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Science Mission Definition Studies for TROPIX

(Final Report)

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Abstract

This document summarizes the results of mission definition studies for solar electric propulsion missions that have been carried out over the last approximately three years. The major output from the studies has been two proposals which were submitted to NASA in response to Announcements of Opportunity for missions and an ongoing Global Magnetospheric Dynamics mission study. The bulk of this report consists of copies of the proposals and preliminary materials from the GMD study that will be completed in the coming months.

Acknowledgment

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Science Mission Definition Studies for TROPIX

1. Introduction

In an effort to generate interest in the use of solar electric propulsion (SEP) for science missions NASA Lewis Research Center put together a small team of scientists who were tasked to examine the possibilities. The team met several times and discussed the types of science missions that could profit from the use of SEP with a focus on missions that could not be done or done efficiently using chemical propulsion. The team also examined the problems of doing science on a satellite with large ion thrusters and how the science would be accommodated. The biggest issues were the use of very large solar arrays, the pointing requirements for thruster operation, and the effects of thruster operation itself. The major output from these studies was a succession of documents by the contributing parties (which are not all reproduced here) that culminated in two different mission proposals that were submitted to NASA in response to Announcements of Opportunity. Finally, the most recent work of the team was in support of a study for a specific mission that is part of NASA's "rodemap" for decade 2000 - 2010; the Global Magnetospheric Dynamics (GMD) Mission. This latter study is still in progress as this grant ends. As a result, only a partial report will be provide on the GMD effort.

2. Proposal and Study Efforts

2.1 TROPIX

The precursor to TEMPEST was the Transfer Orbit Plasma Investigation Experiment or TROPIX mission that was studied as a way to implement the use of a new SEP thruster that was under development by NASA. This study was just starting at the time the PI of this grant was approached to join the study team. The original TROPIX mission goals were to significantly increase our knowledge of the Earth's magnetosphere and to demonstrate an operational solar electric upper stage. Some of the objectives of the TROPIX mission were: 1) To map the energy spectrum of ambient charged particles in the magnetosphere throughout the geotransfer (GTO) orbit and to update environmental models; 2) Evaluate the plasma conditions, both ambient and induced, and characterize energetic particles versus altitude; 3) Evaluate the SEP spacecraft/plume interaction effects and the compatibility of electric thrusters with satellite systems; 4) Demonstrate a long life electric propulsion vehicle, validate guidance, navigation, control and satellite design concepts that allow long duration operations; 5) Measure the effect of radiation exposure on the SEP and satellite systems; and 6) Evaluate ion thrusters as plasma contactors. These were ambitious goals and the study team did address all the aspects of such a mission.

The basis for the SEP thruster accommodation was the NSTAR thruster that was a joint development program between NASA LeRC and JPL. Much of the preliminary SEP and early instrument accommodations and satellite design were described by Herr and Chock (1993) and Hickman et al. (1993). The study team took the work that had been and was being done on TROPIX and used it as a jumping off point for defining a new mission that is described below in section 2.1.2.

2.2 TEMPEST Mission Concept

2.2.1 TEMPEST Overview

Taking the performance parameters from the TROPIX SEP thruster (NSTAR units) and using essentially the same satellite subsystems, structure, etc. the team put together a mission concept that would make a tour of the inner magnetosphere at high and low latitudes from relatively low altitudes out to geocentric distance of 15 R_E (Earth radii). The two orbits were to be phased, by controlling the thrusting programs, so that measurements could be made on the same field lines over a range of equatorial altitudes at nearly the same time. A specific suite of science instruments was selected to make the measurements required to study the scientifically compelling topics of ring current generation and evolution, the impulsive "killer" electron radiation that has been recently discovered in the radiation belts, and the complex substorm processes. The mission required two SEP satellites launched separately on PEGASUS class vehicles into low earth orbit. The SEP systems were to spiral the satellites up towards their ultimate apogees over the period of two years. The instrument complement consisted of a magnetometer, plasma electron and ion sensors, energetic particle sensors, a relativistic (killer) electron sensor, AC and DC electric field sensors, and a spacecraft interactions package. The details of these sophisticated sensors can be found in the TEMPEST proposal (Appendix 1) along with a detailed description of the satellite and mission design. Below, we discuss the complement of energetic particle sensors that were one of Aerospace's major concept contributions to the TEMPEST mission proposal, along with radiation dose and mission constraint studies. Table 2.2.1 shows the top level science topics that Aerospace felt could be addressed by a TROPIX type mission. These also became a core reference of science topics for the TEMPEST mission.

Table 2.2.1 Partial List of the Scientific Objectives for TROPIX and Other SEP Missions - - Particle Perspective

Magnetopause Structure and Dynamics	**Energetic Particles as Tracers**
- Particle transport across the magnetopause	- Measure magnetospheric compression by solar wind
- Remote boundary sensing	- Magnetospheric dilation by ring current
- Energetic particle layers	- Drift-shell splitting effects to predict substorms
Magnetosheath	- Global field line modeling
- Source of sheath energetic particles	- Location of drift boundaries
- Correlations with magnetosheath waves	- Remote sensing plasmapause, plasma sheet, magnetopause
- Some studies of the bow shock and shock accelerated particles	**Radial transport**
Substorms and Tail Dynamics	- Radial-diffusion coefficients
- Plasma sheet energetic particle boundaries	- Convection of tail-accelerated particles
- Energetic particle acceleration	- Test particle adiabaticity
- Hot plasma flow	- Map morphology of nightside acceleration
- Plasma sheet thinning/expansion	- Source of high energy ($E > 1$ MeV) particles
- Plasma pressure gradients	**Relativistic Electron Effects**
- Substorm growth phase and onset timings	- Relativistic electron entry/acceleration
Source and Sinks of Particles	- Formation of transient relativistic electron belts
- Possible ionospheric sources	- Relativistic electron trapping and diffusion
- Field-aligned particle streaming	- Auroral zone electron precipitation spikes
- Pitch-angle evolution	- Ion-cyclotron wave interactions
- Solar particle access	- Relativistic electron coupling to middle atmosphere
- Adiabatic convection and energization	
- Convection boundaries	
Wave-Particle Studies	
- Natural particle precipitation	
- Effect of man-made signals	
- Upper atmospheric effects of precipitation	
- Detailed loss-cone measurements	

2.2.2 TEMPEST Energetic Particle Sensors (TEPS)

More than one type of sensor was required to meet the energetic particle measurement requirements for TEMPEST science. The sensors must provide quality measurements over the wide range of physical space spanned by the LOIS and HI orbits (LOIS and HI were the equatorial and high latitude TEMPEST satellites respectively) and the varied plasma region and processes that would be studied. Energetic particles, with their high velocities and large gyro radii, are excellent probes of the global state of the magnetosphere and provide temporal benchmarks for time dependent processes. In addition, understanding the energization of these particles was itself a fundamental goal of the Tempest Program. The range of energies that were required by the science described above is from 25 keV to 10s of MeV for electrons and to 100s of MeV for protons. The Tempest Energetic Particle Sensor (TEPS) system consisted of two components, the Energetic Proton and Electron Spectrometer system and the Ultra-Relativistic Electron Detector system which are described briefly below. They are state of the art sensors that fulfill all the science requirements for energetic particles (see Table 2.2.2), including the measurement of the notorious "killer" electron fluence and spectra.

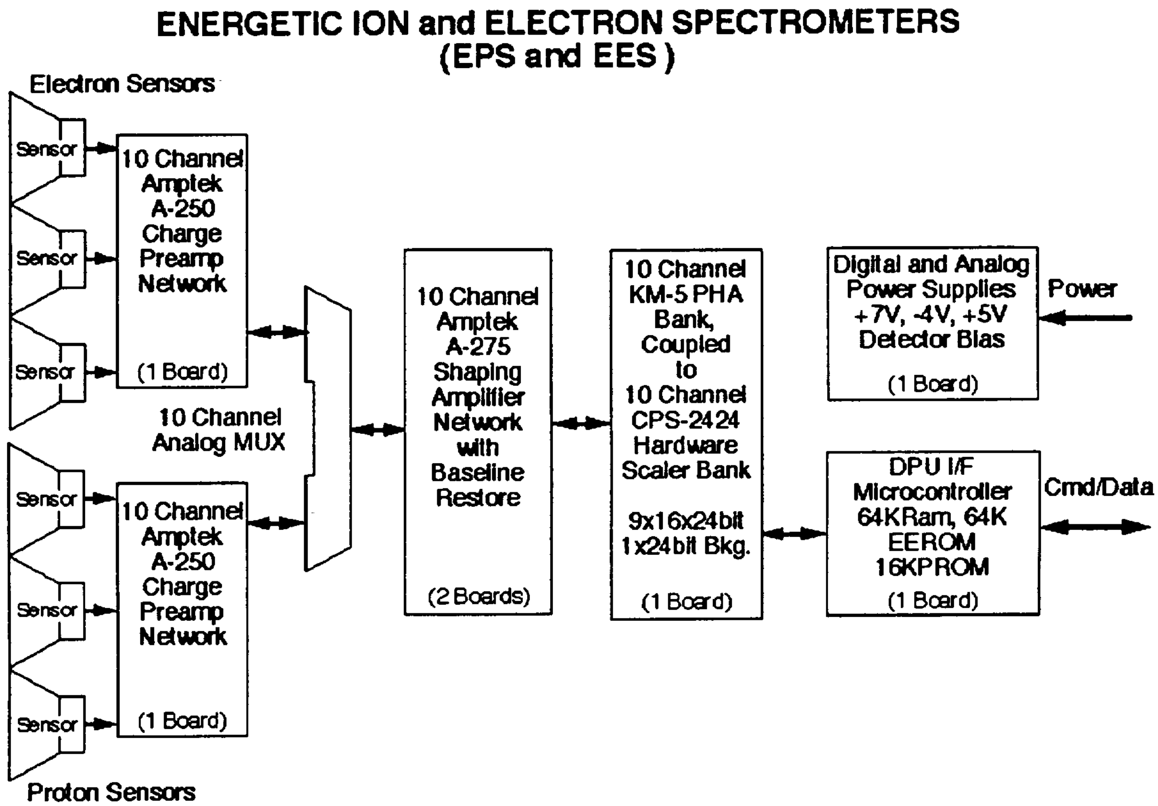
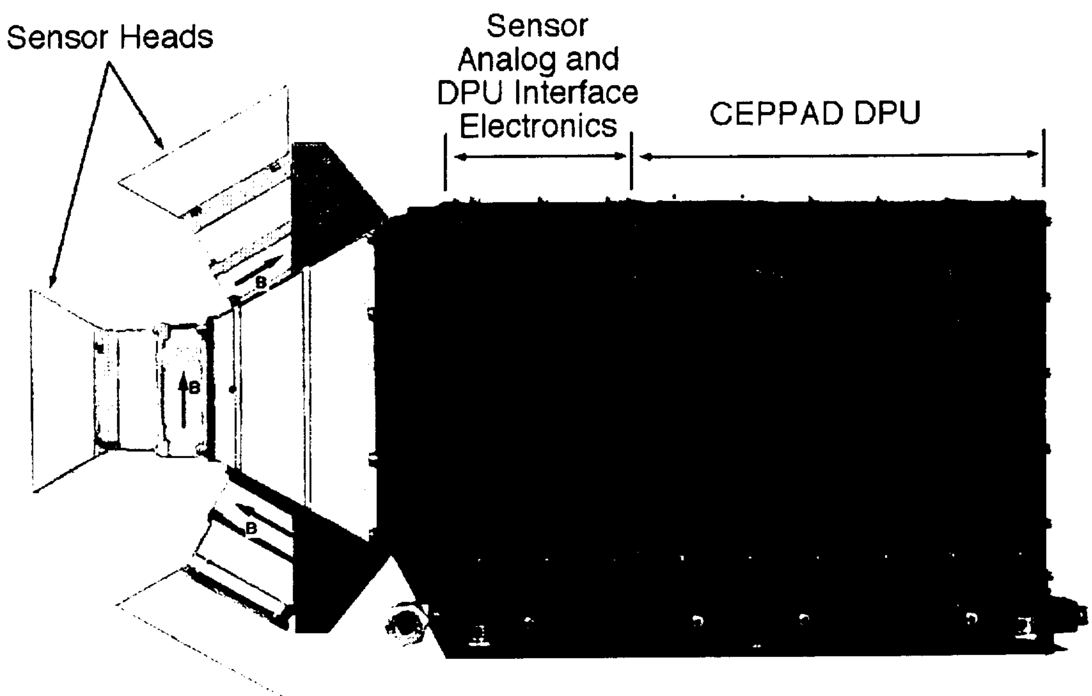


Figure 2.2.2.1 Block diagram of the Energetic Proton Spectrometer (EPS) and Energetic Electron Spectrometer (EES) for the TEMPEST satellites.

2.2.2.1 Energetic Proton and Electron Spectrometers (EPS and EES)

The EPS and EES are extensions of designs used on ISTP POLAR and Cluster spacecraft and their configuration is vary similar to one that will be flown on the European satellite CESAR. Both spectrometers use custom designed ion-implanted silicon strip detectors (Blake et al. 1995) that are coupled to AMPTEK amplifier chains, custom high density pulse height analysis (PHA) and scalar microchips and ACTEL field programmable logic arrays (FPGAs). Fig 2.2.2.1 shows a logic diagram of the EPS and EES system while Fig 2.2.2.2 shows a picture of such sensors as implemented on the GGS/POLAR satellite's CEPPAD experiment. Each spectrometer is composed of three removable/replaceable detector head assemblies that contain multi-pixel detector arrays (each head covers a 60° x 12° FOV), preamplifier and biasing networks plus collimation. The EPS contains, in addition, a broom magnet and yolk which sweeps out electrons up to 1 MeV (stray field < 9 nT at 1m) while the EES contains a light tight foil that keeps out protons up to 500 keV. The combined coverage of the sensors is a fan 180° x 12° and they are mounted so as to maximize the particle pitch angle coverage. The EPS and EES are passively cooled to guarantee useful measurements at and below their nominal stated thresholds of 20 keV. The strip detectors are heavily shielded in all directions other than the aperture and have an integral heavily shielded element to act as a penetrating particle background monitor. These type detectors have successfully flown on CRRES and POLAR and will fly on Cluster. The high density electronics were developed for the SAMPEX and ISTP program missions and have been thoroughly tested. Thus, the EPS and EES have good heritage yet are significantly more compact, are lighter and use less power than the equivalent sensors that were flown on the recent CRRES mission. For example, the equivalent sensors on CRRES had a 90 deg fan, a more limited energy range by a factor of 2 and geometric factors an order of magnitude smaller per pixel than the present units. The CRRES sensors did not provide their own counters yet were significantly heavier and used 33% more power than the EPS and EES. The multiplexing logic (ref. Fig. 2.2.2.1) allows 5 proton and 5 electron pixels to be sampled simultaneously. Ongoing efforts to further miniaturize amplifier chains may allow removal of the multiplexer so that all pixels are measured all the time while achieving further weight and size reduction.



Photograph of GGS/POLAR CEPPAD energetic particle experiment showing the configuration of sensor heads

Figure 2.2.2.2 The CEPPAD EPS sensor flown on the NASA GGS/POLAR mission. This unit also includes the digital processing unit for all the sensors in the CEPPAD experiment

2.2.2.2 Ultra-Relativistic Electron Detector (URED) Description

The URED will measure the spectrum of electrons in the energy range of ~ 1 to 40 MeV. A large, ultra-pure fused quartz Cerenkov radiator stops the electrons as they lose energy and emit Cerenkov radiation. This radiator, cylindrical or conical in shape and with a volume of about 1000 cm^3, must be large enough to stop the straggling electrons as they pass through it and, at the same time, pure enough to allow the Cerenkov light, mostly in the UV wavelength range, to reach the detectors without background from scintillation. Photomultiplier tubes (PMTs), with UV sensitive photocathodes to convert the light to electrical pulses, are used as detectors. The resultant signals are summed into a short fast pulse. The amplitude of the pulse

ULTRA-RELATIVISTIC ELECTRON SENSOR
Block Diagram

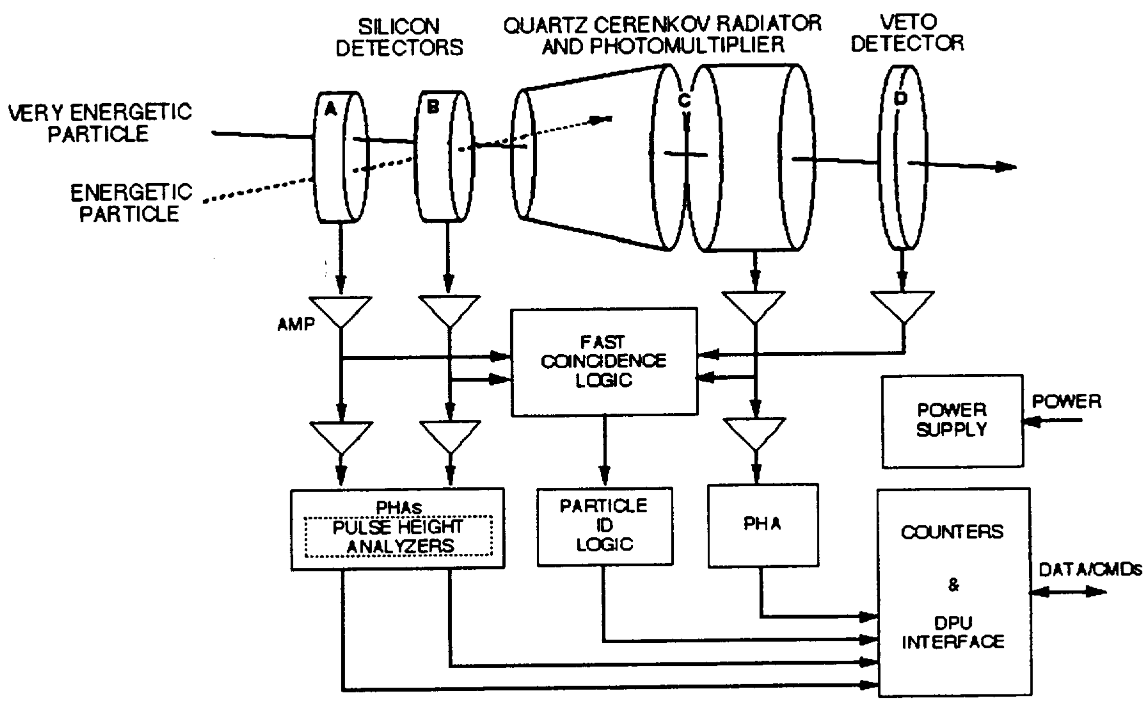


Figure 2.2.2.3 Block diagram of the Ultra-relativistic Electron Detector (URAD) for the low latitude TEMPEST satellite.

depends on the electron path length in the radiator and hence is a measure of the electron energy. Two solid state detectors, co-axial with the radiator and operated in coincidence with the Cerenkov signal (see Fig. 2.2.2.3), form an active collimator which defines a 25° acceptance half-angle and geometric factor of 1 cm^2-sr. An anti-coincidence shield in the form of a thin slab of fast plastic scintillator, viewed by photomultiplier tubes, is placed against the flat radiator side opposite to the collimator, to suppress background due to penetrating relativistic cosmic rays and electrons which fail to stop in the radiator. Amplitude criteria on pulses from the solid state detectors comprising the collimator, combined with coincidence requirements (or lack thereof) on the radiator and anti-coincidence shield, are used to sort out the various particle types detected by the system. The result is a clean measurement of relativistic electrons with high sensitivity.

The URED sensor is physically large because of the Cerenkov radiator volume necessary to stop relativistic electrons and the dimensions of the PMTs (see Fig. 2.2.2.3). While "solid-state PMTs" (SSD-PMTs) are now used in the laboratory, we have chosen for this proposal to design around standard ruggedized PMTs that have a long flight history. We are testing SSD-PMTs now and could have space flight experience with them in time for URED fabrication. If so, it would greatly reduce the size and, somewhat the mass, of the URED system. In any case, the URED as described (see also Table 2.2.2) is an extension of the CEPPAD HIST sensor on POLAR and of experiments flown on Department of Defense satellites and CRRES. For the first time, URED will allow us, to cleanly measure the very energetic electrons (killer electrons) with good sensitivity throughout the equatorial magnetosphere. URED uses many of the same high density amplifier, discriminator and counting microcircuits developed for the ISTP/POLAR CEPPAD experiments. This reduces the part count and volume by about and order of magnitude compared to the type of electronics used on the recent CRRES satellite.

Table 2.2.2: TEPS Instrument Summary

	EPS	EES	URED
Energy Range (keV)			
Protons	20 - 1500	-	2 - 100
Electrons	-	20 - 600	1 - 40
Fields of View			
Protons	180° x 12°	-	-
Electrons	-	180° x 12°	50° Conical
Geometric Factor (cm^2 sr)			
Total	2.5×10^{-2}	10^{-2}	1.0
Large Pixels	2.8×10^{-3}	1.1×10^{-3}	-
Small Pixels	2.8×10^{-4}	1.1×10^{-4}	-
Telemetry Rate (bps)	1500	1500	500
Weight (kg)	- - 3.5 (combined) - -		7
Power (watts)	- - 2 (combined) - -		7
Volume (cm^3)	- - 4400 (combined) - -		5000
Temperature (deg C)			
Operating	-40 to -5	-40 to -5	-15 to 30
Non-operating	-40 to +35	-40 to +35	-25 to +40

2.2.3 TEMPEST Radiation Dose Estimates

The radiation dose estimates for the two TEMPEST satellites were calculated by integrating along the mission orbit profile as provided by NASA LeRC. The NASA AE8 and AP8 radiation models were used to define the radiation environment. The expected dose for the equatorial satellite (TEMPEST - LOIS) is shown in Figure 2.2.3.1.

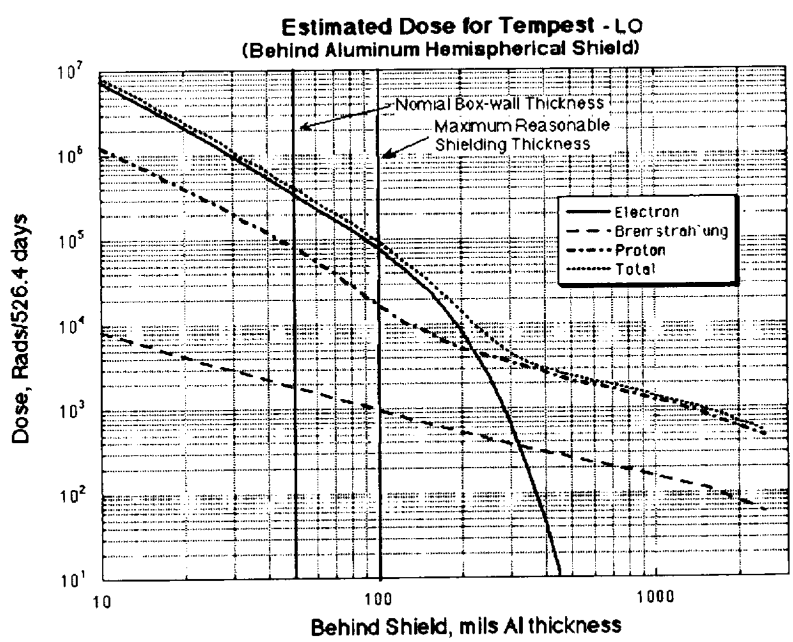


Figure 2.2.3.1 Expected radiation dose for the equatorial TEMPEST satellite.

The dose for the high latitude satellite is shown in Figure 2.2.2.4. The low latitude satellite has a somewhat higher radiation dose than does the high latitude satellite (Note differences in coloring on the two graphs. Follow the legends to identify the curves.) The initial operations of the satellites were to climb as rapidly as possible to get them through the damaging inner radiation zone protons from their initial injection altitudes. Once the geocentric altitude reached 2 R_E for the low latitude satellite and 1.25 R_E for the high latitude satellite the primary science mission began (ref. Appendix A page 7). Thus, the orbital trajectories were optimized to: 1) conserve fuel; 2) reduce radiation dose; 3) maximize the science data gathering using a recently developed program for SEP orbit analysis by Oleson (1993, 1994) and Oleson and Gefert (1994).

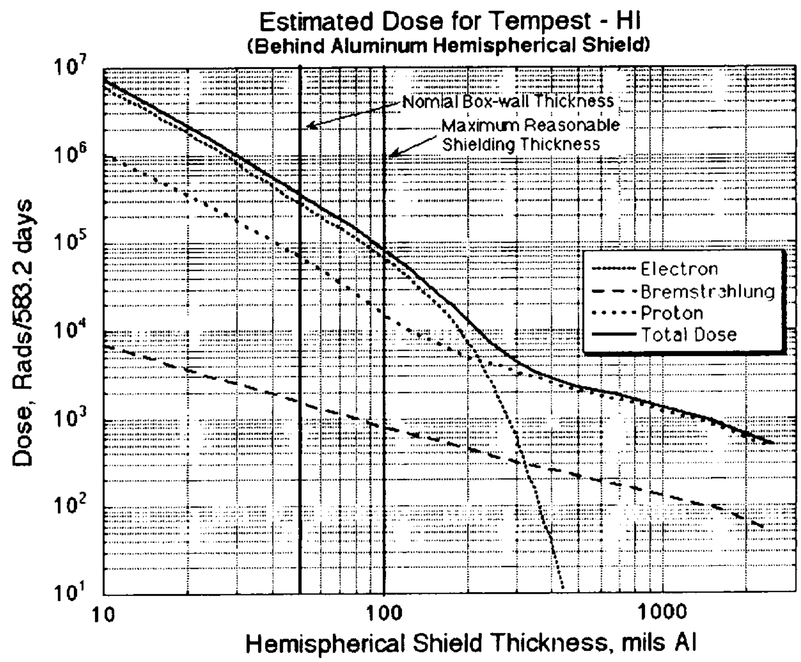


Figure 2.2.3.2 **Expected radiation dose for the high latitude TEMPEST satellite.**

2.3 Solar Electric Stereo Auroral and Magnetospheric Explorer (SESAME)

Following the submission of the TEMPEST proposal, the team continued to examine different science missions as the work on the NSTAR thruster progressed and the life testing of a qualification unit started. We examined several missions including missions to other planets and discussed what it would take for a mission inward towards the sun. The latter would have required other than solar arrays for power because of the high temperatures that would be encountered. After much sole searching, it was decided to put together a detailed proposal for a second near earth mission that would involve the integration of neutral atom imaging, a new and very interesting way of attempting to get an instantaneous "picture" of the magnetosphere.

2.3.1 SESAME Overview (exerpts from proposal: see Appendix B)

The Solar Electric Stereo Auroral and Magnetospheric Explorer (SESAME) attacks the highest priority objective of magnetospheric physics by complementing the simultaneous IMAGE and CLUSTER missions to provide stereo imaging of the dynamic magnetosphere and probe the interplay between its microscale and macroscale processes. SESAME provides critical ground truth enabling the images obtained by IMAGE and SESAME to be inverted to obtain three-dimensional source particle populations. SESAME achieves its high inclined, highly elliptical orbit and affordable cost by launching from the Space Shuttle and then reaching its final altitude with a solar-electric xenon-ion thruster. Its high inclination, 7 RE apogee orbit, is complementary to that of IMAGE. It carries an Energetic Neutral Atom Camera (ENAC), a Miniaturized Optimized Smart Sensor (MOSS) to measure the plasma electrons and ions, an Energetic Particle Sensor (EPS), and a fluxgate magnetometer (MAG).

The three-axis stabilization of SESAME would enable the ENAC to provide images with unprecedented sensitivity.

Recent NRC Committees on Solar and Space Physics and Solar-Terrestrial Research have placed global imaging of the magnetosphere as the highest priority objective of research following the ISTP program. The recent launch of the Equator satellite (2 December 1997) and recent approval of the CLUSTER reflight will complete the ISTP program. The first step in imaging the magnetosphere was taken by analyzing the energetic neutral atom (ENA) emissions detected by AZUR, ISEE, IMP-8 and, more recently by ASTRID and POLAR (Moriz, 1972; Hovestadt and Scholer; 1976; Hovestadt et al., 1972; Roelof, 1987; Roelof et al., 1985; Williams et al, 1992, and Henderson, 1997). The POLAR images show clearly what can be done with ENA imaging of the magnetosphere even with poor resolution (Henderson et al, 1997). Instruments that are designed specifically to measure ENAs, such as the one proposed here for SESAME, will provide high time and spatial resolution "pictures" of the magnetosphere. These combined with the same kinds of sensors on IMAGE will allow a deconvolution of the "images" to obtain the source particle fluxes. To support the ENA observations, SESAME will also make in-situ plasma and energetic particle observations while IMAGE is collecting ENA images. This will generate a ground truth reference for the IMAGE observations. In addition, SESAME carries wave and field measurements to provide a complete in-situ picture of the physical processes that occur throughout its orbit.

In the sections that follow, only the text generated at Aerospace for the SESAME proposal is given in detail. This shows our contribution to the study effort. The sections below also contain a description of the energetic particle instrumentation concepts generated specifically for the SESAME proposal and for SEP missions in general.

2.3.2 Wave Particle Interactions in High Latitude-Mid Altitude Regions (Aerospace input)

There exist old reports, circa 1971, of evidence for strong pitch-angle scattering of energetic electrons by electrostatic waves at moderately low altitudes in the near earth pre-midnight plasma sheet or ionospheric trough region (Vampola et al., 1971; Koons et al., 1972). The evidence indicated that >500 keV electrons were strongly scattered into the loss cone near 3000 km altitude, totally depleting the fluxes in that altitude region while the fluxes at latitudes away from the scattering region still contained significant fluxes. The corresponding signature of electron isotropy was observed at lower altitudes but without the flux reduction and no waves present. The authors indicated the waves were locally produced and were intense enough to locally scatter the electrons strongly in one traversal of the wave region. Such a mechanism could explain the kinds of precipitation spikes recently observed by the SAMPEX team (Blake et al., 1994) in the outer radiation zone and near the trapping boundary and would also be consistent with other observations of energetic electron precipitation. It differs from the conventional wisdom in that the wave-particle interaction does not occur near the equator but at low altitudes. This is one signature that the polar SESAME could easily see as it spiraled outward in polar orbit.

2.3.3 Ring Current

Since the launch of AMPTE CCE in 1984, there has been considerable work done on the ring current. CCE, Viking and, more recently, CRRES data have been used to examine many features of this important magnetospheric phenomena. There has been detailed modeling and observations of the equilibrium (Sheldon and Hamilton, 1993; Sheldon, 1994; Roeder et al., 1995a) and storm-time ring current (Chen, et al., 1993; Hamilton and Gloeckler, 1988; Roeder et al., 1995b). Most of the observational studies have focused on the major ion species H^+, He^+, He^{++} and O^+, while the models have usually focused on $H^+$and sometimes included He^+ and He^{++}. There has not been recent modeling of the oxygen component of the ring current. For that, one must look back to the work of Spjeldvik and Fritz (1978). Recently, Christen et al. (1994) has provided observations of the high charge states of oxygen and carbon in the quasi-trapping region, a source region for the ring current, while Fennell et al. (1995) has provided observations of the oxygen charge state spectra in the ring current. These most recent observations provide a reference for and constraint on ring current models.

Even with the substantial knowledge represented by these recent efforts, we are still unable to answer unambiguously the question: What fraction of the ring current ions are from the solar wind and what fraction are from the ionosphere? It remains for someone to provide a good measurement of the relative abundance of carbon in the ring current as an indicator of the relative solar wind contribution. Carbon is not of ionospheric origin and can be used as a tag of the solar wind source. So far, carbon has been measured in the solar wind (Gloeckler and Geiss, 1989), in the magnetosheath (Gloeckler et al., 1986) and, as mentioned above, the quasi-trapping region inside the magnetosphere. To unambiguously measure carbon in the ring current requires a composition sensor with a resolution , $M/\partial M \geq 20$ and the ability to reject the penetrating particle background experienced there. SESAME provides such a sensor and will spiral out through the ring current both at the equator and in polar orbit. The equatorial orbit will provide good local time coverage at all radial distances in the ring current and beyond to its source region. The polar orbit will provide good coverage from the equator to higher latitudes which will allow a more accurate measurement of the relative ion loss rates as a function of magnetic latitude. The combined set of observations will highly constrain new models of this important magnetospheric energy storage region. Such observations will also provide a reference measure of ring current evolution for future remote measurements such as those the Energetic Neutral Imaging (ENA) technique may provide.

2.3.4 Radiation Belts

The Earth's magnetosphere is known to be a powerful source of energetic particles, as are all known magnetospheres associated with planetary bodies with an intrinsic magnetic field. The most energetic particle populations in the Earth's magnetosphere are from in the ring current (see above) and the radiation belts. Recently, there has been a resurgence of interest in the physical processes acting in the inner magnetosphere and in the radiation belts in particular. This revival of interest has been stimulated by new observations from the CRRES and SAMPEX satellites that emphasize the dynamic nature of what was thought to be a relatively stable and dull region. This is especially true for the >25 keV particles which are the radiation damage causing component of the plasma. There is little, if any, information about latitudinal dependence of the plasma and energetic particle dynamic variations. This is reflected in our limited ability to make predictions of the radiation and satellite charging environments at medium to high inclination, for other than relatively low altitude orbits, even in the average sense. Also, the measurements used in the existing radiation belt models were a patchwork of off-equatorial data taken in the 20-30° inclination range in the radiation belts below geosynchronous altitude but above a few thousand kilometers, geosynchronous altitude data and relatively low altitude polar orbit data. The data coverage is far from complete spatially or temporally. Even the solar cycle coverage is spotty. Making measurements from 10s of eV to 1000s of keV in variable altitude equatorial and polar orbits would provide a new data perspective that has been missing as we built our limited schematic picture of these regions. In addition, it is clear that the radiation belts are a result of a multiplicity of coupled processes. One must understand the individual processes before we can hope to understand and appropriately model the radiation belts themselves.

As an example, the CRRES observations have shown that the radiation belts are very dynamic. There is a significant temporal waxing and waning of energetic particle fluence over a wide range of energies and from a few hundred kilometers to geosynchronous altitude and beyond (Blake, 1992; Blake, et al., 1992; Baker et al., 1994; Vampola, 1995). The most dramatic of these changes was simultaneous with a SSC the occurred during a solar particle event in March 1991. That particular episode caused the creation of new, very energetic proton and relativistic electron radiation belts to form below L=3 (Blake et al., 1992). There were several other significant energetic particle enhancements in the inner magnetosphere and radiation belt regions, during the CRRES mission.

More recently, the low polar orbiting SAMPEX satellite has observed strong relativistic electron precipitation throughout the outer radiation belt, out to auroral latitudes. These changes occur in association with or as a result of solar influences such as solar wind velocity and density variations, energetic solar particle events, and variability of solar photonic illumination of the atmosphere. We are finding that how the magnetosphere convection responds to changes in the solar wind and how it is affected by the variable ionization in the ionosphere are questions important to both the energetic and lower energy components of the plasma in the inner magnetosphere.

2.3.5 Energetic Particle Sensors (EPS/EES) for SESAME

Energetic particles, with their high velocities and large gyro radii, are excellent probes of the global state of the magnetosphere and provide temporal bench-marks for time dependent processes. In addition, understanding the energization of these particles is itself a fundamental goal of the SESAME Program. The range of energies that are required by the science described above is from 25 keV to 500 of keV for electrons and to 1.5 MeV for protons. The SESAME Energetic Particle Sensor (EPS) system consists of two components, the Energetic Proton and the Electron Spectrometer system. They are state-of-the-art sensors that fulfill all the science requirements for energetic particles.

Table 2.1.3 EPS/EES Characteristics

Parameter	Characteristic			
Energy range:	Protons	20-1500 keV	Electrons	20-600 keV
Field of View	180° x 12°			
Volume	4400 cm3			
Temp. Req.	Operating	-40 to 5 C	Non-operating	-40 to 35 C

The EPS and EES are extensions of designs used on ISTP POLAR and CLUSTER spacecraft and their configuration is very similar to one that will be flown on the European satellite CESAR. Both spectrometers use custom-designed ion-implanted silicon strip detectors (ref. 1) that are coupled to AMPTEK amplifier chains and custom high-density pulse-height analysis (PHA), scalar microchips (fig. 2.2.6) and ACTEL field-programmable logic arrays (FPGA). Each spectrometer is composed of three removable/replaceable detector head assemblies that contain multi-pixel detector arrays (each head covers a 60° by 12° FOV), preamplifier, and biasing networks plus collimation. The EPS contains, in addition, a broom magnet and yolk which sweeps out electrons up to 1 MeV (stray field <9 nT at 1m) while the EES contains a light-tight foil that keeps out protons up to 500 keV. The combined coverage of the sensors is a fan 180° by 12° and they are mounted so as to maximize the particle pitch angle coverage.

The EPS and EES are passively cooled to guarantee useful measurements at and below their nominal stated thresholds of 25 keV. The strip detectors are heavily shielded in all directions other than the aperture and have an integral heavily shielded element to act as a penetrating particle background monitor. These type detectors have successfully flown on the CRRES and POLAR satellites. The high-density electronics were developed for the SAMPEX and ISTP programs and have been thoroughly tested. Thus, the EPS and EES have good heritage yet are significantly more compact, are lighter and use less power than the equivalent sensors that were flown on the recent CRRES mission. For example, the equivalent sensors on CRRES had a 90° fan, a more limited energy range by a factor of 2 and geometric factors an order of magnitude smaller per pixel than the present units. The CRRES sensors did not provide their own counters yet were significantly heavier and used 33 percent more power than the EPS and EES. The multiplexing logic (like Fig. 2.2.2.1 above) allows multiple proton and electron pixels to be sampled simultaneously. Ongoing efforts to further miniaturize amplifier chains may allow removal of multiplexers so that all pixels are measured all the time while further mass and size reduction are achieved.

2.4 Global Magnetospheric Dynamics (GMD)

2.4.1 GMD Overview

The Global Magnetospheric Dynamics (GMD) study incorporated many of the elements of the TROPIX, TEMPEST and SESAME efforts. The study team's efforts in developing SEP missions will culminate with the generation of the GMD final report. GMD is a very ambitious program that would use the flexibility of SEP to perform a magnetospheric mapping mission that focused on the microphysics of plasma boundary layers, transition regions, and particle acceleration. The SEP is used to evolve the orbits of four satellites so that they can cover nearly the whole magnetosphere while maintaining them in a tetrahedral configuration. The satellites will start at moderate altitude in a transfer orbit. The orbit inclination will be lowered and apogee raised until the orbit is elliptical with perigee near geosynchronous altitude and the apogee is near 10 R_E geocentric. Then the orbit is circularized at 10 RE. The apogee is slowly raised to ~40 RE and at the same time the SEP thrusting torques the orbit to keep it in the magnetotail. Thus the orbit brushes the magnetopause, the flanks of the magnetosphere, and samples the magnetotail out to 40 RE in the equatorial plane. Finally, the SEP is used to rotate the orbit plane out of the equatorial plane while increasing or reducing the apogee until the final orbit has an inclination of 90° and a shape that conforms to the north - south extent of the magnetosphere and the noon meridian magnetopause shape. These orbit maneuvers will provide the first observations of the magnetopause at all latitudes from the north to the south pole and along the flanks from local noon to somewhat prior to local morning and after local dusk. All the while, the inter-satellite spacing of the tetrahedra will be controlled to correspond to the scale size of the micro physics processes that are occurring in the different regions of the magnetosphere. The complete details of the GMD mission and the science instrumentation will be describe in a forthcoming final report to NASA from UCLA (Prof. C. Russell). Some of the text for the GMD report are summarized below.

2.4.2 Partial Draft of the GMD Report - Preliminary Material Generated by Study Team

2.4.2.1 Global Magnetospheric Dynamics Mission

The Global Magnetospheric Dynamics mission examines the structure and dynamics of all the important currents and boundaries of the magnetospheric plasma using a tetrahedral constellation of solar electrically propelled satellites with variable spacing, that spiral out through the magnetosphere in the equatorial plane and back through the magnetosphere at high inclinations. This mission accomplishes all of the major objectives of the original Grand Tour Cluster or Maxwell mission but does so faster, better and more cheaply by concentrating its observing time on the portions of the magnetosphere that are most important to the energy transfer and momentum coupling process. The full interior volume of the magnetosphere is covered out to 40 Re in the tail. The dayside and nightside magnetopause is explored at both low and high latitude, and the entire forward portion of the magnetosheath and bow shock is explored at both low and high inclinations.

The study team consisting of many of the original members of the GTC working group will review the original objectives of the GTC/Maxwell mission in the light of the returns from the ISTP mission especially those from the Geotail spacecraft. It will review the capabilities of modern miniature sensors and advise on the payload required for these objectives. It will then devise trajectory design suitable to achieve these objectives taking care to obtain sufficient observations in each region of space to probe the processes under a variety of plasma conditions. The team includes all the expertise needed for this study including a professor of aeronautics experienced in solar electric propulsion and advanced mission planners from NASA Lewis. We expect that the resultant mission will be of the solar-terrestrial probe class or possibly somewhat larger.

2.4.2.2 Science Objectives

In the late 1970's the Space Science Board, chaired by Stirling Colgate, undertook a comprehensive study of Space Plasma Physics [National Academy Press, 1978]. Six general plasma physics processes were identified by the Colgate panel as vital to the understanding of space plasmas. These processes were: magnetic field reconnection; turbulent interactions in a magnetized plasma; large scale interactions of flowing magnetized plasmas; acceleration of charged particles; particle confinement and transport; and collisionless shocks. All six areas are relevant to astrophysics and the latter two are relevant to fusion research. Later the Space Science Board's Committee or Solar and Space Physics under C. F. Kennel developed a research strategy for the field [National Academy Press, 1988]. In the area of magnetospheric physics the Kennel Report identified the time-dependent interaction between the solar wind and the Earth as the primary focus involving: the transport of energy, momentum, plasma and magnetic and electric fields across the magnetopause; the storage and release of energy in the Earth's tail; the origin and fate of plasmas in the magnetosphere; and how the Earth's magnetosphere, ionosphere and atmosphere interact.

The International Solar Terrestrial Physics program attempted to address this research strategy with a coordinated series of observations in the solar wind, in the magnetotail and in the polar magnetosphere, together with a cluster of 4 spacecraft at intermediate latitudes with separations of 1000 km or more. In 1990 the Space Physics Strategy Implementation Study recommended a post-ISTP strategy to include the detailed investigation of the following critical unexplored or underexplored regions: the high latitude magnetopause tailward of the Earth; the subsolar magnetopause; the near-Earth equatorial plasma sheet; the auroral acceleration region and the distant magnetotail. In response to this recommendation a study effort of a comprehensive 4 spacecraft mission called Grand Tour Cluster was commenced with a focus on the problems of space plasma physics recommended for study by the Colgate report, namely: the processes occurring at the subsolar magnetopause; the instability in the near-earth nightside magnetosphere that appears to be the initiator of substorms; the nature of the high latitude magnetopause and the polar cusp; and the structure and dynamics of the distant tail. The four spacecraft would use chemical propulsion and gravity assists from the moon to explore first the equatorial magnetosphere out to the distant Lagrangian point and then change inclination to explore high latitudes.

The plans that were made for Grand Tour Cluster are now moot. The original mission was far too expensive for today's available resources. However, there are other problems with the original plan. GEOTAIL has now explored the distant tail and it is clear the substorm processes are initiated well inside the orbit of the moon and that little is to be gained by the distant portions of the GTC trajectory. Second, GTC did not explore completely the unexplored and poorly explored high latitude region. Rather, its high latitude coverage was solely on the surface of a torus. Third, advanced propulsion systems are now ready for flight that enable GTC to be performed faster, more cheaply and better. The objective of this study effort is to develop a plan for such a mission: to refine the objectives in the light of current understanding; to define the optimum payload; trajectory, and spacecraft system that will address all the scientific objectives of GTC in an affordable manner. Since this mission differs extensively from GTC in basic design, we have chosen to rename it after its goals: the Global Magnetospheric Dynamics mission.

2.4.2.3 Science Rationale

The magnetosphere and its surrounding region of shocked solar wind plasma, often called geospace, has been described as a region in which the magnetohydrodynamic equations are generally valid punctuated by a finite number of spots where they are not. Missions such as ISTP have concentrated on the places where MHD is obeyed. The Global Magnetospheric Dynamics mission seeks out those places where it is not. These places are in the thin boundaries that separate the disparate plasmas of the magnetosphere and its surroundings: the tail current and plasma sheets, the magnetopause at the nose and at high latitudes, the polar cusp and the bow shock. We consider each of these regions in turn.

2.4.2.4 The Magnetotail Current and Plasma Sheets

It is clear that the tail undergoes a global instability during substorms. Not only is the entire nightside ionosphere affected by the onset of the substorm but the flux content of the tail is altered to a significant extent. It is also as clear that microscale processes occur as well. Originally it was believed that ion or electron tearing of the current sheet would lead to reconnection of the two lobes and the subsequent collapse of the tail. More recently a current disruption, presumably close to the Earth, has been proposed to be the initiation process. In either case it is the local breakdown of MHD that is believed to be the trigger. In order to study this process we must be able to measure gradients on the scale size of the expected process. Two spacecraft measurements with ISEE have shown that the neutral sheet can reach thicknesses of under 1000 km and "flux ropes" and "neutral points" in the tail can have dimensions of well under 1000 km. We must be able to characterize these features in their full three dimensionality to understanding how they work. We are unable to do this with the two spacecraft, ISEE 1 and 2. We need the 4 spacecraft of the proposed GMD mission that crosses completely through the region of expected instability, from synchronous orbit to nearly the orbit of the moon.

2.4.2.5 The POLAR Cusp

The least explored region in the magnetosphere is the high altitude polar cusp. This region was visited by two missions HEOS 2 and Hawkeye but each had low data rates and limited payloads. Both missions reported evidence for transient events, possibly reconnection but were unable to provide either a complete exploration of this phenomenon, nor completely survey the region around the cusp. Most importantly neither spacecraft was able to measure the velocity of the boundaries or probe the three dimensional structure. The soon to be launched Cluster mission may address some of these areas but its rather large interspacecraft separation, >1000 km, may limit its ability to identify small scale processes, and its limited time in the cusp region will also restrict how much can be learned. It is important to probe this region because this is the region in which magnetosheath plasma has direct access to the ionosphere. It is the region in which plasma, accelerated by dayside reconnection, enters the magnetosphere proper. It is the region in which reconnection is thought to occur for northward IMF leading to the formation of the low latitude boundary layer. However, much of this must remain speculation until we have measurements that can identify and characterize the processes taking place. The Global Magnetospheric Dynamics mission will spend sufficient time in this region and provide the multipoint closely spaced data that will enable processes and features to be fully characterized.

2.4.2.6 The Magnetopause

ISEE 1 and 2 and AMPTE UKS/IRM provided much data near the nose of the magnetopause and much was learned about the formation of the boundary under quiet conditions. Unfortunately during interesting times (i.e. when MHD is not being followed) the dynamics of the boundary cannot be determined from only two spacecraft. Cluster will not address this region of space, nor will it have the interspacecraft separation needed for magnetopause studies, about 500 km or less. However, it is this region that is the key area for controlling flux transfer to the magnetotail. While the low latitude region controls the flux transfer process, the high latitude region is where the energy flows into the magnetosphere. Despite this fact, we have never explored this region even with a solitary spacecraft except with the occasional passage of an interplanetary or planetary mission and the occasional pass of IMP 8. We do not know for example what the high latitude extension of an FTE looks like. We do not know how strong is the normal component across the magnetopause and we do not know over how wide a swath on the boundary this interconnected magnetic flux occupies. The GMD mission will completely cover this region and provide the pioneering observations presently lacking in this area.

2.4.2.7 The Magnetosheath and Bow Shock

The axisymmetric models of the solar wind flow past the magnetosphere of gasdynamics have given way to non-axisymmetric models with MHD flows. The MHD solutions bring the additional complexity of three (propagating) modes: the fast shock, and possible standing Alfven and slow mode waves. These latter two waves are less robust than the fast mode shock and may be difficult to observe without multipoint measurements. In particular the guided propagation of the slow mode wave may lead its effects to be restricted to a thin region of space near the magnetopause and to move as the IMF changes orientation. Moreover, kinetic scale effects may be important here. Especially to be noted are the mirror mode waves in the sheath that are believed to be caused by a kinetic, not MHD process. Finally the bow shock itself is a very thin region, most certainly not obeying MHD. Structures run as thin as a few km at times while the separation distances in earlier missions such as Cluster are far too large to resolve these scales. The separation of the GDM spacecraft will be coordinated with the phenomena to be studied and will probe the shock and its associated processes at the appropriate scale.

2.4.2.8 Acceleration of Charged Particles

Plasma from the two potential sources of magnetospheric particle populations generally has energies much lower than are found in the magnetosphere. This implies the magnetospheric particles have been energized. Much of the energization occurs in the outer regions of the equatorial magnetosphere, in the high latitude auroral regions, and in the magnetospheric boundary and current layers. The GMD mission's variable orbit profile is designed to take the tetrahedral satellite configuration through many of these particle acceleration regions such as the inner magnetotail current sheet, the dayside magnetopause current sheet from the equator to the polar regions, and the nightside substorm injection regions. The tetrad also traverses the auroral field lines over a range of altitudes, crosses all the boundary layers of the magnetosphere and will cover reconnection sites at the magnetopause and in the magnetotail, as discussed above.

Here, we will examine some issues related to particle energization above geosynchronous altitudes. One such energization process that has drawn much interest and controversy is that associated with the substorm process. The present picture of this process is one in which the plasma in the near earth nightside plasma sheet (15 - 30 Re) is accelerated in the substorm electric field associated with the dipolarization of the magnetic field and the associated inductive electric field, such as describe by Birn et al., (1997b) and others. This is one in a class of particle acceleration in direct electric fields. Near geosynchronous observations of dispersionless substorm plasma injections show that the relative motions of the ions and electrons and the measurement platform position determine what is observed. This can range from ion only injection signatures near dusk to electron only signatures near dawn. In between, the ion signature leads, is simultaneous with, or lags the electron signature as the observing platform moves from dusk through midnight to dawn. Following the injections both ion and electrons exhibit temperature increases with the ion increase occurring predominantly in the >40 keV ion fluxes. These signatures have been summarized recently by Birn et al., (1997a).

The substorm injection process has been modeled by many theorists. The particle energization near the expected X line in the near earth magnetotail has been examined and modeled for several years (Birn et al., 1997b; Joyce et al., 1995; Moses et al, 1993; Sachsenweger, et al., 1989). The most recent of these efforts has used MHD simulations to generate the time dependent magnetic and electric fields and then traced the paths of particles through it to find where the energization occurs (Birn et al., 1997b; Joyce et al., 1995; Hesse and Birn, 1991). These calculations provide both estimates on the amount of acceleration that occurs and some estimate of the position in the tail and the scale size of the acceleration regions for the model conditions. The results show that there is a combination of quasi adiabatic and non adiabatic components to the ion energization.

In the tail regions the low energy plasma component **ExB** drifts into regions of increasing magnetic field strength during both quiet and disturbed times. The resultant energization or betatron acceleration of the low energy component occurs more slowly during quiet times but continuously occurs. Thus this process does not produce a dramatic flux enhancement in the low energy plasma fluxes in the near earth regions during enhanced electric field periods relative to pre existing fluxes. It has been shown by Christon et al. (1988; 1991) that the source plasma ion distributions have spectra that are quite flat at lower energies and quite steep at high energies above a characteristic spectral "knee". Thus, any adiabatic heating of the low energy component does not cause a significant flux increase. So, while this process does accelerate the plasma during transport from the outer environs to the inner magnetosphere, it generally does not give rise to dramatic changes in the low energy plasma component. Nevertheless, GMD will make detailed measurements of the plasma drifts and provide significant detail on the strength and scale size of enhanced electric field regions throughout its orbit on spatial scales up to a few Re.

Model calculations show that the high energy component (>10 keV) of the plasma distribution is dramatically energized and modified by non adiabatic processes in the presence of the substorm electric fields and a near-Earth x-type neutral line (i.e. meandering particles). The substorm model electric fields are strongest earthward of the neutral line and this is where the greatest ion energization is predicted to occur. For example, the Birn et al. (1997b) calculations show that the greatest ion energization occurs over a region of a few Re in X_{GSM} earthward of the near-Earth neutral line with the greatest energy gained by ions that have drifted into the strong substorm electric field region (expected to be near $Y_{GSM}=0$ in the tail) from the dawn side of the tail.

The predicted X_{GSM} scale size and position of this strong electric field region, just earthward of the X line, can be tested by GMD. Using a satellite spacing of a few Re and controlling the orbital configuration so that apogee remains in the near earth tail for an extended period allows GMD to make multiple particle distribution function measurements over the whole energy range from thermal to high energies in the critical X_{GSM} = 8 - 40 Re region. Thus we expect that GMD will provide the definitive measurements for testing the models of the substorm energization and injection process.

The magnetopause current sheet system is also a site of magnetic reconnection, much like the tail. The electric field there is related to the magnetic field intensity and direction, the plasma flow velocity, and current density. If the plasma flow and magnetic conditions are right a neutral line can form and reconnection will proceed. The issue is the level of acceleration that the plasma will experience in the process. On most of the dayside magnetosphere the magnetic field generally does not have sharp curvatures like in the tail and particles do not have the ability to travel large distances parallel to the electric field. There is an energy gain associated with the reconnection processes itself. The different reconnection models all show that the thermal speed of the ions increases across the shock that forms at the reconnection site to levels of order of the Alfven speed (a few hundred eV for typical conditions). The electron energy gain depends on the structure of the shock and the nature of the electron - ion coupling. The scale size of the dayside merging site or diffusion regions itself is unknown but expected to less than the few hundred to ~1,000 km thickness of the magnetopause. The tetrad of GMD satellites makes the investigation of the dayside reconnection site possible and would allow the verification of the particle acceleration there.

Recent POLAR observations have indicated that significant particle acceleration may be occurring in the high altitude polar regions near the cusp (Chen, et al., 1997) and possibly on reconnection points on the near cusp tail lobe (Spence, et al., 1997). The Chen et al. (1997) observations are of >100 keV protons and He ions that show trapping signatures in regions that extend through the cusp to the mantle. It is possible that these energetic ions have drifted from the plasma sheet into a trapping geometry associated with the magnetopause currents above the cusp. However, the authors note that their existence in and near the cusp combined with their solar like composition argues for a new acceleration region capable of accelerating solar wind plasma to very high energies there. Sheldon et al., 1997 has argued that the particles can be accelerated via diffusion processes by the fluctuating electric and magnetic fields in this pseudo trapping region.

Spence et al. (1997) observed polar energetic particles (PEPs) which they argued were accelerated from the solar wind at reconnection sites on the high altitude dayside tail lobe. This is based on the fact that a preponderance of the observations occurred during northward IMF conditions. These particles are observed poleward of the cusp and often have solar wind like composition signatures. The PEPs are generally much more spatially localized than the Chen et al. (1977) observations. In either case, the exact spatial dimensions are not known. The GMD tetrad could provide data on the scale size and, because of its more flexible orbit control capability, provide definitive observations that would determine whether there is indeed particle acceleration occurring in and poleward of the dayside cusp/cleft region.

As noted above, the tetrad of satellites will sample the auroral field lines over a range of altitudes and latitudes. The spacing of the satellites will be varied over a range of distances that will include auroral arc scales at satellite altitude. Generally, GMD will be at altitudes relatively high above the region where the auroral acceleration takes place (usually < 4 Re altitude) where it will make detailed observations of the resultant accelerated ion and electron outflow. On the auroral flux tubes the ion acceleration will generally be of two types, field aligned acceleration by parallel electric fields and perpendicular heating by ion cyclotron waves. Recent observations by the Fast satellite (Carlson et al., 1997, Klumpar et al., 1997)) have substantiated the ion conic generation by a "pressure cooker" type mechanism (Gorney et al., 1985) involving ion cyclotron waves, have reconfirmed the existence of the potential drops and parallel electric fields, and have also shown that ionospheric electrons are accelerated upwards as part of a concentrated return current by a weak field aligned electric field (reversed relative to $E_{||}$ in the auroral flux tube). GMD can examine the particle distributions to estimate the magnitude of the field aligned potential drops on auroral flux tubes and the scale size of the potential drop regions and infer the spatial gradients in the field aligned potential drops for comparison with estimates based on low altitude observations (Gorney, 1988) and theoretical considerations (Borovsky, 1993).

The GMD tetrad will traverse the region of the bow shock over a wide range of latitudes and longitudes. The role of the bow shock in accelerating particles to relatively high energies has had a long history. For example, Scholer et al, 1980; Anagnostopoulos and Sarris, 1988 (and references therein) discuss whether acceleration of solar wind ions to high energies via the Fermi mechanism can and has occurred on the quasi-parallel regions of the bow shock and whether solar ions are accelerated during their interaction with the quasi perpendicular regions of the bow shock by drifting parallel to the **V** x **B** electric field at the shock (another meandering particle acceleration). The Fermi mechanism has also been invoked to explain observations of energetic particles moving upstream in the solar wind near the bow shock. However, some have argued that these upstream particles are magnetospheric in origin (Sarris et al., 1987; Sibeck et al., 1988). The bow shock drift-accelerated ions have been called on to explain both upstream and magnetosheath populations of energetic particles. The GMD tetrad, at large separations, will be able to make critical observations upstream, downstream, and in the shock region for shock orientations from perpendicular to parallel and provide conclusive evidence for testing such acceleration mechanisms.

2.4.2.9 Waves and Turbulence.

One of the results of more than three decades of in-situ magnetospheric observations is that turbulence occurs on all length scales from less than 1 km to greater than 10^4 km within the magnetosphere. Turbulence, for convenience, may be divided into a microturbulence regime and a macroturbulence regime. Macroturbulence can be characterized by MHD behavior, that is by fluid-like macroscopic variables. Generally, length scales for macroturbulent phenomena are larger than an ion Larmor radius. Microturulence requires information of the particle-distribution function in phase space. Microturbulence may be further divided into regimes in which wave-wave or wave-particle interactions dominate. In the former, the transfer of energy is among wave numbers spectrum such as a Komogorov spectrum. Where wave-particle interactions dominate, however, there is a narrow range of wave numbers where instabilities occur.

We often discuss the flow of plasma in the magnetosphere on the largest scales as one driven by convection and is sunward on closed-field lines and anti-sunward on open-field lines, such as those of the polar cap. However, these flows are extremely turbulent. The scale sizes displayed by the aurora from the planetary scale of the oval to the micro-scale of discrete arcs illustrate this spectrum of turbulence. On the microscale side, microturbulence relates to reconnection, acceleration of energetic particles, and the confinement or transport of particles.

GMD is well suited to studies which will provide basic insight into several turbulence issues in the magnetosphere. In particular, GMD will provide vector magnetic-field measurements from four variably spaced points with separations from ~50 km to 2 R_E. The rapid accumulation of plasma distributions by state-of-the-art instrumentation will enable progress toward bridging the studies to microturbulence and instabilities to meso- or macro-scale turbulence. Turbulence carried by auroral field lines to the outer magnetosphere such as at the inner edge of the plasma sheet and its boundary layer are an example of the type of problem which may be addressed by GMD. GMD will make multipoint, multiscale observations of these same field lines in the near equatorial outer magnetosphere after the full range of turbulent flows have evolved. The fast plasma sampling will provide insight into how the distributions and flows have evolved both spatially and temporally.

2.4.2.10 Approach

The original Grand Tour Cluster/Maxwell (GTC) mission planned to tour the outer part of the magnetosphere in a finite number of distinct steps including a rearward Lagrangian point tour and a high-latitude leg attained through orbital cranking using lunar gravity. A key element of this mission is that the spacecraft would fly in a much tighter formation where needed than the present ESA Cluster mission and would fly in critical regions missed by Cluster. We retain those features in GDC but have replaced the chemical propulsion with SEP which provides an order of magnitude more specific impulse than chemical rockets. This added capability allows a different approach to exploring the magnetosphere as well as reducing substantially the mass of the four spacecraft. The entire volume of the magnetosphere can be explored, not just certain planes or shells swept by an inclined orbit as the Earth circles the sun. A Delta launch vehicle can put the four GMD spacecraft into a geo-transfer orbit. Once there, the GMD satellites would spiral out slowly, pausing frequently to obtain sufficient sampling and to make observations without thruster operation. During the pauses various inter-satellite separations will be used to probe spatial scales from 10's of km to thousands depending on the radial distance. Experience from the ISEE mission shows that there is not a single optimum separation but a range that should be explored (Russell, 1994). The spiraling would continue through the "current disruption" region, through the near-Earth current sheet and out to 40 R_E. At this furthest point the SEP thrust would be used to change the orbital inclination to nearly polar. Then the satellites will spiral out further tailoring the orbit to the magnetosphere's shape and make frequent observations at a variety of radial distances and separations. We have allowed four years to cover the critical regions of the magnetosphere so that all regions receive adequate observations

2.4.2.11 Science Closure

To illustrate how this mission will resolve many of the outstanding problems of the magnetosphere, we examine first the question of the nature and location of the initial substorm disturbance on the nightside. The GMD mission will be the first four-spacecraft mission to probe this region from synchronous orbit outward. The substorm onset times will be determined from the onboard AKR measurement and the ground-based measurements. then the nature and timing of any disturbances in the field and plasma of the earliest response is found and the nature of that disturbance, (flux rope, neutral point or other) is found. A second objective in the nightside magnetosphere is to determine the geometry and source of plasmoids in the tail. In this study we will use the energetic particle data to probe the openness of the tail field lines when we are in and near plasmoids and compare the observed structure at the four spacecraft with numerical models of plasmoids. If we find that the spacecraft are too close or too far apart the separations will be adjusted. This flexibility is a hallmark of solar electric propulsion (SEP). A third example is the flux transfer event on the dayside magnetosphere. Again we will use the energetic particle data to determine the topology of the magnetic field. We will then compare the plasma characteristics and field characteristics at each of the four sites with models based on the various competing models (impulsive penetration, boundary motion and connected flux rope) to determine which model best explains the observations.

2.4.2.12 Science Requirements for Energetic Particle Measurements

Energetic particles are sensitive to both small and large scale size phenomena. Because of their relatively high velocities, much greater than typical plasma flow velocities, they provide good diagnostics of distant magnetospheric process and are excellent temporal markers of time dependent processes such as substorm onsets. The temporal, energy and angular resolution required for the GMD particle measurements are determined mostly by the scale size and velocity of the regions to be studied. The scale size and velocity of the current layers and boundaries that will be the major focus of the GMD mission range from velocities of 10's to 100's of km/sec with thickness of 10's to 1,000's km for the magnetopause and its current systems to velocities of 100's to 1,000's of km/sec and a few Re in the magnetotail. Previous observations show that the range of particle energies observed extends from plasma energies up through ~1 MeV throughout the magnetospheric regions that will be covered by GMD. In fact, one of the outstanding problems is to understand how >100 keV particles are accelerated in the outer magnetosphere, beyond geosynchronous orbit.

To obtain reasonable sampling of the boundaries, to remotely sense their approach and recession from the GMD spacecraft, and to obtain a good picture of boundary shapes, given their velocities and thicknesses as noted above, requires that the energetic particle sensors have a temporal resolution of order 0.1-0.5 seconds. For example, a magnetopause moving ~50 km/sec relative to the GMD tetrad in the magnetosheath can be sensed ~800 km away with 20 keV protons (gyro radii of ~800 km in 25 nT field) If the 20 keV proton angular distribution is measured faster than 2 samples/sec then about 30 samples can be obtained while the structure is within a gyro radius of GMD. In the near earth plasma sheet the structures move at hundreds to a few thousand km/sec and can be sensed about 4000 km away from the satellites. Thus in the tail one requires sample rates of order 5 samples/sec in order to obtain about 15 to 30 samples as the structure approaches or leaves the satellite region. For geometric factors of order 10^{-3} the counting statistics is tolerable at these sample rates for 20 keV protons (better for electrons) but higher energies require longer sample times in proportion to $\sqrt{E}$. In summary, the energetic particle instruments need to measure particle pitch angle distributions at sample rates ≥ 5/sec, measure particles with energy from 20 to 1,000 keV, and must have geometric factors large enough to provide good counting statistics at the highest sample rates.

2.4.2.13 Aerospace Energetic Particle Spectrometers

Aerospace put forward an energetic particle measurement concept that could meet the science requirements discussed in Sec. 2.4.2.9 above. The Aerospace Energetic Particle Spectrometers (or AEPS) are based on a technology developed for the CRRES, SAMPEX, POLAR and Cluster missions. The AEPS type instruments have continuously evolved over time at Aerospace. The spectrometers themselves use recent advances in both detector and electronics technology. The detector elements are strip detectors of the type produced by Micron Semiconductor Inc. in Great Britain. The hybrid amplifiers and processing logic make use of both large scale integrated (LSI) circuits, application specific integrated circuits (ASICs), and field programmable gate array logic (FPGA) devices to achieve powerful yet compact spectrometers that can provide the full angular and energy distribution of electrons and ions within the required 200 msec time resolution over the energy range discussed above.

AEPS Sensor -- Configuration #1

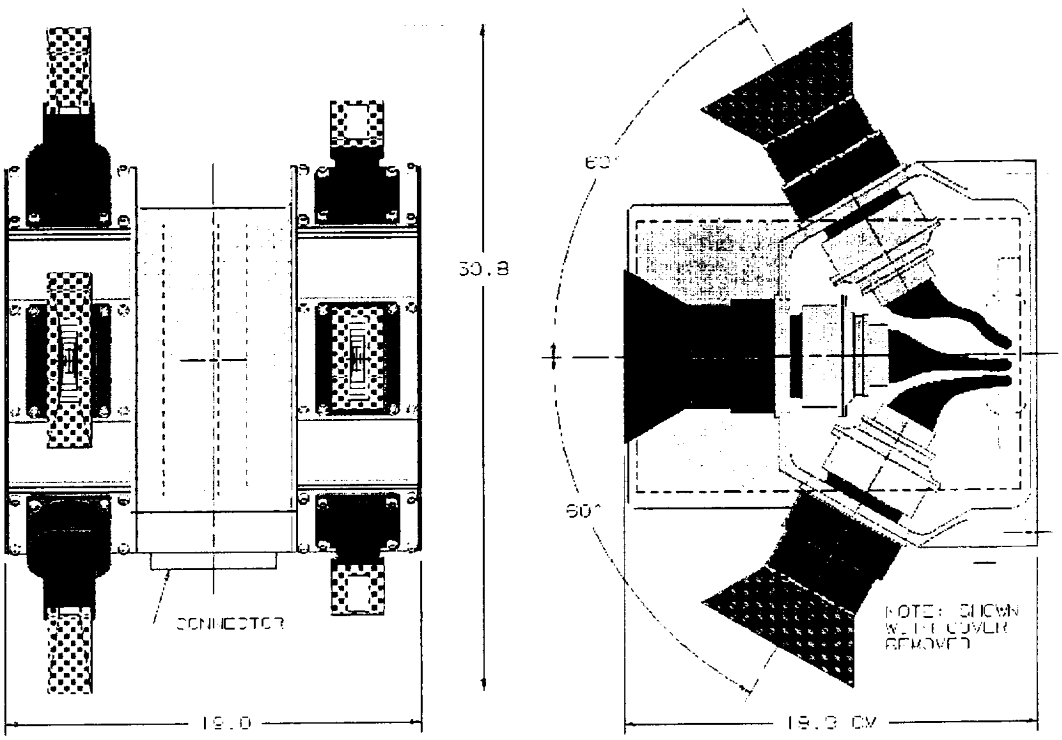


Figure 2.4.2.1 Aerospace Energetic Particle Spectrometers (AEPS) configuration #1. The units in gold with the collimator extensions measure ions while the units in green and without the collimator extensions measure electrons. The ion sensor contains a broom magnet to exclude electrons. The electron sensor uses a thick passive "deadlayer" over the detector element to exclude ions with energies up to 500 keV. (see text)

Possible configurations of the sensors are shown in Figures 2.4.2.1 and 2.4.2.2. In both figures the units with the gold colored housing extension and the black collimator extensions measure ions while the units with the green colored housing extension and without the collimator extensions measure electrons. The ion spectrometers contain broom magnets to exclude electrons with energies up to ~ 1 MeV. The electron spectrometers use a thick passive "deadlayer" over the detector elements to exclude ions with energies up to 500 keV. Both contain shielded detectors that make measurements of the penetrating radiation for background corrections. The two different physical layouts of the AEPS provide some flexibility for accommodation by the satellite contractor. The AEPS as shown can provide complete pitch angle coverage when the magnetic vector lies in their field-of-view plane. Maximum spatial coverage and assurance of complete pitch angle coverage is obtained by mounting the AEPS on a spinning satellite or a scanning platform. It is envisioned that the AEPS would be mounted on a scan platform for the GMD mission because the SEP satellite attitude is controlled to maintain the thrust axis approximately parallel to the satellite's velocity vector and the solar arrays are pointed to the sun. This constrains the satellite attitude such that the magnetic vector cannot be guaranteed to lie in the AEPS measurement plane without scanning the units. The scan table envisioned would be of the type flown on CASSINI or a simpler, less capable version thereof.

AEPS Sensor -- Configuration #2

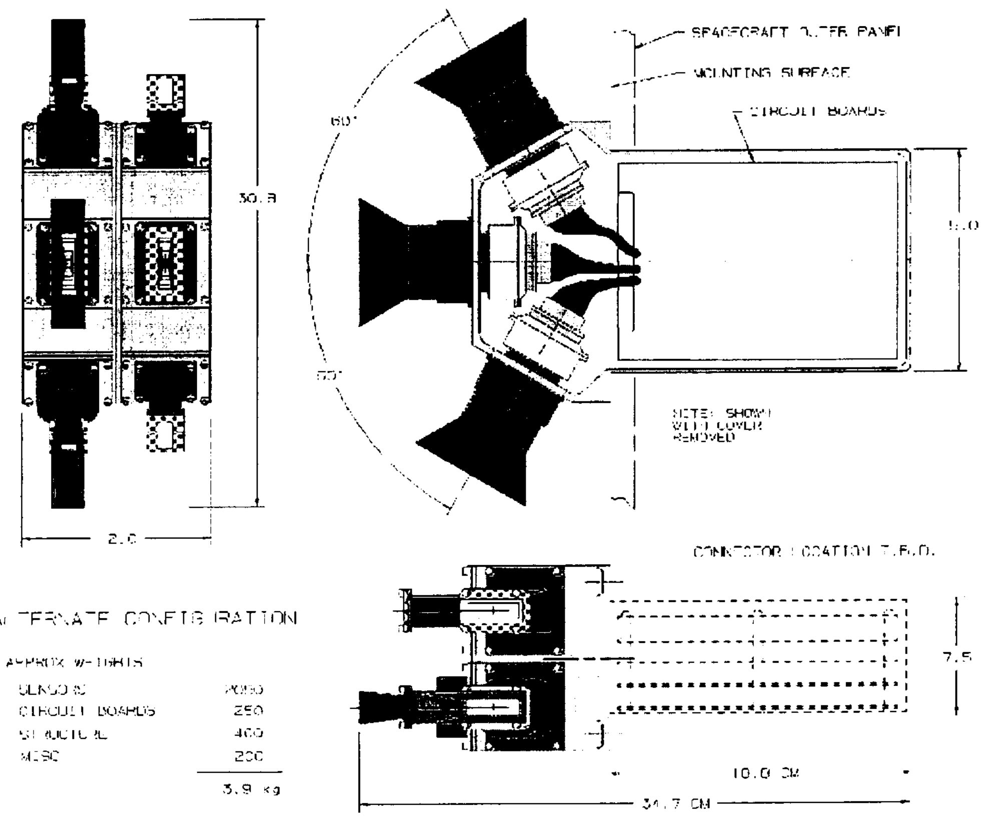


Figure 2.4.2.2 Alternate configuration for the AEPS. The detector elements are the same as in Fig. 2.4.2.1 but the layout of the spectrometer heads and electronics is different (see text).

2.4.2.14 Instrument Accommodation

A main issue for the GMD SEP spacecraft is that of science instrument accommodation. The SEP ion thrusters have strong stray magnetic fields because of the magnetic confinement of the electrons that are used to enhance the generation of ions from the Xenon gas used as fuel (Brinza and Myers, 1994; and Stocky, 1997). The magnetic fields limit the measurement of low energy plasma and magnetospheric magnetic fields and currents. Many of the science sensors require mounting as far as possible from the source of these fields, the SEP thrusters, and their power system. Secondly, the requirements for clear fields of view for the plasma and energetic particle instruments over large fractions of 4π steradian combined with the large size of the solar arrays required for SEP imposes constraints on the placement of the instruments. The combined constraints are best met with a satellite design that has a long relative thin configuration with the SEP thrusters on one end and the science payload on the opposite end. Figure 2.4.2-3 is one example of a configuration that was proposed by Fennell at Aerospace after coordination with the other study team members. The preliminary deck configuration, as of late October 1997, consisted of two panels mounted perpendicular to each other along a common edge. The deck mounted to the spacecraft module with its principle axis parallel to the thrust axis of the SEP thruster. The solar panels were extended along the ± Y direction from the spacecraft module. The AC electric antenna(s) were to extend in the YZ plane roughly along a diagonal line to obtain the proper orientation on orbit and clear the solar arrays with good separation. The DC magnetometer boom would extend along Z (perpendicular to the solar arrays). The plasma and energetic particle instruments view over the decks +X ends to meet their 180° - 360° free field-of-view requirements and minimize the view occlusion by the antenna, booms, and solar arrays. The energetic particle instrument requires a motion table and needed to be mounted near an XY edge with the deck partly cut away to allow its scanned field-of-view to be maximized. All these features could be accommodated by the mounting configuration shown in Fig. 2.4.2.3.

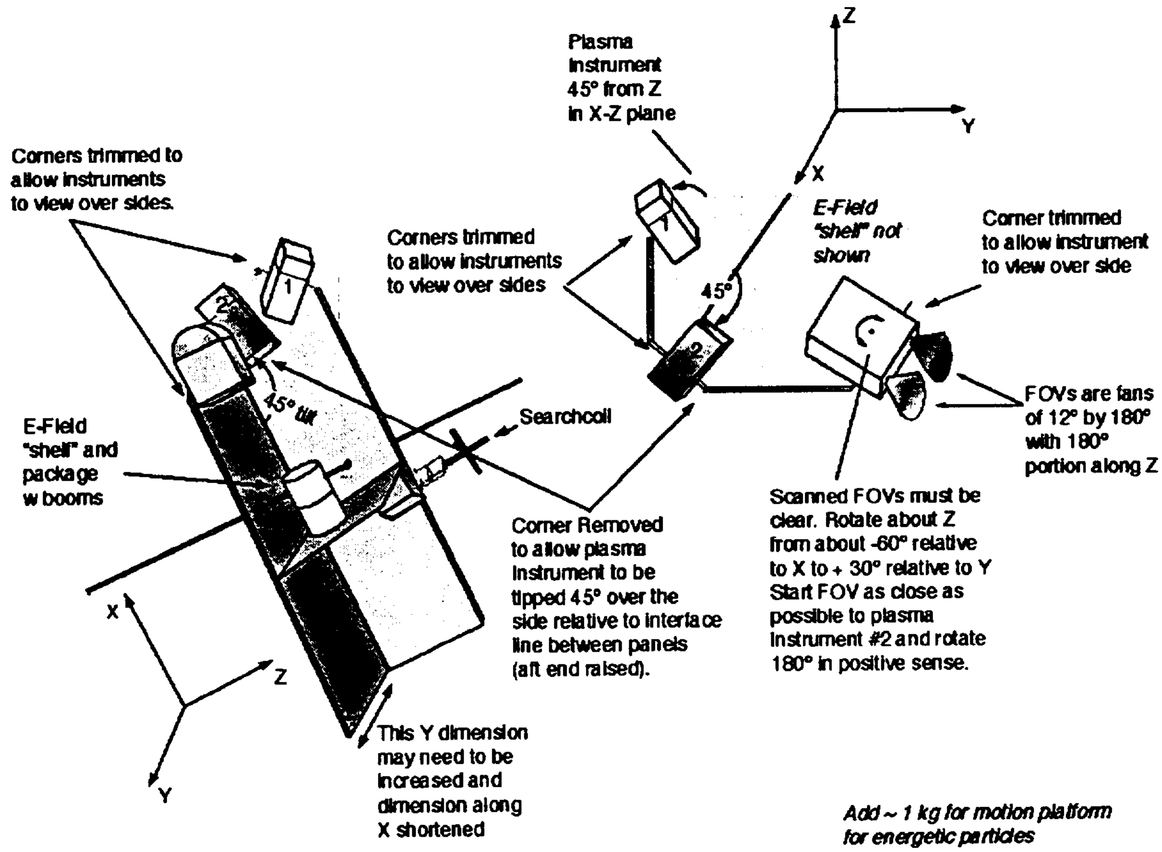


Figure 2.4.2.3 GMD Instrument layout sketch. The sketch shows a payload deck that would be mounted on one end of a SEP satellite. The solar arrays would lie in the XY plane and be extended parallel to Y. The satellite subsystems and SEP thruster would be in a separate module that mated to the payload deck at the -X end of the deck.

2.4.2.15 Radiation Dose Estimates

One of the major issues for the GMD (and all magnetospheric touring type missions) is the total radiation dose that would be received by the satellite. The dose levels have a great impact on satellite and instrument design and cost. Over the course of the GMD study, several different mission profiles were considered. In order to keep launch costs to a minimum, the study team focused on maximizing the fraction of orbital altitude attained by using the SEP thrusters in lieu of large expendable launch vehicles. The more of the mission profile that could be done with SEP the smaller the ground-to-space launch vehicle could be. However, we found that there was an optimum starting orbit that would allow the GMD satellites to minimize the radiation dose experienced. This required getting the highest apogee possible with the smallest launch vehicle that could accommodate the four GMD satellites. A Delta launch vehicle could meet these requirements and would provide a geotransfer orbit injection of the GMD tetrad as a "jumping off point." It became a question of whether it was more effective, in time and accumulated radiation dose, to thrust continuously, thrust only at apogee, to attempt to lower the inclination simultaneous with the perigee raise, etc. Since science needed to be taken throughout the orbit and especially at apogee during the early period, we could not thrust continuously. It was determined that orbit inclination changes were more efficient in fuel use if made when the orbit perigee and apogee were highest. Thus a plan was formed to raise the perigee as quickly as possible but to allow non-thrusting periods of science taking distributed around apogee. Secondly, the orbit would be raised to a 6.6 X 10 R_E configuration before lowering the initial 28° inclination to ~0°. Then the orbit would be circularized at 10 R_E before starting the tail and substorm part of the mission where the apogee would be raised to a 10 X 40 R_E configuration while using the thruster to also keep the apogee in the magnetotail.

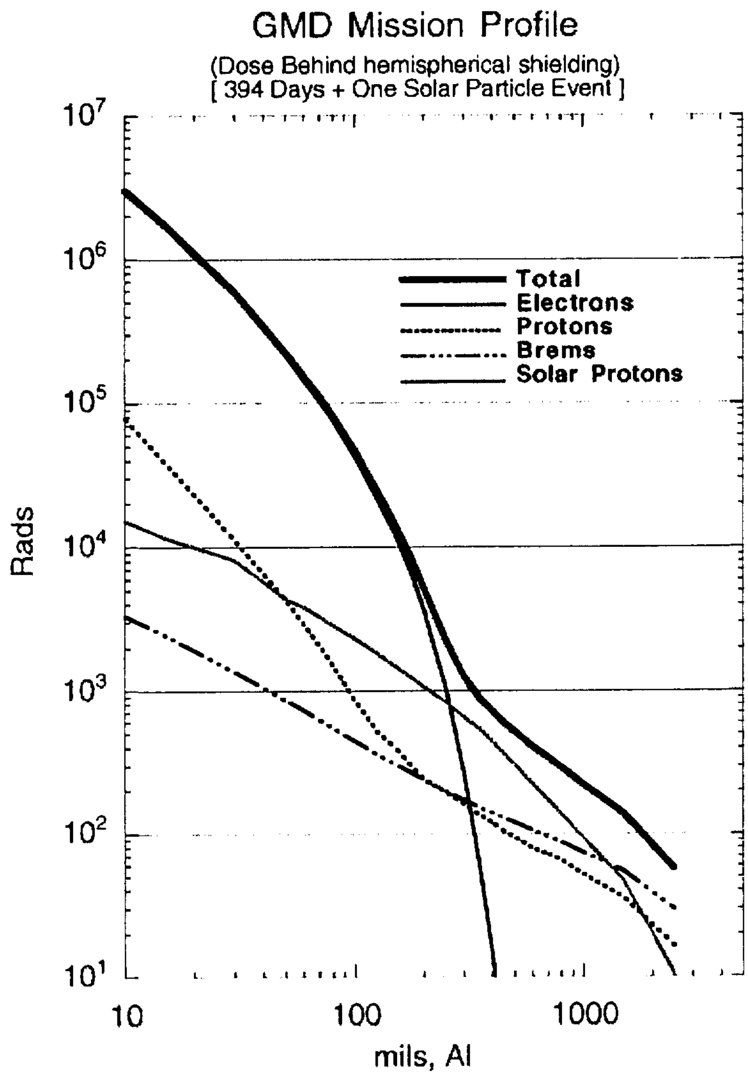


Figure 2.4.2.4 GMD mission radiation dose estimate

As part of the trade-off study for the mission orbit profile, Aerospace modified their programs for calculating radiation dose to accommodate the continuously changing orbit generated by a SEP satellite. Normally, the dose is calculated for a fixed orbit.. Aerospace analyzed dose predictions for several mission profiles and also compared them with the mission dose for Grand Tour Cluster. In the end the mission profile described above gave the smallest dose. The radiation dose, while significantly less that for GTC, is rather high. As Fig. 2.4.2.4 shows, the dose behind 100 mils Aluminum is expected to be about 45 Krads. The majority of this dose comes from the trapped electrons (the proton dose behind 100 mils is < 1 Krad) so spot shielding can be done at the part level to provide the necessary protection. As long as the parts used can tolerate 10 Krad when unshielded we can use the nominal shielding provided by the usual box covers and design part specific shielding to reach acceptable dose levels. (Using parts which have problems at dose levels below 10 Krad is not recommended.) The trapped proton (red dashed curve) and solar proton (gray curve) were provided in Fig. 2.4.2.4 so estimates of solar array degradation could be made. Over the mission life the solar protons and trapped radiation are comparable over the range of shielding thickness usually provide for solar arrays (10- 30 mil cover glasses). If GaAs arrays are used the proton damage can probably be neglected. If silicon cells are used then appropriate shielding or array derating is required.

2.5 GMD Study Team

Professor C. T. Russell is a professor of geophysics and space physics in the Department of Earth and Space Sciences and the Institute of Geophysics and Planetary Physics at UCLA. His research has centered on the solar wind interaction with the Earth and planets and on geomagnetic activity. He is the author of over 750 articles in journals and books on various aspects of planetary and space physics. He will serve as the principal investigator of this effort, leading the scientific and technical aspects of the study and the preparation of the final report. He will also provide his expertise to the team in the area of the fabrication of magnetometers and the magnetic cleanliness of spacecraft.

Dr. James L. Burch is the vice-president of the Instrumentation and Space Research Division at the Southwest Research Institute in Sun Antonio, Texas. His research interests center on the behavior of the low energy plasmas in the auroral and polar regions. He is the author of over 150 articles in refereed journals and books. He will advise on the scientific objectives of the mission and the technical approach to achieving these objectives, and assist with the writing of the final report. He will also provide his expertise to the team in the area of the fabrication of plasma instrumentation and mission design.

Dr. Joseph F. Fennell is a senior scientist in the Space Sciences, Space and Environment Center of Aerospace Corporation. His professional interests include studies of artificially injected and natural trapped particles, solar cosmic rays and particle access to and transport within the magnetosphere. He has also studied energetic particle composition, ring current development, spacecraft charging, and the impact of charging and energetic particles on satellite systems. He will advise the team on the scientific goals and technical approach and will assist with the writing of the final report. He will also provide his expertise in the construction of energetic particle instruments and in data reduction and archiving of data.

Professor Donald A. Gurnett is a professor of Physics and Astronomy at the University of Iowa. His scientific interests includes static and time varying electric fields in plasmas, plasma waves and instabilities throughout the terrestrial and planetary magnetospheres. He is the author or co-author of over 320 articles in scientific journals and books. He will advise the team on plasma waves and instabilities and the technical approach to measuring these waves, and will assist in the writing of the final report. He will provide his expertise and that of his group in the construction of plasma wave instruments.

Dr. Barry Hillard is a member of the Space Environment Branch at NASA Lewis Research Center. His research interests include the varying interactions of the space plasma with various solar array coatings and materials. He has studied current collection and arcing characteristics of solar arrays and means of mitigating these effects, and has investigated plasma interactions in the laboratory. He will provide the study team with his expertise in spacecraft plasma interactions to optimize the design of the spacecraft and assist in the writing of the final report.

Mr. William S. Kurth is a member of the research staff in the Department of Physics and Astronomy at the University of Iowa. His interests cover a broad range of plasma and radio wave phenomena in planetary magnetospheres, including Bernstein waves and upper hybrid emissions on the Earth and non-thermal continuum in various planetary magnetospheres. He is the author of over 140 scientific papers in journals and books. He will provide the team with his expertise in plasma and radio waves, assist in the design of the technical approach to the mission and the approach to data dissemination and archiving. Finally he will assist in the preparation of the final report.

Dr. Ramon E. Lopez holds joint appointments as a research scientist at the University of Maryland, College Park and as Director of Education and Public Outreach for the American Physical Society. His research has focused on observations of the structure of the near-Earth current sheet and the substorm initiation region. He has over 50 refereed publications. He will advise the team on mission design and measurement requirements, especially in the area of current disruption and substorm studies. He will also advise the team on effective means of public education and outreach and contribute to the final report.

Dr. Janet G. Luhmann is a senior fellow in the Space Sciences Laboratory at the University of California Berkeley. Her research interests include cosmic ray propagation, atmospheric x-rays and trapped radiation, the solar wind interaction with magnetized and unmagnetized planets and space weather. She has published over 160 refereed articles in journals and books. She will provide guidance in scientific objectives and the approach to obtaining these goals and the approach to public outreach, as well as aid in writing the final report.

2.6 Summary

Reviewing the documents in the Appendices, especially Appendix A and Appendix B, plus section 2.4 above, it is obvious that solar electric propulsion, SEP, makes possible very interesting and scientifically fruitful missions. It is also clear that these missions are much more capable of returning new and here-to-fore unattainable science measurements because of the flexibility provided by SEP. The satellites can be placed where they need to be to make the necessary measurements and then can be moved throughout the regions unlimited by gravitational and inertial constraints. Finally, SEP missions are able to explore large volumes of the magnetosphere by flying in ever changing orbital configurations from elliptical to circular and from low to high latitudes all within one mission. This capability is unique, especially when one realizes that an enormous launch vehicle is not required to place the system in orbit because the "wet" weight of the spacecraft is much reduced. This reduction results from the high specific impulse of SEP thrusters and thus much less fuel is required to perform the complicated orbital changes. Again, since SEP can be used to get the satellites from low to high earth orbit, the size of the launch vehicle, relative to useful satellite science and orbit changing capability, is much reduced. The overall result is that with SEP we can design science missions that return otherwise unattainable science and still keep the cost of the missions reasonable and the mission profiles and operations highly flexible.

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Appendix A - TEMPEST: Twin Electric Magnetospheric Probes Exploring on Spiral Trajectories

Proposal Submitted in Response to Announcement of Opportunity AO 95-OSS-02

June 20, 1995

Proposal to the

National Aeronautics and Space Administration

in response to

AO 95-OSS-02

for

"TEMPEST: Twin Electric Magnetospheric Probes Exploring on Spiral Trajectories"

01 April 1996 - 01 November 2002

Total Budget: $ 58.03M

MO & DA Budget: $11.85M

Date Submitted: 20 June 1995

By

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Appendix B - Solar Electric Stereo Auroral and Magnetospheric Explorer

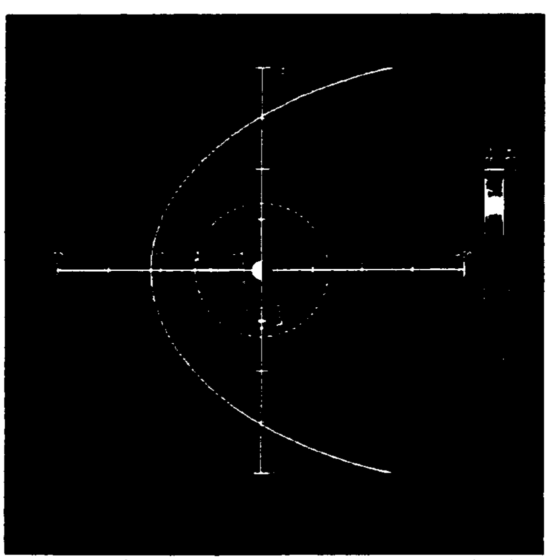
Proposal Submitted in Response to Announcement of Opportunity AO 97-OSS-03

June 12, 1997

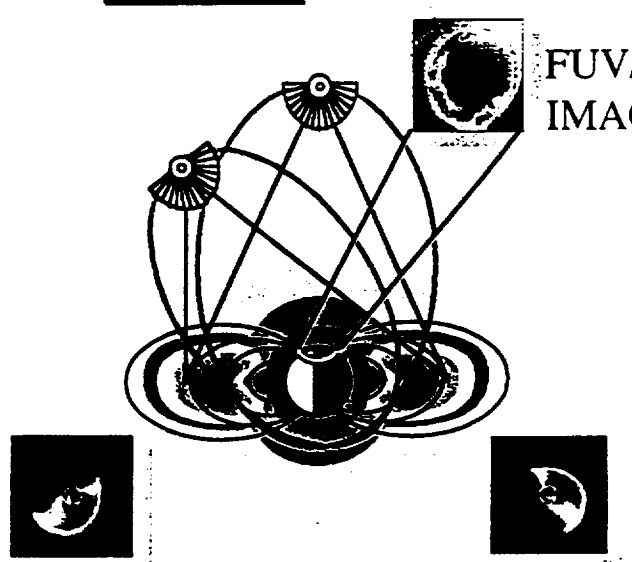
*S*olar *E*lectric *S*tereo *A*uroral and *M*agnetospheric *E*xplorer

A Small Explorer proposal submitted in response to NASA Announcement of Opportunity AO-97-OSS-03

Present Capability ⟶ **SESAME** + IMAGE



CEPPAD/POLAR



FUV/ IMAGE

ENAC/SESAME

HENA/IMAGE

UCLA - The Aerospace Corporation - Boston University - CTA Space Systems - JHU/Applied Physics Laboratory - NASA Goddard Space Flight Center - NASA Lewis Research Center - Southwest Research Institute - UC Berkeley - University of Maryland - University of Missouri

Appendix C

GMD Instrument Accommodation Issues
(Response To: C. Ohrbom of AeroAstro)

by

J. F. Fennell

The Aerospace Corporation
Space and Environment Technology Center
May 14, 1997

Chuck:
Here is an initial data dump. The issue of the motion platform is still in the works. I have presumed that the microprocessor control and support for the sensor is provided, as well as the processed power. I have presumed a Mil 1553 digital interface. Some of the comments on fields-of-view, mounting etc. are orbit profile dependent. As more is known about the expected orbit profile history the better these items can be determined. Basically, we need to get the best view that covers the earth's equatorial plane over as great a range of radial distances from the earth as is feasible while at the same time being able to view north and south along the magnetic field. A motion table helps to maximize this possibility but the base orientation on the s/c, for a given s/c attitude, can be optimized. All pointing considerations will have to be iterated.

1. Instrument mass:
   a.) Without scan platform and power supplies: ~ 4 kg
   b.) Scan platform mass: Unknown as this point. There are two alternatives: build our own or attempt to purchase one. Both options are being evaluated.

2. Dimensions:
   a.) Without scan platform, configuration #1: ~ 31 x 21 x 20 cm mounted on surface or slightly inside of S/C.
   b.) Configuration #2: 31 x 13 x 36 cm with 19.5 cm of the 36 cm dimension inside satellite and mounting feet at the surface. Configuration #2 cannot be used with a scan platform.
   c.) Scan platform dimensions are TBD. Preferred sensor configuration would be #1.

3. Mounting preference:
   a.) Dependent on field of view constraints (see below) and satellite orientation (see below); away from thrusters; most favored is forward end of spacecraft near edge to allow motion table to scan towards the backwards direction)

4. Field of View Requirements:
   a.) Without scan platform: Clear field of view of 180 x 25 deg. 180 deg. plane to contain the celestial Z-X plane and may need to be tilted to view backwards (see crude sketch).
   b.) With scan platform: Depends on type of platform.
      1.] Oscillating: Clear over 180° x ± 80°. with 180° plane to contain celestial Z-X plane and motion to be transverse to Z-x plane (again, see sketch).
      2.] Rotating: Clear over 2π with the rest position of the 180° x 20° sensor fan to contain the celestial Z-X plane as in a.) and b-1).

5. Pointing knowledge requirements:
   a.) Relative to s/c body: ± 1°.
   b.) Relative to external frame: ± 1°.

6. Pointing stability or jitter requirements: minimal to none (± 1°/min)

7. Pointing control requirements for s/c relative to external frame: S/C longitudinal axis approximately parallel to celestial equator combined with (4.) above. This is not a hard requirement, more a best effort request. As more is known about the orbit profile history the better this question can be answered.

8. S/C pointing maneuver requirements:
   see (4) and (7).

9. Downlink T/M req.:
~ 3 kbps

10. Maximum data latency requirements:
a.) Real time operations: ≤ 1 minute
b.) Normal T/M: None

11. Require on-board processing?
Yes, data averaging, moment calculations and spectral fits plus data compression must be done by the s/c processor as well as time assignment and TM packet formation. S/C processor must read out data and re-impose the sensors operational mode on at predetermined (referenced to s/c clock) but programmable (variable sampling rate) basis. If a scan platform is used, the CPU must control the platform mode and rates and synchronize the data sampling with the motions.

12 Max/min temperatures bounds:
a.) operational -40 to +5 deg. C
b.) non operational -40 to +35 deg. C

13. EMI/EMC requirements:
Levels required of the NASA POLAR spacecraft (based on MIL 1541a and 461 with tailoring for the mission). The energetic particle sensors are sensitive to microvolt fluctuations between grounds and to noise or voltage spikes on power lines.

14. Deployables?
None. However, there may be a motion table caging mechanism.

15. Post-installation calibration? In-flight calibration
a.) Post-installation calibration: Require a refurbishment period (~6-8 weeks) to install virgin flight detectors and do final calibrations. In testing, radiation sources will be used as qualitative checks on sensor and electronics calibration.
b.) On orbit calibration command sequences are to be run periodically to monitor sensor performance and electronic calibration.

16. Command upload rate?
Less than or of the order of 1000 bytes/day (< 500 commands/day), covering high level commands (power, mode changes) and memory loads (low level mode changes, data base changes, and code patches).

17. Real time commanding required?
Yes. Some commanding requires near-real-time view of the TM to gauge result and select next command from a list of possible commands.

18. Contamination or clean-room requirements:
Continuous dry nitrogen purge ("3-9s" or better purity). No use of solvents around sensors. (Bag sensors when s/c cleaning being done and flush bag with dry nitrogen.) Relative humidity must be maintained below 50% at all times. Class 10,000 room with surface cleanliness level of 600B.

19. Timing synchronization between satellites:

a.) Without motion table, none required at sensor. High rate mode signal should be possible to simultaneously start high rate data gathering on all satellites.

b.) With motion table, some coordination of the sweeps may be required.

20. Keep-out requirements:

Our preference is to keep the FOV free of sun and s as much as possible. Must not stare at sun. The heat load would do damage. The detectors are light sensitive in the UV and visible. Sun and earth light make the data useless so we do not want to stare at either source. Momentary scanning of the sun or earth does not harm the sensor but the data taken at those times must be discarded. Programming of s/c motion or a motion table must take this into consideration.

21. Voltages and voltage ranges required by instrument:

Regulated: +28. In addition, a switchable (on/off) heater power line at +28 volt (unregulated OK) is required.

22. Average and peak current or power at each voltage:

a.) Heater power ~7 w at +28 V. External on/off control at s/c and internal control in sensor by thermostat.

b.) Without motion table: Regulated 28 V is 2.5 watts average

c.) Motion table power: TBD

23. Regulation requirement on each voltage:

Heater power - unregulated or nominal +28 V $\pm$ 2 volts.

24. Does instrument run continuously or does it have duty cycle?

Instrument runs continuously.

25. Electrical interface:

Connector styles: Cannon standard - depends on number of pins required for interface. prefer separate power and data connectors.

Voltage levels: Mil 1553 data interface was assumed

Data protocols: Mil 1553. Other items are to be negotiated.

Appendix D

SEP Orbit Issues

(Memo To: C Russell)

by

J. F. Fennell

The Aerospace Corporation
Space and Environment Technology Center
July 17, 1997

Notes for SMEX type solar propulsion mission

Questions:

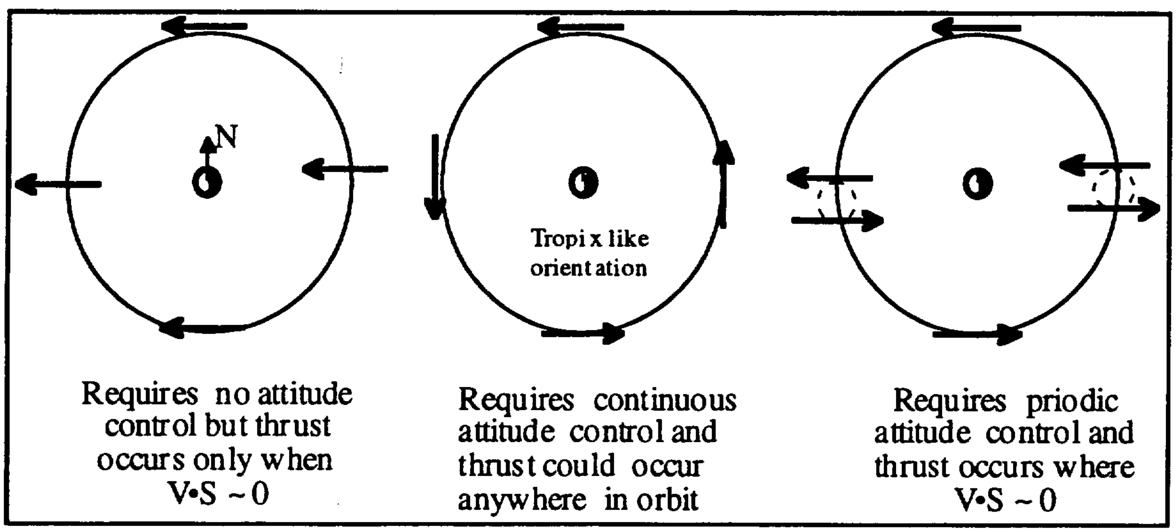
1. What is the energy range of the LENA instrument? 20 keV - ??

2. Can it measure charged particles? Does the large geometric factor for ENAs preclude direct measurement of ions to protect detectors from saturation? Could it be rapidly cycled to alternately measure ENAs and ions to get a full measure of both or would its mode have to be changed by command? Is it well shielded so good measurements are made in the plasma sheet and radiation belts? Expected detector lifetime if ions are measured? Any other difficulties related to measuring ions directly for instrument optimized to measure a relatively weak flux of ENAs.

   A TEPS (CEPPAD IPS) like unit may be required in any case to provide clean in-situ measurements. Generally, combined measurements provide lower quality and limited capability measurements. Trying to stretch a sensor to measure different things generates conflicting requirements and significant trade-offs. Only a specialized sensor optimized to provide a good measurement of either neutral or charged particles, but not both, is most likely required if quality science measurements are to be made.

3. Orbits, what are the tradeoffs?

   a.) Must satellite symmetry axis (thrust axis) vector be always parallel to velocity vector?



[1] [2] [3]

In configuration [1], a rotation of 180° around the symmetry axis twice per orbit would allow one side of the satellite to always view towards the mid-plane or magnetic equator. One would periodically have to go into configuration [2] or [3] for thrusting to raise the orbit or to maintain the orbit shape.

In configuration [2], the one side of the spacecraft has an earthward view. A fixed aperture could be limited in its ability to view the ENAs from the preferred regions. This allows thrusting at all points in the orbit.

In configuration [3], with two "flips" per orbit, one side of the spacecraft would always view towards the mid-plane. This allows thrusting that will support an elliptical orbit and allow the ellipse to "grow" in size.

In general, the ENA observations will be constrained by the freedom we have to control the satellite attitude when making the observations. To reduce attitude control fuel usage, a good maneuvering plan for the mission is required. This involves the kind of trade-offs sketched above.

b.) Must orbit be circular?

Non-circular orbit allows different altitudes for viewing ENAs in a given orbit which effectively changes the gathering power and resolution around the orbit. Can optimize shape of orbit to best benefit the ENA observations in conjunction with enhancing the altitude cuts through the auroral regions. One option would be to use a growing 75°- 90° inclination ellipse to scan through the auroral acceleration region. When the apogee of the ellipse gets well above the acceleration region, rotate the plane of the orbit down towards the equator so that the ENA sensors can look towards the equatorial plane over a significant period of the orbit with only small rolls about the symmetry axis. In this way, the ENA sensor will "hang" out over the inner magnetosphere (i.e. $1.5 < | X_{GSM} | < 8$ or so) with a $| Z_{GSM} |$ of only a fraction of the maximum orbital altitude. This increases spatial resolution and effective gathering power for the ENA measurement..

c.) What is optimum orbital altitude?

For the auroral acceleration region the altitude range of greatest interest is ~ 1.15 - 4 Re with inclination up to 75°. With an elliptical orbit, one could meet this requirement at multiple altitudes with an orbital configuration that has the apogee and perigee increasing with time and the line of apsides slowly changed actively.

A "Molnya" orbit (~1.07 X 7.2 Re, ~63° inclination and 12 hour period) or modification thereof is one possible example [say 2 X 8 Re final orbit inclined at ≤ 60°] for ENA viewing (see Figure D-1. This could be evolved from a low circular orbit over time with management of the apogee/perigee ratio, inclination and line of apsides phase. The evolving orbit would make the measurements in the auroral acceleration region and , depending on the final inclination could continue to make auroral measurements while supporting ENA observations of the inner magnetosphere.

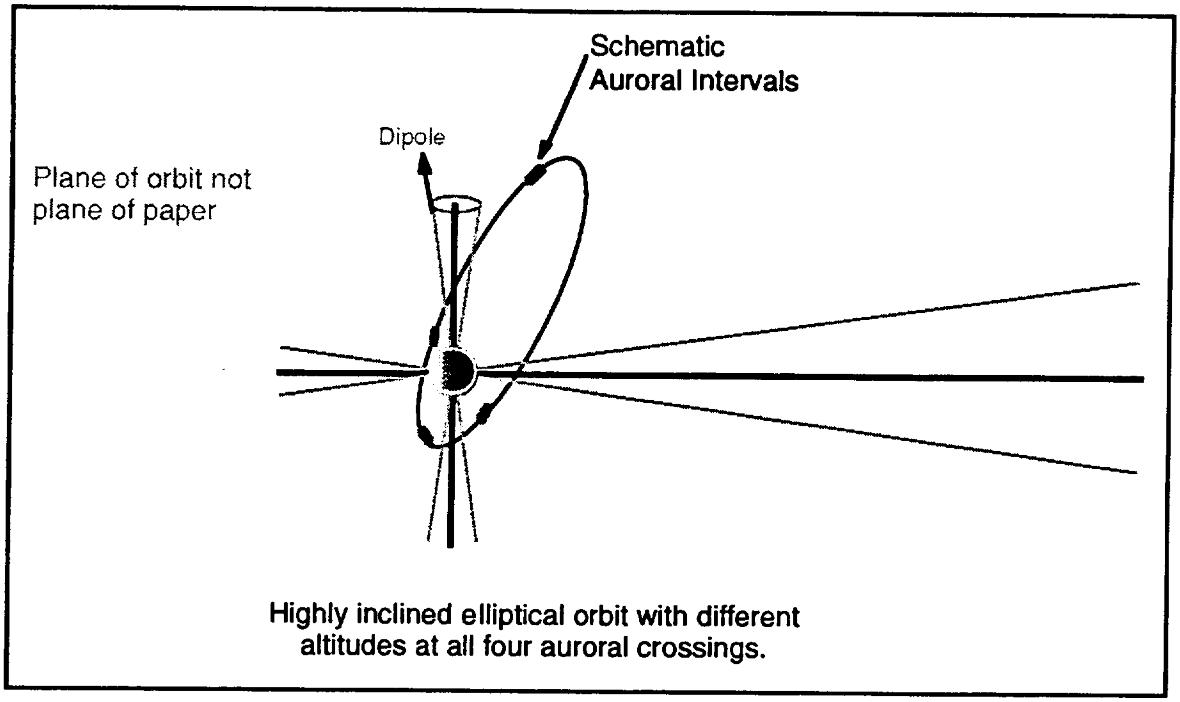


Figure D-1. Example of a highly eccentric high latitude orbit similar to a "Molnya" orbit

Appendix E

Energetic Particle Instrument Field-of-View Issues

(Memo To: Study - Satellite Contractor)

by

J. F. Fennell

The Aerospace Corporation
Space and Environment Technology Center

October 20, 1997

The energetic proton and energetic electron spectrometers (EPS and EES respectively) that can provide the mission data have Field-of-View constraints relative to the orbit plane and satellite velocity vector if their coverage is to be optimized. For a simple sensor configuration that provides 180° coverage in one plane but is of order of 20° in the orthogonal direction the 180° fan must be perpendicular to the orbit plane for low inclination orbits and parallel to the obit plane for high inclination orbits (ref. Figure D1). That is, the 180° fan must have its axis nominally parallel to the Earth's rotation axis. Such an orientation maximizes the probability that the magnetic vector lies in the field-of-view plane. This give the maximum likelihood that the spectrometers will measure the complete pitch angle distribution

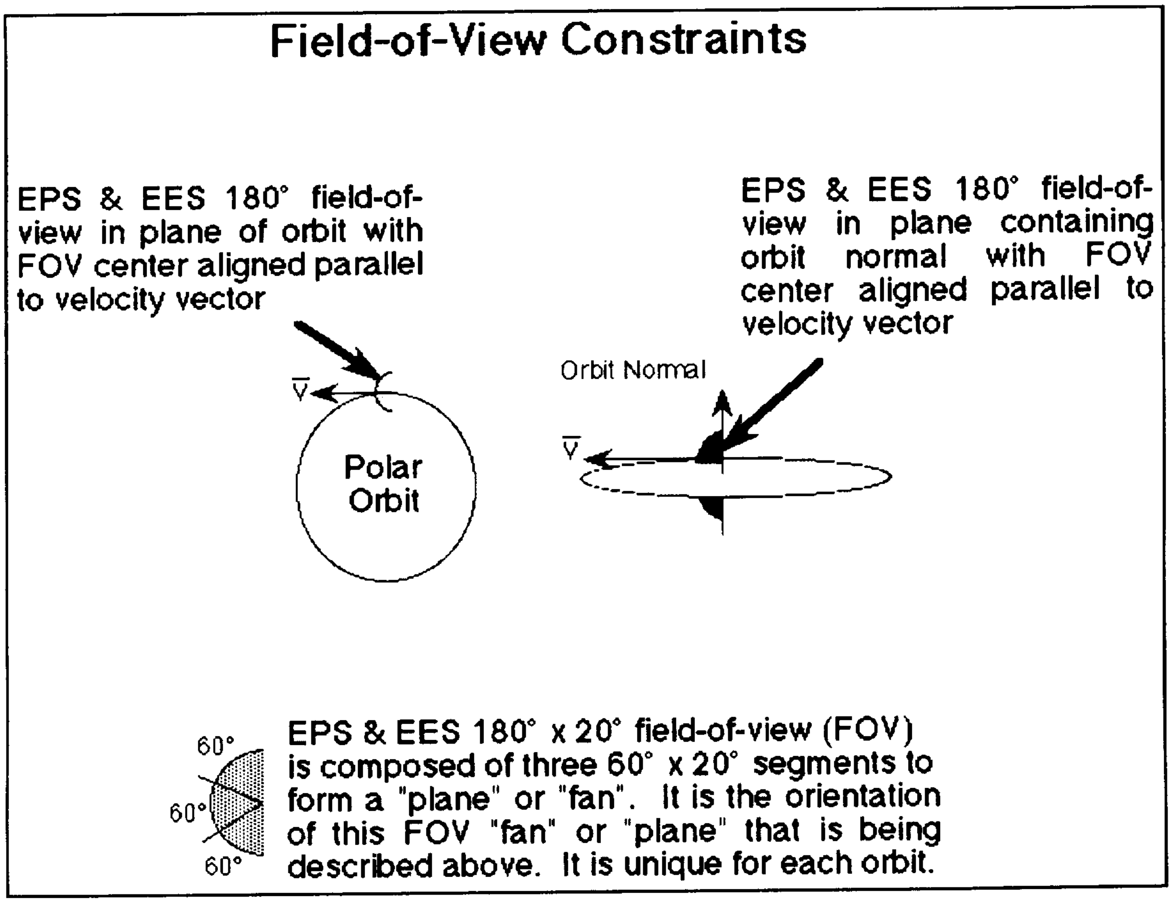


Figure E-1 Energetic Particle Instrument Fields-of-View requirements relative to SEP satellite attitude and orbital configuration.

To guarantee that a sensor measures the complete energetic particle pitch angle distribution one would have to have multiple units or mount a sensor with 180° field-of-view on a motion table so it could scan as much of the 4π steradians as possible. an example of this is shown in Figure C1. This figure is for one possible configuration of a SEP satellite where all the science instruments are mounted on the end of most distant from the ion thrusters.

Appendix F

Strawman Instrument Layout for GMD Concept Spacecraft

(To: Study Team and Satellite Contractor)

by

J. F. Fennell

The Aerospace Corporation
Space and Environment Technology Center
September 8, 1997

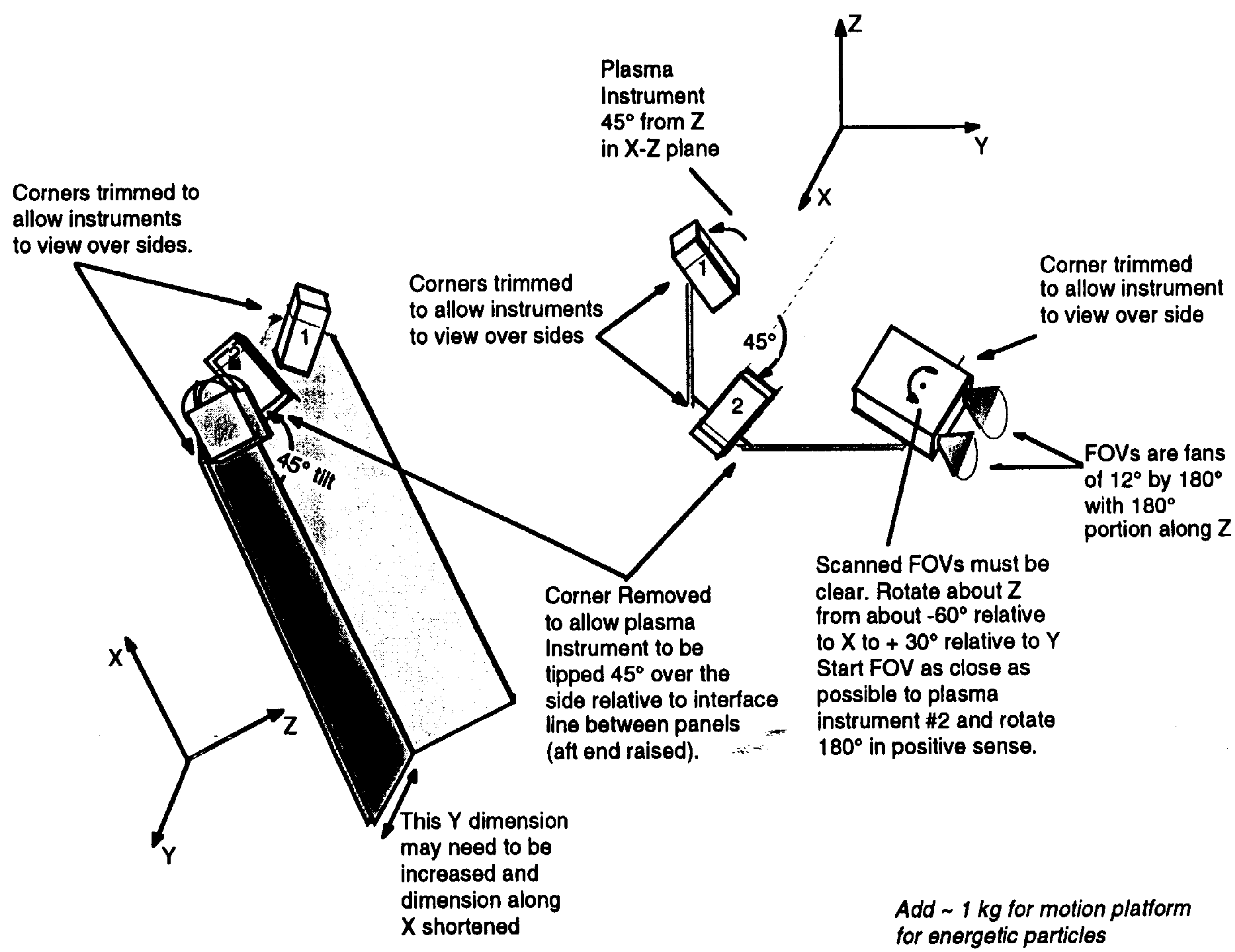


Figure F-1 "Strawman" instrument layout for GMD spacecraft.