PROPULSIVE SMALL EXPENDABLE DEPLOYER SYSTEM (PROSEDS) MISSION AND TELEMETRY SYSTEM OVERVIEW

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ABSTRACT

The National Aeronautics and Space Administration’s (NASA) Marshall Space Flight Center (MSFC) in Huntsville, Alabama will launch the Propulsive Small Expendable Deployer System (ProSEDS) space experiment in late 2000. ProSEDS will demonstrate the use of an electrodynamic tether propulsion system and will utilize a conducting wire tether to generate limited spacecraft power. This paper will provide an overview of the ProSEDS mission and will discuss the design, and test of the spacecraft telemetry system. The ProSEDS telemetry subsystem employs a combination of Commercial Off-The-Shelf (COTS) hardware and launch vehicle telemetry system components to minimize costs as well as power consumption. Several measures were used to aid the conservation of spacecraft power resources. First, the transmitter was modified to limit input power consumption to less than 20 watts while providing approximately two watts Radio Frequency (RF) output power. Secondly, the ProSEDS on board Global Positioning System (GPS) receiver is being used to control input power to the transmitter in order to limit the telemetry operations to occasions when the spacecraft is in proximity to preprogrammed ground station locations.

KEY WORDS

Propulsive Small Expendable Deployer System, electrodynamic tether propulsion, ProSEDS telemetry subsystem, GPS aided transmitter control

INTRODUCTION

Experiments with low earth orbiting masses connected by tethering mechanisms have been conducted since the 1960’s. From the early 1990’s, NASA’s MSFC has led the development of propulsion systems aimed at reducing the cost of space transportation from $10,000 per pound to a few hundred dollars per pound. One innovative technology that is currently being pursued by MSFC’s Advanced Space Transportation program is Tether propulsion. The ProSEDS experiment will demonstrate potential launch system cost savings by flight testing a spacecraft propulsion system that does not require on-board propellants to be carried and stored in order to accomplish orbit changes. ProSEDS, currently slated to be launched later this year, will utilize an electrodynamic tether to lower the rocket stage that
delivers it to orbit. Figure 1 illustrates the concept of using a conducting tether to accomplish electrodynamic propulsion. Essentially, a tether propulsion system functions by extracting the energy available in the surrounding environment and converting it to a propulsive force. The technique makes use of the age old magnetic “like poles repel, opposite poles attract” principle. When ProSEDS is in orbit, it will unwind a 15-km tether. The last 5-km of the tether will primarily be bare conducting wire. As the conducting wire slices through the Earth’s magnetic field in the presence of the low density plasma present in the ProSEDS orbit environment, it will collect electrons and begin to generate an electric current. As current begins to flow, a local magnetic field around the tether will be generated and will begin to “push” against the stronger magnetic field of the Earth. When the tether is oriented in the proper direction, this pushing action will force the spent rocket stage, because of its mechanical linkage to the ProSEDS tether, to a lower orbit.

Studies accomplished to date predict that the rocket stage, to which ProSEDS is attached, will continue to decay at a rate of over 300 meters per orbit thereby reducing reentry time from months to days.

Critical to the success of the ProSEDS mission is, of course, telemetry. Current project requirements do not dictate the need for spacecraft science, health, and status data to be analyzed real-time. Instead, a store and forward method will be used to deliver data to the end user. Data post processing activities will focus on correlating plasma environment measurements with GPS position data and tether propulsion force and orbital decay rate predictions. In the remainder of this paper, a more detailed overview of the ProSEDS mission will be given along with a more detailed description of the ProSEDS telemetry subsystem. Included in the discussion will be a summary of telemetry system testing that has been accomplished at both MSFC and the Goddard Space Flight Center (GSFC) in support of the ProSEDS project.

Figure 1. ProSEDS demonstrates Electrodynamic Propulsion
MISSION OVERVIEW

In December of this year, ProSEDS will be launched from the eastern test range of Cape Canaveral on a Boeing Delta II rocket as a secondary payload to a United States Air force (USAF) GPS constellation replenishment mission. The ProSEDS experiment hardware, which will be mounted to the Delta II second stage guidance section, is comprised of 7 main elements. These are the deployer assembly, tether assembly, electrical control and data management subsystem, GPS receiving subsystem, telemetry transmitter, endmass, and science support instrumentation.

Illustrated in Figure 2, is the fundamental ProSEDS mission sequence of events. After primary payload separation, the Delta II second stage will perform a series of propellant depletion burns which will place ProSEDS into a 400 km circular orbit inclined at 36 degrees. At approximately two hours, Mission Elapsed Time (MET), the Delta II sequencer will send the appropriate signals to release spring loaded clamps holding the endmass. Once ejected, the 20-kg endmass will travel upwards and oriented away from the earth. As the endmass departs the Delta second stage, its initial separation velocity of approximately 2.5 meters per second along with the aid of gravity gradient forces will cause the 15-km tether to be pulled from the tether storage container. A 10-km non-conductive segment of tether composed of flat-braided Spectra® 2000 fiber will unwind first from the tether spool followed by 5 km of conducting tether. The conductive tether segment consists of seven strands of #28 American Wire Gauge (AWG) aluminum twisted around a Kevlar® core.
ProSEDS experiment operations essentially begin with the separation of the endmass. When this occurs, independent telemetry and GPS systems on both the ProSEDS deployer and endmass will be active. Transmitted telemetry data from the tether deployer, attached to the Delta II second stage, and the departing endmass will include health and status telemetry as well as position updates.

Upon completion of tether deployment, additional science instruments will come on line and begin to take measurements of the plasma environment and facilitate the start of current generation in the conducting tether. Referring to Figure 3, current flow in the conducting tether, and finally, system electrodynamic propulsion is accomplished as follows.

As the tether cuts across the earth’s magnetic field, a voltage is induced across the conducting wire in proportion to the length of the wire, Delta II velocity and geomagnetic field strength (~35 to 160 V/km). Electrons, attracted to the positively biased far end of the wire, begin to flow down the aluminum conducting strands in relation to the induced voltage and tether wire resistance. Current flow down the tether during the mission is expected to average ~1.4 amps. The circuit path is completed when the Hollow Cathode Plasma Contactor (HCPC) begins to eject electrons. The HCPC closes the tether current collection circuit through the Earth’s ionosphere by producing and ejecting xenon ions into a region near the Delta II second stage. Finally, as the geomagnetic field interacts with the magnetic field set up around the wire, drag forces will be exerted along the length of the conducting tether in proportion to the tether current and geomagnetic field strength extant along the length of the wire. The drag force experienced by the conducting tether will be mechanically transferred to the Delta II stage. ProSEDS project scientists predict that the propulsive force induced by the conducting tether will result in a 5 km per day decrease in the Delta II second stage altitude and anticipate that stage reentry will occur in less than 21 days MET.

Along with demonstrating significant, measurable, electrodynamic tether thrust in space, other ProSEDS experiment objectives include evaluating the current collection performance of the bare electrodynamic tether under varied ionospheric conditions in order to determine its scalability to future applications. Also, the regulation, storage, and use of tether generated electrical power by using a secondary battery for experiment power and maintaining battery charge via tether current will be demonstrated.

Figure 3. Tether electrodynamics simplified
TELEMETRY SYSTEM OVERVIEW

The ProSEDS mission telemetry system is comprised of two completely independent telemetry subsystems. Each subsystem is controlled by and fed data from independent on-board computers. One of the telemetry subsystems is an element of the tether deployer system while the other subsystem is an element of the endmass data system. The two telemetry systems are similar to the extent that each operates at S-Band (on different frequencies), utilizes a Pulse Code Modulation Frequency Modulation (PCMFM) transmission scheme, and employ COTS transmitters built by Southern California Microwave (SCM). Each telemetry subsystem, however, was designed and built by different engineering teams. Staff engineers at MSFC designed the deployer telemetry subsystem, while the endmass system was designed and built by a team from the University of Michigan. Due to the space limitations of this paper, the endmass telemetry subsystem will not be discussed further in detail except to say that the primary purpose of the endmass telemetry subsystem is to facilitate the return of endmass GPS position and magnetometer data to aid the study of tether dynamics.

The MSFC design team for the ProSEDS deployer telemetry subsystem was required to meet five basic requirements. The subsystem requirements were:

1) To support a low data rate transmission of 19.2 Kbps during tether deployment;
2) To deliver a higher 115.2 Kbps transfer rate during primary mission operations;
3) To have less than a one in $10^5$ Bit Error Rate (BER);
4) To achieve a 3 dB margin for all ground station links;
5) To not consume more than 20 watts of DC input power.

A block diagram of the resultant deployer telemetry subsystem is shown in Figure 4.

![Diagram](image-url)
Four other implicit requirements, constant to most satellite missions of course, were that the system needed to be completely reliable, cost zero dollars, weigh nothing, and occupy no volume in space.

The requirements for zero cost, weight, and volume are, of course, facetious; however MSFC engineers did attempt to minimize as much as possible most of the negative factors. The approach taken to achieve all of the objectives, especially cost, was to use commercially available components with reasonable flight heritage in conjunction with existing flight system hardware.

With link analysis studies indicating that most of the primary requirements could be met with a simple PCMFM transmitter supplying two watts or more of RF output power, a COTS transmitter from SCM was selected and purchased for the program. Cost and reliability concerns were again addressed in selecting the simpler AC coupled transmitter version. An AC coupled transmitter was also an attractive choice because ProSEDS experiment and data system engineers had selected a data formatting scheme which precluded the occurrence of one or zero strings that could contribute significantly to a DC offset bias. Later testing also showed conclusively that the AC coupled transmitter using simulated worst case data did not create a notable difference in $E_b/N_0$ performance relative to an identical SCM DC coupled transmitter. Two modifications, however, were required of the standard SCM COTS transmitter. Input power circuitry was modified in order to meet the twenty watt input power consumption limit while supplying nearly two watts of RF output power; and also, internal cadmium standoffs needed to be replaced in order to meet safety and environmental out-gassing restrictions. The transmitter was also selected to have a RS422 interface for ease of integration with the deployer data system. Both the deployer transmitter and endmass transmitter were optimized in terms of the recommended pre-modulation filter cutoff bandwidth and peak deviation settings for digital PCMFM transmitters. Each was set to a three-dB premodulation filter bandwidth of 80.6 kHz and peak deviation of 40.3 kHz.

One other significant way in which MSFC engineers were able to reduce program costs as well as to reduce the weight, space, and parts count liabilities was to investigate and implement a simple method for making use of telemetry system components already on board the Delta II second stage. Since the Delta II telemetry system would no longer be needed after the delivery to orbit and separation of the primary payload, MSFC engineers requested that a four port hybrid coupler be substituted for the three port coupler normally in place for Delta II launch vehicle telemetry systems. Substituting couplers allowed the deployer telemetry system to make use of the Delta II antenna system upon completion of the Delta II primary mission objectives. The Delta II telemetry antenna system is comprised of a pair of flush mounted, diametrically opposed S-Band, linear, cavity backed slotted resonators. Each antenna provides hemispherical coverage for the Delta second stage.

Referring again to Figures 2 and 4, the ProSEDS deployer telemetry system operates as follows. Shortly after Delta stage three separation, the Delta II sequencer will enable deployer system electronics to be powered up by sending the appropriately timed commands to close the two indicated relay switches. Approximately ten minutes later (83 minutes MET) the deployer On Board Computer (OBC) will enable the telemetry transmitter to begin sending health, status, and GPS position updates. The endmass telemetry system will become activated and begin transmitting after endmass separation (114 minutes MET).

During the tether deployment phase of the ProSEDS mission, the deployer telemetry system will transmit data continuously at the 19.2 Kbps rate. At the end of tether deployment the OBC will
reinitialize the data system to an operational mode format and begin sending data to the transmitter at
the 115.2 Kbps rate. From the beginning of tether deployment through the first seven orbits following
deployment, the transmitter will remain on and will send return link telemetry. However, at around
fourteen hours MET, the OBC will transition to a secondary battery for instrument power. After the
transition to secondary battery power, the OBC will begin using GPS position updates to control the
operation of the transmitter in an effort to conserve battery power. The endmass data system will use a
similar method for transmitter control, but will begin transmitter cycling after about the fourth orbit
following endmass separation. The deployer OBC controls transmitter operation through the use of a
control transistor on the input power feed to the transmitter as depicted in Figure 4.

The decision to turn on or off the transmitter is based on the GPS position data delivered to the OBC
from the deployer GPS receiving system. The OBC compares the current position information with a
lookup table of latitude and longitude values that describe an “acquisition” box around each of the
ground stations contracted for ProSEDS mission support. When the OBC determines that ProSEDS is
within line of sight to a ground station at about five degrees off the ground station view horizon, the
transmitter will be turned on. Likewise, when the OBC determines that the spacecraft has passed out of
ground station visibility, the transmitter will be turned off. This transmitter cycling mode of operation
will continue until either ProSEDS reenters the atmosphere and is destroyed or until the OBC has
determined that the MET has exceeded twenty-one days. After twenty-one days of operation, the OBC
mission software in both the deployer and endmass is programmed to shut down the telemetry
transmitter to comply with NTIA licensing requirements.

**DEPLOYER TRANSMITTER TEST SUMMARY**

Performance tests of the deployer transmitter were conducted at both MSFC and GSFC in Greenbelt,
Maryland. Testing at MSFC was done mainly to ensure compliance with the as ordered specifications.
Output RF power, input power consumption, signal spectrum quality, peak deviation, etc., were
examined and found to be well within specification. However, a more important set of tests was
conducted at GSFC in order to ensure compatibility of the deployer transmitting equipment and signal
with the various supporting ground station receiving equipment.

The ground stations contracted to support the ProSEDS mission include the Wallops Island tracking
facility in Virginia, Santiago tracking station in Chile, Madrid tracking station in Spain, Goldstone
tracking station in California, Canberra tracking station in Australia, the Air Force Satellite Control
Network (AFSCN) Remote Tracking Station (RTS) in Guam, and the AFSCN RTS in Hawaii. The
listed ground stations were selected primarily on the basis of their location relative to ProSEDS orbit
ground track and the ProSEDS program requirement to have at least a once per day telemetry downlink
opportunity.

During testing at GSFC, the deployer transmitter was evaluated for compatibility with each of the
ground station receiving equipment configurations that will be setup to support the ProSEDS mission.
Table 1 attempts to show some of the essential configuration setups that were tested and the results
obtained in terms of $E_b/N_0$ performance at a $10^{-5}$ Bit Error Probability (BEP). It is important to note that
the test result data reflected in the table are values calculated by GSFC test engineers based on estimated
or calculated test setup gains, losses, and receiving equipment bandwidth parameters. In other words,
the tabulated $E_b/N_0$ values were not calculated directly from $C/N_0$ measurements taken at the receiver intermediate frequency (IF) port during testing.

<table>
<thead>
<tr>
<th>Tracking Station Configurations</th>
<th>$[E_b/N_0]_{\text{dB}}$ for $10^{-5}$ BEP</th>
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</thead>
<tbody>
<tr>
<td>Ground Stations</td>
<td></td>
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<tr>
<td></td>
<td>Receiver (IF BW)</td>
</tr>
<tr>
<td>Wallops Island, VA</td>
<td>SA930 (350 kHz)</td>
</tr>
<tr>
<td>Santiago, Chile</td>
<td>MFR (300 kHz)</td>
</tr>
<tr>
<td>Madrid, Spain</td>
<td>MFR (300 kHz)</td>
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<tr>
<td>Goldstone, California</td>
<td>TCP (300 kHz)</td>
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<tr>
<td>Canberra, Australia</td>
<td>TCP (300 kHz)</td>
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<tr>
<td>Guam</td>
<td>1200 MRC (1 MHz)</td>
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<td>Hawaii</td>
<td></td>
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* bit sync locked to data stream but BER measurement not taken.
** bit sync would not lock to data stream

Table 1. ProSEDS deployer compatibility test result summary.

All configurations reflected in Table 1 used a common receive system front end. In other words, the deployer transmitter was connected to laboratory measurement equipment and to a unique ground station receiver/demodulator and bit sync configuration through a common setup of cables, connectors, attenuators, Low Noise Amplifier (LNA), down-converter, couplers, and power splitters.

In the listed configurations, the SA930 is a Scientific Atlanta model 930 receiver and the 7715 is the Data Systems Incorporated (DSI) model 7715 bit synchronizer. The MFR is the standard NASA Ground Network (GN) Multi-Function Receiver and the TCP is a Telemetry Command Processor unit built by Avtec Systems. The TCP is replacing some of the older demodulation and bit synchronizer equipment like the Aydin Monitor model 335 at Deep Space Network (DSN) tracking stations. The TCP will allow DSN sites to become more fully automated.

Several notable results can be obtained from Table 1. First, not a great deal of performance variance was observed between any of the ground station setups for either data rate tested. However, at the 19.2 Kbps rate, overall $E_b/N_0$ performance degraded by approximately three dB. Secondly, no significant performance degradation was observed when Pseudo Random Noise (PRN) test data was used as the modulation source compared to a modulation sources comprised of simulated worst case data (WCD).
The deployer WCD is a data stream that may be composed of 90% zeros and 10% ones or 90% ones and 10% zeros in a maximum length of 10 bits. Finally, only one compatibility problem was observed. When the WCD was used, only the TCP bit synchronizer was unable to lock to the data. This is an issue that will need to be examined further and resolved prior to flight.

CONCLUSIONS

ProSEDS is well poised to become the first space flight experiment to demonstrate significant, measurable, electrodynamic tether thrust in space. Tether propulsion technology has numerous future mission applications. For example, tether propulsion may be used to provide satellite deorbit capability to mitigate orbital debris issues. Also, it estimated that the International Space Station could potentially save over one billion dollars a year by using a tether system to provide propellantless reboost capability. Orbit transfer vehicles could make similar use of a tether propulsion system. Finally, long duration space flights, a Jovian mission for example, could use tethers for both propulsion and power generation.

By combining low cost COTS hardware with the existing Delta II telemetry system, MSFC engineers were able to meet power, weight, and mission requirements while achieving a reliable, inexpensive, telemetry system design.

REFERENCES


