PROPULSIVE SMALL EXPENDABLE DEPLOYER SYSTEM (ProSEDS)

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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 (ELV) second stage. ProSEDS, which is planned to fly in 2001, will use the flight proven Small Expendable Deployer System (SEDS) to deploy a tether (5km bare wire plus 10 km spectra or dyneema) from a Delta II second stage to achieve ~0.4N drag thrust. ProSEDS will utilize the tether-generated current to provide limited spacecraft power. The ProSEDs instrumentation includes a Langmuir probe and Differential Ion Flux Probe, which will determine the characteristics of the ambient ionospheric plasma. Two Global Positioning System (GPS) receivers will be used (one on the Delta and one on the endmass) to help determine tether dynamics and to limit transmitter operations to occasions when the spacecraft is over selected ground stations. The flight experiment is a precursor to the more ambitious electrodynamic tether upper stage demonstration mission, which will be capable of orbit raising, lowering and inclination changes-all using electrodynamic thrust. An immediate application of ProSEDS technology is for the deorbit of spent satellites for orbital debris mitigation. In addition to the use of this technology to provide orbit transfer and debris mitigation it may also be an attractive option for future missions to Jupiter and any other planetary body with a magnetosphere.

PROSEDS MISSION OVERVIEW

ProSEDs is an electrodynamic tether propulsion system space experiment. ProSEDs will fly in 2001 as a secondary payload on a Delta II Global Positioning System (GPS) replacement mission. ProSEDS is based on the flight heritage of the Small Expendable Deployer System (SEDS) deployer hardware. The SEDS deployer has flown successfully 4 times in space. The SEDS Deployer was flown on SEDS-1, SEDS-2, Plasma Motor Generator (PMG) and Tether Physics and Survivability (TIPS) experiment.

The ProSEDS project will be launched on the Delta II second stage. After launch, ProSEDS is delivered on stage II, to its orbit of approximately 400km circular with a 36 +/-1 degree inclination. The ProSEDS data subsystem is activated only after stage III 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 15km of tether attached. The first 10km of tether, which is connected to the endmass, is a nonconductive material which provides the gravity gradient force required to deploy the stiff conductive wire off the spool. The 5km of the of conductive tether remains attached to the Delta II. As the Delta second stage moves through space, electrons are collected from the plasma (see Figure 1). As a current is generated in the wire, the spacecraft passes through the earth s magnetic field , which exerts a force on the electrons flowing through the tether. The resulting force applied to the tether, is perpendicular to the velocity vector, which will cause the altitude of the Delta to decrease. The current flows through the tether, to the Delta stage, where it is used to power ProSEDS subsystems and recharge the secondary 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 it s orbit decay until it burns up upon reentry into the atmosphere. As shown in Figure 2, it has been calculated that the ProSEDS altitude should decrease at an average rate of 14 km per day due to the electrodynamic drag force generated in the tether (Johnson, 2000). The current collected in the tether is highly variable depending upon numerous factors including plasma density, solar activity, tether dynamics, and day/night transition cycles. ProSEDS will measure the tether current and the plasma density during all mission phases.
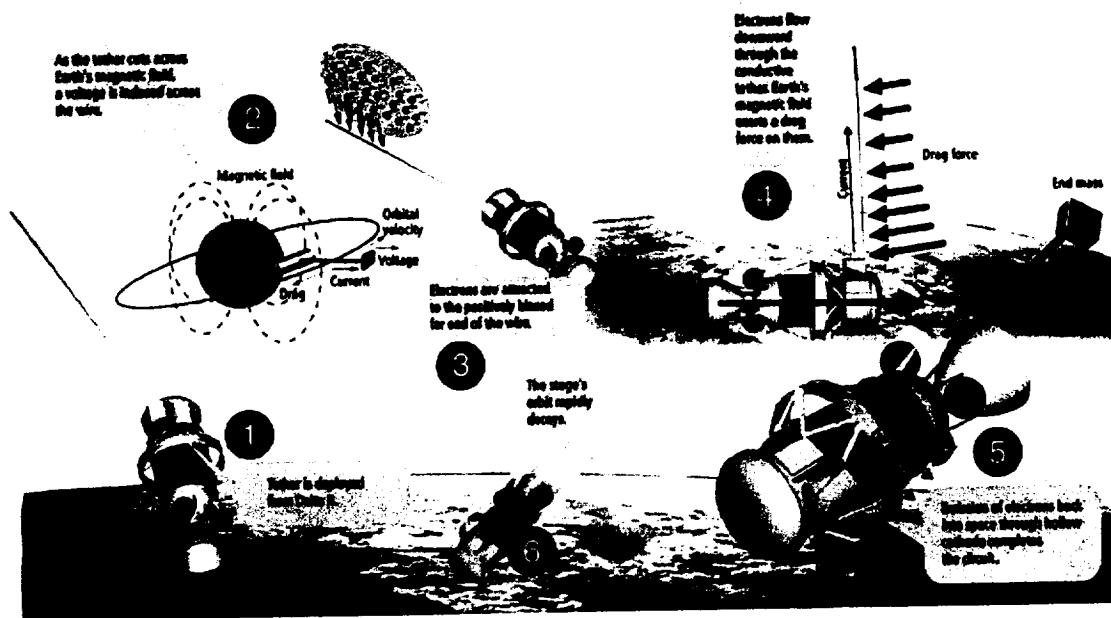
FIGURE1. ProSEDs Mission Overview.

MISSION OBJECTIVES

The ProSEDS project has two primary and four secondary objectives. The first primary objective is to demonstrate significant, measurable 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 5km a day. Simulation models have been developed to predict the orbit decay rate. The second primary objective is to measure the current collection and be able to scale this collection to future applications. This objective is accomplished by measuring the plasma density and comparing it to the current generated in various ionospheric conditions. The data obtained in this primary objective will be applied to existing models, which will in turn be used to predict the performance of future tether missions. The primary objectives can be accomplished in the first 24 hours of the mission. One of the ProSEDS secondary objectives includes the regulation, use, and storage of tether generated electrical power. This is the first time that current has been generated in a bare wire and then used to power subsystems and recharge batteries. Another secondary objective will be accomplished by monitoring, measuring, and assessing the system performance during the extended mission phase (from 24 hours until mission end). The last two secondary objectives are to assess the tether survivability and it s operational dynamics.
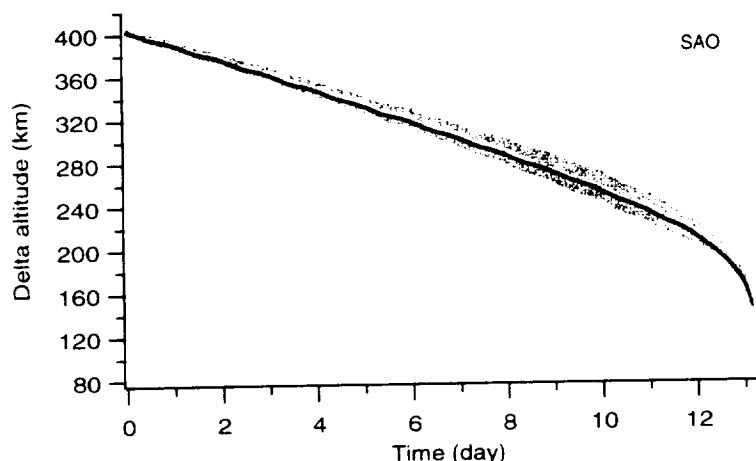

**FIGURE 2.** ProSEDS Predicted Deorbit Rate (Johnson, 2000).

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 will be described in the following sections.

Deployer/Tether subsystem

The Deployer is comprised of an aluminum canister that holds the 15km of tether wound around a core. The canister also houses phototransistors and infrared (IR) light emitting diodes (LEDS) 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 controls the deployment rate of the tether. The brake control law is a modification of what was used on previous SEDS mission. 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. The Deployer canister and brake subsystem was designed and fabricated by Tether Applications.

The tether length is 15 km and it is comprised of three different tether sections (see Figure 3). The tether diameter is different for each section ranging from 0.8mm to 1.6mm. The tether has 10 km of nonconductive tether, which is 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 4840m 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 meters 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 and an atomic oxygen resistant insulation. The 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 accurate measurements of the plasma generated current are obtained 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.

a b   c   d

Endmass   Deployer

e
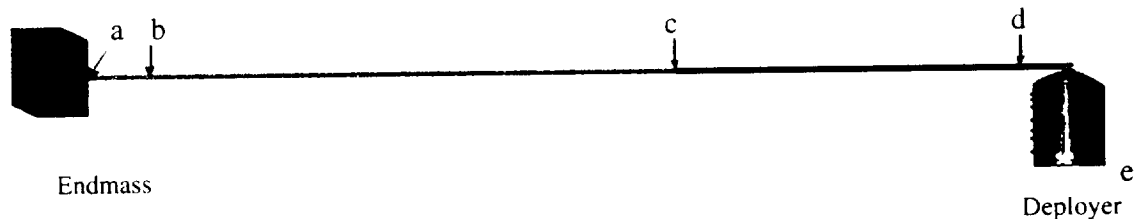
Spectra Tether 10 km, section a-c
- Section a-b: Kevlar coated 20 m section
- Section b-c: Flat Spectra braid, 10 km

Aluminum Tether 5 km, section c-e
- Section c-d: Coated aluminum (Kevlar core) wire, 5 km
- Section d-e: Insulated wire (aluminum with Kevlar core), 160 m section

FIGURE 3. ProSEDS Tether and Deployer.

Endmass

The ProSEDS Endmass weighs approximately 20 kg and it 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 eject the endmass upward away from the Delta II stage at an initial rate of 2.8 meters per second. The endmass acts to pull the tether off the core during deployment. In addition, the endmass helps dampen the tethers dynamic motion. The nonconductive tether is attached to the endmass and it in turn is attached to the conductive tether. The endmass has it s own set of instrument 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 which it will transmit to the ground via it s own transmitter and antenna. The downlink rate for the endmass is 115.2 kilobits per second and the frequency is 2247.5 mega hertz. The GPS data will be used to turn on the transmitter when it is within range of designated ground stations. Solar cells, that are located on all sides of the 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.

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 is 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 the essential and nonessential 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, which include sampling of the plasma conditions, plasma contactor operation, battery recharge, and battery recovery. Contingency or off-nominal operations are also included in the DSEB software design. The DSEB is mounted on the Deployer subassembly. The DSEB is designed and fabricated by Alpha Technology and Marshall Space Flight Center (MSFC). Data from ProSEDS is dowlinked via a commercial off the shelf transmitter through a Delta II provided four-port coupler and antenna system. The Delta II provides two omni-directional antennas located 180 degrees apart on the second stage. The downlink rate is 115.2 kilobits per second and the frequency is 2260MHz. The transmitter has a 20 watt power input with a 2 watt power output (split between the two antennas). During the first three orbits the transmitter will operate continuously. After the first three orbits, if proper operation of the GPS has been confirmed, then the transmitter is turned on only over designated ground stations. If the GPS normal operation can't be verified then the transmitter will remain on continuously throughout the mission. The RF 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, Madrid, Santiago, Goldstone, and Canberra. The transmitter is provided by MSFC.

Power Subsystem

The ProSEDS power subsystem consists of a primary battery, secondary battery, power distribution box (PDB), high voltage control and monitoring (HVCM) system and a hollow cathode plasma contactor. The primary battery provides power during deployment and the first seven orbits. The primary battery is a 50 Ampere-hour (A-hr) lithium thionyl chloride (Li-SOCL$_2$) bromine complex battery. The primary battery is not rechargeable. The primary battery cells are DD size mounted in two parallel strings of eight cells each. The nominal battery voltage is 28Vdc and the battery design contains blocking diodes, shunt diodes and fuses that make them two-fault tolerant. The primary battery was designed and fabricated by MSFC.

The ProSEDs secondary battery is a rechargeable 2.3 A-hr nickel cadmium (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 was fabricated and designed by MSFC.

The Power distribution box (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 it s orbit and the third stage has been ejected from the spacecraft. The PDB provides Turn On power to the DSEB which in turn activates the rest of the hardware on the essential and non-essential buses. The PDB was designed and fabricated by MSFC.

The High Voltage Control and Monitoring (HVCM) System consist 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, short, 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, is used to measure direct tether current. The HVCM relay box is mounted under the deployer canister and the resistor box is mounted on the Delta struts. The University of Michigan designed and fabricated the HVCM.

The Hollow Cathode Plasma Contactor (HCPC) functions to maintain current flow in the tether by collecting and emitting electrons back into the ionosphere. This essentially completes the circuit so tether current will flow to the Delta II. The plasma contactor should also prevent spacecraft charging, which could induce plasma effects such as arcing and sputtering. The HCPC generates a dense plasma cloud by ionizing Xenon, which allows for a low 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 was designed and fabricated by the Electric Propulsion Lab.

ProSEDS Instrumentation

The instrumentation on ProSEDs consist of the following: a Langmuir Probe Spacecraft Potential (LPSP); a Differential Ion Flux Probe with Mass (DIFP/M); a magnetometer; and a GPS receiver with antenna. This instrumentation is required to accomplish the ProSEDS primary and secondary objectives as described in the following sections:

The LPSP main function is to measure plasma characteristics. The LPSP is required to accomplish the ProSEDS second primary objective, which is to scale the ProSEDS results for future missions. The amount of tether current collected is due to the plasma density. The LPSP determines the plasma electron density and electron 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 Langmuir probes assemblies. Each LPSP probe is mounted on the tip of a ~ 0.8m mast. The LPSP mast are mounted onto the Delta II struts at ~ 120 degrees apart, 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. The LPSP was designed and fabricated by the University of Michigan.

The DIFP/M is used to measure non-equilibrium and ambient plasma characteristics. The DIFP/M will measure plasma density, spacecraft potential, ion mass and ion temperature. With it s ion mass capability, the DIFP/M will determine if the measurements being made of the local plasma are true ambient plasma conditions or if they are contaminated by spacecraft emissions. The DIFP/M is composed of an electronics box and three probes that are mounted ~ 120 degrees apart on the Delta II struts. Since the Delta attitude is not controlled, both the DIFP/M and LPSP probes are mounted at intervals around the Delta to insure 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 spin-phase attitude of the Delta II. The Delta stage is free to rotate around the tether axis during the mission so the attitude must be measured. The aspect magnetometer

will measure spacecraft attitude with respect to the geomagnetic field as well as the magnitude of the field. The magnetometer is a MSFC provided commercial off the shelf instrument that is mounted to a Delta strut.

The GPS receiver and antenna are used to determine the position of the Delta II 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 then 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. 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 must meet all of the launch loads and safety requirements for the Delta II spacecraft. The majority of ProSEDs hardware is protoflight, which means that it will undergo a series of environmental test at levels above those expected for flight and then be flown. A full series of system level environmental testing will be conducted at MSFC to include the following; vibration, shock, high voltage, functional, thermal vacuum, thermal balance, electromagnetic interference and electromagnetic compatibility. Deployment test of the 15 km tether will also be conducted in a vacuum chamber under extreme temperature conditions. The Delta II second stage has been 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 already been completed on the Delta II stage at Kennedy Space Center (KSC) to ensure interface compatibility. Once all of the environmental and functional testing is complete, the hardware will be shipped to KSC for integration. ProSEDs will be integrated onto the second stage on the launch pad and interface and limited functional test will be conducted on the pad prior to launch.

SUMMARY

The ProSEDs tether experiment that will be flown in space in 2001. 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 de-orbit, upper stages, and satellite reboost. Electrodynamic tethers can be used to generate power at Jupiter or any other planet with a magnetosphere.

ACKNOWLEDGEMENTS

REFERENCES

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