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Andrew Santangelo
Rich Sturmfels
Dr. Jon Van Noord
Robert Strunce
The Michigan Technic Corporation
Holland, Michigan

Dr. Brian Gilchrist
The University of Michigan
Ann Arbor, Michigan

Dr. John Hoffman
The University of Texas at Dallas
Richardson, Texas

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Andrew Santangelo[1]
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The Michigan Technic Corporation
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The University of Texas at Dallas
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Abstract

A key goal of space exploration is to improve the specific impulse and mass fraction for the orbit transfer of satellites. One of the aspirations of the space tether community is to develop an Electrodynamic (ED) tether facility to place satellites in orbit, change their orbit and/or remove them from orbit without the use of chemical propellants. In this paper we will discuss applications of ED tethers including Orbit Transfer Vehicles, satellite deorbit, and reboost of the ISS. Two missions are discussed, which when successfully completed will signify the start of commercial application of this innovative method of transportation.

I. Introduction

Since the 1960's there have been at least 17 tether missions. In the 1990's several important milstones were reached, including the retrieval of a tether in space (TSS-1, 1992), successful deployment of a 20 km long tether in space (SEDS-1, 1993), and operation of an electrodynamic tether with tether current driven in both directions — power and thrust modes (PMG, 1993). Future tether mission include ProSEDS, an ED Tether Propulsion experiment and the STEP-AIRSEDS mission, which will demonstrate ED propulsion in space

[1] President/CEO, Professional Member, Chairman of the AIAA Michigan Section

over a one year period, including boost, deboost, station keeping and plane changes. From theoretical analyses and preliminary plasma chamber tests, bare tethers (exposed metal wire tethers) appear to be very effective anodes for collecting electrons from the ionosphere and, consequently, attaining high currents with relatively short tether lengths. A predominantly unisulated conducting tether, terminated at one end with a plasma contactor, can be used as an electromagnetic thruster. A propulsive force of F = IL x B is generated on a spacecraft/tether when a current, I, from electrons collected in a space plasma, flows down a tether of length, L, due to the emf induced in it by the geomagnetic field, B. Preliminary tests indicate that a thin unisulated wire could be 40 times more efficient as a collector vs. the previous system used (TSS-1).

In this paper we will discuss applications of ED Tethers. Two missions are also covered in this paper, *ProSEDS* and *STEP-AIRSEDS*, which when successfully completed will signify the start of commercial application of this innovative method of transportation.

II. Applications of ED Tethers

Electrodynamic tethers have many potential applications of interest to NASA and the commercial space industry. They range from satellite deobit and propellantless orbit transfer vehicles to reboost of the International Space Station.

Orbit Transfer Vehicles (OTV)

An electrodynamic tether upper stage could be used as an orbital tug to move payloads within low earth orbit (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*. Figure 1 presents an artists conceptual view of an OTV. 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 low recurring cost space asset. This capability is of particular interest within NASA, in that it may provide a way to allow repeated access to staging orbits for integration and assembly of human exploration vehicles for missions beyond LEO.

The performance of a 10 kW, 10 km tether system for altitude changes is illustrated in Figure 2. The same system can be used to change the orbital inclination of a payload as well. Figure 3 can be used to determine the available inclination change for a particular spacecraft and payload mass by dividing the 'specific inclination rate' indicated by the total system mass as a given altitude.

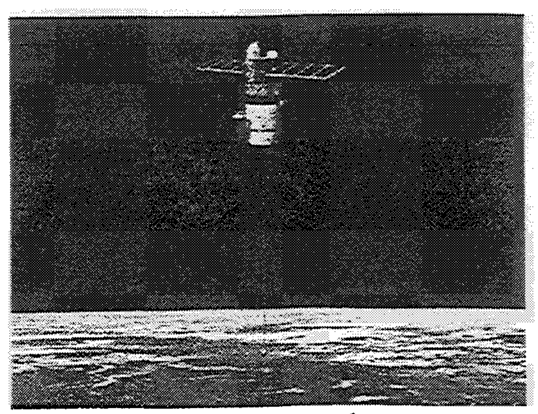

Figure 1. The OTV at work

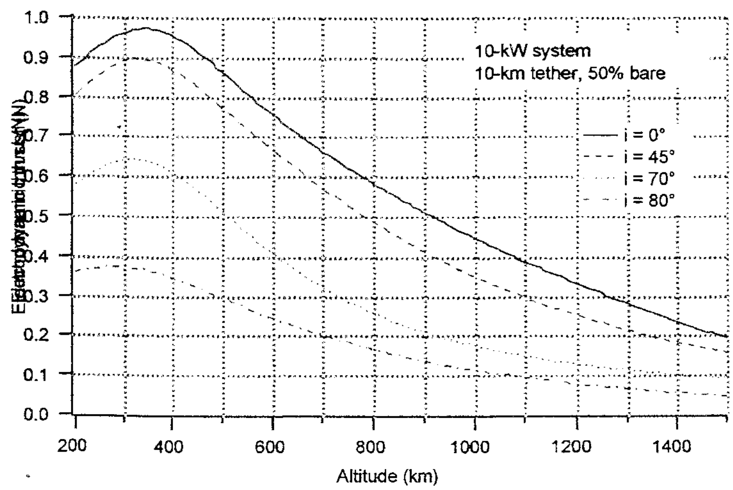

Figure 2. The performance of an electrodynamic tether thruster varies with altitude in the ionosphere (where i is the orbital inclination).

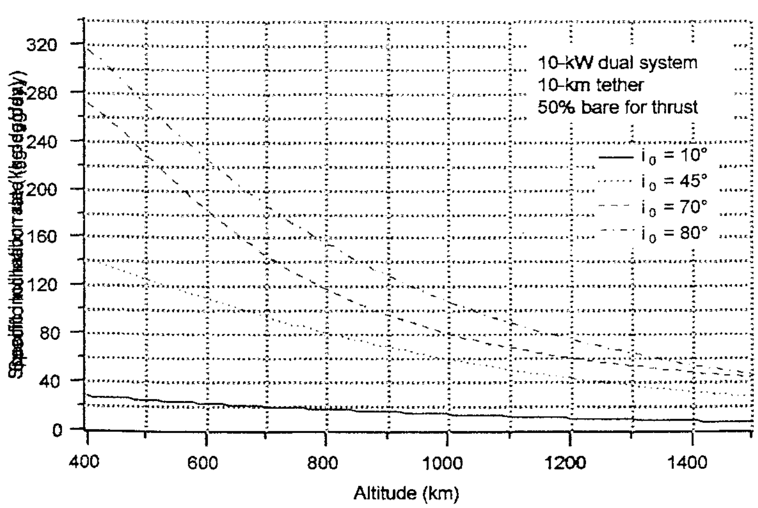

Figure 3. The performance of an electrodynamic tethers thruster for inclination change applications depends strongly on the initial orbital inclination (i_0).

Satellite Deorbit

With the flight of the Propulsive Small Expendable Deployer (ProSEDS) experiment in late 2000, the capability to deorbit payloads with a passive electrodynamic tether will be demonstrated. 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 or satellites that have reached the end of their orbital life. For the former case, the launch service provider need not carry additional fuel for the soon-to-be-required deorbit maneuver, thus allowing all 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.

Reboost of the International Space Station

An electrodynamic tether system could be used on the International Space Station (ISS) to supply a reboost thrust of 0.5-0.8N, thus saving up to 6000kg of propellant per year. The reduction of propellant needed to reboost the ISS equates to a $1-2B savings over it's 10 year lifetime. Other advantages of using the electrodynamic tether on ISS are that the microgravity environment is maintained and external contaminants are reduced.

The value in an electrodynamic tether reboost system lies in its ability to couple power generation with thrust. Heretofore the electrical and propulsion systems have been effectively totally separate entities. Outfitting ISS with an electrodynamic reboost tether severs the most critical and constraining dependency on Earth - propellant resupply. The Station can supply its own power but not its own propellant. Without an electrodynamic tether, the specter of SkyLab and the words "reentry" and "atmospheric burnup" will forever haunt the minds of anyone who has an interest in the program. Add a tether and some additional storage capacity for supplies, and suddenly a one year interval between visits to the Station becomes conceivable.

Even if the current frequency of resupply flights to the Station is maintained, with an electrodynamic tether the Station Program has the option to trade kilowatts for increased payload capacity. Resupply vehicles can deliver useful cargo like payloads, replacement parts, and crew supplies rather than propellant. Within the range of 5 to 10 kW, a crude approximation of 1,000 kg of user payload gained per kW expended per year appears reasonable.

Station users have been allocated a minimum of 180 days of microgravity per year. Current planning essentially halts science activity during reboost maneuvers. Low thrust electrodynamic tether reboost could be performed over long duration, as opposed to short duration, high thrust propulsive maneuvers. The 0.5 to 0.8 N thrust provided by a 10 km tether more than counteracts the Station's atmospheric drag on a daily basis. Recent analysis indicates that an electrodynamic tether can compensate for the drag while it is occurring, without disrupting the microgravity environment.

III. Missions

In order to fully develop the systems which will be utilized in future ED Tether supported missions, two key missions are required to test, demonstrate, understand and develop ED Tether Technologies and methods of applications. These Missions are *ProSEDS* and *STEP-AIRSEDS*.

A. ProSEDS

In June of 2001 NASA MSFC will test in space an electrodynamic tether which will passively deboost a satellite back to Earth. The ProSEDS mission (Propulsive Small Expendable Deployer System) will be the first mission to demonstrate the basic concept of an electrodynamic tether propulsion system. The ProSEDS mission will deploy 5 km of bare wire plus 10 km of Spectra tether from a Delta II upper stage to achieve ~0.4 N of drag thrust, thus de-orbiting the stage. The experiment will use a predominantly 'bare' tether for current collection in lieu of the endmass collector and insulated tether approach utilized on the TSS-1 missions. ProSEDS will also utilize tether generated current to provide limited space craft power. The demonstration mission will last less than one week. Figure 4 shows a conceptual drawing of ProSEDS and diagrams the basic principle.

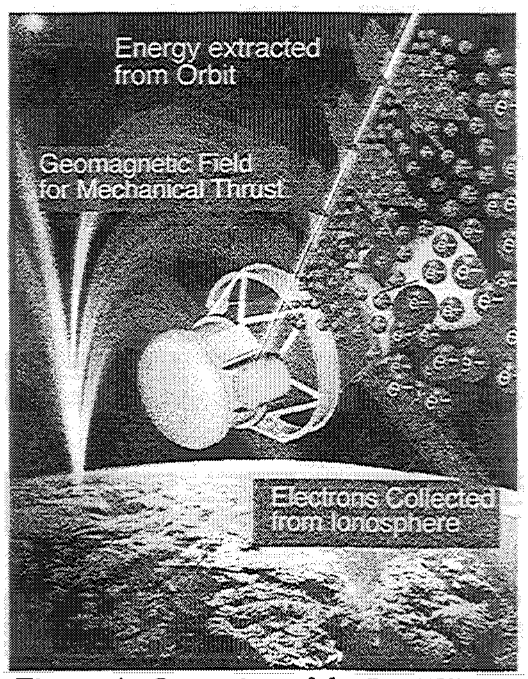

Figure 4. Operation of the ProSEDS ED Tether System.

B. STEP-AIRSEDS

The STEP-AIRSEDS Mission represents a new and innovative method of space transportation — the use of a conducting tether, solar power and the Earth's magnetic field to move a satellite up, down and change planes without the use of chemical propellants in Low Earth Orbit. The STEP-AIRSEDS mission is a demonstration mission to fully study the performance and operation characteristics of an Electrodynamic (ED) tether propulsion system for a range of flight operations.

The primary objectives of the STEP-AIRSEDS mission are:

(1) Demonstrate the predictable Earth maneuvering capability of electrodynamic tethers
(2) Demonstrate electrodynamic tether system dynamic stability during nominal tether operation
(3) Demonstrate long-life tether technology
(4) Characterize the performance of electrodynamic propulsion systems and their operational limits (dynamic and electrodynamic)
(5) Demonstrate low power alternate electron emission technology requiring no consumables

The STEP-AIRSEDS Satellite consists of two units tethered together via a 6 – 7 km Long Life ED Tether. Larger than *ProSEDS*, the total mass of the satellite with tether is approximately 1000 kg; the total length of each unit is 2 m with a 1.2 m diameter. The *Upper Unit* of *STEP-AIRSEDS* drives the boost operations of the satellite; the *Lower Unit* drives the deboost operations. The tether itself connecting the units will support up to a 1,000 Watt load and a peak current of 10 Amps. The tether deployer and separation systems are located in the *Upper Unit*. Both units will have duplicate suites of instrumentation to monitor and study the local environment, the orientation and position of the end masses and the overall performance of the system. Figure 7 presents an artist's conceptual design of STEP-AIRSEDS during deployment operations.

STEP-AIRSEDS Innovations

Due to the "newness" of the program, many innovations will be flown on the STEP-AIRSEDS mission. These innovations will allow ED Tether Propulsive systems to be commercially viable. Listed below are a few of the new innovations of the STEP-AIRSEDS mission.

ED Tether

The Long Life ED tether physically and electrically connects the STEP-AIRSEDS units. The purpose of the tether is to constrain the units, collect electrons from the surrounding plasma, and carry the current. Similar to *ProSEDS*, the ED tether has an exposed segment for current collection and deboost operations. However, being a hybrid system, a segment of the tether is also insulated to support boost operations. Hence we are able to support boost and deboost operations from one single tether, reducing complexity and cost. The Long Life ED Tether is also designed to meet the following requirements:

Survivability requirements

- Maintain 80% of performance level at End-of-Life due to AO degradation.
- 95% survivability over 1 year for micrometeoroid/orbital debris impacts

Electrical requirements

- Partially exposed for collection, partially insulated
- With stand a 1 kW power level
- Specific resistance less than 15 ohms/km
- Maximum tether current of 10 amps

Physical requirements

- Static strength of 15 N
- Dynamic strength of 100 N
- Smooth splicing

Tether Observer

During deployment, boost/deboost and other modes of operations, the ED Tether will experience perturbations which, if unchecked, will drive the tether libration unstable. Control systems will be utilized to maintain stability and dampen tether perturbations. However, to control the motion of the tether it is required to observe the tether. In the past the only methods available was to measure tether deployment rates and to measure the tether tension; in the case of TSS-1 and –1R the shuttle crew served as a supplemental observer. Either method only inferred the tether shape to indicate possible instabilities developing in the system. In order to provide complete observability two additional systems have been introduced — a tether optical observer and a GPS communications system.

The GPS communications system will tell us the overall system librations and the position the Upper and Lower Units relative to one another. A communication link between the units transmitting the GPS data will allow the deployer and other on board control systems to control the system in-plane and out-of-plane libration angles. The tether optical observer will allow the satellite and ground observers to determine the exact shape of the tether hence allowing the controllers to not only control tether motion but also determine if unstable modes are developing.

FEAC

An essential requirement for the ED tether system is to "close the circuit" with the ionosphere at each end of the tether. At the negatively charged end (lower end for deboost, upper end for reboost) electron emission is significantly more efficient than ion collection. Two techniques will be used for this purpose. The first and primary method uses a hollow-cathode plasma contactor (HCPC) which is considered the state-of-the-art. A second, but important electron emission method will be based on field-emitter array cathode (FEAC) technology. Successful demonstration of the FEAC will allow for a truly "propellantless" Orbit Transfer Vehicle.

FEACs are small silicon semiconductor wafer chips consisting of millions of tiny conductive points placed below similarly small conducting holes (gate) which forms an accelerating grid over the tips (see Figures 5 and 6). Because of the small dimensions common to semiconductor processing, low bias potentials can provide the 10^8 V/m electric fields between the grid and points needed to generate electron field emission of microamp level currents from each point. With up to millions of points in a few square centimeters it should be possible to generate the several amps of current needed for STEP-AIRSEDS without the power required to heat a cathode and ionize a gas nor the associated gas tanks and plumbing of an HCPC. FEACs offer the possibility to simplify certain electrodynamic tether applications. However, they have not been demonstrated in space. The principal questions to be tested in-space are (i) the ability of FEACs to emit high currents into the space environment and (ii) their survivability in the non-ultrahigh vacuum spaceflight conditions around a typical spacecraft.

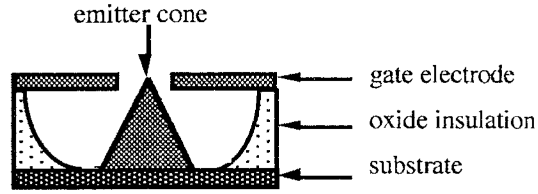

Figure 5. Schematic of a Single Element of a Field Emitter Array Cathode (FEAC).

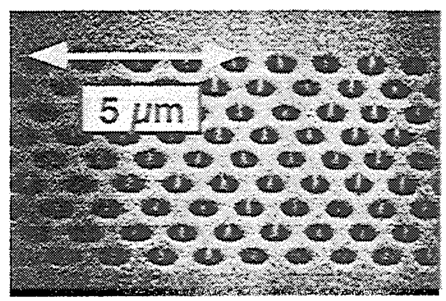

Figure 6. SEM photograph of SRI Ring Cathode developed for the ARPA/NRL/NASA Vacuum Microelectronics Initiative (Emission gated rf amplifier), courtesy of Capp Spindt. These arrays were not resistively protected nor coated, but nevertheless produced 0.67 µA/tip @ a gate voltage of 70 V in a power tube (klystrode) environment.

ED Tether Deployer System

The ED Tether Deployer System is designed to be integrated either with a range of unmanned launch vehicles or the International Space Station. The deployer system is designed to support ED tether lengths up to 15 km and deployment loads up to 100 N. The deployer system consists of the following key elements: the electrical interface, the spool and supporting mechanisms, the tether guide, ED tether material, and the control interface module. The deployer system is capable of both deploying and retrieving the tether.

The tether guide will traverse the length of the spool and not be fixed at one end like the ProSEDS deployer design. The ProSEDS design of a fixed spool creates a twist in the material as it is pulled from the spool. When working with the new, innovative tether designs twisting is not acceptable, as it will cause unnecessary stressing and possible failure of all or a portion of the tether. Therefore STEP-AIRSEDS will have a rotating spool. The ED tether will be hardwired to the spool and that all electrical connections/isolations will be controlled with a surface contact between the spool edge and the rest of the deployer system.

Immediately prior to deployment a cold gas thruster system with approximately 0.5 N of thrust is activated, and is directed along the longitudinal axis of the satellite. Deployment of the ED Tether is conducted once the two units of the satellite are detached via a marman clamp band assembly. Once the satellites are detached, the ED deployer system will begin to feed out the tether while the thruster system will cause the two satellite units to separate. The tension in the tether between the two satellite units during this phase of deployment will be negligible, and a slack tether condition might exist, however a snag condition will not occur while the tether is being fed out and the separation system is activated. The thruster system will be used until the separation distance is sufficient and the gravity gradient can deploy the balance of the tether without the use of the cold gas thrusters. The tether guide mechanism is responsible for not only guiding the tether, but also controlling the deployment velocity and braking.

As indicated, the deployer is not only capable of deploying the ED tether but also of retrieving it back onto the spool. As a result the deployer is capable of winding the tether back on to the spool such that the tether is packaged efficiently and redeployed as required. During the spring of 2001 an optimal winding pattern will be determined for the ED Tether. Both the spool and guide will be locked down prior to launch preventing any premature unwinding.

<u>STEP-AIRSEDS Flight Plans</u>

The *STEP-AIRSEDS* satellite is deployed to an initial altitude of 500 km from a Taurus 2210 Launch Vehicle. Once separated from the launch vehicle and after a complete systems check in orbit, the satellite will split into two segments and deploy the 6 - 7 km Long Life ED Tether.

Eight flight profiles were developed for the STEP-AIRSEDS mission to meet the mission objectives. The goal of the project was to select a range of modes of operation for a range of altitudes to test and demonstrate the full capabilities of the STEP-AIRSEDS satellite throughout Low Earth Orbit (LEO). Table 1 presents the planned Flight Profiles to meet the mission objectives. The table presents the start and end altitude or inclination change for each altitude and the duration of each flight profile, if known.

Table 1. STEP-AIRSEDS Flight Plan

Flight Plan Number	Start (km)	End (km)	MET (day)	Estimated Time Enroute (days)	HCPC Usage Location	HCPC Cycling Per Day
1	500	500	1	10	N/A	N/A
2	500	650	11	28	UU	Continuou
3	650	650	39	45	UU	Continuou
4	650	500	84	10	LU	Continuou
5	500	500	94	45	UU	Continuou
6	500	700	139	32	UU	Continuou
7	700	700	171	30	N/A	N/A
8	700	450	201	10	LU	Continuou
9	450	450	211	5	UU	Continuou
10	450	450 x 1100	216	50	UU	Continuou
11	450 x 1100	450	266	30	LU	Continuou
12	450	450	296	5	UU	Continuou
13	450	700	301	35	UU	Continuou
14	700	700	336	29	UU	Continuou

Flight profiles 2, 6, 10, and 13 represent boost operations; flight profiles 4, 8, and 11 represent deboost operations. If these flight profiles are executed successfully they will satisfy objectives 1 and 4. Flight Profiles 10 and 11 are elliptical orbits maneuvers which allow us to understand the performance of an ED tether at higher LEO altitudes and to understand the performance of the ED tether systems in elliptical orbits. Conducting all flight profiles will allow us to demonstrate electrodynamic tether system dynamic stability during nominal tether operations and characterize the performance of electrodynamic propulsion systems and their operational limits (dynamic and electrodynamic).

The nominal mission life for STEP-AIRSEDS is one year. If the ED tether is not cut and is the entire system is operational by the end of the nominal mission time period the team will have demonstrated long-life tether technology in an actual space environment. Note: not all the flight profiles need be conducted to meet this objective.

Current Research

Work on STEP-AIRSEDS began in March 1999. Initial funding covered the conceptual study of the satellite and its systems. In August 1999, NASA MSFC, TMTC and its subcontractors continued development of the STEP-AIRSEDS mission. During the Phase B period several studies have been completed or are currently under development. This includes ED tether design and development through technology readiness level (TRL) 4, launch vehicle selection, mission definition, near Earth space environment studies including tether survivability, preliminary tether performance and dynamic studies, ED tether operations and control, and deployer requirements definition and design. Other research done has focused on preliminary satellite subsystem design and requirements definition, including power systems, instrumentation, weight control planning, thermal analysis and subsystems, and the attitude control and determination system. Phase B research is currently being conducted by TMTC and its subcontractors and NASA MSFC. Launch is targeted for the 2004/2005 time frame.

IV. Conclusion

STEP-AIRSEDS, and the ProSEDS experiment, will lead to a range of follow-on ED Tether commercial applications. Table 2 presents the STEP-AIRSEDS characteristics in relation to the applications with interest in the characteristic. The table shows qualitatively the correlation between the STEP-AIRSEDS and application characteristic (High, Medium, Low, and N/A).

At the successful conclusion of the *ProSEDS* and *STEP-AIRSEDS* missions, ED tethers will be ready for primetime. During the next 4 years critical ground and space testing of tether systems will be conducted with the goal of developing a system for commercial application. Once testing has been completed, all prerequisites necessary for LEO space operations will be met. And then ED Tether Propulsion will be ready to usher in the next century of flight — in space.

IV. References

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Table 2. STEP-AIRSEDS Characteristics in Relation to Proposed Future Applications of ED Tethers.

STEP-AIRSEDS CHARACTERISTIC	APPLICATIONS WITH INTEREST IN THE CHARACTERISTIC			
	De-Orbit	Large Spacecraft or ISS Stationkeeping	Orbit Transfer Vehicle	Jovian Missions
Long life tether	High	High	High	High
Tether dynamic stability and control	Medium	High	High	High
Powered Boost	N/A	High	High	High
Powered Deboost	Medium	Low	High	High
Precision Orbital Maneuvering	Low	Medium	High	High
Stationkeeping	Low	High	High	Medium
FEAC Demonstration	High	Low	Medium	High
Rendezvousability	N/A	High	High	Low
Inclination Change	Low	Low	High	Low

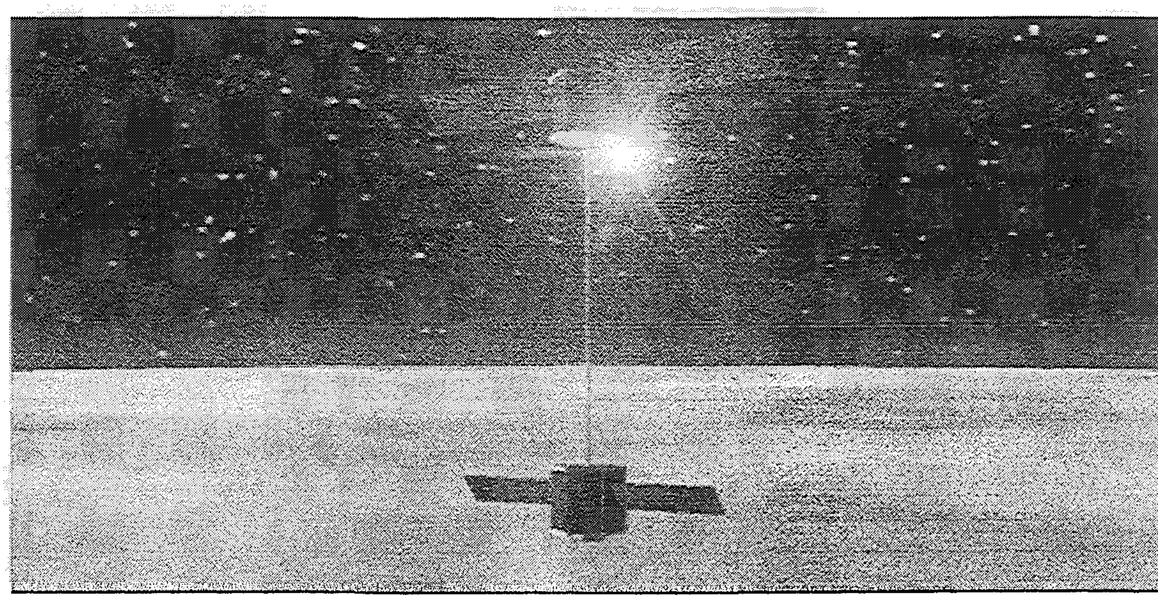

Figure 7. STEP-AIRSEDS during tether deployment.