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Manned GEO Satellite Servicing Mission Environmental Effects Measurements Study

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August 2012

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Introduction

This report summarizes a trade study that was conducted to examine options for a flight experiment designed to collect space environment and effects data in Geosynchronous Earth Orbit (GEO). This effort was a part of the joint NASA/DARPA Manned GEO Satellite Servicing (MGS) study, whose goal was to identify potential architectures, required technologies, and near-term demonstration missions needed to develop a capability to service GEO satellites. The role of the environment study team within the larger MGS project organization is shown in Figure 1.

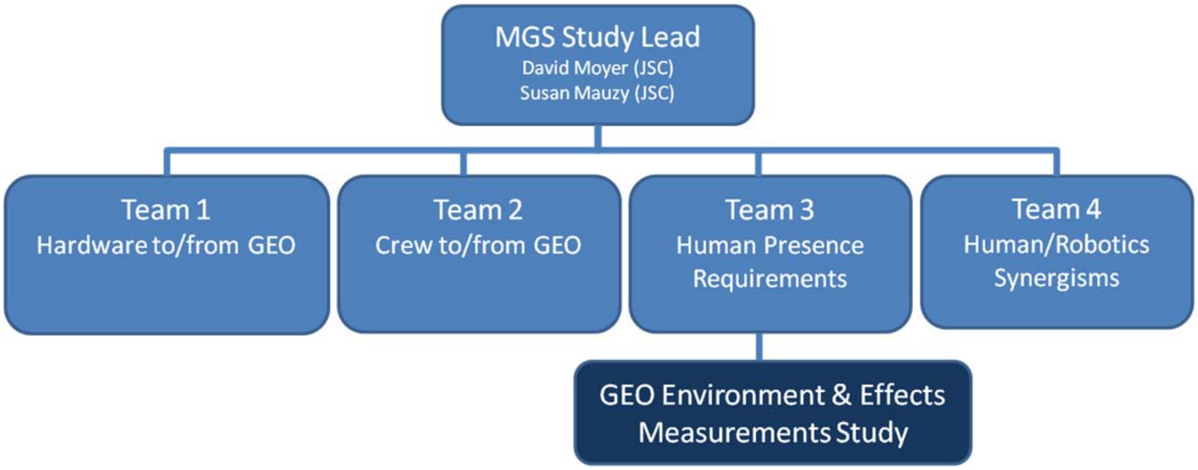


Figure 1. GEO environment study within the MGS team organization.

The aim of this environment study was to provide recommendations to the Human Presence Requirements Team ("Team 3") on the best approach for collecting GEO environment data that will be needed to inform the design of the equipment for a manned GEO mission, including the manned servicing module and suits for extravehicular activity (EVA). The study began by reviewing the existing set of environment and effects measurement priorities identified in previous work by Team 3 and comparing those priorities against known, near term flight environment studies that are already being planned by NASA or other agencies. This evaluation determined that no currently planned environment mission will fully meet the need.

Next, information was collected on the availability and applicability of potential flight measurement instruments in order to understand the rough cost, risk and schedule parameters associated with development of an MGS environment instrument suite. Four notional instrument suites were developed and coarsely evaluated using weighted figures-of-merit (FOMs) developed in conjunction with radiation subject matter experts on the MGS team.

A parallel effort examined the available transportation opportunities to GEO, including three main options: 1) hosted payload; 2) secondary payload; and 3) primary payload. Each of the notional instrument suites were also scored in terms of compatibility FOMs with each of the payload options. The results of the transportation evaluation, including compatibility of the four notional instrument suites, identified the hosted payload as the most promising transportation option.

The study concluded with the development of a trade tree identifying the transportation and notional MGS environment and effects measurement suite options. Preliminary conclusions drawn from the evaluation of each leg in this trade tree are included in this report.

Key Findings of the MGS Environment Measurements Study

- There is a need to collect environment & effects data at GEO to prepare for a manned-servicing mission.
- A suitable science-quality instrument suite can be developed based on existing technologies evolved from flight-heritage components.
- Our desired instrument suite is well suited for a hosted payload option, but can be made compatible with a small secondary bus of the types delivered using the EELV Secondary Payload Adapter (ESPA).
- A dedicated launch to GEO would be inefficient unless partners were identified to fill the spacecraft capacity.
- Due to the availability of compact sensor technologies, our trade space contains a number of feasible fallback options.

Study Motivation

The radiation environment hazards in GEO include energetic electrons, Galactic Cosmic Radiation (GCR) and Solar Particle Events (SPEs). GCR and SPE hazards exist in GEO as well as deep space, while the electron hazard is unique to Earth orbit. GEO lies in the outer radiation belt just beyond the peak intensity of energetic electrons trapped in the Earth's magnetic field (Figure 2). The high energy electrons in this region can penetrate materials and produce internal charging. The low energy electrons can quickly produce significant (kilovolts) surface charges. Damage from charging occurs when the potential difference leads to a discharge event, which can include high currents and arcing. Further, high energy electrons pose a direct harm to human tissue by depositing energy into cells. Because of these effects, electron radiation exposure is a key contributor to mission duration and EVA limits.

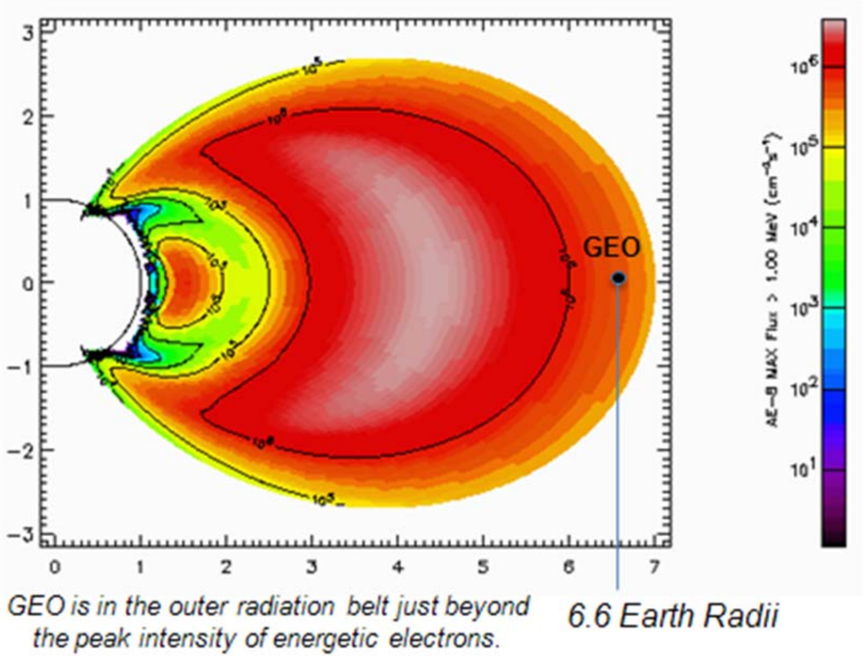


Figure 2. Map of the AE-8 MAX integral electron flux >1 MeV. (SPENVIS User Guide)

Because of the utility of GEO, this regime has always been of interest to spacecraft designers. Mitigation strategies for the harms of the GEO environment, provided by NASA and others, are therefore well developed for unmanned missions (though serious malfunctions of GEO assets attributed to environmental events still occur) (Reedy 1998, NASA-HDBK-4002A). These strategies, which include shielding of electronic components and Faraday cage construction, do not easily meet the needs of a manned mission with EVAs. An ergonomic suit, for example, cannot be made to any desired material thickness. Further, the current standard model of the space environment known as "AE-8" (Vette 1991) has shortcomings for applications in GEO, and is therefore not ideal for developing requirements for an EVA suit design. The following caution, for example, appears in the Space Environment Information System (SPENVIS) user guide: "The AE-8 model has been criticized also for its deficiency in high energy electrons at geosynchronous orbit (Baker et al., 1986). In fact, above 2 MeV, the model is just an extrapolation of unknown validity." An updated model (AE-9) is in development, but like AE-8 is not specifically aimed at meeting the needs of a manned GEO mission.

Measurement of the effects caused by the environmental hazards is a separate but also high priority for MGS. Without correlating the environmental effects (e.g. charging and radiation) in a like material or simulated tissue, the utility of the models for developing the equipment requirements is limited. Such correlating effects measurements are ideally done in situ and collocated with the environment instruments on the same instrument suite (Koons 2004).

Because the characteristics of the Earth’s magnetosphere vary in time and space, separate missions in GEO may be experiencing different effects (Mazur 2007). Ground-based tests may also not meet the need, since it is difficult to account for the simultaneous effects of a range of particle species, energies and flux characteristics. While ground testing of instruments will be conducted as a matter of course to qualify and calibrate the instruments, the addition of tests to thoroughly simulate the GEO environment may incur a significant cost. Further, the effects instrumentation reviewed for this study was generally low cost (compared to the environment suite) and of miniature design, in some cases being of a “patch” type requiring no more space than a paper napkin and utilizing only milliwatts of power. For this reason, each of the proposed notional instrument suites include effects instrumentation to correlate the environment measurements rather than relying on ground-based testing alone.

Study Process

The study was divided into two main tasks: 1) trade space definition and 2) trade space analysis. In task 1, over 70 instruments from more than 30 previous flight missions were identified and categorized by instrument type, measurement parameter range, orbit regime and launch date. Descriptions of many of the instruments considered during this study appear in Appendix B. Several instrument development efforts were also included in this survey. Data for these instruments was gathered primarily from publicly available literature and web pages. Next, a downselect process was used to identify current generation instruments most applicable to the needs of MGS environment study. Data collected for this smaller set included cost, mass, power and volume specifications and a coarse evaluation of the development required to modify the system for use in GEO (for existing hardware) or to complete development to a flight-ready status. For this effort, interviews with the instrument principal investigators (PI’s) augmented the literature search. The coarse assessment of the modifications required to adapt a given instrument was based largely on the current operating regime of the instrument, as well as input from the PI’s. Detailed reviews of the instrument designs were beyond the scope of this task.

Also under task 1, GEO transportation options were reviewed and categorized based on launch vehicle, bus options, transportation availability (frequency of upcoming opportunities), and approximate cost. Both foreign and U.S. launch capabilities and standard bus options were included in this survey. Data on bus options, including the proposed NASA Reusable Earth Synchronous Tele-Operated Refueler (RESTOR) robotic servicing mission, was gathered both from public sources and interviews with persons affiliated with the program.

The final part of task 1 was the development of FOMs to assess both the instrument options and bus options. FOMs were created to address the specific goal of building a flight environment suite in the near term, with a target launch date near 2014.

In task 2, a preliminary analysis of the defined MGS radiation environment and effects mission trade space was performed, with resulting initial recommendations presented to the MGS Team. The recommendations and key findings were presented at the MGS Team Meeting at Johnson Space Center on September 19, 2011.

Analysis of the trade options was performed using a series of matrices with each weighted FOM scored for each trade option. These matrices are included in Appendix A. While this exercise did stratify the instrument options and allowed high value approaches to be identified, the results should be considered preliminary due to the limited time available during the study to compare details of the instrument capabilities against the specific shortcomings of the existing available GEO environment data sets and analytical models. Such a detailed comparison is suggested for a future activity. The results of the preliminary trades do however suggest that a number of good options are available for achieving the MGS environment mission goals with existing instrument technologies and transportation options, and that no major technology gaps would need to be overcome by designers of the flight instrument suite.

Prioritized Environment Data Needs

Table 1 below shows the prioritized data needs identified by radiation subject matter experts on the MGS team at the start of the trade study. The list represents the kinds of measurements that would most benefit the understanding of the space environment specifically for a manned mission to GEO. This prioritization remained unchanged after an assessment of upcoming environment missions was conducted. Note that an implicit desire for all of these measurements is a continuous, prolonged sample (years) at the GEO orbit, within several hundred kilometers of the GEO altitude of 35,786 km, zero eccentricity and within plus or minus five degrees of inclination.

Table 1. Prioritized GEO Environment Data Needs

Priority	Measurement	Benefit
1	High energy electron environment *50 keV to 10 MeV*	Characterize radiation and internal charging environments
2	Low energy electron, ion environment *100 eV to 50 keV*	Characterize surface charging environments
3	Radiation effects in tissue	Correlate harm to humans behind candidate suit materials
4	Electrostatic discharge effects (especially during docking)	Understand discharge events at moment of contact with client vehicle

5	Internal charging effects (Deep dielectric charging)	Correlate charging to environment using candidate suit materials
6	Magnetic field environment	Identify magnetosphere boundary and measure pitch angle particle distributions
7	Surface charging effects	Monitor vehicle surface potential to validate surface charging models

The highest priority measurements are energetic electrons, where it is desired to know the number (flux) and energy of these particles to the greatest resolution possible. Electrons are divided into “High Energy” and “Low Energy” as measured in electron volts (eV) due to the different spacecraft effects associated with each. In the notional instrument suite development activity, the electron environment was divided into three categories, since it was found that effective measurement of electron energy ranges above 4 MeV usually required a dedicated instrument utilizing a different sensing technology than that appropriate for sensors looking at electron energies below that value.

The item of fourth priority on this list, electrostatic discharge (ESD) effects, is intended to address both the well-recognized arcing behavior seen on GEO satellites due to potential build-up on dielectric surfaces and the special situation where two satellites come into contact (e.g. a capture by a grapple fixture). ESD due to a contact event between two spacecraft in GEO has never been measured and constitutes a unique requirement for MGS. The desire for this type of data also informs the GEO transportation evaluation, since only the robotic servicing hosted payload option can meet this need.

Existing and Near Term Space Environment Missions

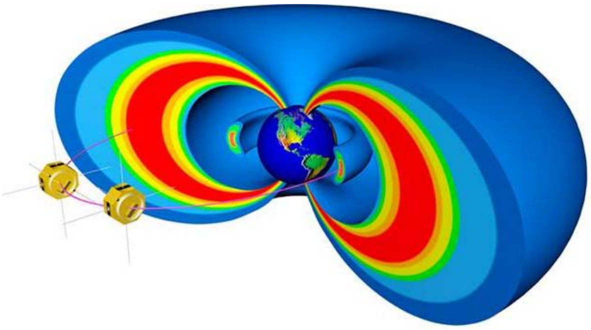


Figure 3. RBSP orbit and the Van Allen radiation belts.

Understanding the space environment by making in-space measurements continues to be a priority for the science and engineering communities, as evidenced by the number and variety of associated flight projects. Decades of data collected from GEO assets operated by the Los Alamos National Laboratory (LANL), the GOES spacecraft operated by the National Atmospheric and Oceanic Administration (NOAA), and others has been used to inform the current standard analytical models, including the soon to be released AE-9 and AP-9 (Onsager 1996, Goka 2007, Reeves 2009). A flagship NASA mission, the

Radiation Belt Storm Probe (RBSP), is being prepared for launch in 2012 and will sample the radiation environment in an elliptical orbit spanning the Van Allen belts (Figure 3). Results from RBSP will be incorporated into the updates to AE(P)-9 in 2015 (Guild 2009). The $150M Demonstration and Science Experiments (DSX) mission, a joint NASA and Air Force project, will perform a survey in Medium Earth Orbit (MEO) of a wide spectrum of energetic particles after launch in 2012 (Schoenberg 2006). Figure 4 shows a map of the particle coverage for each of the instruments on DSX. Figure 5 shows a CAD model of DSX in the stowed configuration.

In 2015, the planned flight of GOES-R will fly the Magnetospheric Particle Sensor (MPS), the next generation of NOAA energetic particle spectrometers in GEO.

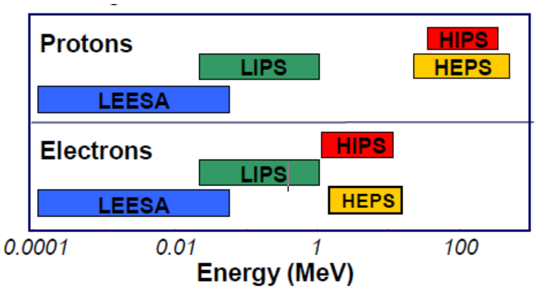


Figure 4. DSX energetic particle coverage.

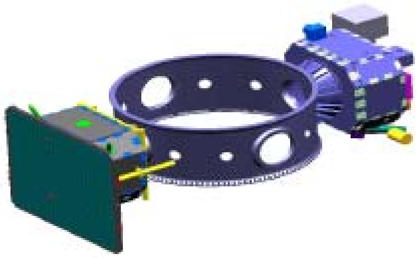


Figure 5. The DSX satellite, stowed.

However, when these and other missions were compared to the MGS need, several gaps were identified. First, **the desired range and resolution of energetic particle samples does not occur for a continuous, prolonged period at GEO**. The science-quality instrumentation on RBSP, for example, will only briefly pass through GEO, whereas the instruments on the GOES satellites (and similar instruments on satellites operated by the Japan Aerospace Exploration Agency/JAXA) at GEO have a limited range and resolution (see the Instrument Data in Appendix B for basic reference data on various instruments surveyed). An extended duration mission is desired due to the dynamic nature of the magnetosphere, where influences such as the 11 year solar cycle play a significant role (Reeves 2009).

Second, **there are few examples of collocated effects sensors at GEO.** The DSX spacecraft, which includes both environment and effects instrumentation, is an example of collocated effects sensor suite but it operates at MEO. A hosted payload experiment by the European Space Agency (ESA) called the Alphasat Environment and Effects Suite (AEEF) was the only mission identified by the study team that largely addressed this need in GEO. The AEEF is scheduled for launch in 2013 and will be attached to an Alphasat communications satellite as a technology demonstration.

AEEF Measurements in GEO

- Incident electrons in the overall energy range ~50 keV - 10 MeV
- Incident protons from ~4 MeV to >300 MeV
- Incident heavy ions in the Linear Energy Transfer (LET) range 15-70 MeV/mg/cm2
- Total ionizing dose measurements utilizing RadFETs, sensitivity of up to 85 mV/rad

Third, **existing or planned efforts will not collect the data desired to specifically address the needs of a manned satellite servicing mission.** Measurement of radiation dose in tissue, for example, is not a feature of the Radiation-Sensing Field-Effect Transistor (RadFET) technology used by the AEEF dosimeter, which is intended to characterize the effect of radiation on electronics. Another gap is in the resolution of highly energetic electrons above 4 MeV, a region of relatively low flux which represents less of a concern for spacecraft electronics but will be a hazard for EVA. Achieving a good signal-to-noise ratio is a challenge for detector design in this regime and has been a factor in the LANL high energy data. A parallel task at LANL is being undertaken to develop a process for reducing noise in the data that has already been collected. The results of this effort, when available, should be used to re-examine the priorities in Table 1.

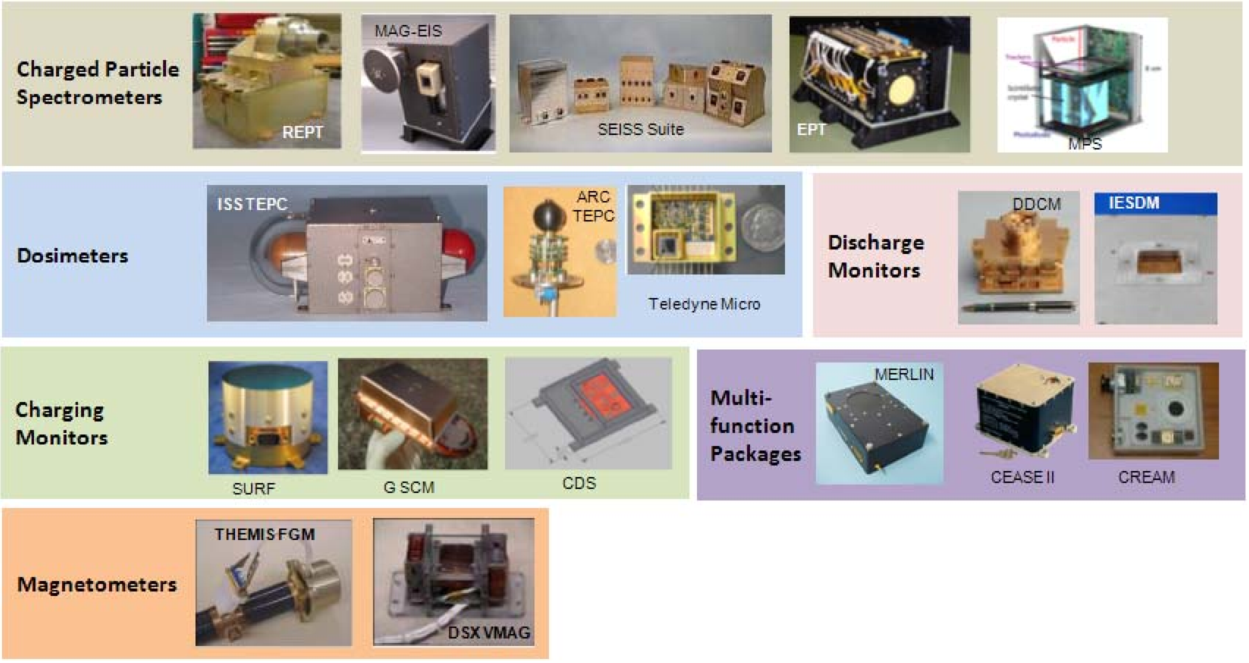
Examples of discharge monitors in flight are also rare. Data collected by the Spacecraft Charging at High Altitude (SCATHA) and Combined Release and Radiation Effects Satellite (CRRESS) spacecraft has been the basis for much of the flight knowledge in this regime (Dyer 1996, Adamo 1996), but neither addresses the effects likely to be important for the MGS EVA suit material or the spacecraft-to-spacecraft contact event during the target capture.

Instrument Review

The technologies for collecting environment measurements listed in Table 1 are generally mature, and modern examples of instruments either with flight heritage or with a short (~1 year) development schedule were identified. Figure 6 shows a collection of instruments of the type that were traded in this study (see Appendix B for more instrument data). The largest instruments in the suite are the particle spectrometers, which range from shoe-box size to small microwave ovens. An exception is the Cosine Multi-function Particle Spectrometer (Cosine MPS), a commercially available product measuring roughly 10 cm on a side. The Cosine MPS uses a scintillator crystal to stratify and measure electrons, protons and ions over a wide range of energies (Lampridis 2008, Maddox 2008). While the Cosine MPS has no flight heritage, units have been qualified for flight on future ESA missions.

The smallest instruments include several "patch" style sensors for charge and discharge monitoring, including the Electronic Discharge Monitor (EDM) and Charge Deposit Sensor (CDS), both under development at the Aerospace Corporation. These patches measure several inches on a side and are several millimeters thick, making them suitable for multiple mounting locations over the spacecraft.

Figure 6. Gallery of modern environment instrumentation.



A review of the literature and interviews with PIs conducted during this study led to the further general findings listed in Table 2 below.

Table 2. Instrument Review General Findings

Instrument Type	General Findings
High energy spectrometer (>4 MeV)	• Few heritage instruments in this energy range • Electron flux is low • Requires solid-state or scintillator technique, which may add noise and resolution challenges • Science quality instruments typically have high mass (10-15 kg) • RBSP instruments are state of the art but have limited field of view, may be over-shielded for GEO work
Medium energy spectrometer	• Good population of flight heritage instrumentation • Electrostatic analyzer technique allows good resolution • Science quality instruments typically have high mass • Multifunction “situation awareness quality” instruments have coverage in this regime
Low energy spectrometer	• Good population of flight heritage instrumentation • May require multiple ‘sensor heads’ to gain wide field of view coverage for non-spinning bus (applies to all spectrometers)
Tissue Equivalent Proportional Counter (TEPC) Dosimeter	• Few instruments in this population, ISS focus • ISS heritage instruments are high Technology Readiness Level (TRL) • Compact TEPC in work at ARC
ESD Monitor	• Few instruments in this population • SCATHA (1979), CRRES (1990), APEX (1994) inform the current models • Micro-sensor from Aerospace Corp. in development
Internal charging monitor (deep dielectric charging)	• Several instruments in this population • Multifunction sensors have coverage in this regime • Dedicated sensors available from Qinetiq, DPL science
Fluxgate Magnetometer	• Widely available • Typically boom mounted, but body mount with calibration strategy will remove some design challenges (e.g. available volume on a smallsat) and bus constraints (e.g. hosted commercial payload may not allow boom) • Engage hosts early to examine spacecraft design issues that may affect the magnetometer (e.g. solar wing wiring).
Surface charging monitor	• Several instruments in this population • Micro-sensor from Aerospace Corp. in development • Multifunction sensors have coverage in this regime
TID Silicon Dosimeter	• Flight micro-sensors commercially available. Lunar Reconnaissance Orbiter (LRO) heritage. (Mazur 2011)

The instruments included in the down-selected set were compared using a coarse evaluation against FOMs developed specifically for the MGS application. Those FOMs are briefly described in Table 3 below.

Table 3. Instrument Review Figures of Merit

FOM	Importance	Description/Comments
Spans Desired Parameter Range	High	Charged particle spectrometers with wide energy range capabilities, for example, are highly rated in this FOM.
High Measurement Resolution	High	Generally the instrument resolution capability is reduced for larger parameter ranges. Science quality instruments are highly rated in both categories but may carry a volume and weight penalty.
Good Noise Mitigation	Medium	Aimed primarily at particle spectrometers; the low flux, high energy regimes pose a challenge for mitigating noise, e.g., due to bremsstrahlung radiation caused by particle collisions.
Latest Generation Instrument	Medium	More recently developed instruments were weighted highly under the assumption that current technologies were incorporated. A detailed evaluation of the technology was beyond the scope of the study.
Low Cost	Medium	Costs were estimated from various sources, including NASA databases and interviews with PIs.
Good FOV Without Spin	Low	Applicable primarily to particle spectrometers; instruments with a wide field-of-view were desirable since there is no guarantee that the bus will be spinning (a feature relied upon by some sensors to sweep across a large range of angles).
Available Soon	Low	Instruments already flown or qualified for space flight were rated highly.
Designed for GEO	Low	Instruments with flight heritage at or near GEO were rated highly under the assumption that a similar unit could be built from minor modifications to the existing design.
Minimal Thermal Requirements	Low	Highly sensitive charged particle instruments may require thermal stability to function at their specified performance.
Low Mass	Low	The MGS instrument suite is not a mass intense payload, but lower mass may still benefit launch costs in some situations.
Low Power	Low	In the trade evaluations, power turned out not to be a discriminating FOM. All instruments have minimal power needs.

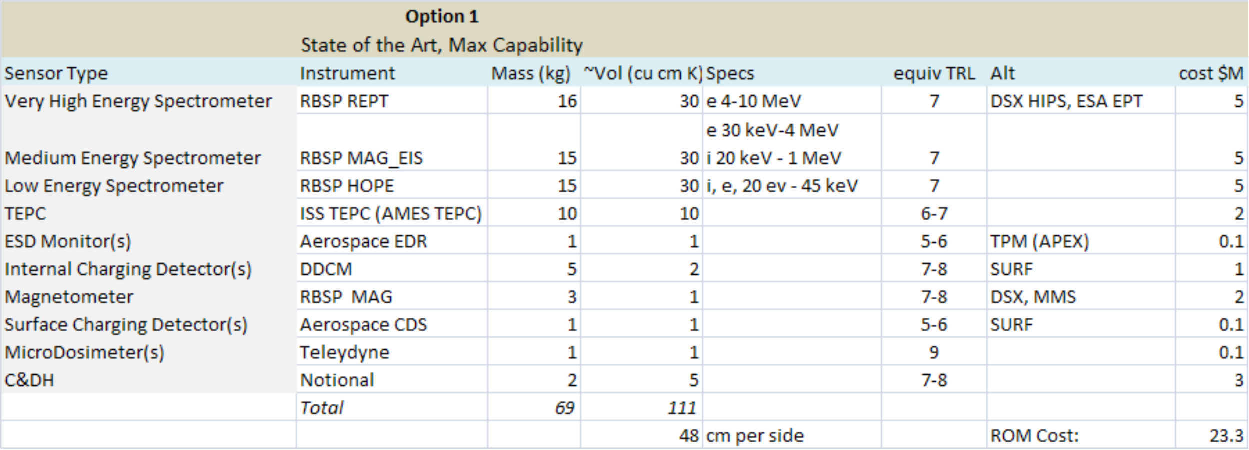
Low Volume	Low	In general, particularly for the particle spectrometers, smaller units had less desirable performance in parameter range and resolution.
Design Life	Low	In the trade evaluations, design turned out not to be a discriminating FOM. All instruments have sufficient design life (> 2 years).

A preliminary comparison of the instruments in the down-selected set was performed by assigning numerical weights to the FOMs using the guidance from the “Importance” column in Table 3. Conversion of the low/medium/high scale to a numerical value was accomplished using engineering judgment for the purposes of the exercise. The tables used for the comparison are shown in Appendix A.

For the purposes of examining the trade space at an end-to-end level, selected instruments from the tables shown in Appendix A were grouped into four notional experiment suites that could serve the MGS need. The notional experiment is referred to here as the “MGS Environment and Effects Suite” (MEES). The four configurations were designed to address different driving priorities and were grouped into four options as shown in the summary tables below (Tables 4 through Table 7).

- Option One: State of the art, maximum capability
- Option Two: Minimum development, high capability
- Option Three: Low cost, reduced resolution
- Option Four: Size constrained

Table 4. MEES Option 1 “State of the Art, Maximum Capability”



	Option 1 State of the Art, Max Capability						
Sensor Type	Instrument	Mass (kg)	~Vol (cu cm K)	Specs	equiv TRL	Alt	cost $M
Very High Energy Spectrometer	RBSP REPT	16	30	e 4-10 MeV	7	DSX HIPS, ESA EPT	5
Medium Energy Spectrometer	RBSP MAG_EIS	15	30	e 30 keV-4 MeV i 20 keV - 1 MeV	7		5
Low Energy Spectrometer	RBSP HOPE	15	30	i, e, 20 ev - 45 keV	7		5
TEPC	ISS TEPC (AMES TEPC)	10	10		6-7		2
ESD Monitor(s)	Aerospace EDR	1	1		5-6	TPM (APEX)	0.1
Internal Charging Detector(s)	DDCM	5	2		7-8	SURF	1
Magnetometer	RBSP MAG	3	1		7-8	DSX, MMS	2
Surface Charging Detector(s)	Aerospace CDS	1	1		5-6	SURF	0.1
MicroDosimeter(s)	Teleydyne	1	1		9		0.1
C&DH	Notional	2	5		7-8		3
	Total	*69*	*111*				
			48	cm per side		ROM Cost:	23.3

Option 1 utilizes the highest scoring instruments in parameter coverage and resolution, with each measurement category having a dedicated sensor (no multifunction elements).

Note that the column “equivalent TRL” is used here as a coarse gauge of the viability of the existing design for the purposes of the MGS application, and may not be equal to the TRL of the instrument for its original intended purpose. Costs were estimated using available NASA databases, interviews with the PIs, or comparison with known values from similar projects.

A command and data handling unit (C&DH) was included in each configuration as a placeholder for the avionics and telemetry system that would be required to support the sensor suite.

Table 5. MEES Option 2 “Minimum Development, High Capability”

Option 2
Minimum Development, High Capability

Sensor Type	Instrument	Mass (kg)	~Vol (cu cm K)	Specs		Alt	cost $M
Very High Energy Spectrometer	RBSP REPT	16	30	e 4-10 MeV	7	DSX HIPS, ESA EPT	5
Medium Energy Spectrometer	GOES MPS-Hi	10	30	e 30 keV - 4 MeV p 30 keV - 1Mev	8		5
Low Energy Spectrometer	GOES MPS-Lo	8	30	e 30 ev -30 keV p 30 ev - 30 keV	8		5
TEPC	ISS TEPC	10	10		6-7		2
ESD Monitor(s)	Aerospace EDR	1	1		5-6		0.1
Internal Charging Detector(s)	SURFi	1	1		8-9		0.1
Magnetometer	RBSP MAG	3	1		7-8		2
Surface Charging Detector(s)	SURFs	1	1		8-9		0.1
MicroDosimeter(s)	Teleydyne	1	1		9		0.1
C&DH	Notional	2	5				3
	Total	*53*	*110*				
			48	cm per side		ROM Cost:	22.4

Option 2 reduces development risk while sacrificing some capability. The GOES-R spectrometers replace the RBSP elements since the GOES systems are already designed for operation on a body-stabilized spacecraft in GEO.

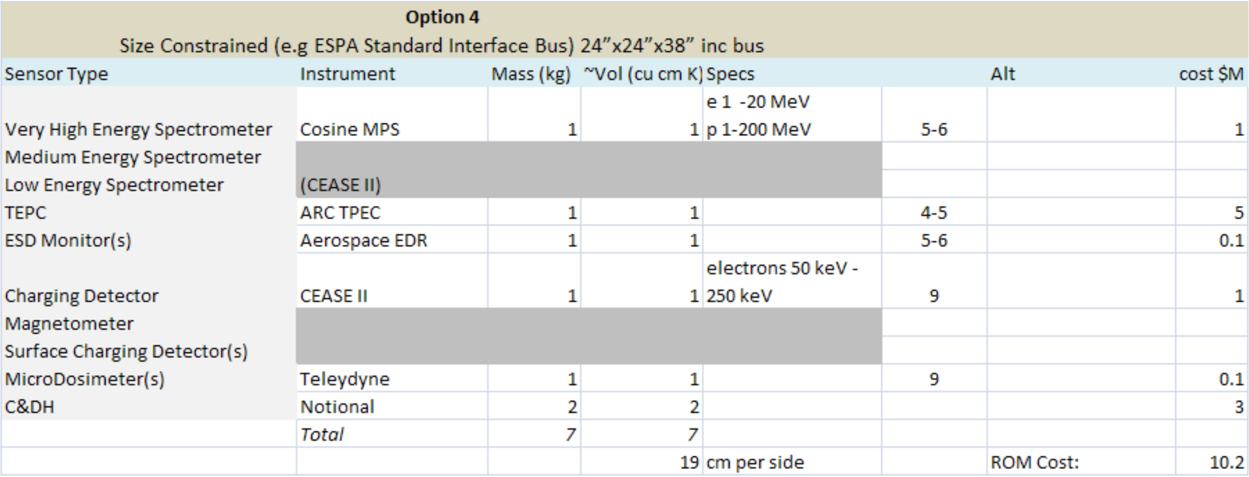
Table 6. MEES Option 3 “Low Cost, Reduced Resolution”

Option 3
Low Cost, Reduced Resolution

Sensor Type	Instrument	Mass (kg)	~Vol (cu cm K)	Specs		Alt	cost $M
Very High Energy Spectrometer							
Medium Energy Spectrometer	ESA CSR EPT	6	8	0.2-10 MeV electrons 4-300 MeV H and 16-1000 MeV He ions	8-9	Alphasat MFS, MPS Hi	3
Low Energy Spectrometer	DSX LEESA	2	2	e,p 100 ev - 50 keV	7-8		4
TEPC	ISS TEPC	10	10		6-7		2
ESD Monitor(s)	Aerospace EDR	1	1		5-6		0.1
Internal/External Charging	CEASE II	2	1		9	MERLIN	1
Magnetometer	DSX VMAG	1	1		7-8	THEMIS	1
Surface Charging Detector(s)							0
MicroDosimeter(s)	Teleydyne	1	1		9		0.1
C&DH	Notional	2	5				4
	Total	*25*	*29*				
			31	cm per side		ROM Cost:	15.2

Option 3 makes use of less precise instrumentation and multifunction systems such as the commercially available “CEASE II” from Amptek. Such systems are typically used for spacecraft health monitoring.

Table 7. MEES Option 4 “Size Constrained”



Option 4

Size Constrained (e.g ESPA Standard Interface Bus) 24”x24”x38” inc bus

Sensor Type	Instrument	Mass (kg)	~Vol (cu cm K)	Specs		Alt	cost $M
Very High Energy Spectrometer	Cosine MPS	1	1	e 1 -20 MeV p 1-200 MeV	5-6		1
Medium Energy Spectrometer							
Low Energy Spectrometer	(CEASE II)						
TEPC	ARC TPEC	1	1		4-5		5
ESD Monitor(s)	Aerospace EDR	1	1		5-6		0.1
Charging Detector	CEASE II	1	1	electrons 50 keV - 250 keV	9		1
Magnetometer							
Surface Charging Detector(s)							
MicroDosimeter(s)	Teleydyne	1	1		9		0.1
C&DH	Notional	2	2				3
	Total	*7*	*7*				
			19	cm per side		ROM Cost:	10.2

In Option 4 miniature components are used where possible and some instruments are removed.

The four options presented here will be revisited after a review of the bus options in the next section.

Bus Review

The MGS environment measurement suite configurations identified in Tables 4 through 7 were developed independently from the transportation options. In this section of the report, those transportation options are described and their evaluations summarized such that a trade of the complete system may be conducted. Three transportation options to GEO were identified: 1) Hosted Payload, 2) Secondary Mission, and 3) Primary Mission. Each of these options is discussed below.

(1) Hosted Payload

The Hosted Payload category involves all of the options that rely on utilizing space on another mission’s spacecraft. The spacecraft primary mission offers the use of excess platform capability in power, mass, and volume at a cost that is much lower than typical costs for space access. The cost of these accommodations depends directly on the schedule and resource impacts to the primary mission. The lower the burden on the primary mission, the less expensive the resource utilization becomes.

To increase the likelihood of low impact accommodations, interested parties typically come together 24 to 36 months before the planned launch date. This allows time for both sides to handle design changes necessary to meet the larger shared requirement set. The actual time required is typically defined by the development schedule of the primary mission, but can also be impacted by specific needs of the hosted payload. Delivery of the final payload is normally required at least 12 months before launch, to allow for adequate time for integration and test with the primary mission (Andraschko 2011, Futron 2010).

For the purposes of this study, all hosted payloads can be divided into two categories: A) robotic servicing missions and B) geosynchronous communication missions. While the basic characteristics of these missions are similar, the distinguishing feature for this study is the possible presence of a “contact event” between two spacecraft. In the robotic servicing missions, there exists the possibility of an electrostatic discharge event just prior to contact between two spacecraft.

A) Robotic Servicing Mission

This section describes the more promising of the two hosted options. All missions identified in this type provide one or more spacecraft contact events, providing the only opportunity to measure electrostatic discharges between two spacecraft. Without these contact events, the full set of desired measurements cannot be made.

Further, the investigational nature of robotic servicing missions may allow the hosted payload to gain concessions on bus design features to accommodate special needs. Features such as boom mountings and a spin stabilized bus are far more likely to be accommodated on a demonstration mission than on a communications asset, for example.

Four robotic servicing missions of opportunity reviewed for this study were the NASA RESTOR mission, ATK Space Systems ViviSat, the DLR (German Aerospace Agency) Deutsche Orbitale Servicing Mission (DEOS), and MDA Corp. (MacDonald, Dettwiler and Associates) Space Infrastructure Services (SIS).

RESTOR: This is a NASA GSFC mission that expands on the current robotic servicing efforts at the International Space Station (ISS) (NASA GSFC 2010). RESTOR seeks to demonstrate the capability to rendezvous with and tether to a spacecraft already in GEO, then provide servicing and refueling through the use of a dexterous robotic arm. The mission would provide at least one contact ESD event observation opportunity for each satellite serviced. Disruptions of the MGS environment measurements due to movement of the RESTOR spacecraft to client locations are unlikely to significantly degrade the MGS environment data, since such transportation events are relatively infrequent and occur at or near GEO. Because RESTOR is a NASA mission, it likely offers the most flexibility to accommodate requirements for MGS. Under the umbrella of an internal NASA mission, payload requirements beyond those of the primary mission (e.g. spin stabilization mode of operations, deployable boom for the magnetometer instrumentation, and location of instrumentation) can be assessed based on the cost and value returns to the entire platform, rather than just the cost and risk to the primary mission.

ViviSat: The ViviSat mission is an ATK program that focuses on extending the life of existing GEO satellites through the addition of a secondary propulsion system (ViviSat 2011). Under the current ATK design, each ViviSat platform would be configured to dock with the apogee kick motor of the customer spacecraft, allowing the ViviSat propulsion system to be used for maneuvers such as station keeping, reboost, and transfer to a disposal orbit. Depending on the customer satellite characteristics, Vivisat may extend the mission lifetime of the client spacecraft by up to 16 years. As Vivisat is designed to be an attachment to pre-existing spacecraft, features that may be desirable for the MGS measurement suite, such as spin stabilization and deployable booms, are not likely to be acceptable to the customer spacecraft. Data on the expected data flow between ViviSat and the customer spacecraft was not available for this study. Depending on the communications load already existing on the spacecraft, very little may be available to downlink additional data.

DEOS: The DLR DEOS mission is similar to the NASA RESTOR mission in that it intends to demonstrate on-orbit rendezvous and servicing capabilities (DEOS 2011). While the first DEOS demonstration mission is limited to LEO operations, subsequent missions are intended to extend the mission capability to GEO. This mission shares many of the advantages listed for the RESTOR mission, but any payload requirement that introduces additional limits on or risk to the primary mission will be less of a shared responsibility and more of a burden for the MGS team to resolve. Additionally, communications capability will be prioritized to the primary mission and NASA will not have direct control over the spacecraft lifetime or the length of the data record.

MDA SIS: The SIS mission is MDA’s proposal for establishing a capability to refuel satellites in GEO (MDA 2011). SIS is distinguished from the other missions by being designed for reusability. Once the spacecraft has expended its initial supply of fuel, MDA can launch a replacement fuel canister to resupply the robotic spacecraft. This capability greatly enhances the expected useful lifetime of the robotic servicer and provides the opportunity for a long duration measurement set. Similar to the DEOS mission, this platform will have limited flexibility to offer the MGS payload accommodations, but the communications capabilities of the spacecraft may be more advanced. The current operations plan calls for ground controlled servicing and should provide a significant telemetry stream to the payload when the primary mission is not using it to enable servicing.

B) Commercial Communications Satellites

As shown by the desire to build servicing spacecraft, there exists a large commercial market in GEO. The hundreds of existing assets in GEO are typically replaced at a rate of 15 to 20 new launches per year. As the expense of maintaining an orbital fleet has increased, commercial entities have increased efforts to find ways to offset the upfront costs of placing new assets into orbit. In recent years, many have begun to explore the option of opening unused capability on their spacecraft in order to host secondary payloads. This sharing of capability is advantageous to both sides, as the commercial provider receives a fee for the opportunity and the hosted payload gains access to space at a fraction of the traditional cost.

Several exploratory projects have sought to test the waters with commercial partnerships and have collected lessons learned. Recently, the U.S. Air Force commissioned Intelsat to document experiences with hosted payloads and to generate a set of guidelines for parties interested in such a partnership (Intelsat Web 2011). Futron Corporation and NASA have also examined the challenges and opportunities associated with secondary hosting on commercial assets.

The Hosted Payload Guide Book (Futron 2010) provides an overview of the entire hosting process from the point of view of the payload provider, as well as pertinent lower level considerations during each phase. Additionally, the manual identifies the currently planned commercial satellites during the 2011-2016 timeframe. Based on this list, there are approximately 15 promising launch opportunities with seven of those having a significant probability to launch on a US launch vehicle.

In 2011, Andraschko, et al. documented a NASA study of five recent government payloads that were hosted on commercial communications satellites. They reported several key technical parameters that informed our study. First, results from discussions with the satellite bus manufacturers indicated that almost all options could provide at least 50 kg of mass and more power than the radiation instrumentation suite will require. Additionally, telemetry data rates from even the least capable bus allowed 70 Mbps, far in excess of the needs of the MGS environment suite. The reference also provided a first order cost estimate trend, derived from the five identified projects, pricing a 50kg allocation at approximately $15M (FY10). The trend is provided below.

$$\text{Cost} = 0.1592*(\text{mass in kg}) + 6.6343$$

These factors make the commercially hosted payload an attractive option. In addition to the cost savings, the high launch rate of commercial satellites to GEO makes missed opportunities recoverable. If circumstances force the program to be delayed, future missions will typically be available at a rate of at least two to three per year. Lastly, the nature of the platform provides the hosted payload a stable, long duration observation window with an effectively unconstrained data rate for returning science data to Earth.

While the commercial hosting option provides one of the most compelling cases found in this study, it is not without its own set of challenges. Commercial time tables are fairly short and do not easily accommodate schedule slips. A hosted payload must work with the bus provider very early on (especially if non-standard options are being requested) to ensure compatibility with all involved parties. Options such as a spinning bus and deployable boom mounts are not likely to be considered by the commercial provider, which places additional engineering and ground testing burdens on the payload development. Fortunately, techniques have already been demonstrated to mitigate these issues. Many radiation instruments are being designed with three-axis controlled spacecraft in mind, making adjustments to current designs more of an engineering development rather than a technology effort. Additionally, careful treatment of the solar panel electrical wiring and other bus electronics can limit the magnetic contamination enough that ground characterization efforts can remove most of the noise generated by the spacecraft if the magnetometer cannot be boom mounted.

(2) Secondary Payload

Secondary payloads take advantage of excess capability on a launch vehicle that is already planning to go to the desired location. Sometimes this happens through planned cooperation of multiple missions, but often it is coordination through the vehicle provider or the sponsoring agency that brings these opportunities to life. The Ariane V launch vehicle routinely lofts multiple spacecraft to GEO Transfer Orbit (GTO), but our research did not identify any US launches that achieved the same (Aziz 2000, Space Launch 2011). The highly configurable nature of the US fleet and the lack of a developed multiple payload interface on the current EELVs may contribute to this situation.

Three primary options were identified for this category of launch opportunities: A) standard secondary payloads; B) extremely small satellites capable of attaching to the standard ESPA ring adapter used on the current US EELVs, and C) a Lunar Crater Observation and Sensing Satellite (LCROSS) derived bus that uses an ESPA ring as the primary bus structure. Each of these options is discussed below.

A) Standard Secondary Payload

In order to assess the feasibility of this option, a first order spacecraft sizing effort was undertaken using the LaRC SmallSat model (Ferebee 1997). For the spacecraft mass estimates, the radiation suite was assumed to be a static payload of 100 kg requiring 150W of power. It was assumed that the payload had no significant unique thermal requirements and that a system capable of operating reliably for more than five years was necessary. Additionally, the flight system had to be capable of (1) performing the orbital transfer from GTO to GEO and station keeping, and (2) providing 10 mbps capacity in the communications system. Combined, these requirements translated into a flight system that was on the order of 1000 kg (including contingency). A second pass through the requirements set reduced the flight hardware mass to approximately 700 kg. This reduction was achieved through significant relaxation of the station keeping requirements and specific orbital planning to reduce station keeping propellant usage. The reduction in station keeping propellant provided substantial additional mass savings in the propellant necessary to perform the GTO to GEO transfer burns.

After completing initial sizing of the spacecraft bus, a first order cost estimate was developed using the Small Satellite Cost Model (SSCM) (Aerospace Web 2010). This model is maintained by The Aerospace Corporation and uses parametric cost estimating relationships (CERs) to produce a first order cost of the spacecraft. The spacecraft bus is estimated to cost on the order of $50M (FY11).

Since a significant mass driver in the preliminary sizing effort was the propellant required, a subsequent effort examined electric propulsion options. However, this option could not be addressed effectively at the same level of fidelity and required some gross assumptions to be made. In the end, all of the mass saved from the conversion (and then some) went back into the system to provide significantly increased power and to address growth in the other flight system components. Based on the resulting mass, the electric propulsion system did not provide a benefit sufficient to offset the additional system complexity.

To complement the first order sizing of an electric propulsion bus, a literature survey was conducted to see if any similar systems existed or were in development. The research found the CX2 spacecraft bus, a small (approximately 1200 kg) GEO-class bus that uses electric propulsion for both the GTO to GEO transfer and GEO operations (Dutch Space 2009). The CX2 is designed to fit inside the Ariane V and utilizes some of the typically unused volume and mass allocations of that launch vehicle. It has a nominal payload mass of 100 kg and is designed as a communications platform. This allowed a straight forward comparison to the previous sizing attempt. While the CX2 is slightly heavier and more capable, the comparison between the chemical propulsion and the CX2 remains the same as the in-house sizing attempt. However, the CX2 platform does have several advantages in that it is already mostly designed, has a planned demonstration near the end of 2012, and is specifically configured to work within the Ariane V launch constraints. This combination offers significant potential cost savings, and the expected cost of the CX2 system, including launch and insurance costs, is expected to be on the order of $100M.

Use of the Ariane V or other foreign launch vehicles is limited by NASA to circumstances in which the launch is 100% contributed (no U.S. government investment). Such a limitation is likely to dramatically reduce the opportunities for pursuing this option.

Without a multiple payload adapter for GTO payload delivery, the use of the U.S. EELV fleet is also unlikely to yield standard secondary payload opportunities in the near future. If such an adapter became available (for example, the Atlas V has a design that has completed PDR at this time), it would provide some additional options that are described here. The mass of any additional hardware necessary to support the launch of multiple full mission-class payloads was not included, and evaluations relative to both the base loft capability of the 5m shroud option and the incremental lift capability were assessed. For the Atlas V, the step size in loft capability was found to be on the order of 1000 kg per increment. Based on our minimum 700 kg mass requirement, it is not likely that our additional mass can be accommodated within the configuration selected for the primary mission with enough margin to make the primary mission comfortable. The addition of a single increment in capability could accommodate the secondary payload, but the secondary payload would most likely have to pay both a share of the base launch vehicle costs as well as the entire cost of adding the additional capability. The Delta IV has some larger increments and the heavy variety would likely have enough excess capability to absorb the mass of the small secondary payload.

B) The EELV Secondary Payload Adapter (ESPA) Ring

The ESPA ring is a secondary payload adapter designed to accommodate several small payloads in the excess capacity of the EELV fleet. It mounts below the primary spacecraft and acts as a structural support between the EELV cone adapter and the primary payload fairing. An image is shown below in Figure 7.

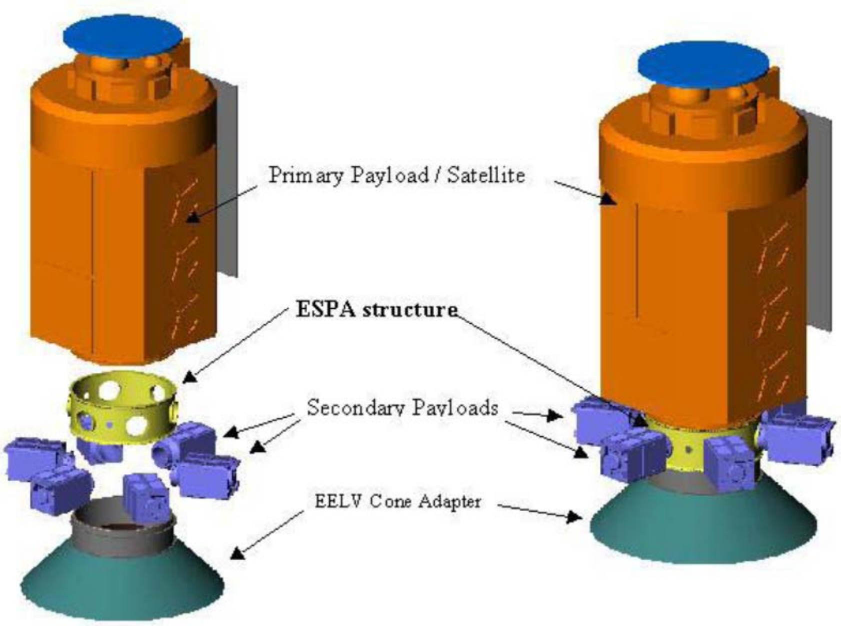


Figure 7. ESPA configuration diagram from the ESPA User's Guide.

The ring is capable of supporting up to six small secondary payloads and can be equipped with a "soft ride" system to limit the potential shock and vibration environment the payloads endure. Additional development efforts are under way to provide smaller and larger versions of the ESPA. The smaller version is designed to provide the ESPA capability to the smaller class launch vehicles (e.g. Delta II class) while the large version is designed to increase the payload mass limit on each port for the EELVs. A novel use of the entire ring as a bus structure for a single secondary satellite was successfully implemented on LCROSS (launched in June, 2009) and is planned for DSX (scheduled for launch in October, 2012). Options for using the ESPA ring both as a small satellite deployment mechanism and as a primary structure were examined for this study. Note that the ESPA Payload Planners Guide recommends submitting a spacecraft questionnaire to the Space Test Program (STP) three years prior to the desired launch opportunity (DoD STP 2001).

C) ESPA Small Satellite Payload

The ESPA payload satellites are small spacecraft that fall between "cubesats" and traditional spacecraft in terms of size. Satellites of this class are designed to anchor to the ESPA ring utilizing pre-determined bolt holes and specified mass and volume constraints. A picture of the size and attachment location is shown below in Figure 8. Full specifications on the satellite constraints can be found in the ESPA User's Guide (DoD STP 2001).

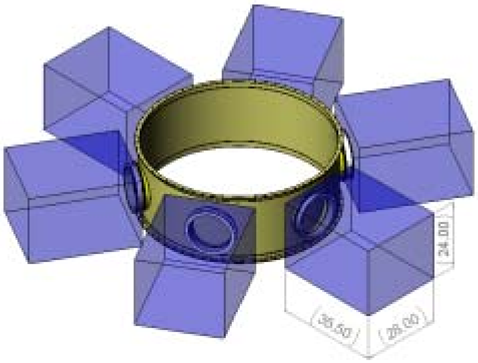


Figure 8. ESPA ring (payload volumes in inches: 35.50" x 28.00" x 24.00").

Figure 9. A spacecraft built using the ESPA Standard Interface Vehicle (SIV).

As shown by the dimensions in Figure 8, this option is extremely volume limited. Additionally, each payload has a not to exceed (NTE) mass of 180 kg, which can be further limited by the launch authority if needed to maintain center of gravity (cg) balancing. Using the STP's Standard Interface Vehicle (SIV) as a reference point, only 60 kg of the mass is available for payload. An image of the SIV is shown above in Figure 9 to illustrate the relative size.

While this option is limited in what instrumentation it can accommodate, it does offer a significant advantage: the STP office will supply the access to space at no cost to the payload.

To qualify, the requesting party must submit a proposal to the STP review board and be accepted into their candidate pool (Marlow 2011). The STP expects to provide at least one opportunity per year for these flights, with a fraction of those going to GEO.

D) Lunar Crater Observation and Sensing Satellite (LCROSS) Derived ESPA Bus

This option is an enhancement to the standard ESPA class mentioned above. This vehicle uses the full ring as the basic bus structure and builds control modules that can be attached to the ring. This configuration allows the craft to use the full mass and volume allocation available to the ESPA secondary payload.

The first mission to show the viability of this concept was LCROSS (shown in Figure 10). LCROSS was a competitively selected mission borne out of the excess capability available once LRO was moved from a Delta II to an Atlas V (Lo 2008). The DSX vehicle design used a similar approach, proving the concept had general applicability. Based on these successes, versions of this spacecraft bus have been made available on the NASA Rapid Spacecraft Development Office (RSDO) catalog offerings. A notional version of a powered ESPA ring is shown in Figure 11.

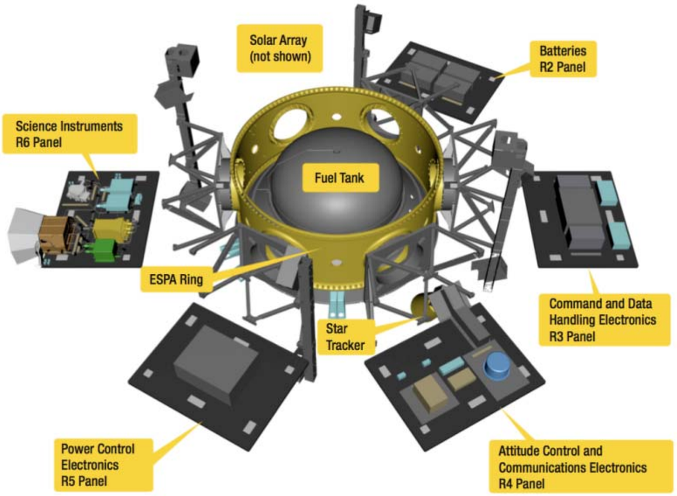


Figure 10. LCROSS

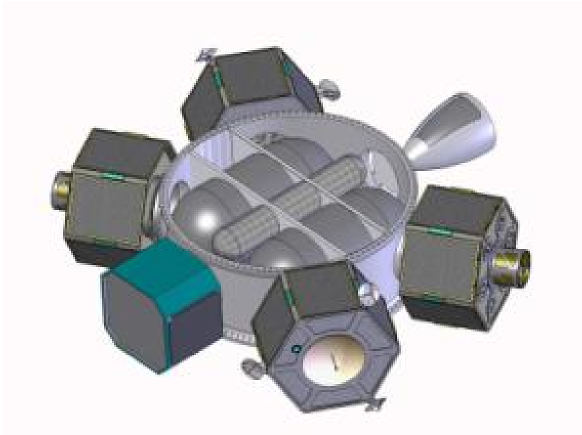


Figure 11. Notional powered ESPA ring (image by Vector Design)

The biggest challenge to this design for the purposes of GEO spacecraft is the propulsive needs of the mission and the volume available for propellant tanks. None of the current RSDO offerings for this bus option can support a mission to GEO. However, Northrop Grumman has been working on a design capable of doing the orbital transfer and relevant station keeping while maintaining enough resiliency to ensure several years on orbit (Drucker 2011). Based on the LCROSS bus development costs, we estimate the LCROSS-derived ESPA bus cost to be in the $50-60M dollar range.

3) Primary Payload

This option is the path that most missions follow. In this option, a custom, dedicated bus is built and the mission procures its own launch services. Due to the prevalence of the commercial market, there are many standard options for both spacecraft buses and launch services to GEO. Based on the general availability and the unique customization this option allows, no significant effort was spent to identify specific available options. However, typical mass and power capabilities were examined to provide the springboard for the identification of pathways forward.

Based on the sizing done for the "Secondary Payload" option, all standard GEO platforms provide mass, power, and volume capacity well beyond anything our suite could effectively utilize. As the least capable launch vehicles have loft capability well above our secondary payload mass, there exists very little reason to not utilize a platform similar in size to the average communications spacecraft.

The use of an average communications spacecraft size bus makes a significant amount of mass, volume, and power available for other uses. Under this scenario, the mission could host other payloads and experiments. NASA could use this platform to develop a competitive selection of secondary experiments and greatly increase the science returns of the mission.

Should NASA decide not to fund extra payloads, it is possible that the excess capability could be utilized to forgo the deployment of the spacecraft at GTO and instead have the launch vehicle (LV) do the insertion burn. This is not commonly done by US vehicles but does sometimes happen for foreign launches. The data and analysis required to determine the viability of this option is beyond the scope of this task, though the authors believe that this option is unlikely to represent substantial benefits over the other options presented.

The following FOMS for the GEO transportation options were developed to enable a coarse, quantitative trade and are summarized in Table 8.

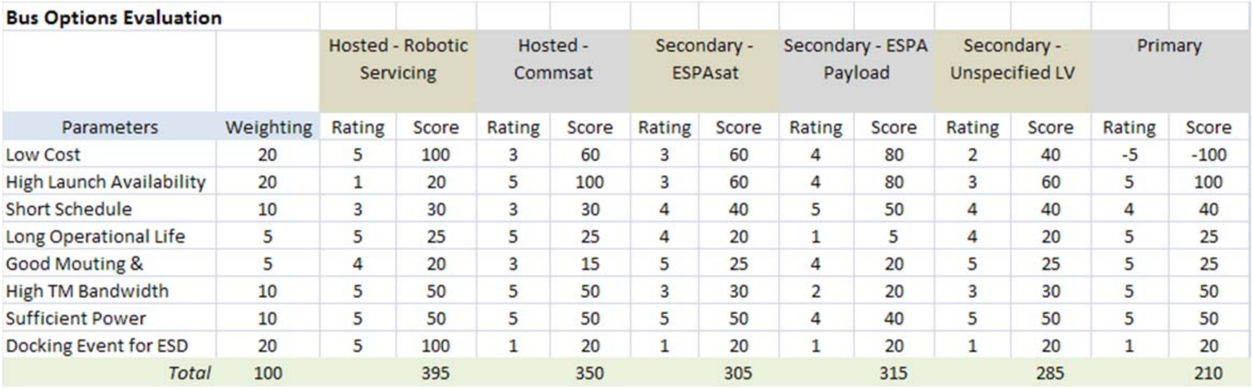
Table 8. GEO Transportation Options Figures of Merit

FOM	Importance	Description/Comments
Cost	High	Addresses the cost of delivery of the payload to orbit and relevant operations costs. Its weighting is derived from the idea that the higher the data per dollar ratio the mission achieves, the more likely it is to be developed.
Launch Availability	High	Addresses the expected rate of flight of each option. The weighting is based on the desire to avoid "one shot" opportunities which may or may not be compatible with the necessary development schedule.

External Schedule Dependency	Medium	Addresses the influence of the platform option on the payload's development schedule. The weighting is based on the significant impact such dependencies can have on the payload's development plans.
Operational Life	Low	Addresses the expected length of the data record. The weighting is derived from the short time available to influence new EVA suit design.
Mounting & Pointing	Low	Addresses the ability of the platform to meet the measurement field of view needs. The weighting is based on the ability of instrument design to mitigate issues of this type.
Telemetry Bandwidth	Medium	Addresses the downlink capabilities of the platform.
Power	Low	Addresses the platform's capability to meet the base power requirements of the payload. The weighting is based on the potential impacts of power shortfalls.
Docking Event for ESD	High	Assessment of whether or not the option will provide contact events between two spacecraft. The weighting is due to the inability to complete the full measurement set without this event.

Scores for each option based on weighted FOMs are shown below in Table 9. The hosted robotic servicing mission, with a FOM score of 395, was determined to be the best opportunity for GEO transportation.

Table 9. Bus Options Evaluation



Bus Options Evaluation

		Hosted - Robotic Servicing		Hosted - Commsat		Secondary - ESPAsat		Secondary - ESPA Payload		Secondary - Unspecified LV		Primary	
Parameters	Weighting	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Low Cost	20	5	100	3	60	3	60	4	80	2	40	-5	-100
High Launch Availability	20	1	20	5	100	3	60	4	80	3	60	5	100
Short Schedule	10	3	30	3	30	4	40	5	50	4	40	4	40
Long Operational Life	5	5	25	5	25	4	20	1	5	4	20	5	25
Good Mouting &	5	4	20	3	15	5	25	4	20	5	25	5	25
High TM Bandwidth	10	5	50	5	50	3	30	2	20	3	30	5	50
Sufficient Power	10	5	50	5	50	5	50	4	40	5	50	5	50
Docking Event for ESD	20	5	100	1	20	1	20	1	20	1	20	1	20
Total	100		395		350		305		315		285		210

The ranking of all options considered based on score is shown below. Note that in the ranking we further distinguish a government robotic servicing mission from a commercial opportunity, since the former may represent a greater opportunity to affect the bus design.

Ranked Bus Options

1. Hosted, Government Robotic Servicing Mission
2. Hosted, Commercial Robotic Servicing Mission
3. Hosted, Other GEO Sat
4. Secondary ESPA Payload
5. Secondary ESPASat
6. Secondary, Unspecified Launch Vehicle
7. Primary Payload

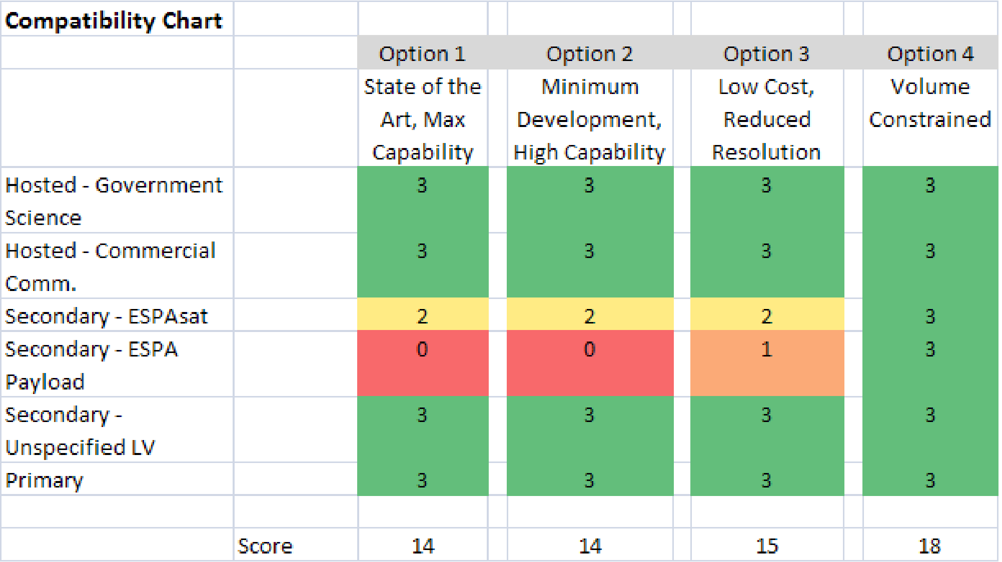
Bus and Instrument Trade Space

The final part of the MGS measurements trade study examined paths through the complete trade space by evaluating the instrument suites using weighted "Instrument Suite" FOMs, including a metric called "Bus Flexibility." This FOM was used to track any drawbacks that a given MEES configuration would incur on a given bus. Only the volume-constrained configuration, for example, is likely to fit into the available volume on an ESPA smallsat payload. A total of five FOMs were used to rank the instrument suite configurations as shown in Table 10. Table 11 shows a coarse numerical evaluation used to quantify the Bus Flexibility metric, and Table 12 shows the numerical evaluation of the four MEES configurations.

Table 10. Instrument Suite Figures of Merit

FOM	Importance	Description/Comments
High Data Value	High	Suites that include the highest capability instruments with good coverage of the parameter range and high resolution score well in this FOM.
Low Cost	High	Includes the estimate for modifying the instrument for GEO applications, if required.
Bus Flexibility	Medium	The ESPA payload transportation option will not accommodate all of the MEES options. A separate quantitative compatibility evaluation was done to create a compatibility score.
Short Development Time	Low	A general assessment of the availability of the instruments in the configuration within a short time frame.
Low Development & Operational Risk	Low	A general assessment of the overall readiness of the configuration for application to MGS.

Table 11. MEES Compatibility with Bus Options

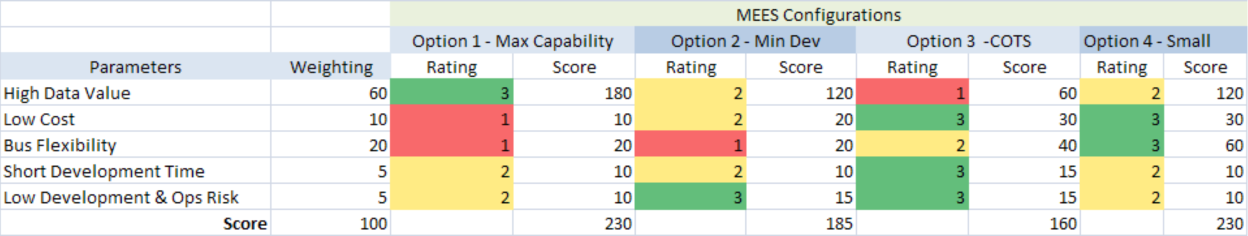


Compatibility Chart					
		Option 1	Option 2	Option 3	Option 4
		State of the Art, Max Capability	Minimum Development, High Capability	Low Cost, Reduced Resolution	Volume Constrained
Hosted - Government Science		3	3	3	3
Hosted - Commercial Comm.		3	3	3	3
Secondary - ESPAsat		2	2	2	3
Secondary - ESPA Payload		0	0	1	3
Secondary - Unspecified LV		3	3	3	3
Primary		3	3	3	3
	Score	14	14	15	18

Note: Cell colorization is for enhanced readability only.

The compatibility comparison shown in Table 11 indicates that the notional MEES experiment can be well accommodated on most bus options (shown in the green areas). Space constraints may be a factor for the ESPAsat (using the ESPA ring as a primary structure) and will be almost certainly a limiting factor for an ESPA payload option (using the ESPA Standard Interface Vehicle).

Table 12. MEES Configuration Evaluations



		MEES Configurations							
		Option 1 - Max Capability		Option 2 - Min Dev		Option 3 -COTS		Option 4 - Small	
Parameters	Weighting	Rating	Score	Rating	Score	Rating	Score	Rating	Score
High Data Value	60	3	180	2	120	1	60	2	120
Low Cost	10	1	10	2	20	3	30	3	30
Bus Flexibility	20	1	20	1	20	2	40	3	60
Short Development Time	5	2	10	2	10	3	15	2	10
Low Development & Ops Risk	5	2	10	3	15	3	15	2	10
Score	100		230		185		160		230

Table 12 compares the MEES configurations using weighted FOMs. The results equally favor the maximum capability approach ("Max Capability" = 230) or a volume optimized approach ("Small" = 230). Clearly, the high weighting of "High Data Value" is significantly affecting the outcome, and revised weightings and finer resolution in the FOM ratings will produce different results. One interpretation of these preliminary results is that investment in an MGS instrument suite should be "all-or-nothing" in the sense that the cost and development savings for a less than ideal system also greatly undermines the utility. Having a viable "small volume" option, however, is also valuable due to the ability to capitalize on a greater variety of transportation opportunities, especially since GEO is not a common destination for secondary payloads. Because of the FOM weightings used in this table, a key contributor to the high score of the small volume configuration was the Cosine MPS energetic particle spectrometer. This instrument advertises good resolution over a wide energy range and is flight qualified, but does not have flight heritage (Maddox 2008). Further evaluation of the capabilities of the Cosine MPS by independent instrumentation experts is suggested as future work for the MGS team.

Figure 12 depicts the entire trade tree of the options discussed in this study. In general we see that while all bus options are viable, the Hosted options are recommended. Becoming a hosted payload on a robotic servicing mission is of particular value due to the opportunities to measure contact ESD events; a U.S. government mission is recommended due to potentially increased ability to influence the system design requirements. The “Other GEO Sat” branch includes commercial communications satellites, where frequent launch opportunities are found. MEES Option 1 is recommended due to high science return, and Option 4 is recommended for cost or size constraints that may be encountered once the actual vehicle is identified and the program budget determined.

The Secondary branch is rated as a feasible fallback option rather than a recommended option due largely to the need to invest in a spacecraft bus. Further, the capability to deliver GEO payloads using the ESPA has been proposed but not demonstrated, and is unlikely to become as common as primary launches to GEO. The secondary payload approach is also identified as viable but not recommended due to the lack of launch opportunities, since this approach is not in use for U.S. vehicles and foreign launches may not be purchased by NASA. Use of a Primary launch is likely to be viable only if a collection of other experiments can be assembled to justify the cost.

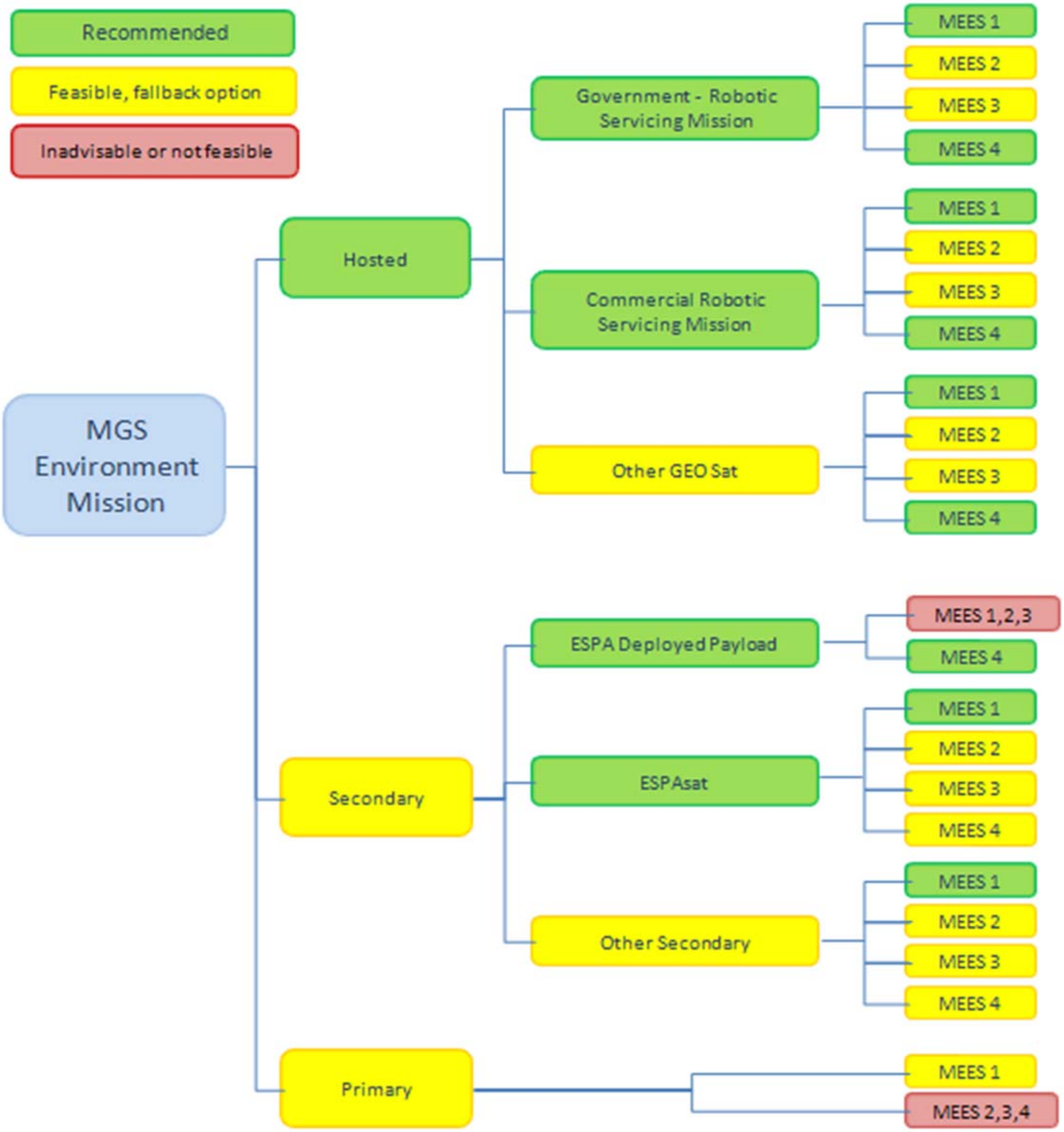


Figure 12. MGS environment study trade tree.

Conclusion

The desire to conduct a manned mission in Geosynchronous Earth orbit requires a thorough understanding of the space environment in order to design vehicles and suits that will provide sufficient protection for astronauts and equipment. Predictive models used to develop requirements for such designs have not historically been exercised for manned GEO missions, and do not at present provide sufficient confidence for MGS needs. While efforts to refine the models are on-going, the challenges of predicting space weather prescribe the need for sustained, long duration flight data in the regime of interest.

The data needed for the success of MGS can be gathered by developing an instrument suite to collect both environment and effects measurements. These data can then be used to refine the predictive models and inform the design of mitigation strategies for radiation harms and damaging discharge currents. The instruments comprising this suite are of sufficient technology readiness to enable near term development, and have relatively low mass, volume, power and telemetry resource needs. A compact system capable of being operated as a hosted payload on a GEO asset is recommended. This study presented representative configurations of known instruments of the type that could collect the desired data and evaluated these notional instrument suites using weighted FOMs informed by subject matter experts in radiation and spacecraft effects. Suggestions for further study include revisiting the data needs after the completion of the ongoing LANL spectrometer data analysis task and conducting a survey of instrument providers in the form of a Request for Information to collect more detailed instrument design and cost data.

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Henry Garrett	Jet Propulsion Laboratory
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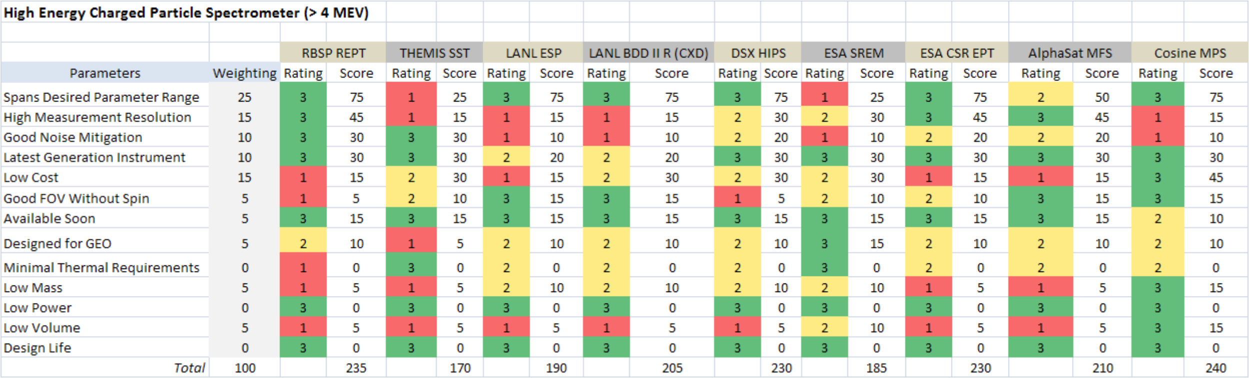
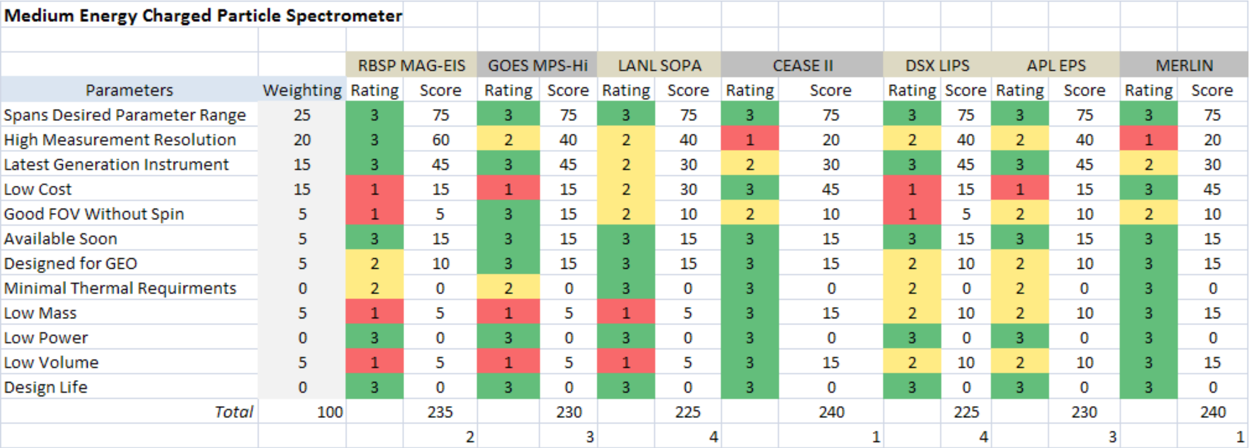
APPENDIX A: Instrument Comparisons



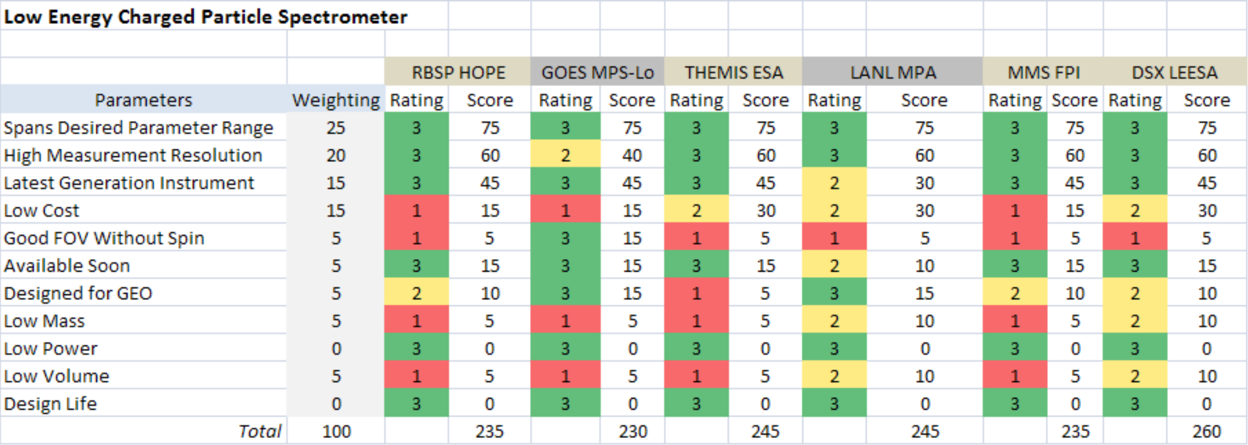
High Energy Charged Particle Spectrometer (> 4 MEV)

		RBSP REPT		THEMIS SST		LANL ESP		LANL BDD II R (CXD)		DSX HIPS		ESA SREM		ESA CSR EPT		AlphaSat MFS		Cosine MPS	
Parameters	Weighting	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Spans Desired Parameter Range	25	3	75	1	25	3	75	3	75	3	75	1	25	3	75	2	50	3	75
High Measurement Resolution	15	3	45	1	15	1	15	1	15	2	30	2	30	3	45	3	45	1	15
Good Noise Mitigation	10	3	30	3	30	1	10	1	10	2	20	1	10	2	20	2	20	1	10
Latest Generation Instrument	10	3	30	3	30	2	20	2	20	3	30	3	30	3	30	3	30	3	30
Low Cost	15	1	15	2	30	1	15	2	30	2	30	2	30	1	15	1	15	3	45
Good FOV Without Spin	5	1	5	2	10	3	15	3	15	1	5	2	10	2	10	3	15	3	15
Available Soon	5	3	15	3	15	3	15	3	15	3	15	3	15	3	15	3	15	2	10
Designed for GEO	5	2	10	1	5	2	10	2	10	2	10	3	15	2	10	2	10	2	10
Minimal Thermal Requirements	0	1	0	3	0	2	0	2	0	2	0	3	0	2	0	2	0	2	0
Low Mass	5	1	5	1	5	2	10	2	10	2	10	2	10	1	5	1	5	3	15
Low Power	0	3	0	3	0	3	0	3	0	3	0	3	0	3	0	3	0	3	0
Low Volume	5	1	5	1	5	1	5	1	5	1	5	2	10	1	5	1	5	3	15
Design Life	0	3	0	3	0	3	0	3	0	3	0	3	0	3	0	3	0	3	0
Total	100		235		170		190		205		230		185		230		210		240



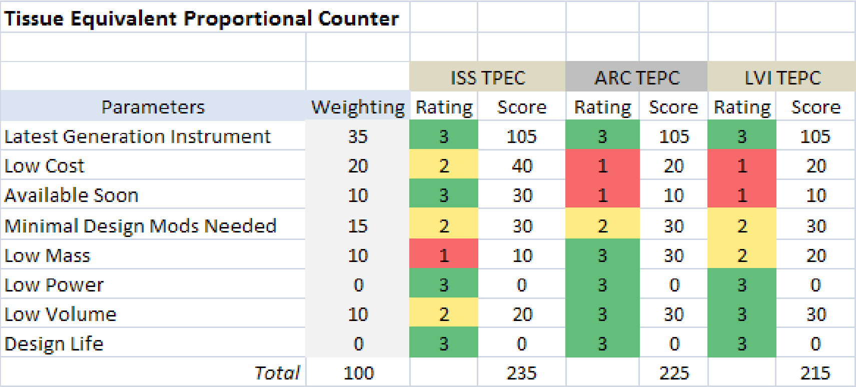
Medium Energy Charged Particle Spectrometer

		RBSP MAG-EIS		GOES MPS-Hi		LANL SOPA		CEASE II		DSX LIPS		APL EPS		MERLIN	
Parameters	Weighting	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Spans Desired Parameter Range	25	3	75	3	75	3	75	3	75	3	75	3	75	3	75
High Measurement Resolution	20	3	60	2	40	2	40	1	20	2	40	2	40	1	20
Latest Generation Instrument	15	3	45	3	45	2	30	2	30	3	45	3	45	2	30
Low Cost	15	1	15	1	15	2	30	3	45	1	15	1	15	3	45
Good FOV Without Spin	5	1	5	3	15	2	10	2	10	1	5	2	10	2	10
Available Soon	5	3	15	3	15	3	15	3	15	3	15	3	15	3	15
Designed for GEO	5	2	10	3	15	3	15	3	15	2	10	2	10	3	15
Minimal Thermal Requirments	0	2	0	2	0	3	0	3	0	2	0	2	0	3	0
Low Mass	5	1	5	1	5	1	5	3	15	2	10	2	10	3	15
Low Power	0	3	0	3	0	3	0	3	0	3	0	3	0	3	0
Low Volume	5	1	5	1	5	1	5	3	15	2	10	2	10	3	15
Design Life	0	3	0	3	0	3	0	3	0	3	0	3	0	3	0
Total	100		235		230		225		240		225		230		240
			2		3		4		1		4		3		1



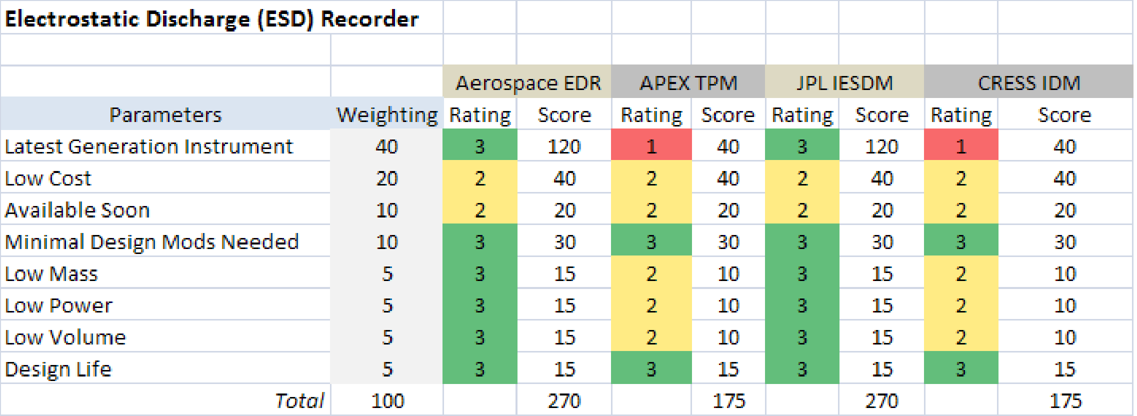
Low Energy Charged Particle Spectrometer

		RBSP HOPE		GOES MPS-Lo		THEMIS ESA		LANL MPA		MMS FPI		DSX LEESA	
Parameters	Weighting	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Spans Desired Parameter Range	25	3	75	3	75	3	75	3	75	3	75	3	75
High Measurement Resolution	20	3	60	2	40	3	60	3	60	3	60	3	60
Latest Generation Instrument	15	3	45	3	45	3	45	2	30	3	45	3	45
Low Cost	15	1	15	1	15	2	30	2	30	1	15	2	30
Good FOV Without Spin	5	1	5	3	15	1	5	1	5	1	5	1	5
Available Soon	5	3	15	3	15	3	15	2	10	3	15	3	15
Designed for GEO	5	2	10	3	15	1	5	3	15	2	10	2	10
Low Mass	5	1	5	1	5	1	5	2	10	1	5	2	10
Low Power	0	3	0	3	0	3	0	3	0	3	0	3	0
Low Volume	5	1	5	1	5	1	5	2	10	1	5	2	10
Design Life	0	3	0	3	0	3	0	3	0	3	0	3	0
Total	100		235		230		245		245		235		260



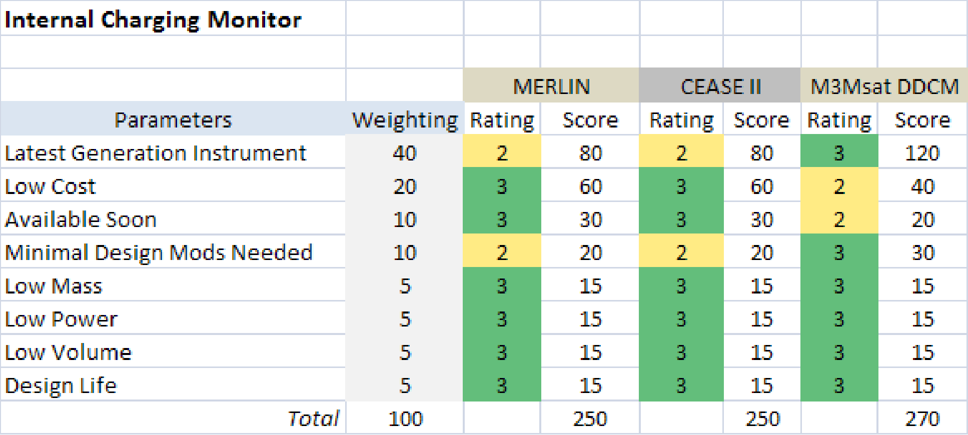
Tissue Equivalent Proportional Counter

		ISS TPEC		ARC TEPC		LVI TEPC	
Parameters	Weighting	Rating	Score	Rating	Score	Rating	Score
Latest Generation Instrument	35	3	105	3	105	3	105
Low Cost	20	2	40	1	20	1	20
Available Soon	10	3	30	1	10	1	10
Minimal Design Mods Needed	15	2	30	2	30	2	30
Low Mass	10	1	10	3	30	2	20
Low Power	0	3	0	3	0	3	0
Low Volume	10	2	20	3	30	3	30
Design Life	0	3	0	3	0	3	0
Total	100		235		225		215



Electrostatic Discharge (ESD) Recorder

		Aerospace EDR		APEX TPM		JPL IESDM		CRESS IDM	
Parameters	Weighting	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Latest Generation Instrument	40	3	120	1	40	3	120	1	40
Low Cost	20	2	40	2	40	2	40	2	40
Available Soon	10	2	20	2	20	2	20	2	20
Minimal Design Mods Needed	10	3	30	3	30	3	30	3	30
Low Mass	5	3	15	2	10	3	15	2	10
Low Power	5	3	15	2	10	3	15	2	10
Low Volume	5	3	15	2	10	3	15	2	10
Design Life	5	3	15	3	15	3	15	3	15
Total	100		270		175		270		175



Internal Charging Monitor

		MERLIN		CEASE II		M3Msat DDCM	
Parameters	Weighting	Rating	Score	Rating	Score	Rating	Score
Latest Generation Instrument	40	2	80	2	80	3	120
Low Cost	20	3	60	3	60	2	40
Available Soon	10	3	30	3	30	2	20
Minimal Design Mods Needed	10	2	20	2	20	3	30
Low Mass	5	3	15	3	15	3	15
Low Power	5	3	15	3	15	3	15
Low Volume	5	3	15	3	15	3	15
Design Life	5	3	15	3	15	3	15
Total	100		250		250		270

Fluxgate Magnetometer

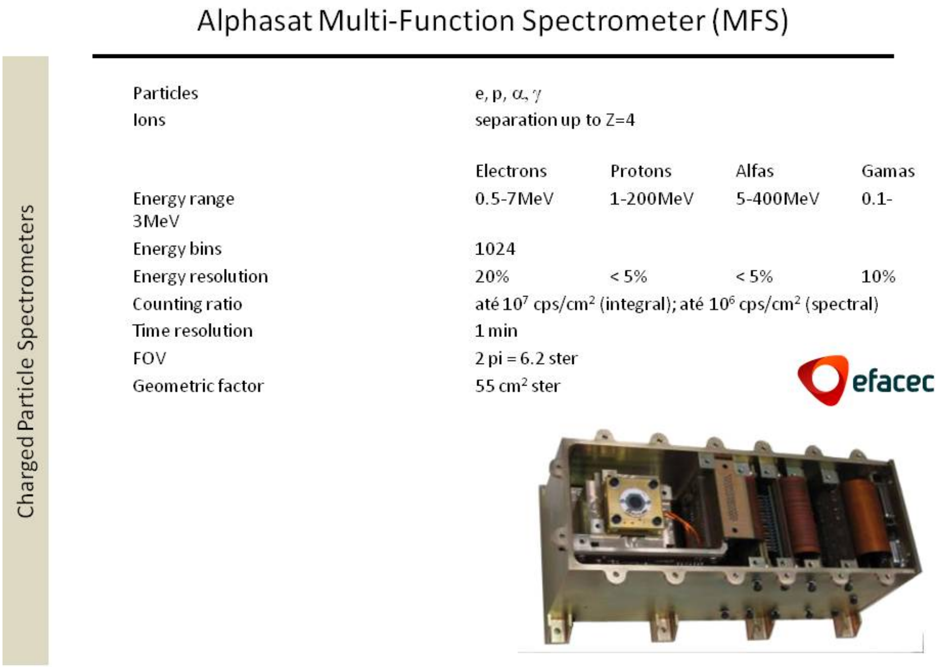
		RBSP MAG		THEMIS FGM		MMS FGM		DSX VMAG	
Parameters	Weighting	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Latest Generation Instrument	45	3	135	3	135	3	135	3	135
Low Cost	20	1	20	3	60	3	60	3	60
Available Soon	10	3	30	3	30	3	30	3	30
Minimal Design Mods Needed	10	3	30	3	30	3	30	3	30
Designed for GEO	5	2	10	2	10	2	10	2	10
Low Mass	5	3	15	3	15	3	15	3	15
Low Power	0	3	0	3	0	3	0	3	0
Low Volume	5	3	15	3	15	3	15	3	15
Design Life	0	3	0	3	0	3	0	3	0
Total	100		255		295		295		295

Surface Charging Monitor

		Aerospace CDS		JPL CREAM		Goembel SCM		DSCS	
Parameters	Weighting	Rating	Score	Rating	Score	Rating	Score	Rating	Score
Latest Generation Instrument	45	3	135	3	135	3	135	2	90
Low Cost	25	2	50	2	50	2	50	2	50
Available Soon	10	2	20	2	20	3	30	3	30
Minimal Design Mods Needed	10	3	30	3	30	2	20	2	20
Low Mass	5	3	15	3	15	1	5	1	5
Low Power	0	3	0	3	0	3	0	3	0
Low Volume	5	3	15	3	15	1	5	1	5
Design Life	0	3	0	3	0	3	0	3	0
Total	100		265		265		245		200

APPENDIX B: Instrument Data

Note: Slides contain partial information and, in some cases, estimated information and are provided for reference only. Please refer to the instrument PI for complete data.



Alphasat Multi-Function Spectrometer (MFS)

Charged Particle Spectrometers

Particles	e, p, α, γ			
Ions	separation up to Z=4			
	Electrons	Protons	Alfas	Gamas
Energy range	0.5-7MeV	1-200MeV	5-400MeV	0.1-3MeV
Energy bins	1024			
Energy resolution	20%	< 5%	< 5%	10%
Counting ratio	até 10^7 cps/cm^2 (integral); até 10^6 cps/cm^2 (spectral)			
Time resolution	1 min			
FOV	2 pi = 6.2 ster			
Geometric factor	55 cm^2 ster			

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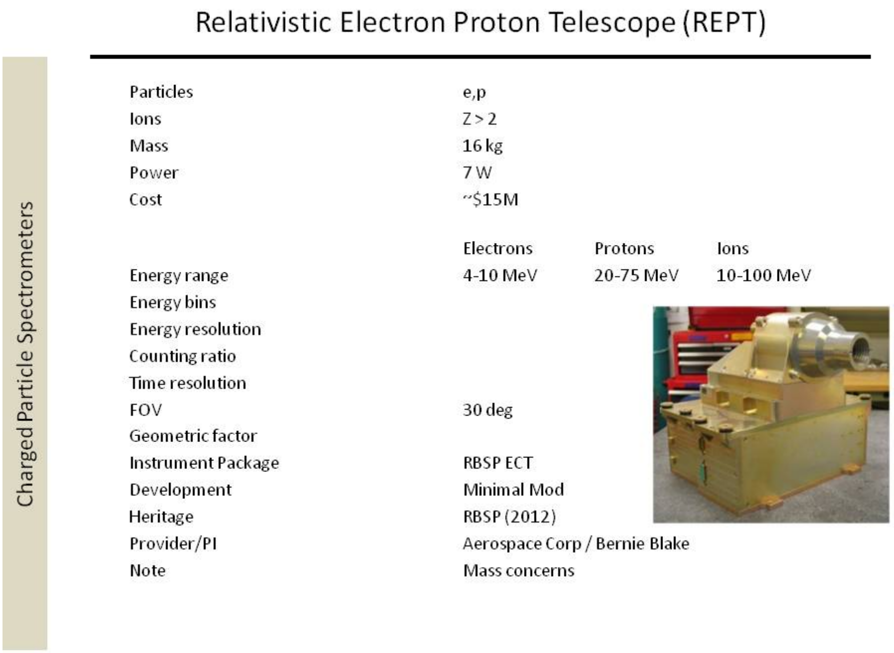


Relativistic Electron Proton Telescope (REPT)

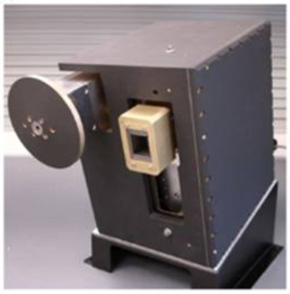
Charged Particle Spectrometers

Particles	e,p		
Ions	Z > 2		
Mass	16 kg		
Power	7 W		
Cost	~$15M		
	Electrons	Protons	Ions
Energy range	4-10 MeV	20-75 MeV	10-100 MeV
Energy bins			
Energy resolution			
Counting ratio			
Time resolution			
FOV	30 deg		
Geometric factor			
Instrument Package	RBSP ECT		
Development	Minimal Mod		
Heritage	RBSP (2012)		
Provider/PI	Aerospace Corp / Bernie Blake		
Note	Mass concerns		

Charged Particle Spectrometers

Magnetic Electron Ion Spectrometer (MAGEIS)
High Energy

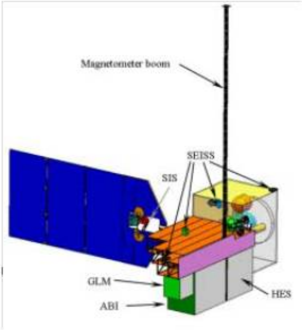
Particles	e,ions			
Ions				
Mass	15 kg			
Power	8-14 W			
Cost	~$15M			
	Electrons	Protons	Alfas	Gamas
Energy range	30 keV – 4 MeV	20keV-1Mev		
Energy bins	256 channel			
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package	RBSP ECT			
Development	Minimal mod			
Heritage	RBSP (2012)			
Provider/PI	JHU APL / Harlan Spence			
Note				



Charged Particle Spectrometers

Magnetospheric Particle Sensor (MPS-High)

Particles	e,p			
Ions				
Mass	~13 kg			
Power	12.6 W			
Volume	22,500 cm3	40 cm max dim		
Cost	~$5M / box			
	Electrons	Protons	Alfas	Gamas
Energy range	50 keV-4 Mev	80 keV-12 MeV		
Energy bins	10 bins (log)	11 bins (log)		
Energy resolution	>2 MeV interval			
Counting ratio				
Time resolution	<30 sec			
FOV	15 deg			
Noise	<10 keV for 50 -100 keV			
Geometric factor				
Instrument Package	SEISS			
Development	Minimal Mod			
Heritage	GOES-R (2015)			
Provider/PI	Assurance Tech. / Gary M			
Note				



ESA CSR Energetic Particle Telescope (EPT)

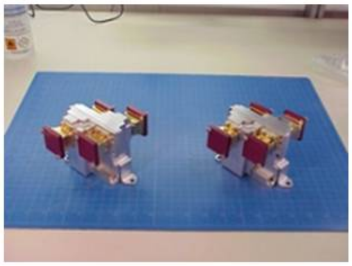
Charged Particle Spectrometers

Particles	e,p			
Ions	He+			
Mass	6 kg			
Power	6 W			
Volume	205 mm x 205 mm x 190 mm			
	Electrons	Protons	He+	Gamas
Energy range	0.2-10 Mev	4-300 MeV	16-1000 MeV	
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV	max 50 deg			
Geometric factor	1.5 cm2sr			
Instrument Package				
Development	Minimal mod			
Heritage	Proba-V 2012			
Provider/PI	Center for Space Radiations			
Note				

THEMIS Solid State Telescope (SST)

Charged Particle Spectrometers

Particles	e,p			
Ions				
Mass	1.43 kg			
Power	1.2 W			
	Electrons	Protons	Alfas	Gamas
Energy range	25 keV -900 keV	25 keV- 6 MeV		
Energy bins	16			
Energy resolution				
Counting ratio				
Time resolution				
FOV	78 deg (36 per sensor)			
Geometric factor				
Instrument Package				
Development				
Heritage	THEMIS (2007)			
Provider/PI	UCB			
Note				



LANL Energy Spectrometer for Particles (ESP)

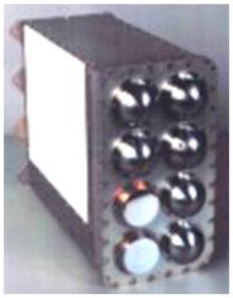
Charged Particle Spectrometers

Particles	e			
Ions				
Mass				
Power				
Volume	3.81 x 3.81 x 0.63 cm			
	Electrons	Protons	Alfas	Gamas
Energy range	0.7-10 MeV	11-100+ MeV		
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV	22 deg			
Geometric factor				
Instrument Package				
Development				
Heritage	LANL (1989)			
Provider/PI	R.C. Reedy			
Note	Scintillator			

LANL Burst Detector Dosimeter II (BDD II-R)

Charged Particle Spectrometers

Particles	e,p			
Ions				
Mass				
Power				
	Electrons	Protons	Alfas	Gamas
Energy range	0.08 – 5 MeV	1.3-54 MeV		
Energy bins	8 channels			
Energy resolution				
Counting ratio				
Time resolution				
FOV	120 deg			
Geometric factor				
Instrument Package				
Development				
Heritage	1998			
Provider/PI				
Note				

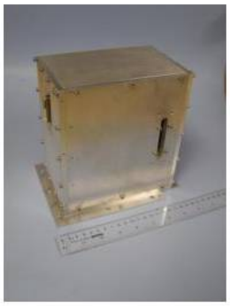


High Energy Imaging Particle Spectrometer (HIPS)

Charged Particle Spectrometers

Particles	e,p
Ions	
Mass	5 kg
Power	14 W
Volume	200 x 210 x 120 mm
Cost	~$20M for SWx

	Electrons	Protons	Alfas	Gamas
Energy range	1-10 MeV	30-300 MeV		
Energy bins	12 bins			
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package	DSX SWx			
Development				
Heritage	DSX (2012)			
Provider/PI	Physical Sciences Inc.			
Note				



JHU APL Energetic Particle Sensor (EPS)

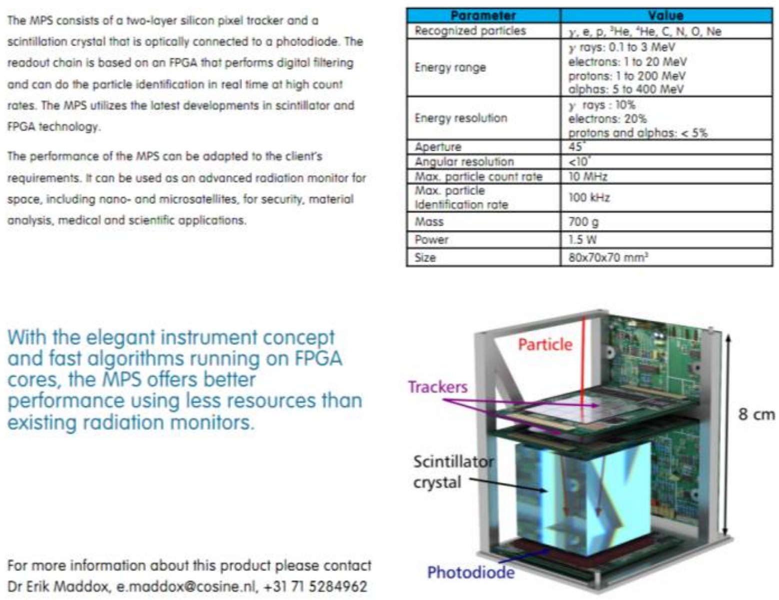
Charged Particle Spectrometers

Particles	e (?)
Ions	
Mass	
Power	

	Electrons	Protons	Alfas	Gamas
Energy range	30 keV-2.5 MeV			
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package	SEM-N			
Development				
Heritage	DWSS (NPOESS) 2018			
Provider/PI	JHU APL / Dr. Tom Sotirelis			
Note				

Charged Particle Spectrometers

Cosine Multifunction Particle Spectrometer (MPS)



The MPS consists of a two-layer silicon pixel tracker and a scintillation crystal that is optically connected to a photodiode. The readout chain is based on an FPGA that performs digital filtering and can do the particle identification in real time at high count rates. The MPS utilizes the latest developments in scintillator and FPGA technology.

The performance of the MPS can be adapted to the client's requirements. It can be used as an advanced radiation monitor for space, including nano- and microsatellites, for security, material analysis, medical and scientific applications.

Parameter	Value
Recognized particles	γ, e, p, ^{3}He, ^{4}He, C, N, O, Ne
Energy range	γ rays: 0.1 to 3 MeV electrons: 1 to 20 MeV protons: 1 to 200 MeV alphas: 5 to 400 MeV
Energy resolution	γ rays : 10% electrons: 20% protons and alphas: < 5%
Aperture	45°
Angular resolution	<10°
Max. particle count rate	10 MHz
Max. particle Identification rate	100 kHz
Mass	700 g
Power	1.5 W
Size	80x70x70 mm^3

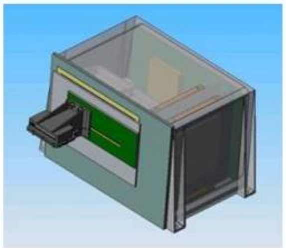
With the elegant instrument concept and fast algorithms running on FPGA cores, the MPS offers better performance using less resources than existing radiation monitors.

For more information about this product please contact Dr Erik Maddox, e.maddox@cosine.nl, +31 71 5284962

Charged Particle Spectrometers

Magnetic Electron Ion Spectrometer (MAGEIS)
Low Energy

Particles	e, ions			
Ions				
Mass	15 kg			
Power	8-14 W			
Volume				
Cost	~$15M			
	Electrons	Protons	Alfas	Gamas
Energy range	.03-4 MeV	.02-1 MeV		
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package	RBSP ECT			
Development				
Heritage	RBSP 2012			
Provider/PI	JHU APL/Harlan Spence			
Note				



Charged Particle Spectrometers

Helium Oxygen Proton Electron

Particles	e,ions			
Ions				
Mass	~15 kg			
Power				
Volume				
Cost	~$15M			
	Electrons	Protons	Alfas	Gamas
Energy range	20 eV – 45 keV			
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package	RBSP ECT			
Development	Minimal Mod			
Heritage	RBSP 2012			
Provider/PI	JHU APL/Harlan Spence			
Note	May not need heavy ion info			

Charged Particle Spectrometers

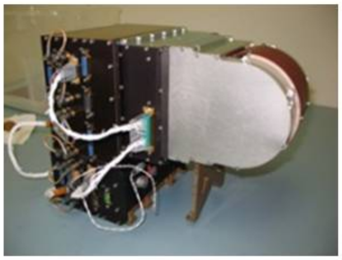
Magnetospheric Particle Sensor (MPS-Low)

Particles	e,p			
Ions				
Mass	8 kg			
Power	7 W			
Volume	12,384 cm3	31 cm max dim		
Cost	~$5M per box			
	Electrons	Protons	Alfas	Gamas
Energy range	30 eV – 30 keV	30 eV – 30 keV		
Energy bins	15			
Energy resolution				
Counting ratio				
Time resolution				
FOV	Two 90 deg sensor heads			
Geometric factor				
Instrument Package	SEISS			
Development	Minimal Mod			
Heritage	GOES-R (2015)			
Provider/PI	Assurance Tech./Gary Mullen			
Note	check contamination			

THEMIS Electrostatic Analyzer

Charged Particle Spectrometers

Particles	e (?)			
Ions				
Mass	2.96 kg			
Power	1.7 W (?)			
Volume	1.7 (?)			
	Electrons	Protons	Alfas	Gamas
Energy range	3 eV – 30 keV			
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package				
Development				
Heritage	THEMIS (2007)			
Provider/PI	C.W. Carlson, UCB			
Note	sensitivities in belts			



LANL Synchronus Orbit Particle Analyzer (SOPA)

Charged Particle Spectrometers

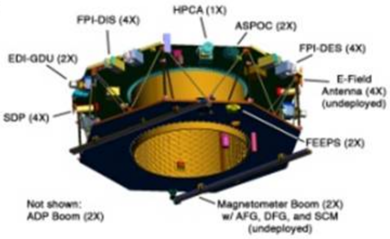
Particles	e			
Ions				
Mass				
Power				
Volume				
	Electrons	Protons	Alfas	Gamas
Energy range	50 keV – 1.5 keV			
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package				
Development				
Heritage	LANL (1989-1997)			
Provider/PI	Richard D. Belian			
Note				

Charged Particle Spectrometers

Fast Plasma Instrument (FPI)

Particles	e, ions
Ions	
Mass	
Power	
Volume	

	Electrons	Protons	Alfas	Gamas
Energy range	10 eV – 30 keV			
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package	SMART			
Development	Minimal Mod			
Heritage	Magnetospheric Multiscale (2014)			
Provider/PI	Tom Moore, GFSC			
Note				

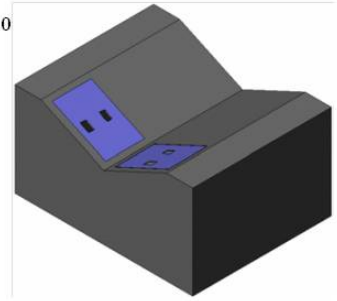


Charged Particle Spectrometers

Low Energy Electrostatic Analyzer (LEESA)

Particles	e,p
Ions	
Mass	
Power	5 W
Volume	
Cost	~$20M for SWx

	Electrons	Protons	Alfas	Gamas
Energy range	100 eV – 50 keV	100 eV – 50 keV		
Energy bins	20-30 channels (log spaced)			
Energy resolution				
Counting ratio				
Time resolution	1-5 sec	5-10		
FOV	25-50 deg			
Geometric factor				
Instrument Package	DSX SWx			
Development				
Heritage	DSX, SSJ4 DMSP			
Provider/PI	Amptek Inc., AFRL			
Note				

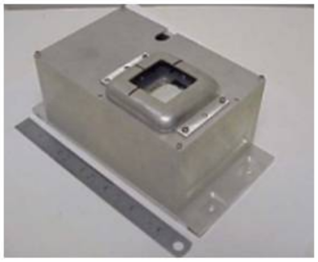


Low Energy Imaging Particle Spectrometer (LIPS)

Charged Particle Spectrometers

Particles	e
Ions	
Mass	0.8 kg
Power	1.6 W
Volume	90 x 90 x 176 mm
Cost	~$20M for SWx

	Electrons	Protons	Alfas	Gamas
Energy range	20 keV-1MeV			
Energy bins				
Energy resolution	dE/E = 1.0 e	dE/E = 0.5 p		
Counting ratio	<2 x 10^5 cps			
Time resolution				
FOV				
Geometric factor				
Instrument Package	DSX SWx			
Development				
Heritage	DSX (2012)			
Provider/PI	PSI			
Note				



ISS Tissue Equivalent Proportional Counter (TEPC)

Dosimeters

Particles	e
Ions	
Mass	~4.5kg
Power	
Volume	30 x 14 x 14 cm

	Electrons	Protons	Alfas	Gamas
Energy range	25 keV/micron through channels > 1000 keV/micron lineal energy range from 0.76 to 1250 keV/micron			
Energy bins	1024/256 channels (Low/High Gain)			
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Development	TRL 8?			
Heritage	ISS on STS-118/13A.1			
Provider/PI	Fadi M. Riman, Houston, TX			
Note	Outer wall too thick for GEO electrons			

ARC Compact TEPC

Dosimeters

Particles				
Ions				
Mass	0.3 kg			
Power	1 W			
Volume	3 x 3.75 x 1"			
	Electrons	Protons	Alfas	Gamas
Energy range	radiation-dose, dose eq., LET			
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Development	TRL 6?			
Heritage	in development			
Provider/PI	Tor Staume, ARC			
Note	Need a thin-walled TPEC			

T. Borak, L. Braby, T. Straume
- EVA Dosimeter

LVI TEPC Microdosimeter

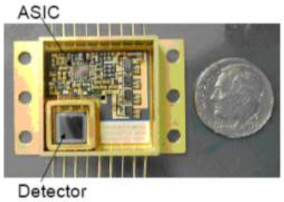
Dosimeters

Particles				
Ions				
Mass	8 oz			
Power	100 mW			
Volume	2.5 x 4.5 x 1"			
Cost	~$1M to complete development			
	Electrons	Protons	Alfas	Gamas
Energy range	max 2047 keV/micron			
Energy bins	2048 channels at 1 keV/micron			
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Development	TRL 4?			
Heritage	STS SBIR			
Provider/PI	LVI / T. Conroy			
Note				

Aerospace/Teledyne ADS02 (MinD)

Dosimeters

Particles				
Ions				
Mass	20 g			
Power	390 mW			
Volume	dime size			
Cost	$10k			
	Electrons	Protons	Alfas	Gamas
Energy range	one low LET and one high LET			
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package	Dosimeter-on-a-chip			
Development				
Heritage	LRO QAM as tech demo			
Provider/PI	Aerospace/Bernard Blake			
Note	Dose in silicon			



CRRES IDM AFGL-701-1B

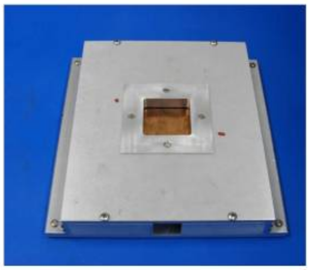
Discharge Monitors

Particles				
Ions				
Mass				
Power				
Volume				
	Electrons	Protons	Alfas	Gamas
Energy range				
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package	SPACERAD (Air Force Geophysics)			
Development				
Heritage	CRRES 1990			
Provider/PI	Gary Mullen			
Note				

Internal Electrostatic Discharge Monitor (IESDM)

Discharge Monitors

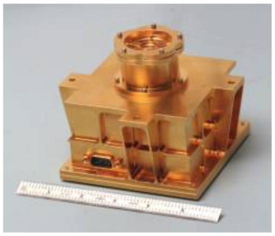
Particles				
Ions				
Mass				
Power				
Volume				
	Electrons	Protons	Alfas	Gamas
Energy range	potentials as a function of dielectric depth			
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package				
Development	TRL 6?			
Heritage	In development			
Provider/PI	JPL/Wousik Kim			
Note				



Dielectric Deep Charge Monitor (DDCM)

Discharge Monitors

Particles				
Ions				
Mass	800 g			
Power	800 mW			
Volume	125 x 125 x 100 mm			
Cost	$650k			
	Electrons	Protons	Alfas	Gamas
Energy range	uses vibrating electrode to find electric potential			
Energy bins	0-20 kV			
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package				
Development				
Heritage	M3Msat 2011 (LEO)			
Provider/PI	DPL Science/Mark de Payrebrune 450-458-0852			
Note				



Magnetospheric Particle Sensor (MPS-Low)

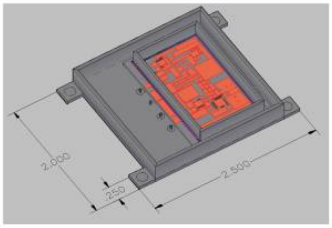
Charging Monitors

Particles				
Ions				
Mass	8 kg			
Power	7 W			
Volume	12,384 cm3 31 cm max dim			
	Electrons	Protons	Alfas	Gamas
Energy range	30 eV – 30 keV	30 eV-30 keV		
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package	Space Environment In-Situ Suite (SEISS)			
Development				
Heritage	GOES-R (2015)			
Provider/PI	Assurance Technologies/Gary Mullen			
Note				

Aerospace Charge Deposit Sensor (CDS)

Charging Monitors

Particles				
Ions				
Mass	1 kg			
Power				
Volume	patch			
Cost	$50k			
	Electrons	Protons	Alfas	Gamas
Energy range				
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package				
Development	TRL 6?			
Heritage	Bogorad 1995 (paper)			
Provider/PI	Aerospace Inc.			
Note				

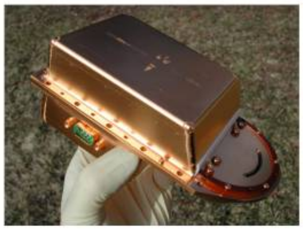


Goembel Spacecraft Charging Monitor (SCM)

Charging Monitors

Particles	
Ions	
Mass	650 g
Power	2 W
Volume	1 ?
Cost	$600k

	Electrons	Protons	Alfas	Gamas
Energy range	SCM-2 designed for +5 to -10,000 V			
Energy bins				
Energy resolution				
Counting ratio				
Time resolution	once per minute			
FOV				
Geometric factor				
Instrument Package				
Development				
Heritage	Phase II SBIR, TSAT (DoD) cancelled			
Provider/PI	Goembel Instruments			
Note				



DSCS Charge Control System (CCS)

Charging Monitors

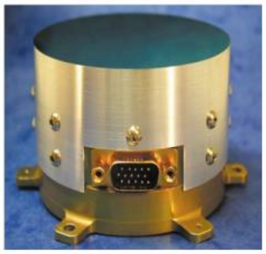
Particles	
Ions	
Mass	
Power	
Volume	

	Electrons	Protons	Alfas	Gamas
Energy range				
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package	SPM-based detectors			
Development				
Heritage	USAF DSCS-III B-7 / FDMS (Hughes)			
Provider/PI				
Note				

Qinetiq SURF

Charging Monitors

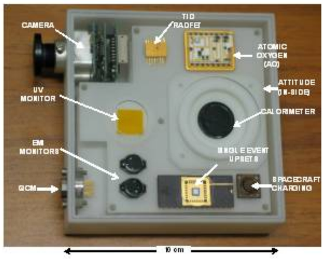
Particles				
Ions				
Mass	300 g			
Power	300 mW			
Volume	9 x 9 x 5 cm			
Cost				
	Electrons	Protons	Alfas	Gamas
Energy range	Internal and external			
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package				
Development				
Heritage				
Provider/PI				
Note				



CREAM

Charging Monitors

Particles				
Ions				
Mass	1 kg			
Power	10 W			
Volume	10 x 10 x 3 cm			
	Electrons	Protons	Alfas	Gamas
Energy range	surface differential voltage			
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package				
Development				
Heritage				
Provider/PI	Insoo Jun, JPL			
Note				



Triaxial Magnetometer (MAG)

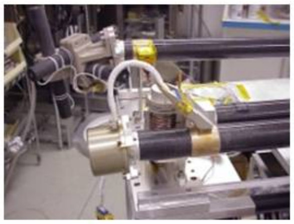
Magnetometers

Particles				
Ions				
Mass	~3 kg			
Power				
Volume	boom mount			
Cost	$2M			
	Electrons	Protons	Alfas	Gamas
Energy range				
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package	Electric and Magnetic Field Instrument Suite (EMFISIS)			
Development	Minimal Mod			
Heritage	Radiation Belt Storm Probe (2012)			
Provider/PI	Univ. Of Iowa / Dr. Craig Kletzing			
Note				

THEMIS FGM

Magnetometers

Particles				
Ions				
Mass	1.54 kg			
Power	0.85 W			
Volume	boom mount			
	Electrons	Protons	Alfas	Gamas
Energy range	0.5 nT/10 ms			
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package				
Development				
Heritage	THEMIS (2007)			
Provider/PI	K.H. Glassmeier, TU-BS			
Note				



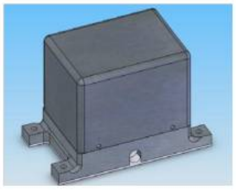
MMS Analog Fluxgate (AFG) and
Digital Fluxgate (DFG) Magnetometer

Magnetometers

Particles				
Ions				
Mass	2.5 kg			
Power				
Volume	7 x 4 x 3”			
	Electrons	Protons	Alfas	Gamas
Energy range	0.5 nT / 10 ms			
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package	SMART			
Development				
Heritage	Magnetospheric Multiscale (2014)			
Provider/PI	C.T. Russell, UCLA			
Note				

DSX DC Vector Magnetometer (VMAG)

Magnetometers



Particles				
Ions				
Mass	0.6 kg			
Power	0.55 W			
Volume	4 x 4 x 6 cm			
	Electrons	Protons	Alfas	Gamas
Energy range	100-10,000nT	+/- 0.1 nT @ 20 Hz		
Energy bins				
Energy resolution				
Counting ratio				
Time resolution				
FOV				
Geometric factor				
Instrument Package	DSX Wave-Particle Interaction Experiment			
Development	Minimal Mod			
Heritage	DSX (2012), ST-5, Polar, FAST, Galileo			
Provider/PI	UCLA			
Note				

Compact Environment Anomaly Sensor (CEASE II)

Multifunction Packages

Table 1 - Summary of CEASE Properties	
Property	**CEASE II**
Size	4.0 x 5.1 x 3.2 "
Mass	1.3 kg
Power*	1.7 Watts
Standard Interface	RS422 or MIL-STD-1553B
Telemetry (minimum)	10 bytes per 60 sec
Diagnostic Sensors	Lightly Shielded Dosimeter Heavily Shielded Dosimeter SEE Detector Particle Telescope Electrostatic Analyzer

Table 2 - CEASE Hazard Registers

Name	Acronym	Description	Typical Dynamic Range
Lightly Shielded Dose	LSD	Mission integrated radiation dose behind 0.08" of Al	0.2 to 118 krad
Heavily Shielded Dose	HSD	Mission integrated radiation dose behind 0.25" of Al	0.1 to 59 krad
Lightly Shielded Dose Rate	LSR	Radiation dose rate over the last minute behind 0.08" of Al	0.04 to 27 rads/hr
Heavily Shielded Dose Rate	HSR	Radiation dose rate over the last minute behind 0.25" of Al	0.04 to 27 rads/hr
Surface Dose	SUD	Solar panel damage parameter: "effective 1 MeV electron fluence"	1.8×10^{13} to 5.6×10^{16} electrons/cm^2
Single Event Effect	SEE	Register value is proportional to SEE probability	0 to 15 events/minute
Surface Dielectric Charging	SDC	Electron flux responsible for surface dielectric charging ($50 < E < 250$ keV)	5.0×10^4 to 2.3×10^9 electrons/cm^2-sec
Deep Dielectric Charging	DDC	Electron flux responsible for deep dielectric charging ($E > 250$ keV)	4.2×10^3 to 1.9×10^8 electrons/cm^2-sec

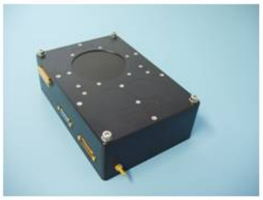
Energy Range	50-250 keV
Cost	$500k
Instrument Package	DSX SWx
Development	Minimal Mod
Heritage	DSX (2012), TSX-5, STRV-1C
Provider/PI	Amptek, Inc.
Note	possible resolution limitations

http://amptek.com/cease.html

MERLIN

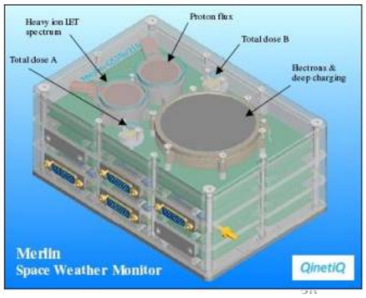
Multifunction Packages

Merlin is a space weather hazard monitor, which provides a comprehensive space environment monitoring capability on Giove-A. Merlin measures key parameters of the space environment which have practical importance for spacecraft in medium Earth orbit (MEO), namely: internal charging currents, energetic proton fluxes, ion LET spectra and total ionising dose rates in silicon.



Protons	> 40 MeV flux
Heavy ions	LET spectrum from 100 MeV g^{-1} cm^2 to 25100 MeV g^{-1} cm^2
Total dose	Measurements in krad (SiO$_2$) at two shielding depths
Internal charging/electrons	Internal charging currents (fA cm^{-2}) at three shielding depths. Detects electrons in range 200 keV to 2MeV (three channels)
Surface charging (optional)	Surface differential voltage or current (using remote unit)
Mass, power consumption	1.7 kg for standard unit, < 2.5 W
Instrument size	126 mm x 185 mm x 60 mm
Data interface	EIA RS422 standard, (others available)
Data storage	24 hours storage at standard sampling rate
Cost	$400k

http://events.eoportal.org/presentations/182/10000376.html



Heritage	GIOVE-A,CREDO,SURF,Shuttle,Skynet,UoSAT,STRV
Provider/PI	Qinetiq
Note	likely low fidelity

Multifunction Packages

ESA Standard Radiation Environment Monitor (SREM)

Particles	e ,p
Ions	
Mass	2.6 kg
Power	2.5 W
Volume	20 x 12 x 10 cm
Cost	~$500k

	Electrons	Protons	Alfas	Gamas
Energy range	0.5-1.5 MeV	10-20 MeV		
Energy bins	15			
Energy resolution				
Counting ratio				
Time resolution	100 kHz			
FOV				
Geometric factor				
Instrument Package				
Development	Minimal Mod			
Heritage	STRV-1C			
Provider/PI	Contraves Space / PSI			
Note				

APPENDIX C: Acronyms

APEX	Advanced Photovoltaic and Electronics eXperiments
AEEF	Alphasat Environment and Effects Suite
ARC	Ames Research Center
CDS	Charge Deposit Sensor
CER	Cost Estimating Relationship
CG	Center of Gravity
CRRES	Combined Release and Radiation Effects Satellite
DLR	Deutsches Zentrum fur Luft-und Raumfahrt (German Aerospace Agency)
DEOS	Deutsche Orbitale Servicing Mission
DPAF	Dual Payload Attachment Fitting
DSX	Demonstration and Science Experiments Mission
EDM	Electronic Discharge Monitor
EELV	Evolved Expendable Launch Vehicle
ESA	European Space Agency
ESD	Electrostatic Discharge
ESPA	EELV Secondary Payload Adapter
eV	Electron Volt
EVA	Extravehicular Activity
FOM	Figure of Merit
FOV	Field of View
FY	Fiscal Year
GCR	Galactic Cosmic Radiation
GEO	Geosynchronous Earth Orbit
GSFC	Goddard Space Flight Center
GTO	GEO Transfer Orbit

ISS	International Space Station
LANL	Los Alamos National Laboratory
LaRC	Langley Research Center
LCROSS	Lunar Crater Observation and Sensing Satellite
LEO	Low Earth Orbit
LET	Linear Energy Transfer
LRO	Lunar Reconnaissance Orbiter
LV	Launch Vehicle
Mbps	Megabits per second
MEES	MGS Environment and Effects Suite
MEO	Medium Earth Orbit
MGS	Manned GEO Satellite Servicing
MPS	Magnetospheric Particle Sensor
MPS	Multifunction Particle Spectrometer
NOAA	National Atmospheric and Oceanic Administration
NTE	Not to Exceed
PDR	Preliminary Design Review
PI	Principle Investigator
RBSP	Radiation Belt Storm Probe Mission
RESTOR	Reusable Earth Synchronous Tele-Operated Refueler
RSDO	Rapid Spacecraft Development Office
SCATHA	Spacecraft Charging at High Altitude
SIS	Space Infrastructure Systems
SIV	Standard Interface Vehicle
SPE	Solar Particle Event
SSCM	Small Satellite Cost Model
SPENVIS	Space Environment Information System
STP	Space Test Program Office

TEPC	Tissue Equivalent Proportional Counter
TID	Total Ionizing Dose
TRL	Technology Readiness Level
USAF	United States Air Force

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A trade study was conducted to evaluate options for collecting space environment data in geosynchronous earth orbit to support a future manned satellite servicing mission.

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Dosimeter; EVA; GEO; Magnetometer; Radiation; Satellite servicing; Space environment; Spacecraft charging; Spectrometer

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