a hard wire link, the Autonomous Payload Control System (APCS), derived from the GAS program. The APCS allows the Shuttle crew to perform system status checks (go/no go) and to enable/disable certain Spartan systems.

The ACS provides pointing and stabilization for Spartan. The system uses cold gas thrusters for rotational control only. Spartan has no translational capability. The thrusters are solenoid actuated. Various sensors are used to maintain pointing and stabilization. They include solar sensors, star trackers, and Tuned Rotor Inertial Gyros (TRIGs). The ACS can be preprogrammed to perform a desired set of maneuvers.

Spartan is expected to operate properly within a temperature range of 0 to 50 degrees centigrade. The ACS electronics, tape recorder, and other heat producing components are mounted on two aluminum plates that serve as radiators to space. These plates are covered by thermal louvers. Additionally, the selective placement of heaters is used to maintain thermal balance as required. The exterior surfaces are typically covered with multilayer blanket insulation.

A summary of the Spartan carrier's capabilities available for the experiment is presented in table 2.

APPLICABILITY OF SPARTAN TO A FIELD SURVEY MISSION

In order to assess the applicability of Spartan for the field survey mission, the following paragraphs will discuss requirements and areas of concern relating to the science hardware, mission design, tracking, attitude determination, magnetic cleanliness, and thermal control.

Science Hardware: The science instruments consist of either two magnetometers (one vector and one scalar) and their associated electronics or one scalar magnetometer and its associated electronics. The magnetometer outputs are digitized by their supporting instrumentation packages. The digital outputs provide a resolution of better than one nanotesla (one gamma) in each axis throughout the 64,000 nanotesla range of the magnetometers. The data rate to the PCM would be on the order of 2-3 kbps. The magnetometers and their supporting electronics weigh in the neighborhood of 20-25 pounds. The power required is about 20 watts, including heater power. The instrument system will be fully qualified and flight ready when delivered for Spartan integration.

Mission Design: Spartan can provide a free flyer mission with a minimum science time of 40 hours. The standard batteries can provide about 22 KW hours of power. The basic carrier consumes about 350 watts (ACS, data handling, heaters, etc.). If a conservative estimate of 400 watts is used for the carrier including the science requirements, it is feasible to support a mission length of up to 55 hours without additional batteries. Adding more batteries is feasible up to the point where Spartan weight limits are reached. Mission length may also be affected by thermal constraints or ACS gas consumption.

After deploying Spartan, the orbiter would perform a separation maneuver to trail behind Spartan. The separation distance would increase to about 100 miles before it performs a burn maneuver to return for rendezvous with the Spartan for retrieval. Spartan would accept (selectively perhaps) the altitude and inclination as manifested for the particular Shuttle launch. Launches from the Kennedy Space Center typically have inclinations of either 28.5 or 57.0 degrees with altitudes of 150 to 256 nautical miles (the most common mission has an altitude of 160 N.M. with a 28.5 degree inclination). Launches planned for the Vandenberg Air Force Base (non-DOD) have about a 99 degree inclination with altitudes ranging from 160 to 250 N.M. These numbers reflect Shuttle missions as currently planned through STS 81-S. As presently configured, Spartan would by necessity be deployed and retrieved on the same Shuttle mission.

Tracking: The Working Groups' requirement is for a $\pm$50 meter tracking accuracy in all three axis. Discussions indicate that the requirement actually refers to determining the orbit to within 50 meters with the tracking data correlated to the science data on the tape recorder. This is not a real time requirement. Postflight orbit determination is adequate. Two problems are present. First, Spartan currently operates off of a time code generator which measures mission elapsed time from the time the RMS releases the grapple. The release time in GMT is duly noted by the astronauts which should be accurate to within a very few seconds. At orbital velocities this should tie down our position to within 10 or 20 kilometers (not quite to spec). In other words, all of the radar data needs to be very accurately correlated to the magnetometer data being recorded. A possible solution is to use a beacon or transponder with an encoded time signal which is read onto the data tape for post flight correlation to the radar data. The other problem concerns the ability to track Spartan with an accuracy and orbital coverage consistent with the requirement of defining Spartan's orbit to the required accuracy. Presently, Johnson Space Center (JSC) plans on skin tracking Spartan with an estimated accuracy of at least 300 meters. This is for purposes of orbiter rendezvous maneuvers. A system using beacons, transponders, the Global Positioning System (GPS) or some other method needs to be investigated. This problem is beyond the scope of standard Spartan support activities. The solution and its implementation are a user responsibility. However, the Spartan Program would stay involved and cooperate in every reasonable way to implement a solution.

Attitude Determination: The science requires attitude determination to within 15 arc-seconds. Spartan sensors include star trackers, sun sensors, and the TRIG gyros. The star tracker will point to a $\pm$1 one arc-minute accuracy while the sun sensors can point to within $\pm$10 to 15 arc-seconds. When maneuvering to a nontrackable target, the TRIG gyros provide an accuracy of $\pm$3 arc-minutes. Gyro drift is less than 0.1 degrees per hour. The sun sensors can provide the required pointing accuracy, but only during the dayside of the orbit.

A polar, sun syncronous orbit would present no problems. Otherwise, when the payload moves into the nightside of an orbit, the ACS would need to maintain an inertial hold using the gyros. The drift would then become a problem, but perhaps not an insurmountable one. Gyro drift, although not predictable beforehand, is a constant at each occurrence. Therefore, at sunrise of each orbit, the pointing errors measured by the sun sensors could be linearly interpolated to estimate the attitude on the nightside. This may be sufficiently accurate to satisfy the requirements.

Magnetic Cleanliness: The science instruments have a resolution of better than one nanotesla. The science would like the magnetic disturbance from Spartan to contribute less than one nanotesla at the magnetometers' location. The magnetic properties of a Spartan are not defined at the present time. There will be no information available until this fall when Spartan 201 goes through magnetic calibration. However, given that the Spartan systems contain a tape recorder, solenoid actuated valves, gyros, etc., it is reasonable to assume that a boom of some sort will be required for the magnetometers. The addition of a deployable/retractable boom to Spartan is a nonstandard service resulting in additional cost. Placing the sun sensors next to the magnetometers on the end of a rigid boom would allow the ACS to point the end of the boom rather than worry about relative distortions between the carrier and the end of the boom. Since weight will probably not be a driving factor for this Spartan mission, the boom could be made reasonalbly rigid without exotic weight control measures.

Thermal Control: The magnetometers require a temerature limit of 30 +/- 20 degrees centigrade with no more than a 0.5 degree gradient across the sensor. The magnetometers have their own heaters and controls so that this should not be a problem. Similarly, the Spartan systems will provide for their own thermal control. The thermal interfaces between the experiment and carrier appear to be minimal.

COST ESTIMATES (FY84 DOLLARS)

The Special Payloads Division estimates that the cost of a new Spartan carrier, including the first flight, is $2M with 24 to 30 months of support for a first flight. The cost of a reflight is estimated to be $500K and 6 to 9 months of support. These prices only cover the standard support offered by the Division. Additional costs will be incurred by the anticipated requirement to provide a deployable/retractable boom and the requirement to determine orbital position to within 50 meters. The cost of a boom mechanism is estimated to be around $100K per boom. A minimum of two booms should be purchased (flight and backup). This price does not include the cost of environmental testing, of any ancilliary hardware to accommodate the boom system, or any life cycle costs such as refurbishment to support a 20 mission model. The additional cost of the tracking requirement is dependent upon the methods used and any compromises accepted. Determination of that cost will require an independent study.

In addition to the costs mentioned above, there is the cost of the Spartan Flight Support Structure (SFSS) which supports the Spartan in the Shuttle bay and the REM (release/engage mechanism) which allows for berthing and unberthing. The cost of an SFSS with REM is about $1.5M. The planned SFSS life is for about 25 missions while the above plan calls for about 20 flights.

Standard services are defined as:

a. Development and delivery of the Spartan carrier and its subsystems (ACS, Power, Data Handling, Thermal).

b. Normal testing and integration activities at Goddard Space Flight Center.

c. Standard KSC operations support.

d. A copy of the flight data tape.

Non-standard services costing extra include:

a. The science instruments (including support electronics).

b. Thermal design of the science.

c. Fracture control for the science hardware.

d. Tracking

e. Trajectory analysis (orbit determination).

f. Boom mechanism and ancilliary hardware/analysis.

g. Orbiter/STS optional services.

h. Science data tape reduction.

Future Enhancements

Enhancements will be introduced, as appropriate, into future Spartan missions. The implementation of the enhancements will be consistent with the investigator's requirements and available resources. Candidates for potential enhancements include:

a. *Increased data rates.*

b. *Orbiter/Spartan/Ground command/data links.*

c. *Solar panels for increased duration and support of Spartan retrieval.*

d. *Improved valve controller to reduce jitter.*

e. *Increased memory for pointing programs.*

f. *Improved attitude sensors.*

g. *Development of heavier payload carrying capabilities.*

SUMMARY

The scientific community feels that there are compelling reasons to fly a magnetic mapping mission in the near future. Spartan could provide a low cost opportunity for multiple, short duration missions spanning a number of years. Two major areas of concern are the tracking requirements and the magnetic cleanliness requirements. Tracking needs a separate study (regardless of the carrier used) to define reachable goals and costs. The issue of magnetic cleanliness can probably be handled by using a sufficiently long and rigid boom. The costs involved for flying on a Spartan are $2M and 24-30 months of support for the first flight and $500K and 6-9 months for reflights. These costs reflect standard Spartan services only. The tracking and magnetic cleanliness requirements will incur additional costs to the user. The Spartan carrier with its current capabilites (primarily a minimum mission duration of 40 hours) seems to adequately meet the science needs defined by Dr. Webster. However, planned enhancements to the Spartan carriers which could provide significantly longer future missions would greatly benefit the scientific return.

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Enclosures: 3

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Mr. Smith/420
Dr. Paddack/402
Mr. Keller/402
Mr. Busse/700
740 Codes
Mr. Arnowitz
Mr. Lane/742
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Table 1. Spartan Field Survey Requirements

Launch Date:	1st launch in 1987-88 (near solar minimum)
Mission Duration:	40 hour minimum science mission
Reflights:	2 per year for 10 years
Orbital Requirements:	28.5 deg minimum inclination (the higher the better, polar orbit preferred) 300 km altitude separation of at least 1 km forward of the orbiter
Attitude Determination:	±15 arc-sec
Tracking Requirement:	±50 meter positional determination
Instrument Thermal Constraint:	30 ±20 deg Centigrade with less than 1/2 degree gradient across sensor
Data Rates:	2-3 Kbps
Power Required:	20 Watts (maximum science requirement)
Magnetic Cleanliness:	Spartan carrier to contribute less than one nanotesla at the magnetometers

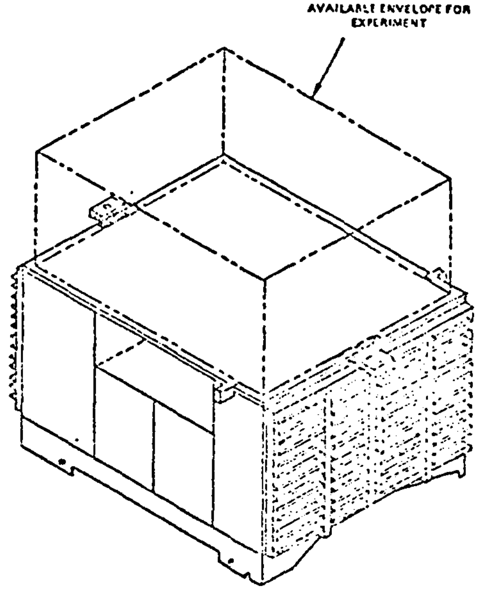
Table 2. Spartan Capabilities Available to the Instruments

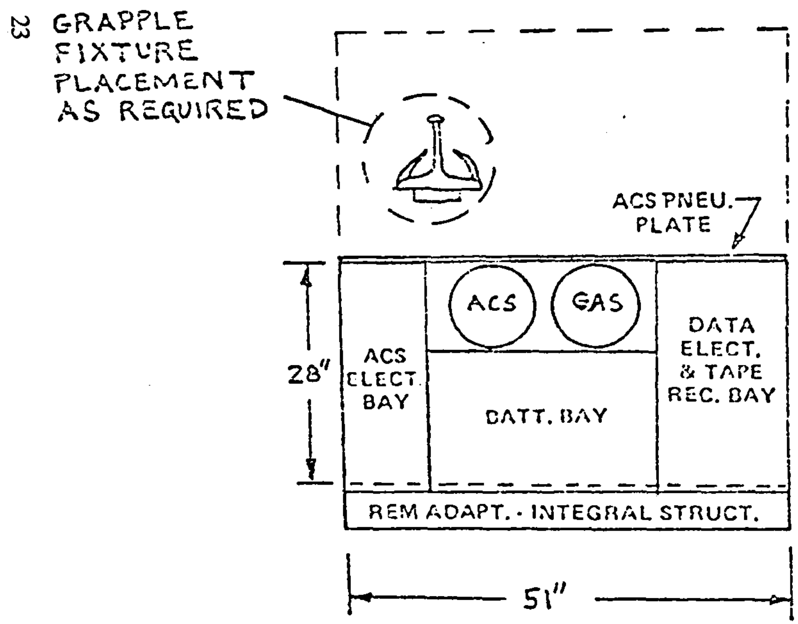
Experiment Chargeable Weight:	*up to 500 pounds*
Physical Envelope:	*see Figure 1.*
Power:	*28V ± 5 VDC (silver zinc batt's)* *up to 8 Kwhrs*
Data Storage:	*tape recorder with 10^{10} bit capacity of which approximately 5×10^{8} is available to the instrument*
Data Encoding:	*Pulse Code Modulation (PCM) System* *digital or analog inputs* *- 9 bit binary word (+ one parity)* *- 0-5 VDC signal* *80 samples/sec to 1 sample per 13 seconds data rates*

<u>SERVICE MODULE ESTIMATED WEIGHT</u>

STRUCTURE	370 LBS
ACS	370 LBS
DATA HANDLING & ELECT.	320 LBS
BATTERIES	820 LBS
THERMAL CONTROL & MISC.	120 LBS
	2000 LBS

THIS LEAVES APPROXIMATELY 500 LBS AVAILABLE FOR THE EXPERIMENT, ITS SUPPORT ELECTRONICS, ADDITIONAL HARDWARE AND STRUCTURE AS REQUIRED.





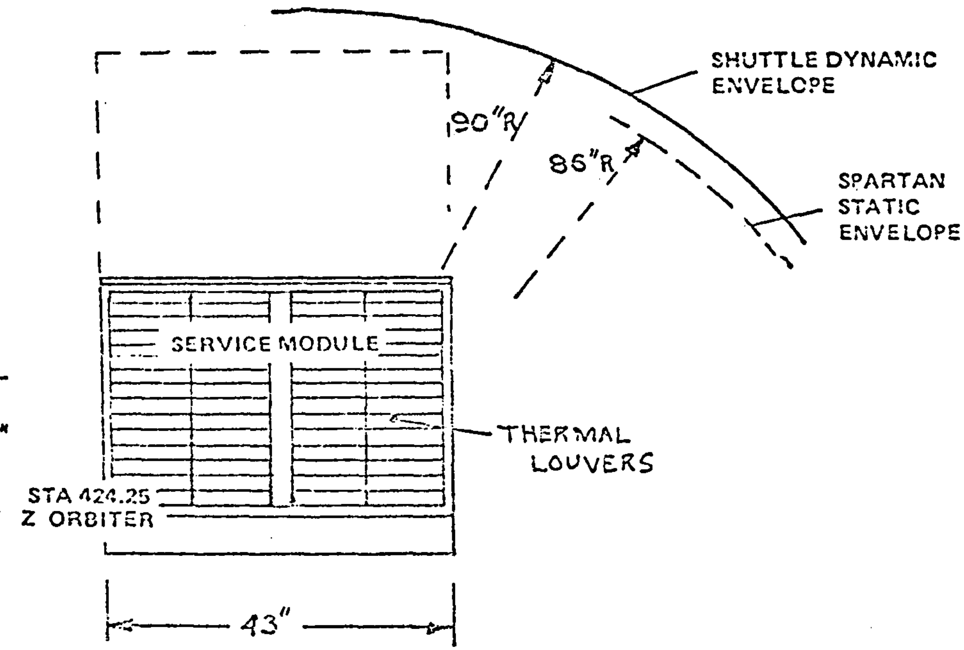


FIGURE 1. SPARTAN SERVICE MODULE

APPENDIX 2

ORI
Silver Spring, Maryland 20910

SPARTAN/MAGNETOMETER EXPERIMENT
MAGNETIC SURVEY OPTION ANALYSIS

TASK 07 UNDER NASA CONTRACT NAS5-28057

15 OCTOBER 1984

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1.0 ABSTRACT

This study was undertaken at the request of the National Aeronautics and Space Administration through Goddard Space Flight Center to explore the possibility of and problems in using a magnetometer on a Spartan spacecraft to map the Earth's magnetic field. Spartan is a reusable, autonomous subsatellite which is released from the Space Shuttle and returned within the same mission. The magnetometer would provide precision magnetic field measurements for scientific and navigation uses.

Adding a magnetometer to the basic Spartan 2 requires adding a boom to isolate the sensor from the magnetic fields of the spacecraft, providing knowledge of ground track to 50 meters or less, and extending the mission lifetime from the design life of 40 hours to five of seven days. The use of Spartan for magnetic measurements is both effective in cost and for scientific research compared to a permanent satellite and the present airborne program.

2.0 INCREASED MISSION LIFE

Extending the lifetime requires changes in three main areas: data recording, attitude control, and power. With close scrutiny of the data requirements and perhaps some data compression, the present MARS 1400 tape recorder will be sufficient for data recording over seven days. With the addition of more gas bottles and thruster improvements such as pulse width modulation instead of pulse frequency modulation, the present attitude control system will be adequate for moderate pointing requirements. Finally, to meet the proposed power load requirements, extra batteries or solar arrays will be necessary in addition to reducing the load with less power-consumptive components.

2.1 Data Recording

The presently planned data recording mechanism for Spartan 2 and 3 is a modified Bell and Howell MARS 1400 LTB tape recorder with a 14-track head and total capacity of 10^{10} bits. Two tracks are used for clocking, leaving either 12 tracks for data with no redundancy or 6 tracks with redundancy.

Each pass can be up to 16 hours long, allowing up to 96 or 192 hours of recording. The proposed GPS receiver would provide precision time data, replacing the pre-recorded clock tracks.

Assuming 2-3 kilobits-per-second (kbs) of data from the magnetometer instrument over seven days, the data storage required is (3000)(60)(24)(7) = 1.8×10^9 bits leaving 8.2×10^9 bits. Areas for improvement include buffer storage especially for housekeeping data, reduction of sampling rate, duty cycle, precision and information redundancy, and other data compression and encoding techniques.

2.2 Attitude Control

Presently, two to four tanks of pressurized gas are planned for cold gas attitude control for short Spartan missions. The amount of gas required is highly dependent on mission length and pointing accuracy requirements. A seven day mission with high pointing accuracy requirements might require twelve bottles of gas with their attendant weight and space requirements and additional danger of explosion.

Fine tuning the individual impulses and using less than full bursts will significantly increase the efficiency of the cold-gas system. Balancing the spacecraft aerodynamically and reducing the pointing accuracy requirements, particularly for yaw, will also hold down the amount of gas required. The Spartan project office is currently exploring the use of pulse-width modulation for smaller pulses rather than the present pulse frequency method.

2.3 Power

The maximum estimated power requirements are 150 Watts for attitude control, 150 Watts for data storage, 25-125 Watts for thermal control, 45 Watts for the GPS receiver, and 2-5 Watts for the magnetometer for a total power load of 372-475 Watts. These are very conservative numbers; 300 Watts appears reasonable.

The present Spartan 2 design calls for two LR350 and one LR40 (only for back-up recovery operations) Silver-Zinc batteries. Each LR350 battery weights about 180 kg and produces up to 550 Amp-hours (A-hr) at 28 Volts nominal, yielding 15,400 Watt-hours (W-hr). Four batteries would provide 60,000 W-hr for 150 hours with a 400 W load and weigh 720 kg.

Silicon solar arrays cost about $1000 per Watt for space quality and 300-400 Watts are required. Exact sizes and costs depend on the Shuttle's orbit, eclipse time, orbit temperature, and magnetic requirements. Due to the extra power conditioner equipment required, problems in stowage and maneuverability, and expense, solar arrays are not as practical as extra batteries for a short mission.

3.0 EMI/EMC ANALYSIS

3.1 Spacecraft Magnetic Fields

The major magnetic sources are the batteries (very low for Silver-Zinc), tape recorder (especially the magnetic head), data control electronics, attitude control system, and all the wiring. An in-depth model of the Spartan magnetic environment is not available. Measurements made on similar equipment used in the sounding rocket program indicate magnetic magnitudes at one meter of 290 nT in the X-direction, 477 nT in the Y-direction, and 203 nT in the Z-direction. These numbers are very rough as changes in orientation, materials, construction techniques, and power loads radically alter the magnetic field.

3.2 Methods of Field Suppression

Magnetic fields from the spacecraft must be limited to 0.5 nT at the magnetometer in order to use the full sensitivity of the sensor. Low frequency and DC fields are most troublesome; high frequency perturbations can be filtered out. Shielding is almost useless at low frequencies and is required only for the tape recorder. Using non-magnetic materials and twisted-pair wire will be most effective and magnets can be carefully placed to cancel remaining fields (still a black art). The present design of the

Spartan is magnetically dirty and will require isolation of the sensor from the spacecraft with a extensible boom. The length of the boom can not be calculated exactly until the spacecraft design is complete, but will need to be about 6-9 meters.

4.0 POSITION KNOWLEDGE

Several navigation systems are available that provide precision spacecraft tracking with a ground track accuracy of better than 50 meters in real time or by post-flight analysis. The Ground Spaceflight Tracking and Data Network (GSTDN) and the Tracking and Data Relay Satellite System (TDRSS) will provide on the order of 700 meter position accuracy after extensive processing by the GSFC Operational Support Computing Facility. These systems require a very accurate onboard clock and TDRSS requires a special transponder.

The Smithsonian Astrophysical Observatory (SAO) Laser Tracking Network will use lasers to track spacecraft-mounted corner cube reflectors and will provide 5-15 centimeter accuracy. It, also, will require complex data gathering and processing and will not be continuous nor global.

The Global Positioning System (GPS) is a space-based radio positioning, navigation, and time-transfer system and will be fully operational in 1989 with 18 spacecraft in six orbital planes. The GPS spacecraft transmit two L-band frequencies (1575.42 and 1227.6 MHz) with either precise or clear/acquisition signals superimposed with navigation and system data, including GPS spacecraft ephermeris, atmospheric progagation correction data, and GPS spacecraft clock bias information. A receiver on the Spartan would use two hemispherical antennas to receive signals from multiple GPS spacecraft and compute the Spartan's position in latitude, longitude, and altitude to 5-10 meter accuracy with exact time information as well.

5.0 PROPOSED DESIGN

Table 1 shows the weight, size, power, data rate, and cost for the proposed Spartan/Magnetometer mission, assuming a five day mission and use of the backup MAGSAT magnetometer. Figure 1 shows a possible layout of the spacecraft.

TABLE 1

SPARTAN/MAGNETOMETER SUMMARY

		Weight	Size	Power	Data Rate	Cost
Basic Spartan 2		900 kg	1.09 x 1.30 x 1.32 m	250-400 W	Housekeeping < 0.1 kbs	$2.0 M
Magnetometer	Sensor	0.6 kg	11.4 x 5.72 x 5.8 cm	2.0 W	2-3 kbs	$0
	Electronics	2.6 kg	22.2 x 17.8 x 11.4 cm			
Boom (Astromast)		6-8 kg	0.46 x 0.3 x 0.3 m	10-20 W (movement only)	-	$0.5-2.0 M
Extra Batteries (2 LR350 Ag-Zn)		360 kg	0.43 x 0.6 x 0.6 m	supply 30,000 W-hr	-	$40-50 K
GPS Receiver		20-30 kg	0.4 x 0.3 x 0.2 m	43 W	0.064 kbs*	$0.05-1.4 M
Redesign Electronics				minus ? W		$50 K ?
Launch						Unavailable $4 M ?
Project Support						Unavailable
Refurbishing Each Launch						$50 K ?
Initial Total		1301.2 kg		295-445 W+	2-3.164 kbs	$2.64-5.23 M
Total per Launch (20 Flights)						$0.2-0.3 M

*32 bit digital registers read every 0.5 seconds
+60,000 W-hr from 4 batteries will last 135-203 hours

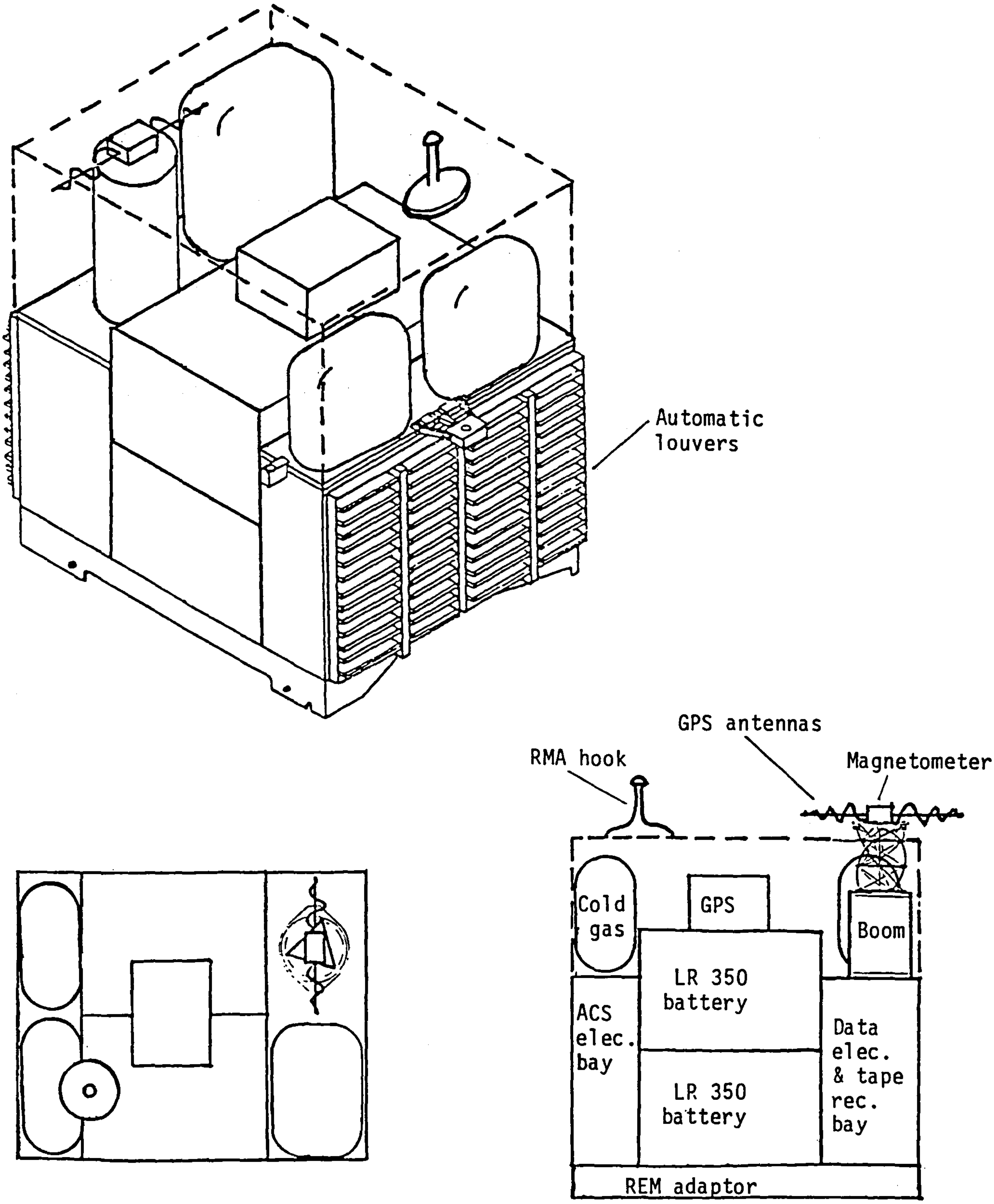

FIGURE 1: Possible Design of Spartan/Magnetometer

6.0 COMPARISON OF OPTIONS

Table 2 compares magnetic field surveys using the present MAGNET aircraft, a Spartan experiment twice a year for ten years, and a permanent spacecraft similar to MAGSAT and lasting 5-10 years. Although MAGNET is presently in service and provides near-surface measurements, only a small area can be covered. A permanent spacecraft would provide continuous and global coverage with additional scientific benefits; but it would be initially expensive, difficult to repair and re-calibrate, and provide low ground resolution. Spartan provides medium ground resolution, easy service, almost global coverage and the lowest cost per area covered.

TABLE 2

SURVEY OPTIONS COMPARISON

	Cost/Year	Area Covered	Cost/Area	Cost/Area/Res*
MAGNET Aeromagnetic	\$4.04 M	400,000 x 10 km^2	\$1.01/km^2	\$0.101/km
Spartan/Magnetometer	\$0.4-0.6 M	360 x 10^6 km^2	\$0.0018/km^2	\$0.011 x 10^{-3}/km
with Launch (\$4 M)	\$8.4-8.6 M		\$0.024/km^2	\$0.16 x 10^{-3}/km
Permanent Satellite (\$200 M + \$20 M launch, 8 yrs)	\$27.5 M	510 x 10^6 km^2	\$0.054/km^2	\$0.18 x 10^{-3}/km

*Resolution assumed equal to altitude (MAGNET 10 km, Spartan 150 km, Permanent 300 km)

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Eric P. Osborne, GSFC Code 716.1
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16. Abstract

The shuttle-deployed and recovered Spartan shows promise as an inexpensive and simple support module for potential field measurements. The results of a preliminary engineering study on the applications of the Spartan carrier to magnetic measurements shows:

(1) Extension of the mission duration to as long as 7 days is feasible but requires more reconfiguration of the internal systems.

(2) On-board recording of Global Positioning System signals will provide position determination with an accuracy consistent with the most severe requirements.

(3) Making Spartan a magnetically clean spacecraft is straight forward but requires labor-intensive modifications to both the data and power systems.

As a magnetic survey took, Spartan would allow surveys at regularly spaced intervals and could make quick-reaction surveys at times of instability in the secular variation.

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