AFRL-RV-HA-TR-2007-1077

Vector Fluxgate Magnetometer (VMAG) Development for DSX

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Scientific Report No. 2

2 July 2007

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
02-07-2007

2. REPORT TYPE
Scientific Report No. 2

3. DATES COVERED *(From - To)*
April 2006 - April 2007

4. TITLE AND SUBTITLE
Vector Fluxgate Magnetometer (VMAG) Development for DSX

5a. CONTRACT NUMBER
FA8718-05-C-0025

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62601F

6. AUTHOR(S)
Mark B. Moldwin

5d. PROJECT NUMBER
1010

5e. TASK NUMBER
RR

5f. WORK UNIT NUMBER
A1

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
UCLA
Institute of Geophysics and Planetary Physics
Department of Earth and Space Sciences
3845 Slichter Hall
Los Angeles, CA 90095-1567

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
29 Randolph Road
Hanscom AFB, MA 01731-3010

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RVBXR

AFRL/RVBXR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RV-HA-TR-2007-1077

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for Public Release; Distribution Unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
UCLA is building a three-axis fluxgate magnetometer for the AFRL-mission. The instrument is designed to measure the medium-Earth orbit geomagnetic field with precision of 0.1 nT and provide the field direction to within 1 degree. The instrument will provide the DC magnetic field for phase space density calculations of energetic particles, the magnetic field vector information for the Loss Cone Imager (LCI) payload, and the ULF wave environment. The project is on schedule for engineering unit completion in May 2007 and flight unit delivery in March 2008.

15. SUBJECT TERMS
Space instrumentation, Magnetometer, Radiation belts

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	SAR	20	Daniel L. Elsner, 2dLt
					19b. TELEPHONE NUMBER *(include area code)*

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1. INTRODUCTION

This effort is in response to the Battlespace Environment Division, Space Vehicle Directorate, Air Force Research Laboratory's (AFRL) call to develop and provide a vector fluxgate magnetometer to support both the Space Weather (SWx) and Wave Particle Interaction (WPIx) payloads on the Demonstration and Science Experiment (DSX), which will be launched into the Medium-Earth Orbit Space Environment Regime.

Included as part of the DSX payload is a vector magnetometer. The vector magnetometer provides measurements of the terrestrial field, which is essential to fulfill the two primary goals of the DSX science program. The fluxgate magnetometer provides the necessary data to support both the Space Weather (SWx) specification and mapping requirements and the WPIx requirements. The magnetic field is necessary to reconstruct pitch-angle distributions (PADs), to calculate phase space densities, and to determine important local plasma parameters such as plasma beta and the local index of refraction. The fluxgate magnetometer provides measurements of the magnetic fields caused by currents that flow into and above the Earth's ionosphere. These currents close with currents in the Earth's magnetosphere, via field-aligned currents, and measuring these currents is essential for improvements in magnetospheric specification models.

This Report describes UCLA's year two effort (April 2006 – March 2007) in designing and building the Engineering Unit of the vector magnetometer for the DSX program. This magnetometer is based on the fluxgate design that has been developed over the years by UCLA. We have developed a magnetometer that easily conforms to the DSX requirements (as specified in L0/L1 Requirements Document and Common Requirements Document Rev D), with a high degree of reliability and a low impact on spacecraft resources in terms of mass, power, and volume.

The Report briefly summarizes our activities, accomplishments, and lessons learned during this year. It also contains the VMAG Interface Control Document (ICD) Rev B, that describes the design of the instrument and its mechanical and electrical interfaces. The reader is referred to the Year 1 Annual Report (AFRL-VS-HA-TR-2006-1079) for a description of the science objectives and heritage of the instrument. Other information regarding the VMAG instrument is found in the Preliminary Design Review and Critical Design Review documentation submitted to the DSX Project Management Office as part of the regular reporting process.

2. BACKGROUND

This section provides some background and introductory material. The subsequent sections present a summary of the activities conducted for this project this past year. In Section 3, we present the magnetic specification developed for DSX. Section 4 contains a narrative of the design and hardware development accomplishments during this reporting period.

2.1. Science Rationale

As an educational institution, UCLA's primary motivation in providing fluxgate magnetometers for DSX is directed to the scientific return from the mission. Improving our scientific understanding often goes hand-in-hand with improving the technology of our scientific instrumentation. Hence, UCLA's strong interest over the years in continuing to develop science-grade magnetometers. The DSX mission clearly benefits from this extensive heritage in scientific instrumentation. Moreover, UCLA's effort will contribute to the operational goals of DSX, which allows UCLA to provide an immediate societal benefit. This return of investment for the nation is also important for UCLA, allowing us to show the value in conducting basic research.

The magnetometer is essential for fully characterizing the particle and wave data to meet the Space Weather and WPIx goals. However, in addition to the supporting role of the magnetometer, the data provided by the instrument will clearly be a valuable resource for the Space Physics Community on its own. At UCLA, our scientific efforts are centered around the observations of magnetic fields due to current systems in the Earth's ionosphere and magnetosphere and to the ULF wave environment. There have been very few spacecraft with research-quality vector magnetometers flown in MEO. Therefore, the DSX mission will be ground-breaking in terms of providing information about the Earth's geomagnetic field and ULF wave environment in the inner magnetosphere.

The MEO magnetospheric regime has not been extensively studied because most scientific satellites are either in LEO-Low Earth Orbit (e.g., SAMPEX), HEO-highly elliptical orbit (e.g., SCATHA, AMPTE, ISEE 1/2), or at GEO-Geosynchronous orbit (e.g., GEOS 2, the LANL spacecraft). MEO covers a range of interesting space physics regimes including the radiation belts, the ring current, and the plasmasphere and is home to a growing number of satellites (such as GPS) so understanding the MEO space weather environment is becoming more and more important [e.g., *Le and Russell,* 1993].

2.2. The DSX Mission VMAG Science Objectives

The specific region of the magnetosphere to be explored by the DSX satellite between 10,000- and 20,000-km altitude (*L* between 1.5 to 3.1) is now known to be an extremely dynamic region overlapping the radiation belt slot, a region where the plasmapause often resides (Figure 1), and a place of intense wave activity (Figure 2) [e.g., *Baker et al.*, 1994, *Moldwin et al.*, 2002, *Bortnik et al.*, 2003, *O'Brien et al.*, 2003].

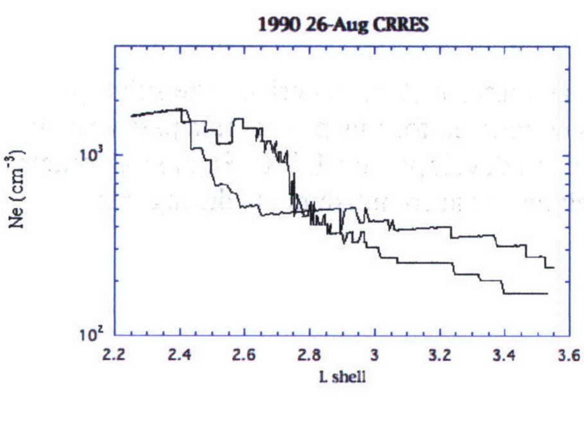

Figure 1. CRRES plasma density data for an inbound and outbound orbit showing the plasmapause and density structure between *L* of 2.5 and 3.

In addition, DSX will provide the study of ring current dynamics and field-aligned currents (FAC) from a unique perspective deep in the inner magnetosphere. Two specific questions to be addressed by DSX are (1) what is the ULF wave environment in the inner magnetosphere during severe geomagnetic storms? And (2) what is the configuration of the inner magnetospheric magnetic field during storms? With one satellite, it is difficult to place the observations into global context – however, UCLA operates three mid-latitude magnetometer chains (MEASURE, SAMBA, and McMac) that span the DSX *L* shells and can be used to estimate the inner magnetospheric mass density, independently estimate the location of the plasmapause, and characterize the global ULF wave environment. The PI on this proposal is the PI on MEASURE and a co-PI on SAMBA and McMac.

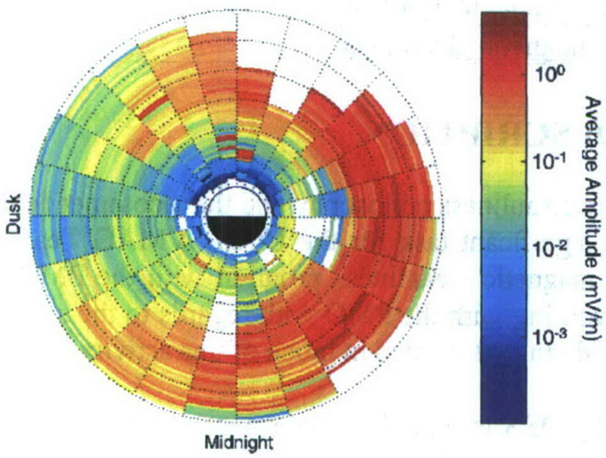

Figure 2. Average equatorial lower-band chorus amplitudes for *Kp* 4–6, observed by CRRES [from *O'Brien et al.*, 2003].

These complementary ground-based datasets will be used in addressing both questions. Specifically, for question (1), we will compile a database of ULF wave power as a function of LT, Magnetic latitude, *L* shell, and geomagnetic activity (as indicated by Dst, Asym, SymH, Kp, and AE) by automatically calculating dynamic power spectra. The result will be similar to the survey of AMPTE data by *Anderson et al.* [1990], but will cover the inner magnetospheric region.

For question (2), a satellite in a 10,000 x 20,000 elliptical orbit would have an orbital period of about 3 hours and 20 minutes. This is comparable to the time scale of the main phase of a geomagnetic storm. Therefore, DSX will sample a range of local times during the main phase of each storm allowing for the examination of the evolution of the partial ring current for a variety of storms. Recent studies have shown that the inner magnetosphere can be severely distorted during geomagnetic storms due to the growth of the partial ring current [e.g., *Tsyganenko et al.*, 2003].

2.3. The UCLA VMAG Effort

This section provides information on the UCLA VMAG team, and the Statement of Work defining UCLA's effort.

2.3.1. The UCLA Team

The project team for the UCLA VMAG project is shown in Table 1. Ms. Kathryn Rowe has been added to the team and has provided valuable reporting support.

Table 1. UCLA VMAG Project Team and Basic Responsibilities

Name	Role and Responsibilities
Dr. Mark Moldwin	PI, overall project oversight, interface to DSX PMO, coordination of efforts of various project members, science lead
Dr. Robert Strangeway	Science Team
Mr. Joe Means	Project Manager, Schedule, budget manager
Mr. Dave Pierce	Electrical Engineer Design
Ms. Kathryn Rowe	Systems Engineer Design and Testing
Mr. Don Dearborn	Digital Engineer Programming and Testing
Mr. William Greer	Electronic and Mechanical Technician Fabrication and Testing
Mr. Bob Snare	Q&A testing, magnetic cleanliness

3. MAGNETIC CLEANLINESS DESCRIPTION

This section describes briefly the magnetic cleanliness philosophy and the recommended magnetic cleanliness program for DSX. A significant task for the UCLA VMAG Team during this year was the development of a magnetic cleanliness program with the PMO. This included developing a guidebook and working with the PMO with regards to the solar panel PDR activity. Bob Snare and Mark Moldwin participated in much of this activity.

The degree of magnetic control required by DSX is essentially the same as that achieved on past programs except for the added emphasis placed on achieving a low spacecraft magnetic remnant field that is within manageable low cost constraints and available resources. The level of magnetic control is the result of concern about magnetic materials and devices and an effort to reduce or eliminate sources that may yield significant magnetic fields at the outboard and inboard magnetometer sensor locations.

The required magnetic control is governed by the sensitivities of the magnetometer sensors whereby the magnetic field must be reduced to a level where science is not affected. The basic magnetic requirement for this program is for the spacecraft to limit its overall magnetic fields at the outboard magnetometer sensor location to no more than 0.1 nanoTeslas* (or 12.5 nT at one meter). It is also required that the dynamic (or varying) field be less than 0.1 nanoTeslas at the outboard magnetometer sensor location. This dynamic field requirement applies primarily to changes in the magnetic field over a period of a few seconds to several weeks and includes magnetic fields due to changing flow of currents in the spacecraft or to repositioned or moving magnetic devices.

In order to ensure that spacecraft magnetic fields are within the magnetometer science requirements, subsystem level magnetic requirements are contained in this plan for all major spacecraft subsystems. The magnetic cleanliness will then be assessed at the subsystem level as well as at the system level. In this program, it is planned to place emphasis on early testing of suspect hardware. Instruments with permanent magnets or solenoid devices should be tested or analyzed in order to identify problem areas that can be addressed early in the design stages. Recognizing that some instruments may have difficulty in achieving magnetic requirements due to the nature of their functions, their respective impact to magnetometer science will be assessed and a waiver, if appropriate, will be initiated by the cognizant engineer. Hardware with high power or high currents, likewise, will be given special attention.

A system level magnetic compatibility test is planned for the DSX spacecraft in addition to the subsystem level measurements. The system level will determine the overall spacecraft magnetic field at the magnetometer sensor locations. Subsystem level measurements will be used to determine the approximate magnetic field at the outboard and inboard sensor by analysis prior to the system level test. To improve the accuracy of this analysis, accurate magnetic characterization measurements of each subsystem will be made.

3.1. Magnetic Cleanliness Program Description

The DSX magnetic control program is an effort to ensure that DSX spacecraft has reasonably low magnetic field levels which are consistent with the overall magnetic cleanliness requirements at the magnetometer sensor locations and to maintain the flight hardware at its lowest magnetic field condition within reasonable cost constraints prior to launch. In order to achieve these goals, it is necessary to impose design requirements on hardware and to test and evaluate hardware to verify compliance with design requirements. The present DSX magnetic design requirements are based on these premises.

A Magnetics Control Engineer from UCLA (Bob Snare) will be available in order to provide assistance to DSX Cognizant Engineers regarding magnetic cleanliness matters on their respective instruments, to identify potential threats posed to the magnetometer instrument and to recommend solutions to these concerns. Assistance from UCLA will be available to hardware Cognizant Engineers for determining the most desirable hardware design approach for achieving DSX magnetic cleanliness goals. A set of guidelines are contained in this document to assist DSX Cognizant Engineers in developing the best design which produces the least amount of magnetic fields. It is required that all hardware Cognizant Engineers verify the adequacy of their magnetic control design as early as possible by having these parts assessed and magnetic measurements performed by UCLA on representative magnetic devices planned for use in their subsystem. The Magnetics Control Engineer will work closely with Cognizant Engineers for those instruments that are found to be the worst-case sources of magnetic field generation. Advice as to what are the most desirable non-magnetic materials will also be provided. Furthermore, the Magnetics Control Engineer and the magnetics test facility will be available for evaluation and tests of parts, particularly those within close proximity to the magnetometer sensors.

The magnetic testing of DSX subsystems should be performed as early as possible. In testing, some of the subsystems may be energized in worst-case modes to determine the magnetic fields due to their current flow. Magnetic tests consist of, first, measuring the subsystem, then demagnetizing the subsystem in a zero field ambient and next measuring its residual magnetic field in a zero field. This test should be performed just prior to delivery to Orbital. Subsequent to the demagnetization, any hardware removed from the DSX spacecraft for reworking or modification must be remeasured prior to delivery and may be demagnetized if the residual magnetic field has changed. This post-demagnetization control will be continued from the moment the DSX spacecraft leaves MSI for the Eastern Test

Range (ETR). In order to ensure that the DSX spacecraft was never subjected to high magnetized or perm conditions during transport to ETR, calibrated magnetic sensors will be placed, before spacecraft shipment, on the surfaces of the spacecraft and/or shipping containers. These calibrated magnetic sensors will easily magnetize in the presence of a strong magnetic field and, hence, determine the extent of the external magnetization exposure that the DSX instrument received. These sensors will then be measured at ETR to determine the extent of magnetization and whether demagnetization of any hardware is found to be necessary.

Measurements of the effect of current loop fields and other dynamic effects at the magnetometer sensor locations caused by the operation of the spacecraft in various modes are recommended during spacecraft level functional testing. Solar arrays should be analyzed and tested to ensure the absence of large current loops in its design.

4. YEAR IN REVIEW

The main result of this last year's effort was the finalization of the VMAG Design post-CDR, the development of the mechanical and electrical interface control document and the fabrication of the Engineering Unit

The CDR was held at UCLA on June 22 and 23, 2006, and involved a number of team participants from AFRL, the PMO, and MSI. A number of Action Items (AI) were developed out of that CDR. One of the most significant aspects of the CDR and the closing out of the AI was our ability to finalize our Interface Control Documents. This was essential for early testing with the ECS and working with the (at that time, yet to be selected) boom provider.

In the 2nd Quarter of 2006, we were able to build a VMAG simulator that generated known signals through our electronic interface. This simulator was sent to PSI in Melbourne, Florida, and was successfully integrated and the interface was successfully tested with the ECS.

During the 3rd Quarter of 2006, with the selection of ATK as the boom provider, we worked closely with them in developing integration plans for the VMAG sensor and the boom deployment. This included discussions with regard to sensor placement and cable routing. It was determined that the VMAG sensor mass model should be developed. We also began the build of the cable for delivery to ATK and worked on the problem of fabricating backshell connectors. Figure 3 shows our solution.

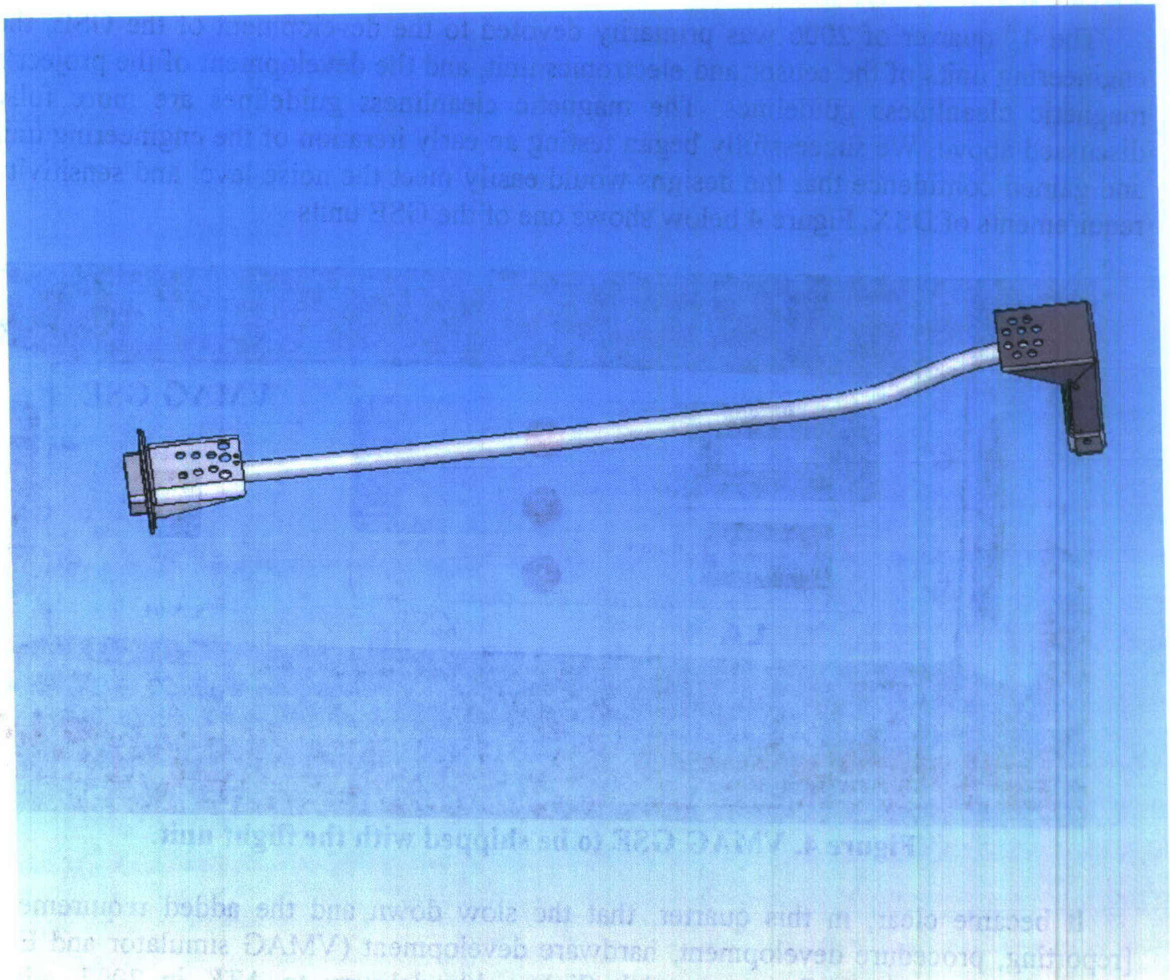

Figure 3. VMAG cable with backshell connectors.

We also closed out the dozen AI from the CDR. The most important with regards to schedule impact was developing the documentation for parts waivers concerning the radiation requirements. We were able to find testing results and work with manufacturers to demonstrate that the parts we had incorporated into our design would meet the radiation requirements. Where this was not possible, alternate parts that were designed to meet the radiation specs and had minimal impact on our design were identified. The parts that we requested radiation waivers for were the HIS-302RH (CMOS dual DPST analog switch), OMR-185SR (low dropout regulator), and the IS-139 (Quad voltage comparator). Delays in our progress were due to the project's funding slow-down. We redeveloped schedules and budgets and were able to move ahead going into the last part of the year. In response to the reporting requirements, procedure documentation, and development of test plans from the PMO, we added Kathryn Rowe (an Electrical Engineer) to the project prior to the CDR. Her value to the project quickly became apparent in the preparation for the CDR and the development of the close-out work regarding the action items. She took the lead with regard to working with ATK to allow smooth communication and work on integration and testing procedures.

The 4th quarter of 2006 was primarily devoted to the development of the GSE, the engineering units of the sensor and electronics unit, and the development of the project's magnetic cleanliness guidelines. The magnetic cleanliness guidelines are more fully discussed above. We successfully began testing an early iteration of the engineering unit and gained confidence that the designs would easily meet the noise level and sensitivity requirements of DSX. Figure 4 below shows one of the GSE units.

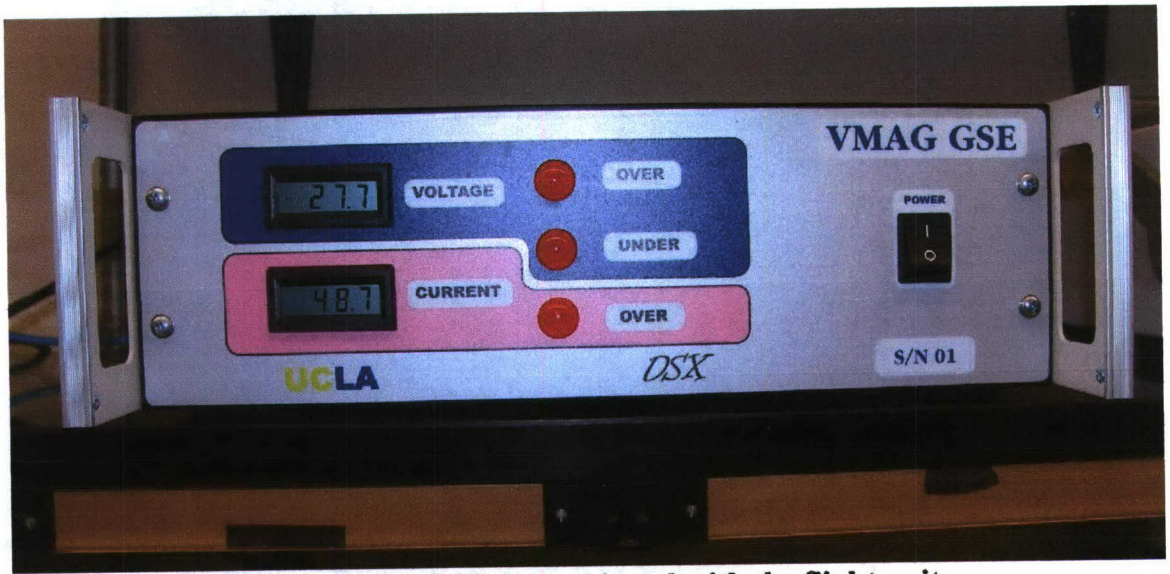

Figure 4. VMAG GSE to be shipped with the flight unit.

It became clear, in this quarter, that the slow down and the added requirements [reporting, procedure development, hardware development (VMAG simulator and ECS interface testing, VMAG mass model, flight cable delivery to ATK in 2007, added integration and test requirements (Helmholtz coil, shield can), and magnetic cleanliness guideline development] significantly raised the cost of the originally bid project. In light of these new costs, a supplementary budget and schedule were prepared and sent to the PMO in November of 2006.

The first quarter of 2007 saw the continued development of the second GSE unit and the development of the engineering electronics and sensor units. We developed the integration and testing procedures for the sensor and cables. All flight parts were also ordered and received during this quarter, eliminating a major Risk Item. In response to the sensor integration and test plan developed the previous quarter, we developed a shield can manual to enable the project to carry out system-level testing of the VMAG. The cost of the shield can was included in the supplemental budget request.

During the reporting period VMAG successfully passed the Critical Design Review and finalized the mechanical and electrical designs and interfaces. We were able to identify space-qualified parts that met the projects radiation requirements, order and receive them. The Ground Support Equipment was designed and built, and much progress was made on the development of the engineering electronics and sensor units. The VMAG team contributed to the development of a magnetic cleanliness document and built and provided a VMAG simulator to test the interface with the PSI-built ECS.

Despite the slowdown due to budget pressures, we positioned ourselves to successfully complete the development of the engineering unit and begin flight unit production at the end of 2007. However, we needed to submit a supplemental budget request in order to complete the flight unit build. We worked closely with ATK in developing an integration and testing procedure for the VMAG sensor and the boom. Other than funding issues during the reporting period, all issues that could impact the schedule (parts waivers, parts selection, parts delivery, and engineering design) were successfully overcome.

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List of Symbols, Abbreviations, and Acronyms

A/D	analog to digital
ADC	analog to digital converter
AFGL	Air Force Geophysics Laboratory
AMPTE	Active Magnetospheric Particle Tracer Explorer
ATS	Applications Technology Satellite
CCE	Charge Composition Explorer
CVCM	Collected Volatile Condensable Material
CY	Calender Year
DOC	Department of Commerce
DOD	Department of Defense
DSRD	Draft Sensor Requirements Document
DSX	Demonstration and Science Experiments
ECS	Experiment Computer System
EDR	Environemental Data Record
EDU	Engineering Development Unit
EMC	Electromagnetic Compatability
EMI	Electromagnetic Interference
EU	Engineering Unit
FAC	Field-Aligned Current
FAST	Fast Auroral Snapshot Explorer
FedSat	Federation Satellite (Australia)
FPGA	Field Programmable Gate Array
FU	Flight Unit
FY	Fiscal Year
GEO	Geosynchronous Orbit
GEOS 2	Geosynchronous Orbit Scientific Satellite 2
GMR	Gross Magnetoresistive Resistor
GPS	Global Positioning System
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
I&T	Integration and Test
ICD	Interface Control Document
IGPP	Institute of Geophysics and Planetary Physics
IMF	Interplanetary Magnetic Field
IPO	Integrated Program Office
ISEE	International Sun-Earth Explorer
ISO	International Standardization Organization
ITAR	International Traffic in Arms Regulations
JPL	Jet Propulsion Laboratory
LANL	Los Alamos National Laboratory
LSB	Least Significant Bit
McMac	Mid-Continent Magnetoseismic Chain
MEASURE	Magnetometers Along the Eastern Atlantic Seaboard for Undergraduate Research and Education

MEO	Medium-Earth Orbit
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NPSL	NASA Parts Selection List
OGO	Orbiting Geophysical Observatory
PC	Personal Computer
PCAD	Personal Computer Aided Design
PDE	Principal Design Engineer
PET	Principal Electronic Technician
PF	Protoflight
PI	Principal Investigator
PPL	Preferred Parts List
PVO	Pioneer Venus Orbiter
QA	Quality Assurance
RDR	Raw Data Records
RF	Radio Frequency
RMS	Root mean square
SACI-1	Satélite de Aplicações Cientificas
SAMBA	South American Meridional B-field Array
SCATHA	Spacecraft charging at high altitude
SDE	Senior Development Engineer
SMALL	Sino Magnetic Array at Low Latitudes
SRD	Sensor Requirements Document
ST5	Space Technology 5
TID	Total Integrated Dose
TBS	To be Specified
TML	Total Mass Loss
UCLA	University of California Los Angeles
UCOP	University of California Office of the President
VMAG	Vector Magnetometer
WMM	World Magnetic Model