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PROPULSIVE SMALL EXPENDABLE DEPLOYER SYSTEM (ProSEDS) EXPERIMENT: MISSION OVERVIEW AND STATUS

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Abstract

The Propulsive Small Expendable Deployer System (ProSEDS) space experiment will demonstrate the use of an electrodynamic tether propulsion system to generate thrust in space by decreasing the orbital altitude of a Delta II expendable launch vehicle second stage. Electrodynamic tether thrusters work by virtue of the force the Earth's magnetic field exerts on a wire carrying an electrical current, achieving thrust without the expenditure of propellant. ProSEDS, which is to launch on an Air Force Global Positioning System (GPS) satellite replacement mission in early 2004, will use the flight-proven Small Expendable Deployer System (SEDS) to deploy a tether (5 km bare wire plus ≈7 km nonconducting Dyneema®) from a Delta II second stage to achieve a peak drag thrust of ≈0.4 N.

ProSEDS MISSION OVERVIEW

ProSEDS is an electrodynamic tether propulsion system space experiment that will fly in 2004 as a secondary payload on a Delta II GPS replacement mission. ProSEDS is based on the flight heritage of the SEDS deployer hardware. The SEDS deployer has flown successfully four times in space. The SEDS deployer was flown on SEDS–1,[1] SEDS–2, and on the Plasma Motor Generator[2] and Tether Physics and Survivability experiments.

The ProSEDS project will be launched on the Delta second stage. After launch, the Delta stages I and III separate, and ProSEDS is delivered on stage II to its orbit of ≈285-km circular with a 36°±1° inclination. The ProSEDS data subsystem is activated by the Delta avionics only after stage II separation of the primary payload. Once the ProSEDS orbit is achieved, the endmass is kicked off of the Delta via a marmon clampband spring assembly. The endmass is deployed upward, away from the Earth, with the 12 km of tether attached. The first 7 km of tether, which is connected to the endmass, is a nonconductive material that provides the gravity gradient force required to deploy the stiff conductive wire out off the spool. The 5 km of the conductive tether[3] remains attached to the Delta II. As the Delta second stage moves through space, electrons are collected from the plasma (Fig. 1). The current in the wire in the presence of the Earth's magnetic field causes a force on the wire, which has a component antiparallel to the spacecraft velocity vector. This drag force causes the Delta altitude to decrease. The current flowing through the tether to the Delta stage is used to power the ProSEDS subsystems and restore capacity to a rechargeable battery. A plasma contactor is used to emit electrons back into space to complete the circuit. The Delta II stage, with ProSEDS attached, will continue its orbit decay until it burns up upon reentry into the atmosphere. It has been calculated that the ProSEDS altitude should decrease at an average rate of 9 km per day due to the electrodynamic drag force generated in the tether. The current collected in the tether is highly variable depending upon numerous factors, including plasma density, solar activity, tether dynamics, and the angle between the spacecraft velocity and the magnetic field.

MISSION OBJECTIVES

The ProSEDS project has two primary and five secondary objectives (Table 1). The first primary objective is to demonstrate significant electrodynamic tether thrust in space. This objective is accomplished by demonstrating that the tether-generated electrodynamic thrust can lower the orbit of the stage by at least 5 km a day. Simulation models have been developed to predict the orbit decay rate (Fig. 2). The second primary objective is to determine the collection chracteristics of the "bare" tether.[3,4] This objective is accomplished by measuring the tether current, plasma density, and EMF over various ionospheric conditions and comparing these values to the prediction of existing models. The primary objectives can be accomplished in the first 24 hr of the mission. The scalability of the bare tether collection

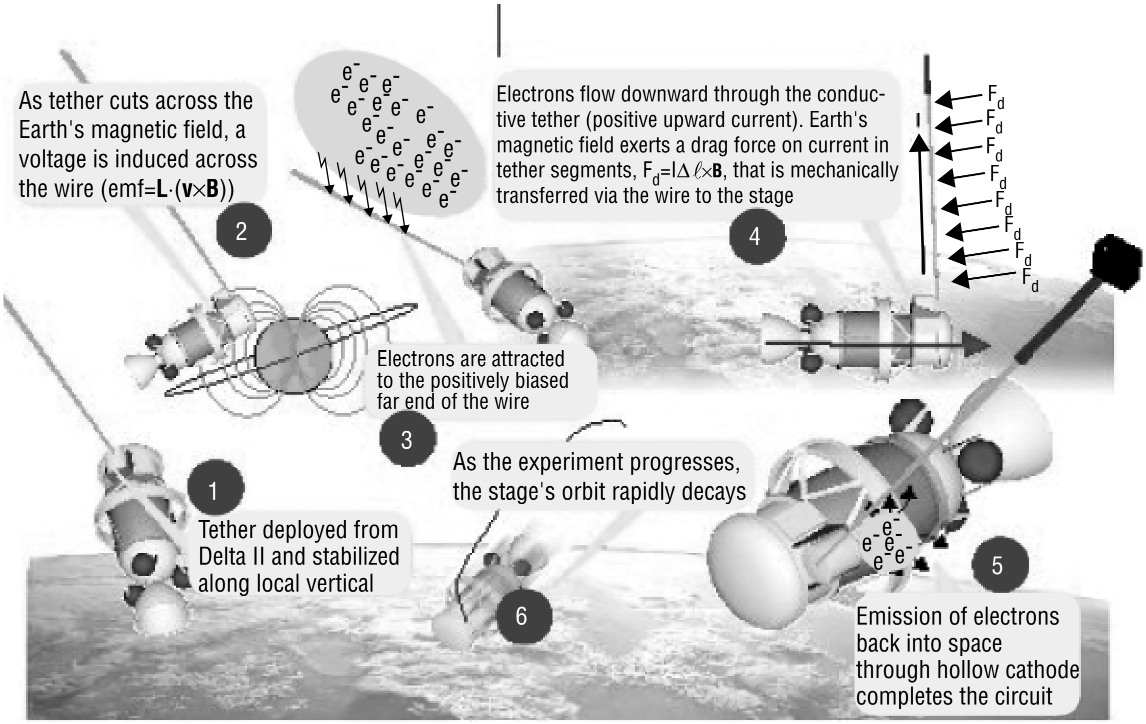

Fig. 1. ProSEDS mission overview.

Table 1. ProSEDS objectives.

ProSEDS Objectives	Criteria for Success	Measurements Required	Instruments Required
Primary 1—Demonstrate significant electrodynamic tether thrust in space	Demonstrate an orbital decay rate of at least 5 km per day	Change of orbital position	GPS Ground radar Ground telescope
Primary 2—Measure the current collection performance of the bare electrodynamic tether under varied ionospheric conditions	Obtain data over five orbits	Tether voltage Tether current Magnetic field orientation Spacecraft potential Ambient plasma density Ambient electron temperature Absolute position of Delta Relative position of tether	Voltmeter Ammeter Magnetometer DIFP, Langmuir probe Langmuir probe, DIFP Langmuir probe GPS, ground radar Turns counter
Secondary 1—Demonstrate the regulation, storage, and use of tether-generated electrical power	Observe an increased state of charge in the battery or a slower battery discharge rate than is predicted by the actual loads	Battery temperature Power system voltage Power system current	Thermistor Voltmeter Ammeter
Secondary 2—Determine system performance during the extended mission phase (begins after orbit 5)	Collect available tether performance data	Telemetry, if available Change of orbital position	All functioning instruments GPS, ground radar Ground telescopes
Secondary 3—Assess tether survivability in atomic oxygen, meteoroid, and orbital debris environment	Observe tether integrity	Tether observation(s) Tether voltage Tether current	GPS, radar, telescopes Voltmeter Ammeter
Secondary 4—Assess tethered system dynamics during electrodynamic operation	Stable (bounded) dynamic envelope	Endmass relative position and Delta attitude versus time	GPS (endmass) Magnetometer (endmass)
Secondary 5—Assess the scalability of bare tether anode current collection to future applications	Obtain data over varied ionospheric conditions	Tether voltage Tether current Magnetic field orientation Spacecraft potential Ambient plasma density Ambient electron temperature Absolute position of Delta Relative position of tether	Voltmeter Ammeter Magnetometer DIFP, Langmuir probe Langmuir probe, DIFP Langmuir probe GPS, ground radar Turns counter

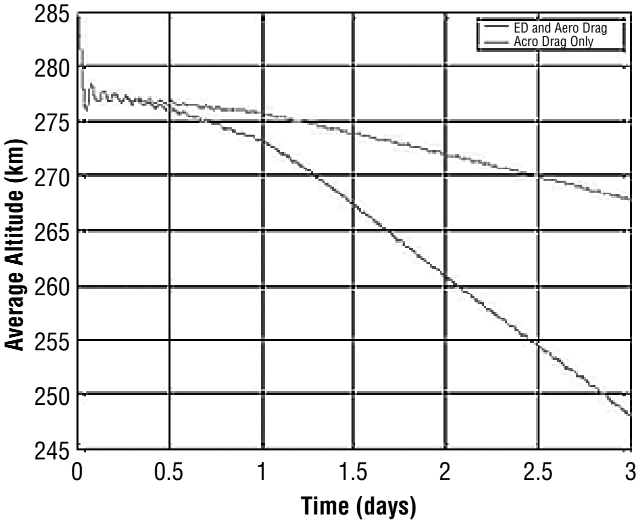

Fig. 2. ProSEDS predicted deorbit rate.

toward future tether missions will be examined as one of the secondary mission objectives.

One of the ProSEDS secondary objectives includes the regulation, use, and storage of tether-generated electrical power. This is the first time that current generated by an ED tether system is used to power subsystems and recharge batteries. Another secondary objective is accomplished by monitoring, measuring, and assessing the system performance during the extended mission phase (from 24 hr until mission end). The last two secondary objectives are to assess tether survivability and electrodynamic-dynamic coupling.

ProSEDS SUBSYSTEMS

The major subsystems in the ProSEDS experiment are the deployer/tether subsystem, the endmass, the data subsystem, the power subsystem, and the performance instruments. All of these subsystems are described in the following sections.

Deployer/Tether Subsystem

The deployer is comprised of an aluminum canister that holds the 12 km of tether wound around a core. The canister also houses phototransistors and infrared light-emitting diodes that act as turns counters to monitor the length of tether that has been deployed. After the endmass is ejected, the brake is applied at various times during deployment to control the deployment rate of the tether. The brake control law is a modification of what was used on previous SEDS missions. The control law has been tested numerous times during deployment testing of the tether in a vacuum chamber at Marshall Space Flight Center (MSFC). The control law and brake settings are preprogrammed into the data subsystem electronics box (DSEB) before launch because there is no uplink command capability. The deployer subsystem is mounted to the guidance section of the Delta II via Boeing-provided longerons and a bottom tube. The deployer canister is mounted with the DSEB, GPS, ammeter, and the high-voltage control and monitoring (HVCM) relay box (Fig. 3). The Deployer canister and brake subsystem was designed and fabricated by Tether Applications.

The tether length is 12 km and is comprised of four different sections (Fig. 4). The tether diameter is different for each section, ranging from 0.8 to 1.6 mm. The tether has 7 km of nonconductive tether made of a Dyneema® braid that is 13/100 denier. The nonconductive tether is used to provide the gravity gradient forces required to pull the wire tether off of the canister core. The 4840 m of conductive tether is made of seven strands of 28 AWG 1350–0 aluminum wire which has been coated with an atomic oxygen-resistant conductive polymer coating. Each wire is individually coated, then twisted around a KEVLAR® core. The last 160 m of tether that connects to the Delta II is the same seven strands of the aluminum wire that have been coated with both a polyimide-resistant and an atomic oxygen-resistant insulation. A KEVLAR® core is in the center of the entire length of the wire tether (both conductive and insulated). A kevlar overbraid covers the insulated tether portion and the interface to the endmass. This overbraid provides additional protection against surface abrasion. The insulated tether is required close to the Delta II stage to ensure that electrons from the plasma contactor do not return to the nearby tether and that there is no arcing close to the Delta. The three sections of the tether are joined by splices and cold butt welds, which have been tested to ensure that the tether has a minimum breaking strength of 250 N. The tether was fabricated and processed by Tether Applications, Cortland Cable, and Triton.

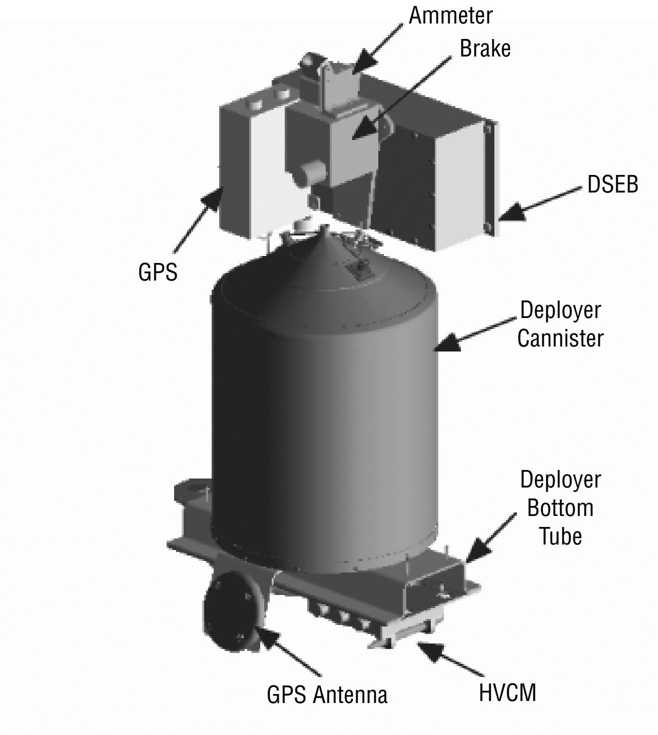

Fig. 3. ProSEDS deployer-mounted subassembly.

Endmass

The ProSEDS endmass weighs ≈20 kg and is ejected from the Delta II via a Boeing-provided marmon clampband and a set of pyrotechnic bolts. When ProSEDS reaches its designated orbit, the Delta II sends a signal to fire the pyrotechnic bolts and ejects the endmass upward, away from the Delta II stage, at an initial rate of 2.8 m/s. The endmass acts to pull the tether off the core during deployment. In addition, the endmass helps dampen the tether's dynamic motion. The nonconductive tether is attached to the endmass and it in turn is attached to the conductive tether (Fig. 4). The endmass has its own set of instruments that are activated at deployment. The endmass is comprised of a computer, a GPS receiver, a magnetometer, solar cells, a rechargeable battery, and a transmitter. The endmass is not electrically connected to the rest of the ProSEDS hardware that remains attached to the Delta. The endmass will gather GPS and magnetometer data that it will transmit to the ground via its own transmitter and antenna. The downlink rate for the endmass is 115.2 kbit/s and the frequency is 2247.5 MHz. The GPS data will be used to turn on the transmitter when it is within range of designated ground stations. Solar cells located on all sides of the endmass

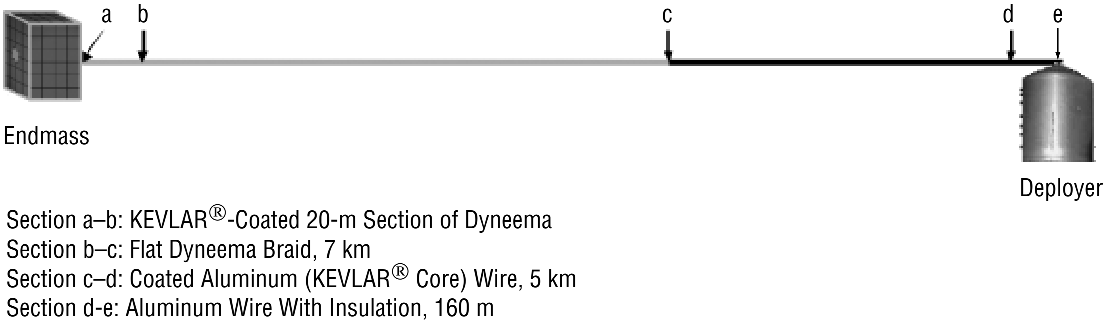

Fig. 4. ProSEDS tether and deployer.

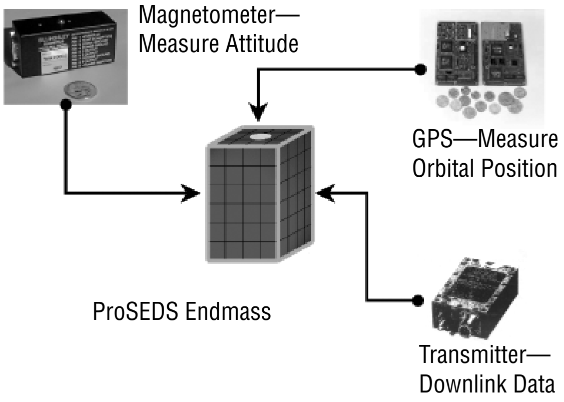

Fig. 5. ProSEDS endmass.

will provide power to recharge the nickel-cadmium (Ni-Cd) batteries and all of the instruments. The data gained from the endmass will be used to help assess tether dynamics. The endmass was designed and fabricated by a student team from The University of Michigan (Fig. 5).

Data Subsystem

The data subsystem is comprised of a Data Subsystem Electronics Box (DSEB) and a transmitter. The DSEB provides the computer control for the entire mission. The ProSEDS experiment has no uplink capabilities so all of the mission control must be programmed into the system before launch. The DSEB provides computer control and receives data from all ProSEDS hardware except the endmass. The data are formatted into a data stream and sent to the transmitter for downlink when ProSEDS is over a designated ground station. The DSEB also activates and controls all of the hardware on two power buses via discrete and analog interfaces. The DSEB is a modification of the data system used successfully on the SEDS missions. The ProSEDS mission timeline is controlled by the DSEB and operation is divided into two phases—a deployment phase and an operations phase. During the operations phase, the hardware is cycled in four modes—sampling of the plasma conditions with the plasma contactor off, shunt, load resistor, and battery recharge, all with the plasma contactor on. Contingency or off-nominal operations are also included in the DSEB software design. The DSEB is mounted on the deployer subassembly (Fig. 3). The DSEB is designed and fabricated by Alpha Technology and MSFC.

Data from ProSEDS is dowlinked via a commercial off-the-shelf transmitter through a Delta-provided four-port coupler and antenna system. The Delta provides two omnidirectional antennas located 180° apart on the second stage. The downlink rate is 115.2 kbit/s and the frequency is 2260 MHz. The transmitter has a 20-W power input with a 2-W power output, split between the two antennas. During the first five orbits, the transmitter will operate continuously. After that, if proper operation of the GPS has been confirmed, the transmitter is turned on only over designated ground stations. If the GPS normal operation cannot be verified, the transmitter will remain on continuously throughout the mission. The radio frequency transmission license agreement requires that the transmitter be deactivated after 21 days on orbit. The ground stations that ProSEDS will use are Wallops, Guam, Hawaii, Vandenberg Air Force Base, Madrid, Santiago, Goldstone, and Canberra. The transmitter is mounted on the ProSEDS instrument panel assembly (Fig. 6). The transmitter is provided by MSFC.

Power Subsystem

The ProSEDS power subsystem consists of a primary battery, secondary (rechargeable) battery, power distribution box (PDB), HVCM system, and a hollow cathode plasma contactor (HCPC).

The primary battery provides power during deployment and the first seven orbits. The primary battery is a 50-Ahr lithium thionyl chloride bromine complex battery. The primary battery cells are DD size (nonrechargeable) mounted in two parallel strings of eight cells each. The nominal battery voltage is 28 Vdc and the battery design contains blocking diodes, shunt diodes, and fuses that make them two-fault tolerant. The primary battery, which is mounted on the ProSEDS instrument panel (Fig. 6), was designed and fabricated by MFSC.

The ProSEDS secondary battery is a rechargeable 2.3-Ahr Ni-Cd battery. The battery will be recharged entirely from the current collected in the tether as the spacecraft moves through the space plasma. The secondary battery contains 100 cells mounted in four cell packs. The battery recharge cycle is controlled by the DSEB. The secondary battery, which is mounted on the instrument panel (Fig. 6), was fabricated and designed by MSFC.

The PDB provides two redundant relays that interface to the Delta II for ProSEDS activation. The Delta II activates ProSEDS only after the primary payload has been delivered to its orbit and the third stage has been ejected from the spacecraft. The PDB provides turn-on power to the DSEB that in turn activates the rest of the hardware on the essential and nonessential buses. The PDB, which is mounted on the instrument panel (Fig. 6), was designed and fabricated by MSFC.

The HVCM system consists of a relay box, a resistor box, and an ammeter. The HVCM relay provides control and monitor functions for the tether current. The HVCM provides three high-voltage relay switches that switch the tether current between open, shut, load resistor box, and the secondary battery.

These switches are controlled by the DSEB and are a part of the four modes of operation. A separate resistor load box is used during voltage measurements. An ammeter, which is mounted at the exit guide of the brake box (Fig. 3), is used to measure tether current. The HVCM relay box is mounted under the deployer canister (Fig. 3) and the resistor box

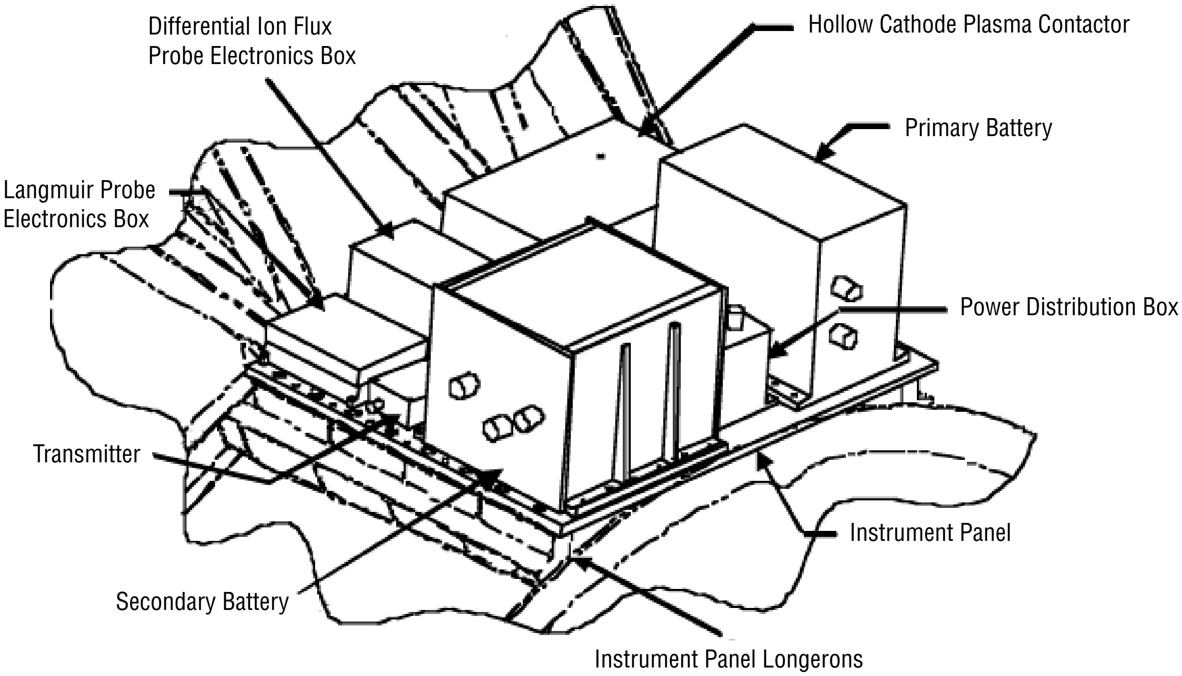

Fig. 6. ProSEDS instrument panel assembly.

is mounted on the Delta struts (Fig. 7). The University of Michigan designed and fabricated the HVCM.

The HCPC functions to maintain current flow in the tether through electron emission to the ionosphere. The plasma contactor serves as a low impedance connection to the local ionospheric plasma. The HCPC generates a dense plasma cloud by ionizing xenon, which allows for an emission of electrons back into space. The ProSEDS HCPC utilizes a small xenon gas tank and flow system with a specially designed hollow cathode. The HCPC, which was designed and fabricated by the Electric Propulsion Laboratory, is mounted on the instrument panel (Fig. 6).

ProSEDS Instrumentation

The instrumentation on ProSEDS consists of the following: a Langmuir probe spacecraft potential (LPSP), a differential ion flux probe with mass analysis (DIFP/M), a magnetometer, and a GPS receiver with antenna. This instrumentation is required to accomplish the ProSEDS mission objectives previously outlined.

The LPSP's main function is to measure plasma characteristics. The tether current collected is due to the local ambient plasma density, and the LPSP determines the plasma electron density and temperature. Another function of the LPSP is to measure the potential of the Delta II stage with respect to the surrounding plasma. The LPSP is composed of an electronics box and three probe assemblies. Each LPSP probe is mounted on the tip of an ≈0.8-m mast. The LPSP mast is mounted onto the Delta II struts at ≈120° apart (Fig. 7) and extended via a pin puller/pivot mechanism. The extension of the LPSP probes away from the Delta II allows for measurement of ambient plasma conditions. The LPSP electronics box is mounted to the instrument panel (Fig. 6). The LPSP was designed and fabricated by The University of Michigan.

The DIFP/M is used to measure both nonequilibrium and ambient plasma characteristics. The DIFP/M will measure plasma density, plasma flow velocity, spacecraft potential, ion mass, and ion temperature. With its ion mass capability, the DIFP/M will determine if the measurements being made of the local plasma are true ambient plasma conditions or if

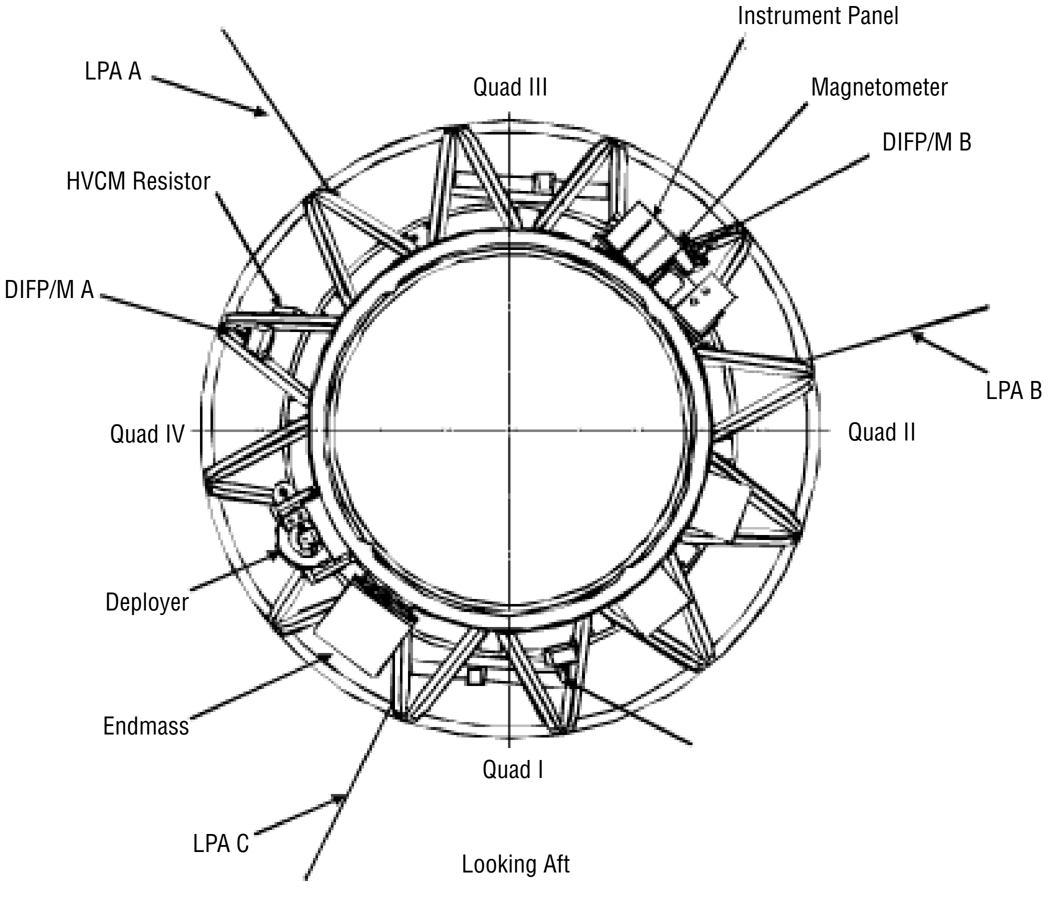

Fig. 7. ProSEDS hardware layout.

they are contaminated by spacecraft emissions. The DIFP/M is composed of an electronics box and three probes that are mounted ≈120° apart on the Delta II struts (Figs. 6 and 7). Since the Delta attitude is not controlled, both the DIFP/M and LPSP probes are mounted at intervals around the Delta to ensure that one probe will always be in the ram direction. The DIFP/M was designed and fabricated by MSFC.

The ProSEDS magnetometer is used to correctly determine the attitude of the Delta II second stage. The stage has no attitude control capability during the ProSEDS mission operations phase and is free to rotate around the tether axis. The aspect magnetometer will measure spacecraft attitude with respect to the geomagnetic field as well as the magnitude of the field. The magnetometer is an MSFC-provided commercial off-the-shelf instrument that is mounted to a strut (Fig. 7).

The GPS receiver and antenna are used to determine the position of the Delta and to measure the system orbital decay rate. Another function of the GPS will be to determine when ProSEDS is over an assigned ground station so that the transmitter can be activated to downlink ProSEDS data. The GPS determination of ground station location will be utilized to save power when the ProSEDS is out of range from the ground stations. If the GPS does not function properly, the default mode is to leave the transmitter on continuously. The tether dynamics are not controlled, thus the tether will be moving due to the electrodynamic force and other factors such as day/night transitions. An identical GPS unit is mounted in the endmass so that a determination of tether dynamics can be made. Although the two GPS units may not be locked to the same set of satellites, useful tether dynamics data will be obtained. The GPS receiver and antenna are mounted with the ProSEDS deployer canister (Fig. 3). The GPS receiver card is a commercial off-the-shelf technology but the software and the power supply board were developed and fabricated by Alpha Technology and MSFC.

PROSEDS TESTING AND INTEGRATION

ProSEDS meets all of the launch loads and safety requirements for the Delta II spacecraft. The majority of ProSEDS hardware is protoflight, which means that the flight unit has completed a series of environmental tests at levels above those expected for flight. A full series of system-level environmental testing has been conducted at MSFC to include the following: high voltage, functional, thermal vacuum, electromagnetic interference/compatibility, and mission sequence. Deployment tests of the tether were performed in vacuum under a range of temperature conditions. The Delta II second stage will be modified for the ProSEDS hardware to mount to the guidance section and the struts. Modifications of the stage include the addition of plume shields, installation of instrument panel and deployer longerons, installation of the marmon clampband assembly, and mounting holes added to the struts. A fit check of flight hardware has been completed on the Delta II stage at Kennedy Space Center (KSC) to ensure interface compatibility. After completion of final functional testing, the hardware will be shipped to KSC for integration onto the Delta II. ProSEDS will be integrated to the second stage on the launch pad and limited functional test will be conducted prior to launch.

SUMMARY

The ProSEDs tether experiment will be flown in 2004 (Fig. 8). ProSEDS will utilize a conductive wire tether to generate electrodynamic propulsion and onboard power. ProSEDS will demonstrate propellantless propulsion of the Delta II stage by collecting electrical current from the space plasma as the tether interacts with the Earth's magnetic field. Electrodynamic tether propulsion technology has many useful future applications, including satellite deorbit, upper stages, and satellite reboost.[5] Electrodynamic tethers can be used to generate power at Jupiter[6] or any other planet with an ionosphere and magnetic field.

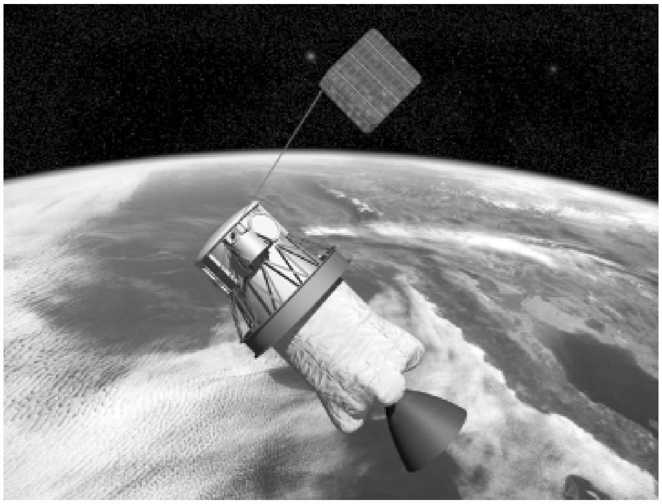

Fig. 8. Depiction of ProSEDS in flight over the Earth.

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