JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 37, No. 2, March–April 2000

Propulsive Small Expendable Deployer System Experiment

Les Johnson*
NASA Marshall Space Flight Center, Huntsville, Alabama 35812
Robert D. Estes† and Enrico Lorenzini‡
Harvard–Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138
Manuel Martínez-Sánchez§
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139-4307
and
Juan Sanmartín¶
Polytechnic University of Madrid, 28040 Madrid, Spain

Relatively short electrodynamic tethers can extract orbital energy to "push" against a planetary magnetic field to achieve propulsion without the expenditure of propellant. The Propulsive Small Expendable Deployer System experiment will use the flight-proven Small Expendable Deployer System to deploy a 5-km bare aluminum tether from a Delta II upper stage to achieve ≈ 0.4-N drag thrust, thus lowering the altitude of the stage. The experiment will use a predominantly bare tether for current collection in lieu of the endmass collector and insulated tether used on previous missions. The flight experiment is a precursor to a more ambitious electrodynamic tether upper-stage demonstration mission that will be capable of orbit-raising, -lowering, and -inclination changes, all using electrodynamic thrust. The expected performance of the tether propulsion system during the experiment is described.

Nomenclature

$\boldsymbol{B}$ = local magnetic field strength
$\boldsymbol{F}_d(\ell)$ = drag force induced on the tether
$\boldsymbol{L}$ = tether vector
$\boldsymbol{v}$ = system velocity

Introduction

SINCE the 1960s, at least 17 tether missions have been flown in space. In the 1990s, several important milestones were reached, including the retrieval of a tether in space [Tethered Satellite System-1 (TSS-1)[1]], successful deployment of a 20 km tether in space [Small Expendable Deployer System-1 (SEDS-1)[2]], closed-loop control of tether deployment (SEDS-2),[2] and operation of an electrodynamic tether (EDT) with tether current driven in both directions: power and thrust modes [plasma motor generator (PMG)[3]]. A list of known tether missions is shown in Table 1. The Propulsive Small Expendable Deployer System (ProSEDS) experiment will build upon the technology heritage of these missions and demonstrate the use of long EDTs for space propulsion. It will involve the deployment of a 5-km bare-wire tether from the SEDS deployer and the subsequent collection of 1–2 A of current from the ionosphere along the length of the tether. The interaction of the tether current with the Earth's magnetic field will produce a drag thrust, lowering the altitude of the upper stage by at least 5 km/day. Instrumentation will characterize the ambient space plasma environment as well as the performance of the tether as a current collector under varied ionospheric conditions. The experiment is manifested for flight in August 2000 as a secondary payload aboard a Delta II rocket.

EDT Propulsion Principles

An EDT generates and forms part of a unique type of electrical circuit that has been successfully demonstrated in space.[4] The tethered system extracts electrons from the ionospheric plasma at one end (upper or lower) and carries them to the other end, where it returns them to the plasma. The circuit is completed by currents in the plasma. In a normal circuit (a current-bearing closed loop of wire), the net force caused by a uniform magnetic field acting on the current is zero because the force on one length of wire is canceled by that on another in which the current is flowing in the opposite direction. In the EDT, however, because there is no mechanical attachment of the tethered system to the plasma, which is just the rarefied medium through which the system is traveling magnetic forces on the plasma currents do not affect the tether motion. In other words, we have a length of wire with a unidirectional current flowing in it, and this wire is accelerated by the Earth's magnetic field.

The bias voltage of a vertically deployed metal tether, which results from its orbital motion through the Earth's magnetic field, is positive at the top and negative at the bottom with respect to the ambient plasma. Thus the "natural" current flow is the result of electrons being attracted to the upper end and returned to the plasma at the lower end. For an eastward-moving system, such as most Earth-orbiting spacecraft, the field is such that the electrical potential decreases with increasing altitude (at a rate of ≈ 100 V/km for a 400-km circular orbit). The magnetic force in this case has a component opposite to the direction of motion and thus leads to a lowering of the orbit and eventually to reentry. That the basic physics works in space was verified by the TSS-1R and PMG missions, but no measurements were made to quantify the resulting orbital changes, nor was the high-current bare-tether concept demonstrated.

The motion of the system through the Earth's magnetic field induces a voltage emf $= \boldsymbol{L} \cdot (\boldsymbol{v} \times \boldsymbol{B})$ between the two ends of the tether, where $\boldsymbol{L}$ is a vector parallel to the tether whose magnitude is the length of the tether, $\boldsymbol{v}$ is the velocity of system through the ionosphere, and $\boldsymbol{B}$ is the local value of the Earth's magnetic field vector.

The current in the tether varies along its length as collected electrons accumulate in an increasing downward stream in the wire. Denoting by $I(\ell)$, the current in a segment of tether $\Delta\ell$ at a distance ℓ from the lower end of the tether we have $\boldsymbol{F}_d(\ell) = I(\ell)\Delta\boldsymbol{\ell} \times \boldsymbol{B}$ for the drag force on this tether segment, where $\Delta\boldsymbol{\ell}$ points in the direction of the current flow. The total drag force on

---

Received 21 September 1998; revision received 12 April 1999; accepted for publication 12 June 1999.

*Principal Investigator, Mail Code TD15, ProSEDS Experiment, Advanced Space Transportation Program.

†Physicist, Radio and Geoastronomy Division, 60 Garden Street. Senior Member AIAA.

‡Head of Special Projects Group, Radio and Geoastronomy Division, 60 Garden Street. Senior Member AIAA.

§Professor of Aeronautics and Astronautics, 77 Massachusetts Avenue. Senior Member AIAA.

¶Escuela Técnica Superior de Ingenieros Aeronáuticos.

Table 1 Summary of known space tether missions

Name	Date	Orbit	Length	Comments
Gemini 11	1966	LEO	30 m	Spin stable 0.15 rpm
Gemini 12	1966	LEO	30 m	Local vertical, stable swing
H-9M-69	1980	Suborbital	500 m	Partial deployment
S-520-2	1981	Suborbital	500 m	Partial deployment
Charge-1	1983	Suborbital	500 m	Full deployment
Charge-2	1984	Suborbital	500 m	Full deployment
ECHO-7	1988	Suborbital		
Oedipus-A	1989	Suborbital	958 m	Spin stable 0.7 rpm
Charge-2B	1992	Suborbital	500 m	Full deployment
TSS-1	1992	LEO	< 1 km	Electrodynamic, partial deploy, retrieved
SEDS-1	1993	LEO	20 km	Downward deploy, swing and cut
PMG	1993	LEO	500 m	Electrodynamic, upward deploy
SEDS-2	1994	LEO	20 km	Local vertical stable, downward deploy
Oedipus-C	1995	Suborbital	1 km	Spin stable 0.7 rpm
TSS-1R	1996	LEO	19.6 km	Electrodynamic power generation and science
TiPS	1996	LEO	4 km	Long-life tether
ATEx	1999	LEO	< 30 m	Incomplete deployment

the system is then the sum of the $\boldsymbol{F}_d(\mathscr{L})$ over the full length of the tether.

To get an orbit-raising thrust, a current in the opposite direction must be obtained. This requires a reversal of the natural electrical bias (i.e., that due to the motion through the magnetic field) by means of an electrical power supply, which can, of course, use solar energy. PMG[3] has successfully demonstrated this mode of operation using batteries, though no thrust measurements were made.

One of the most important features of EDT thrust is that no onboard power source is required to drive the electrical current flow in either the orbit-raising or the orbit-lowering mode; sources inherent to Earth orbit are used. To raise the orbit, the energy of the sun can be converted to the electrical energy required to drive the tether current. To lower the orbit, the orbital energy itself (supplied by the Earth-to-orbit launcher when it raises the system into orbit) is the energy source of the tether current. ProSEDS will operate in the orbit-lowering mode, and, rather than dissipating all of the electrical energy it generates in its operation, it will use some of the energy to recharge batteries.

The previously cited EDT missions, although verifying that the basic principles of tether operation are sound, did not establish scalability to useful applications. ProSEDS aims to do this through the use of a more efficient current-collection design.

Collecting electrons from the ionosphere proves to be much more difficult than expelling them into it. Previous experiments relied on either a large metallic surface (TSS-1R satellite) or a hollow cathode (PMG) to collect electrons from the ionosphere. PMG currents[5] were disappointing, and achieving higher currents by satellite surface collection requires ever larger satellites, quickly invoking the law of diminishing returns. For ProSEDS the electron expulsion task will be handled by a hollow cathode device that requires a small amount of gas to operate. In future applications, field emitter arrays may eliminate the need for even this consumable.

ProSEDS will use a radically different collection scheme, which promises to be much more efficient and easily scalable to practical applications such as propulsive thrust. Most of the metallic tether will be left exposed to the plasma rather than covered with an insulating sleeve, as in previous EDT missions. The bare tether itself will collect electrons directly. A well-developed theory of current collection by thin wires,[6] verified in plasma chamber tests, indicates that the ProSEDS tether will be an order of magnitude more efficient in electron collection than tethers in previous space experiments, with even greater enhancements possible in the future. Before we can proceed to the design of an operational system, however, we must test the bare tether design in low Earth orbit (LEO). So far, neither theory nor laboratory tests have modeled the effects of the motion of the tether through the plasma. Although there is no obvious reason why these effects should significantly affect current collection, prudence demands that we verify the bare tether's performance, in space, with a real deployed tether system. ProSEDS will provide that verification, and the data collected by the various ProSEDS instruments will thoroughly characterize the space environment, thus giving analysts a chance to determine the reason for any deviation from predicted performance.

ProSEDS Experiment

The ProSEDS experiment will be placed into an approximately 400-km circular orbit as a secondary payload from a Delta II rocket. Once on orbit, the SEDS will deploy 10 km of nonconducting Spectra$^{\text{TM}}$ tether attached to an endmass, followed by 5 km of predominantly bare-wire tether. Upward deployment will set the system to operate in the generator mode, thus producing drag thrust and electrical power. The drag thrust provided by the tether, with an average current of 0.5 A, will lower the altitude of the Delta II upper stage (Fig. 1). If the tether system were to survive micrometeoroids, orbital debris, and atomic oxygen (AO) in the orbital environment, the stage would deorbit in < 17 days vs its nominal ≥ 6-month lifetime in a 400-km circular orbit.

The specific goals and success criteria for the experiment are described in Table 2. The thrust measurements will be accurately determined by measuring the change in orbital position of the stage using the Global Positioning System (GPS) and through ground tracking. A differential ion flux probe (DIFP) and Langmuir probe will be used to characterize the ambient plasma environment.

The rate of altitude change is strongly dependent on the current collected by the tether, as can be seen in Fig. 2. The current collection varies dramatically as a function of plasma density as well as the orientation of the tether with respect to the magnetic field (Fig. 3). There are times in the orbit when both the induced electromotive force (emf) and the plasma density are low, thus decreasing the thrust of the system. These two parameters are independent and will be measured by onboard instrumentation. Performance and diagnostic instruments mounted on the Delta II will be used to correlate the propulsive forces generated by the EDT and the existing plasma conditions. These instruments will measure plasma density, temperature, energy, and potential.

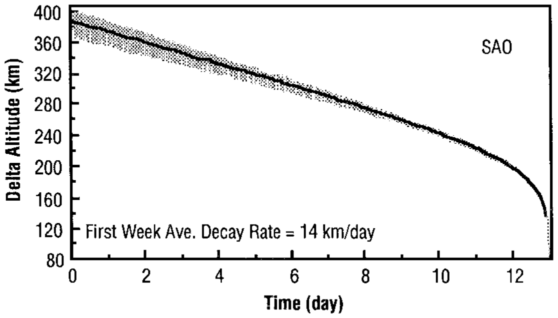

Fig. 1 Electrodynamic tether dramatically reduces the orbital lifetime of the upper stage.

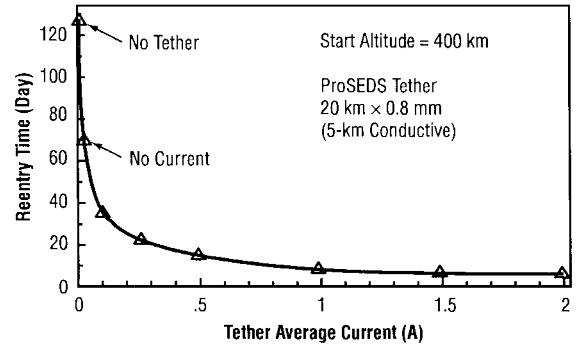

Fig. 2 Orbital lifetime of the stage vs orbital average current collected.

Table 2 ProSEDS experiment objectives

Objectives	Critera for success (performance metrics)	Measurements required	Instruments required
Primary: Demonstrate significant, measurable EDT thrust in space	Demonstrate an orbital decay rate of at least 5 km/day	Change of orbital position	GPS Ground radar Ground telescopes
Primary: Measure the current collection performance of the bare EDT under varied ionospheric conditions and determine its scalability to future applications	Obtain data over 16 orbits (obtain continuous data for the first three orbits and sampling over the remaining 13)	Voltage Current Magnetic field orientation Spacecraft potential Plasma density Ambient electron temperature Absolute position of Delta Relative position of tether (estimate)	Voltmeter Ammeter Aspect magnetometer DIFP, Langmuir probe Langmuir probe, DIFP Langmuir probe GPS, ground radar Turns counter
Secondary: Demonstrate the regulation, storage, and use of tether-generated electrical power	Generate a current of at least 1.5 A (orbital average)	Battery temperature Voltage Current	Thermistor Voltmeter Ammeter
Secondary: Determine system performance during the extended mission phase (begins after orbit 16)	Collect available tether performance data	Telemetry (if available) Change of orbital position	All functioning instruments GPS, ground radar Ground telescopes
Secondary: Assess tether survivability in AO, meteoroid, and orbital debris environment	Observe tether integrity	Tether observation(s) Voltage Current	GPS, radar and telescopes Voltmeter Ammeter
Secondary: Assess tethered electrodynamic system operations	Stable (bounded) dynamic envelopes	Endmass relative position and attitude vs time	GPS Magnetometer

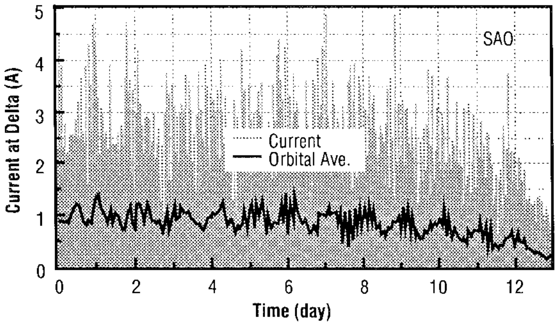

Fig. 3 Current at Delta vs mission elapsed time.

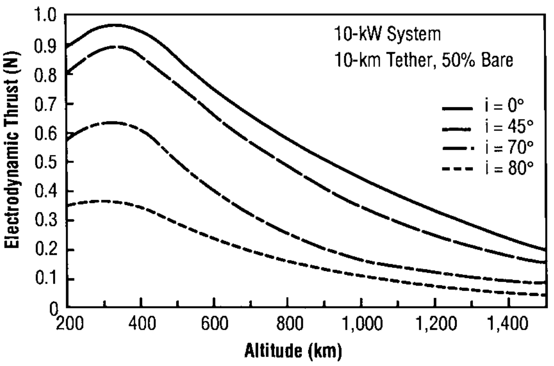

Fig. 4 Estimated propulsive performance of an upper-stage demonstrator vehicle using EDT thrust.

Potential Applications of the Technology

The primary advantage of EDTs is that they can be used as propellantless space propulsion systems; no resupply is required. Tethers take advantage of the natural plasma environment and sunlight to provide thrust and power. For example, if solar arrays and an external power supply are used, an emf can be generated in the tether such that current collected from the ionosphere produces thrust rather than drag. This thrust can then be used to raise the orbit of the system or change its inclination, all without propellant or rocket engines. It is envisioned that this type of propulsion could be used on a reusable upper stage to provide a low-cost alternative to chemical stages. An EDT upper stage could be used as an orbital tug to move payloads within LEO after insertion. The tug would rendezvous with the payload and launch vehicle, dock/grapple the payload, and maneuver it to a new orbital altitude or inclination within LEO without the use of boost propellant. The tug could then lower its orbit to rendezvous with the next payload and repeat the process. Such a system could conceivably perform several orbital maneuvering assignments without resupply, making it a low-recurring-cost space asset. A follow-on mission to the ProSEDS is being considered to demonstrate the orbit-raising and orbit-lowering capabilities of EDTs. The project, tentatively called Space Transfer using Electrodynamic Tethers (STEP), would be a 500-kg-class satellite with dual tethers and an onboard power system. Its expected performance is illustrated in Fig. 4.

A ProSEDS-derived system could be used operationally to extend the capability of existing launch systems by providing a propellantless system for deorbiting spent stages. The launch service provider need not carry additional fuel for the soon-to-be-required deorbit maneuver, thus allowing all of the onboard fuel to be used for increasing the vehicle's performance. Similarly, satellites thus equipped could safely deorbit at their end of life without using precious onboard propellant. Both of these applications would help reduce the increasing threat posed by orbital debris.

An EDT system might also be used on the International Space Station (ISS) to supply a reboost thrust of 0.5–0.8 N, thus saving up to 6000 kg of propellant per year.[7] The reduction of propellant needed to reboost the ISS equates to a savings of $2 billion over its 10-year lifetime. Other advantages of using the EDT on the ISS are that the microgravity environment is maintained and external contaminants are reduced.

Conclusions

Tether technology has advanced significantly since its inception over 30 years ago. The recent successes of the SEDS system show that tethers are ready to move from experiment and demonstration to application. One of the most promising applications for tethers is space propulsion and transportation. The ProSEDS mission will demonstrate the ability of an EDT to produce thrust by lowering the altitude of a Delta II rocket. Its performance as a propulsion system is heavily dependent on the ambient environmental conditions (plasma conditions and magnetic field strength).

References

[1] Strim, B., Pasta, M., and Allais, E., "TSS-1 vs. TSS-1R," *Proceedings of the Fourth International Conference on Tethers in Space*, Smithsonian Inst., Washington, DC, 1995, pp. 27–41.

[2] Smith, H. F., "The First and Second Flights of the Small Expendable Deployer System (SEDS)," *Proceedings of the Fourth International Conference on Tethers in Space*, Smithsonian Inst., Washington, DC, 1995, pp. 43–55.

[3] McCoy, J. E., Grossi, M. D., and Dobrowolny, M., "Plasma Motor Generator (PMG) Flight Experiment Results," *Proceedings of the Fourth International Conference on Tethers in Space*, Smithsonian Inst., Washington, DC, 1995, pp. 57–82.

[4] Stone, N. H., Wright, K., Winningham, J. D., Gurgiolo, C., Samir, U., Bonifazi, C., Gilchrist, B., and Dobrowolnt, M., "Identification of Charge Carriers in the Ionospheric Branch of the TSS–1 Tether Generated Current System," *Proceedings of the Fourth International Conference on Tethers in Space*, Smithsonian Inst., Washington, DC, 1995, pp. 359–371.

[5] Lilley, J. R., Greb, A., Katz, I., Davis, V., McCoy, J. E., Galofaro, J., and Ferguson, D. C., "Comparison of Theoretical Predictions with Plasma Motor Generator (PMG) Experimental Data," *Proceedings of the Fourth International Conference on Tethers in Space*, Smithsonian Inst., Washington, DC, 1995, pp. 1847–1856.

[6] Sanmartin, J. R., Martinez-Sanchez, M., and Ahedo, E., "Bare Wire Anodes for Electrodynamic Tethers," *Journal of Propulsion and Power*, Vol. 9, No. 3, 1993, pp. 353–360.

[7] Johnson, L., and Herrmann, M., "*International Space Station* Electrodynamic Tether Reboost Study," NASA TM-1998-208538, 1998.

I. E. Vas
Associate Editor