In-Space Transportation with Tethers

NASA Grant NAG8-1303

Annual Report #2

For the period 1 September 1997 through 31 August 1998

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SCOPE

This is the Second Annual Report for Grant NAG8-1303 entitled "In-Space Transportation with Tethers" prepared by the Smithsonian Astrophysical Observatory for NASA Marshall Space Flight Center. The technical monitor for this grant is Les Johnson. This report covers the period of activity from 1 September 1997 through 31 August 1998.

SUMMARY

The annual report covers the research conducted on the following topics related to the use of spaceborne tethers for in-space transportation:

ProSEDS tether modeling
Current collection analyses
Influence of a varying tether temperature

ProSEDS mission analysis and system dynamics
Tether thermal model
Thermo-electro-dynamics integrated simulations

ProSEDS tether development and testing
Tether requirements
Deployment test plan
Tether properties testing
Deployment tests

Tethers for reboosting the space-based laser
Mission analysis
Tether system preliminary design
Evaluation of attitude constraints

1.0 ProSEDS Tether Modeling

1.1 Analyses of current collection

1. One of the ways to quantify the advantage a bare tether collector has over a TSS-1 "ball and chain" type collector, in which the wire is insulated and all collection is done by a large conductive sphere, is to compare the current collected for equal surface areas by the two types. Various figures were floating around, so SAO undertook to calculate the current for a range of electron densities. These results are shown in Figure 1.1. The figure reveals that the advantage of the bare tether becomes greater as the density becomes lower (and this would increase further at nighttime values). Boosting the current collected by the sphere by a factor of three (maximum factor observed in TSS-1R) over the plotted results, we still see the bare wires of equal area collecting from 6-8 times greater in the case of a 2 mm diameter and 3-5 times greater in the case of the smaller diameter of 0.7 mm. These diameters were chosen to fall within the range of those under consideration for the ProSEDS tether. They are smaller than what is envisioned for an operational system however, for which non circular cross-sections for the tether would also be likely. The trend is clearly for higher and higher differentials as the diameter of the wire increases.

2. The first results on bare wire collection seen in plasma chamber tests carried out at MSFC showed currents roughly 64% of Orbital-Motion-Limited (OML) current. Conditions in the plasma chamber deviate in certain significant ways from those in space. Juan Sanmartín of the Polytechnic University of Madrid and R. Estes of SAO have investigated how the maximum wire radius for which OML collection will apply varies with the ratio of electron to ion temperature. Some of their results are shown in Figure 1.2 where the maximum radius (in units of electron Debye length) is plotted versus the bias voltage. normalized to the electron thermal energy. For the MSFC test results, the wire radius exceeded the maximum for which OML current could have been expected by a large factor due to the high electron to ion temperature ratio. Thus, the results are actually encouraging. The ProSEDS tether radius is well below that for which OML collection applies.

3. Choice of the tether conductive tether material has proved to be one of the most difficult tasks for ProSEDS. One of the earliest comparisons between Al and Cu wires made for ProSEDS is shown in Figure 1.3. It is clear from the figure that the Al wire, while

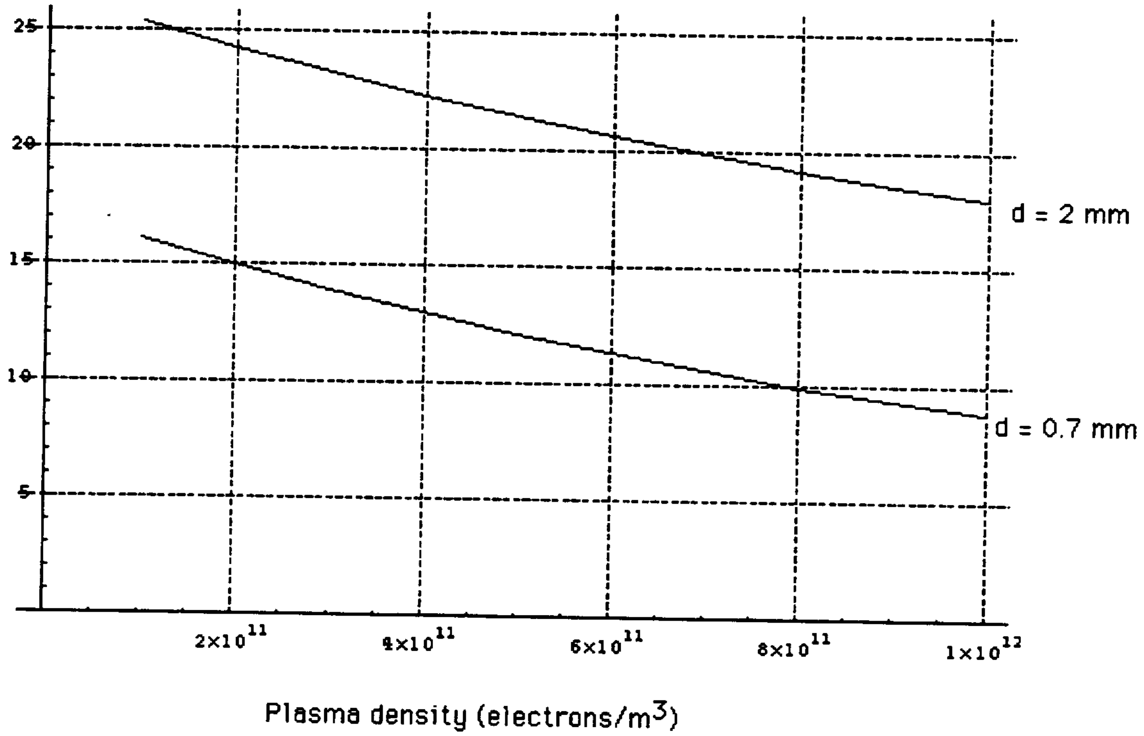
weighing 20 lbs. less than the Cu wire can collect as much current (at the expense of some volume, however).

4. As tether development and analysis proceeded, it became apparent that heating might be a significant problem. While this first arose as an issue of whether the hot Al would be able to withstand periodic relatively large tension spikes that were seen to occur in simulations, it also became a concern from the standpoint of electrical resistance. Figures 1.4(a) and 1.4(b) depict results of the first calculations to show the effect of tether heating with and without an emissive coating.

Bare tether current collection compared to sphere of equal area.

Ratio of current collected by a bare tether (orbital motion limited) to that collected by a sphere of equal area (assuming Parker-Murphy limit) for 5 km tethers of 0.7 mm and 2.0 mm diameter. Cu tether assumed. End-to-end motional emf is 750 V. The 0.7 mm diameter is what we have been using for ProSEDS calculations. Magnetic field of 0.3 G and electron temperature of 0.1 eV assumed in sphere calculations.

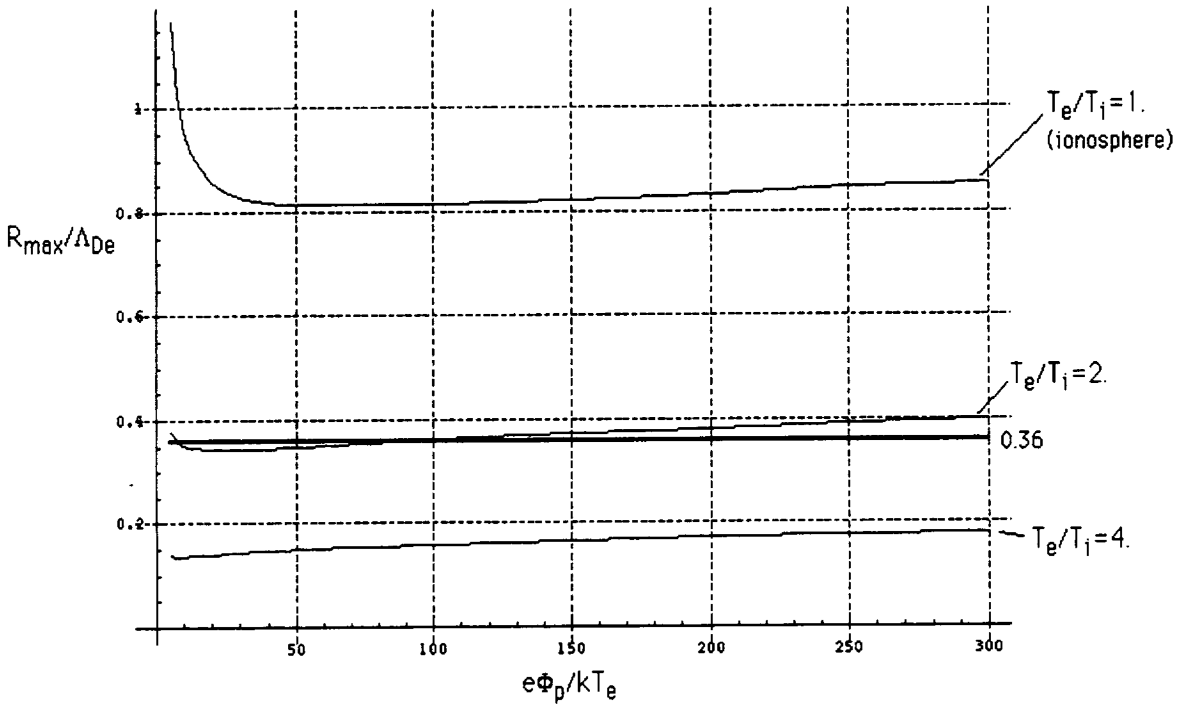
Note that Parker-Murphy limit assumes a static collector, and TSS-1R found current collected exceeded this limit by a factor of two or more.



Bob Estes, SAO
8/7/97

Fig 1.1. Bare tether current collection compared to sphere of equal area.

Maximum wire radius (relative to electron Debye length) for which orbital-motion-limited (OML) current collection applies is displayed here as a function of normalized bias voltage for different ratios of electron temperature to ion temperature. Magnetic field absent.



The wire radius for which OML collection applies is seen to drop with increasing T_e/T_i. The results are relevant to the last (April) plasma chamber tests conducted by MSFC on bare wire collection. In those tests, the temperature ratio was something like 10., while the ratio of the wire radius to the electron Debye length was about 0.36. Thus the wire radius substantially exceeded the maximum for which OML collection could be expected. Even so, the current collected was roughly 64% of OML with no applied magnetic field. Details of the calculation will be presented at the upcoming TIM in September.

Juan Sanmartin, UPM/SAO
Bob Estes, SAO
8/19/97

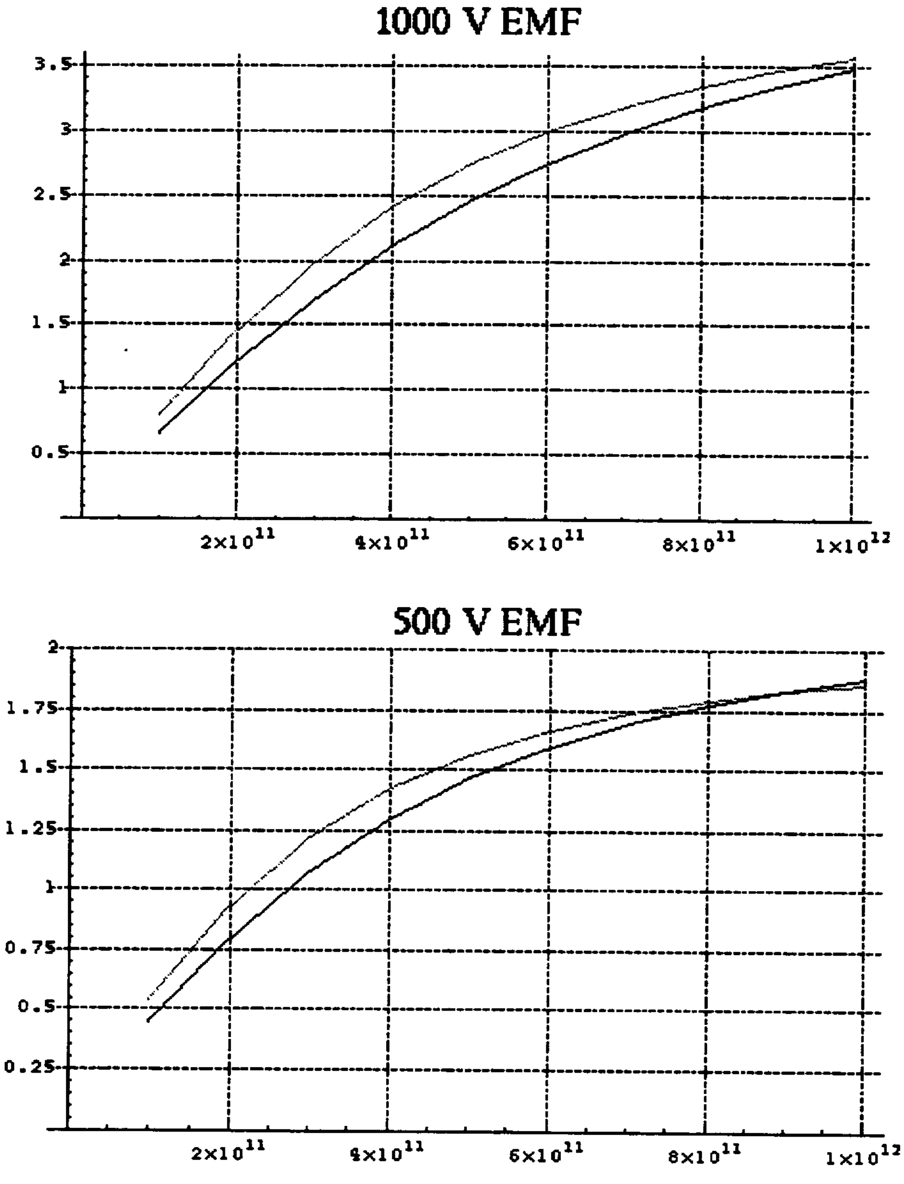
Fig. 1.2. Maximum wire radius for which the OML current collection applies.

Comparison of current collection of two 5 km wires:

(1)Aluminum wire (in red) with diameter 0.9 mm. R = 225 ohms, M = 8.6 kg.
(2) Copper wire with diameter 0.714 mm. R = 208 ohms, M = 17.9 kg.

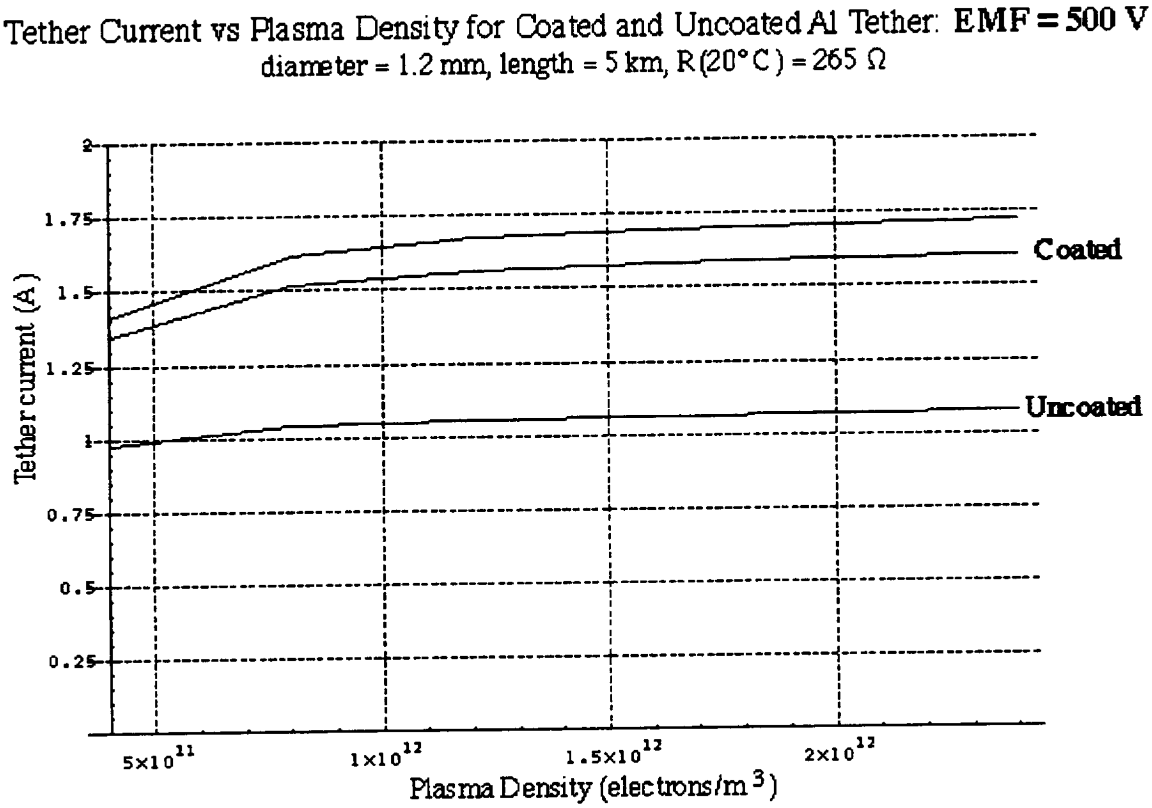
Current (A) measured at Delta plotted versus electron density in electrons/m^3 for two end-to-end emf values (500 V and 1000 V).

Conclusions: We can get comparable current from Al wire of somewhat larger diameter than the previously considered Cu wire, while saving 9.3 kg (20.5 lbs). Increased collecting surface roughly compensates for slight increase in resistance.



Bob Estes, SAO
8/20/97

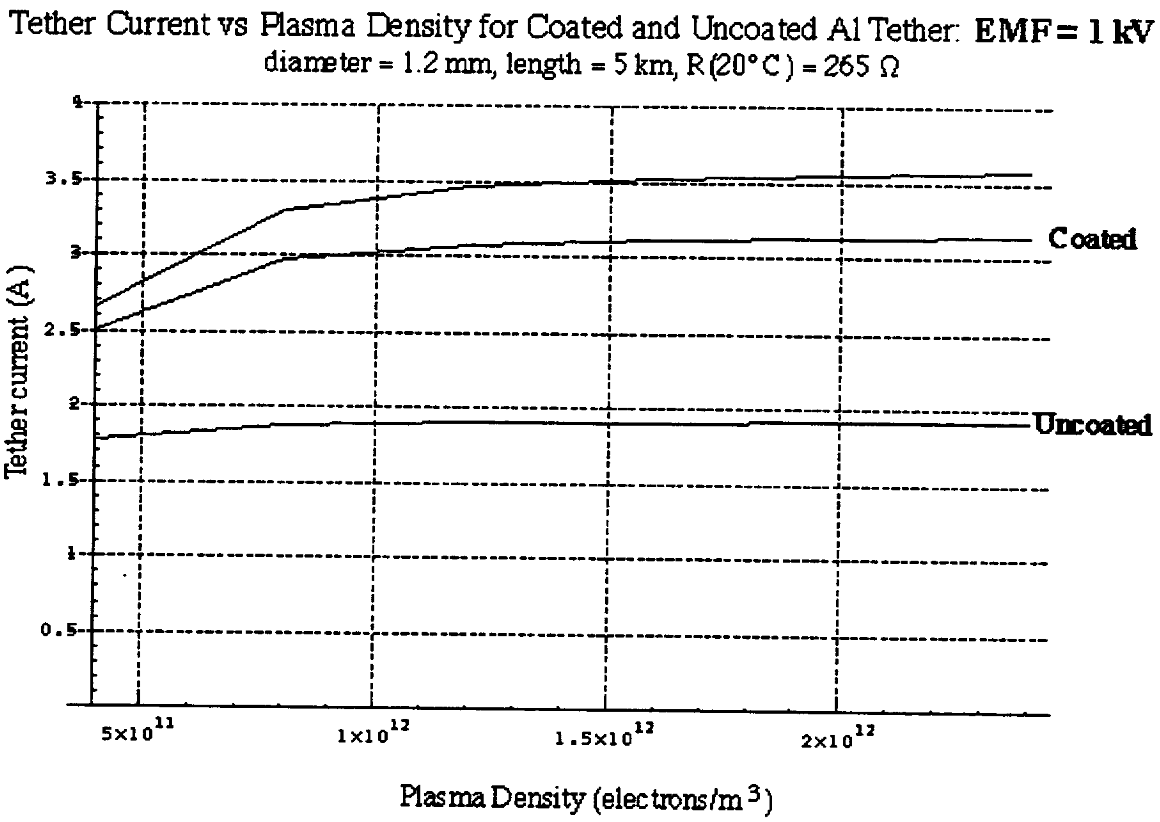
Fig. 1.3. Comparison of current collection of two 5-km wires of different materials.



Coated tether: $\alpha = 0.95$, $\varepsilon = 0.8$; $T = 40\text{-}42°\,C$; $R = 283\text{-}285\ \Omega$
Uncoated tether: $\alpha = 0.14$, $\varepsilon = 0.03$; $T = 195\text{-}202°\,C$; $R = 423\text{-}429\ \Omega$
Solar flux = 1350 W/m^2

Bob Estes, SAO
4/27/98

Fig. 1.4(a). Tether current vs. plasma density for coated and uncoated Al wires for EMF = 500 Volt (the top curve is the benchmark case of a 265-ohm constant resistance wire).



Coated tether: α = 0.95, ε = 0.8; T = 52-61° C; R = 294-302 Ω
Uncoated tether: α = 0.14, ε = 0.03; T = 263-279° C; R = 485-499 Ω
Solar flux = 1350 W/m^2

Bob Estes, SAO
4/27/98

Fig. 1.4(b). Tether current vs. plasma density for coated and uncoated Al wires for EMF = 1000 Volt (the top curve is the benchmark case of a 265-ohm constant resistance wire).

2.0 ProSEDS Mission Analysis and System Dynamics

2.1 Introduction

ProSEDS exhibits features that are unlike any other space vehicle for what concerns the strong coupling among dynamics, electrodynamics and thermodynamics of the system. In fact, the tether temperature changes significantly the electrical conductivity of the wire that, in turn, affects the tether current and, consequently, the dynamic of the system. The dynamics itself couples into the current collection ability through changes in the tip-to-tip EMF acting on the tether and, through the Joule heating, into the tether temperature.

Consequently, the accurate simulation of ProSEDS requires a computer code that combines dynamics, electrodynamics and thermodynamics of the system. Our tether system simulation code at SAO has all these features. It combines an electron collection model in the orbital-motion-limited (OML) regime with a lumped-mass dynamic model of the system and a thermal model of the tether. It also have an IRI95 model of the ionosphere, a MSIS86 model of the atmosphere, an IGRF model of the magnetosphere and a $J_0 + J_2$ model of the Earth's gravity field. The thermal model of the tether takes into account all the relevant thermal flows in and out of the tether as follows: Sun's solar illumination (with eclipses), Earth's albedo and IR radiation, ohmic heating and emitted radiation. Once the tether temperature is computed along the tether, the temperature at the tether attachment point to the Delta stage (where the current is at a maximum) is utilized to determine the wire effective resistance and compute the current collected from the ionosphere.

2.2 Numerical Results

A number of simulations have been carried out to analyze the response of ProSEDS under different conditions and assumptions. The changes in the system dynamics as a function of the tether electrical resistance and also depending on whether or not the resistance is assumed constant or varying with the temperature is of particular interest. Figures 2.1(a)-2.1(e)show the response of a bare (without any coating) aluminum wire with an electrical resistance of 265 ohm at 20 °C. The wire is actually made of 7x28 AWG aluminum strands wrapped around a kevlar core according to the present tether configuration (see next section of this report).

The current is controlled according to duty cycles that repeat themselves throughout the mission duration. Two duty cycles are adopted during the mission. The first one is the primary battery duty cycle that is utilized only during the first 3 orbits when the system is powered by the primary batteries. The second one is the secondary battery duty cycle that is utilized after the first 3 orbits till the end of the mission. The primary-battery duty cycle is as follows:

Overall duration of primary-battery duty cycle = 60 s.

Mode 1 – 35-s at zero current;

Mode 3 – 5-s with a 1000-ohm resistor in series to the tether;

Mode 2 – 20-s with the tether in a shunt mode (no load).

The secondary-battery duty cycle is as follows:

Overall duration of secondary-battery duty cycle = 80 s.

Mode 1 – 35-s at zero current;

Mode 3 – 5-s with a 1000-ohm resistor in series to the tether;

Mode 2 – 5-s with the tether in a shunt mode (no load);

Mode 4 – 35-s with the tether connected to the secondary batteries.

The following simulations were run with the current controlled by the secondary-battery duty cycle throughout the duration of the simulation.

One more comment, in the simulations shown here the current along the tether is modelled as follows: the value of the current at each lump location is assigned to the lump. This discretization leads to a slight overestimate of the average current along the wire that, in turn, determines the system decay rate. In future simulations we will assign to each wire lump the average value of the current in the wire segment above the lump. This latter technique leads to a less accurate point value of the current but to a better estimate of the average current along the tether. *The overestimation affecting the average current along the tether and decay rates shown in the following simulations is about 14%.* Consequently, the decay rates shown in the following plots should be decreased by about 14%.

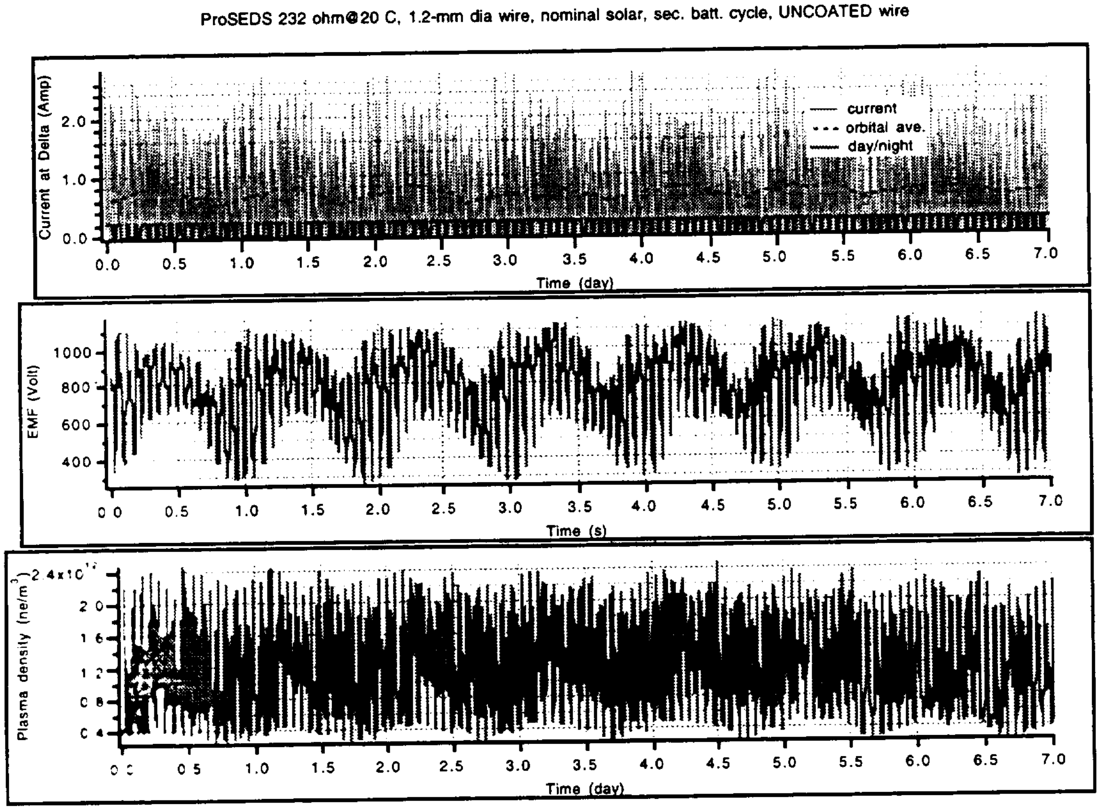


Fig. 2.1(a). Simulation of ProSEDS with 265-ohm (at 20°C) bare aluminum tether.

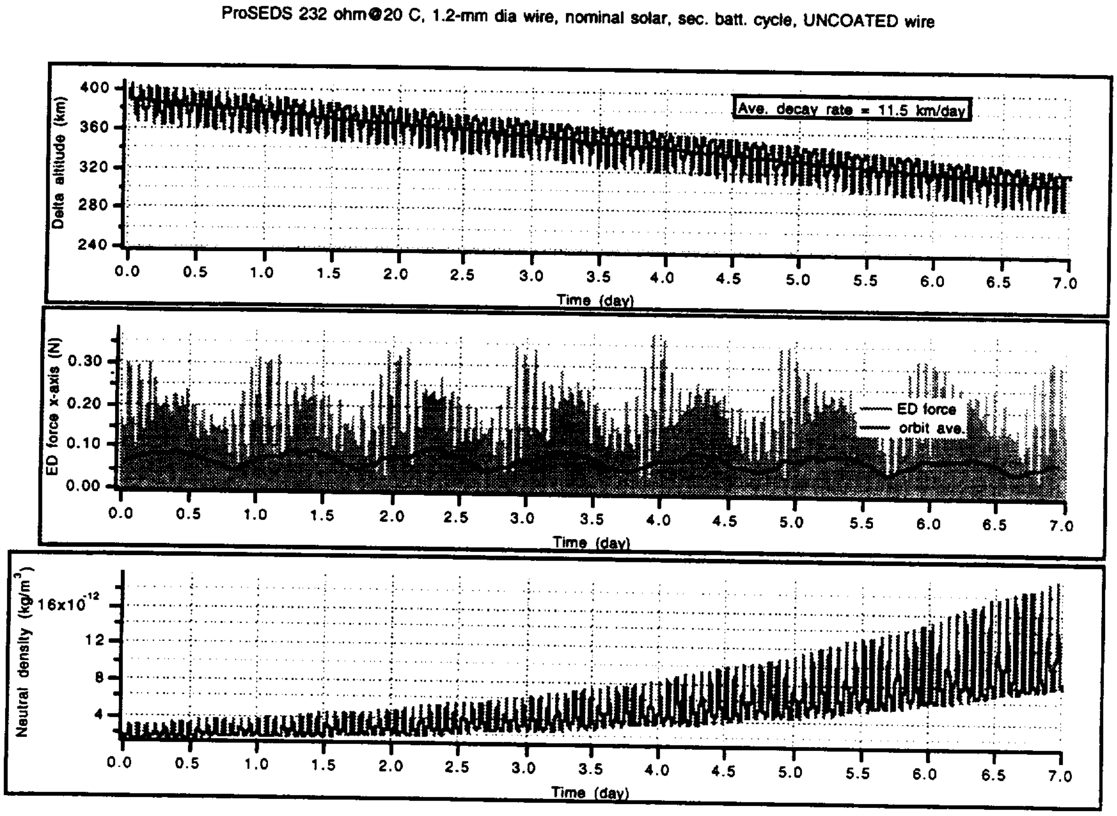

ProSEDS 232 ohm@20 C, 1.2-mm dia wire, nominal solar, sec. batt. cycle, UNCOATED wire

Fig. 2.1(b). Simulation of ProSEDS with 265-ohm (at 20°C) bare aluminum tether.

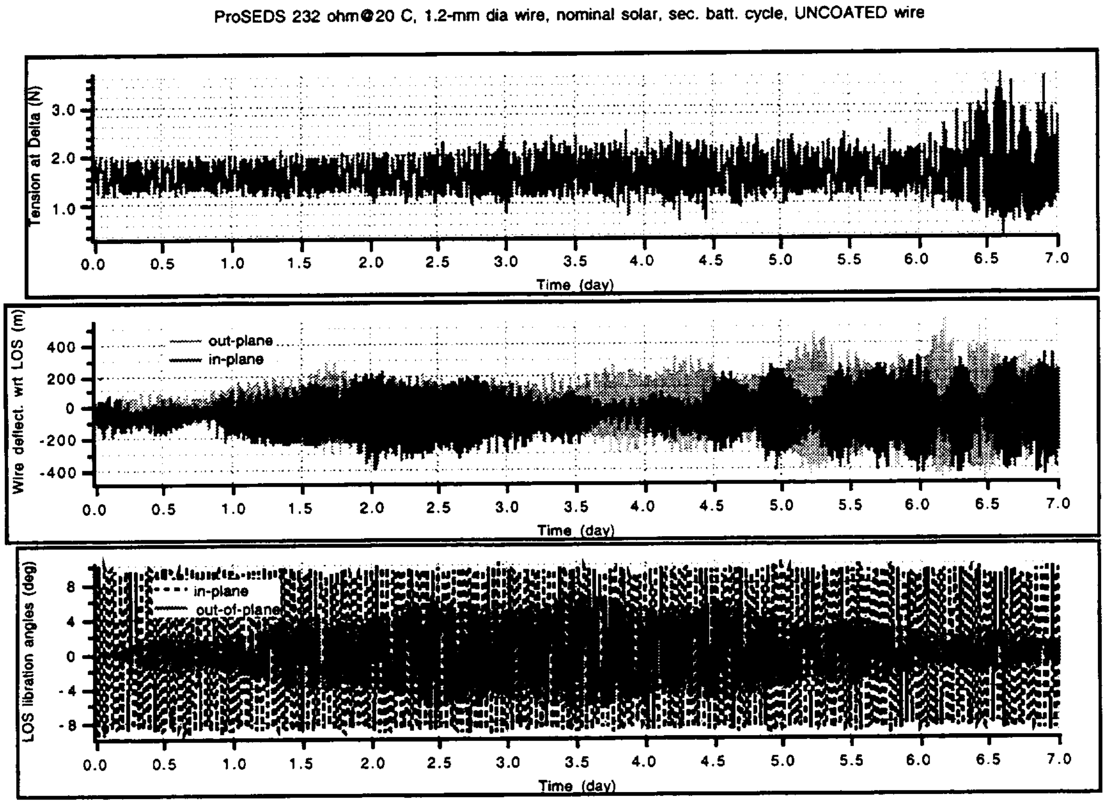


Fig. 2.1(c). Simulation of ProSEDS with 265-ohm (at 20°C) bare aluminum tether.

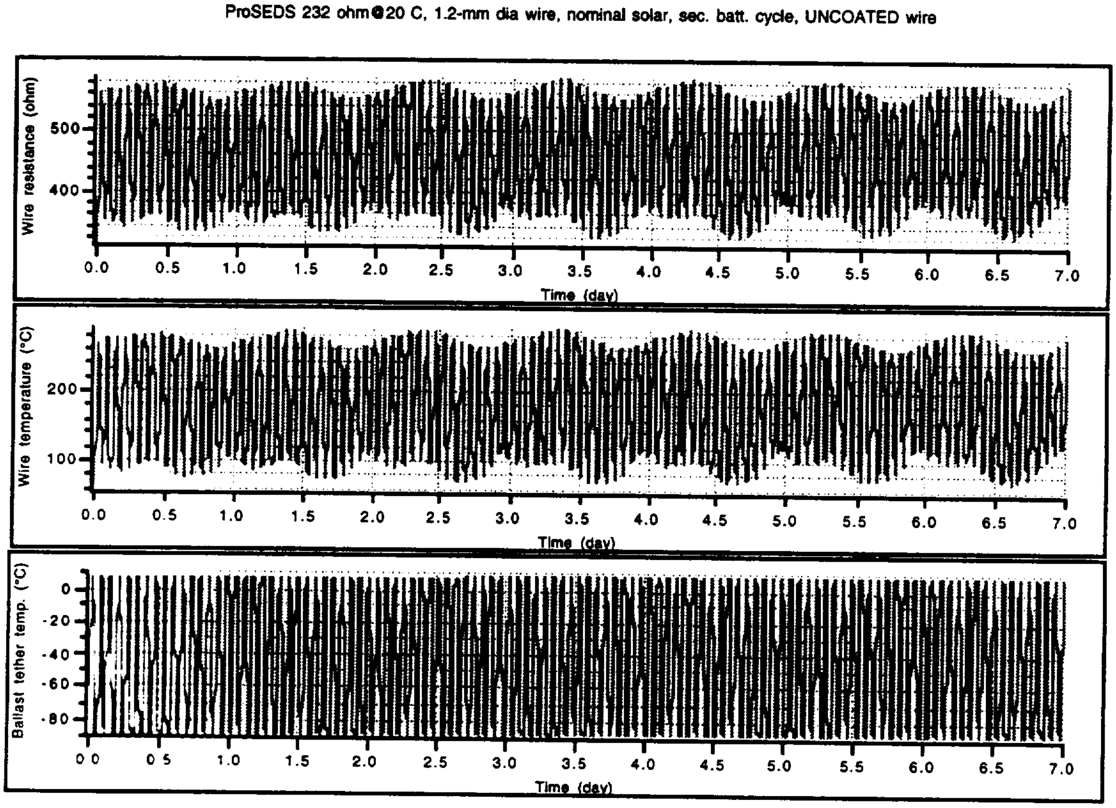


Fig. 2.1(d). Simulation of ProSEDS with 265-ohm (at 20°C) bare aluminum tether.

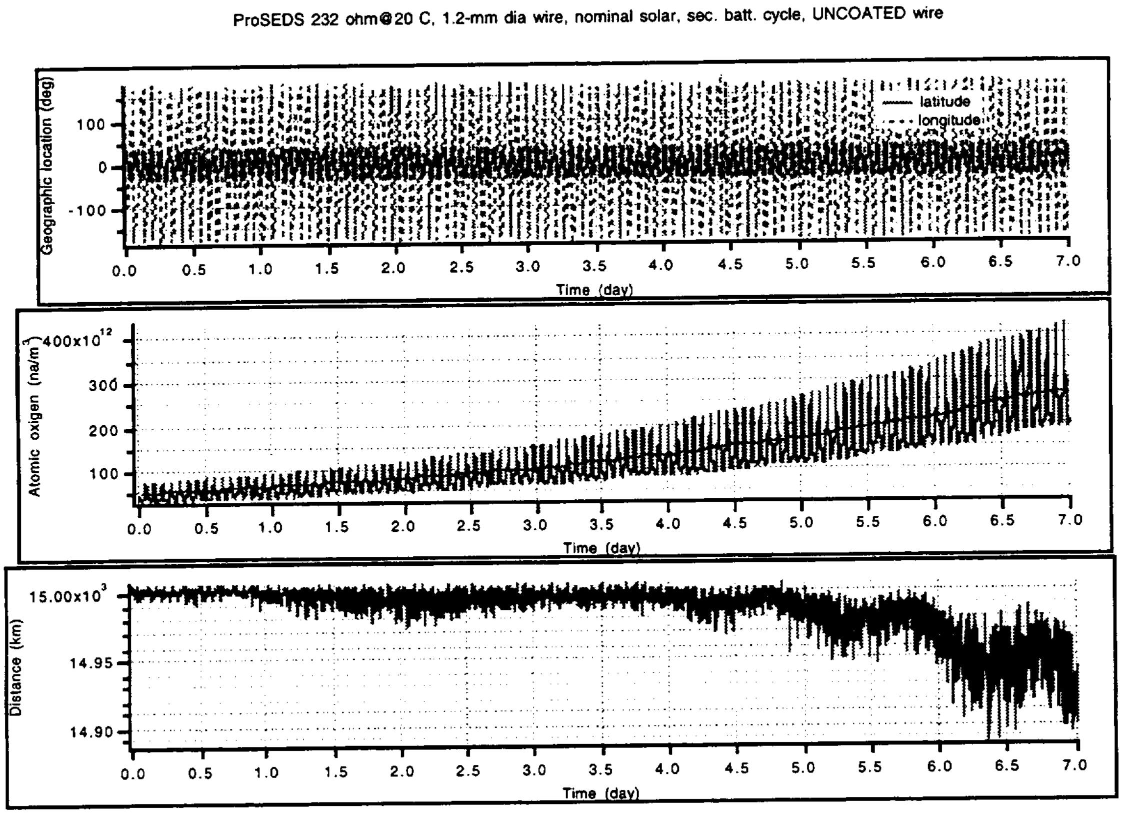


Fig. 2.1(e). Simulation of ProSEDS with 265-ohm (at 20°C) bare aluminum tether.

Figure 2.1(d) clearly shows that the wire temperature is relatively high ranging between 70 °C and 290 °C. The high temperature has two undesirable effects: (1) it weakens intolerably the aluminum and the load-carrying kevlar core and (2) it increases the electrical resistance (that depends on the temperature) and, consequently, reduces the tether current.

ProSEDS Conductive Tether Thermal Optical Properties[1]

Sample Description	Initial Solar Absorptance	Initial Infrared Emittance	α/ε
Aluminum Foil (1856 Alloy) Dull Side	0.115	0.034	3.38
Aluminum Foil (1856 Alloy) Shiny Side	0.140	0.018	7.78
Alodined Aluminum Foil (1856 Alloy) Dull Side	0.346	0.040	8.65
Alodined Aluminum Foil (1856 Alloy) Shiny Side	0.351	0.030	11.7
Copper Foil-99.998% Pure	0.298	0.033	9.03
Aluminum Foil w/ C-COR (15% PANi)	0.824	0.901	0.91
100% PANi on microscope Slide	0.959*	0.798*	1.2*

- Not exact ProSEDS Tether Configuration

This is a result of the high absorptivity/emissivity ratio (α/ε) of bare metals like aluminum and copper. In order to mitigate this problem, techniques were investigated for reducing the α/ε ratio of bare metals while preserving the ability to collect electrons. Various surface treatments and coatings were explored and the optical characteristics measured by Jason Vaughn at the EL Laboratory of NASA/MSFC as shown in the table above

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[1] This table contributed by Jason Vaughn of NASA/MSFC

As shown in the table, the alodine treatment worsened the optical ratio while the best results from the optical (and thermal) point of view were obtained with a polymer-based coating (developed by Triton) doped with polyaniline (PANi) to give the coating electrical conductivity. The results are shown in the table at the entries C-COR/15%-PANi and 100%-PANi.

An alternative to the conductive coating has been proposed by Joe Carroll of Tether Applications. It consists of partially covering the bare conductor with a high-emissivity-material overwrap (e.g., PTFE, TOR or PBO). Some preliminary tests were carried out by Jason Vaughn to quantify the effect of the overwrap on the overall emissivity of the composite configuration (i.e., an aluminum plate with stripes of TOR or PBO). Results indicate that in order to attain an overall emissivity of $\varepsilon = 0.8$ the aluminum must be covered with about 85% of TOR or 70% of PBO. Data on the change in absorptivity are not available and, consequently, a final conclusion about the effect of the overwrap on the α/ε can not yet be drawn. Also, in the Carroll's configuration the lowering of the conductor temperature has to rely on the transfer of heat from the conductor to the overwrap which is the main emitting element. Data on the efficacy of the heat exchange between the metallic conductor and the overwrap are not available.

Figures 2.2(a)-2.2(e) show the results of a simulation in which the conductive tether was coated with the 100% PANi (see previous table for the optical properties of the coating). The 100% PANi is attractive from the point of view of electron collection because it is perfectly transparent to the electrons (i.e., no voltage losses across the coating thickness). However, it is not very durable which may create problems during deployment. For this reason, other coating mixtures with less dopants will be developed by the coating manufacturer.

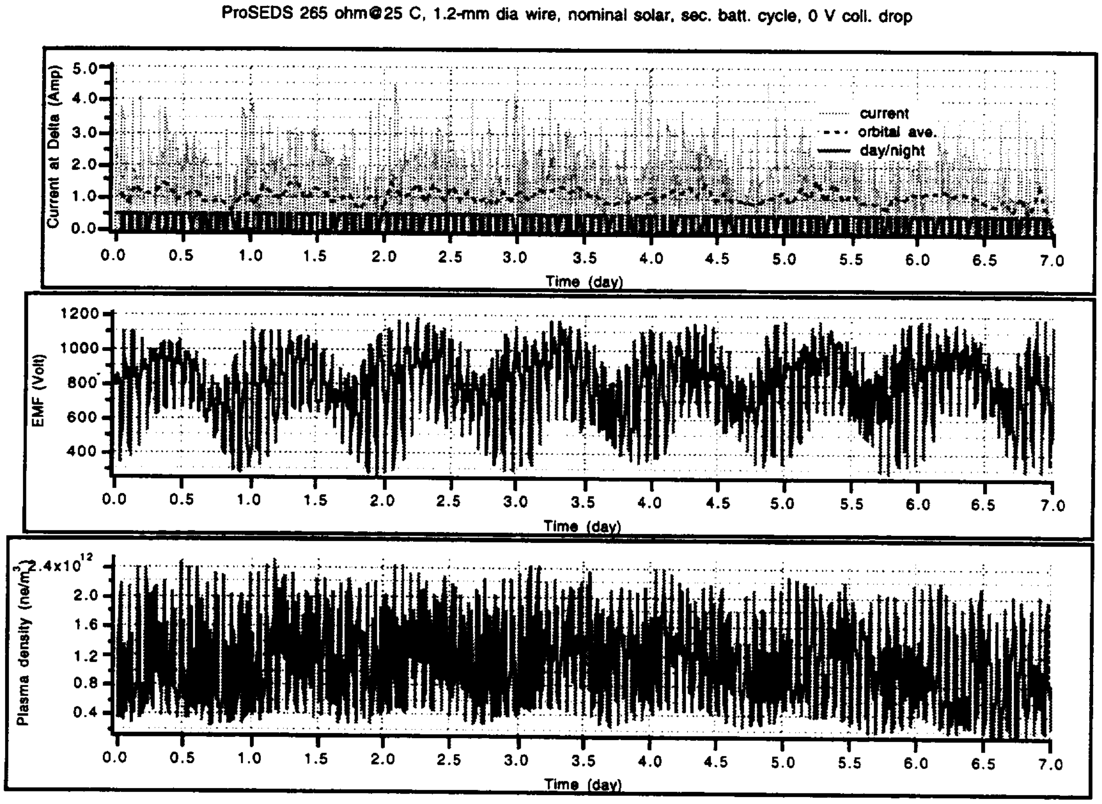
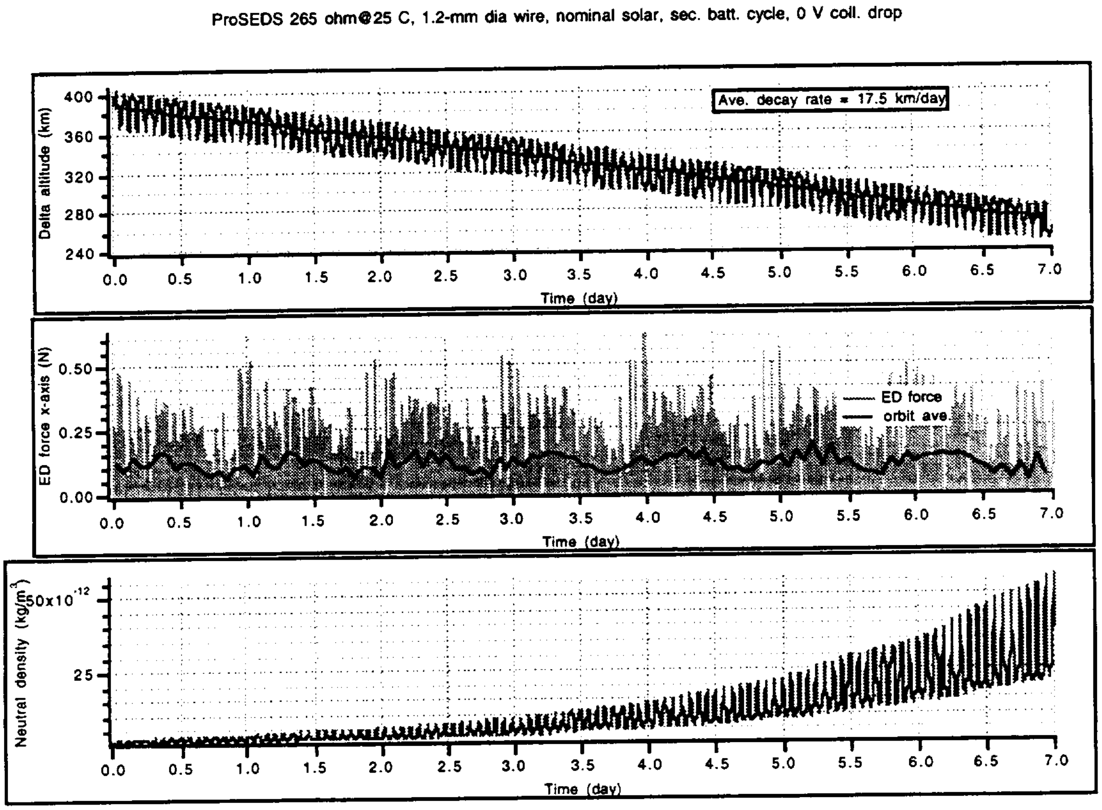


Fig. 2.2(a). Simulation of ProSEDS with 265-ohm (at 20°C) aluminum tether coated with a 100% PANi without collection losses.



ProSEDS 265 ohm@25 C, 1.2-mm dia wire, nominal solar, sec. batt. cycle, 0 V coll. drop

Fig. 2.2(b). Simulation of ProSEDS with 265-ohm (at 20°C) aluminum tether coated with a 100% PANi without collection losses.

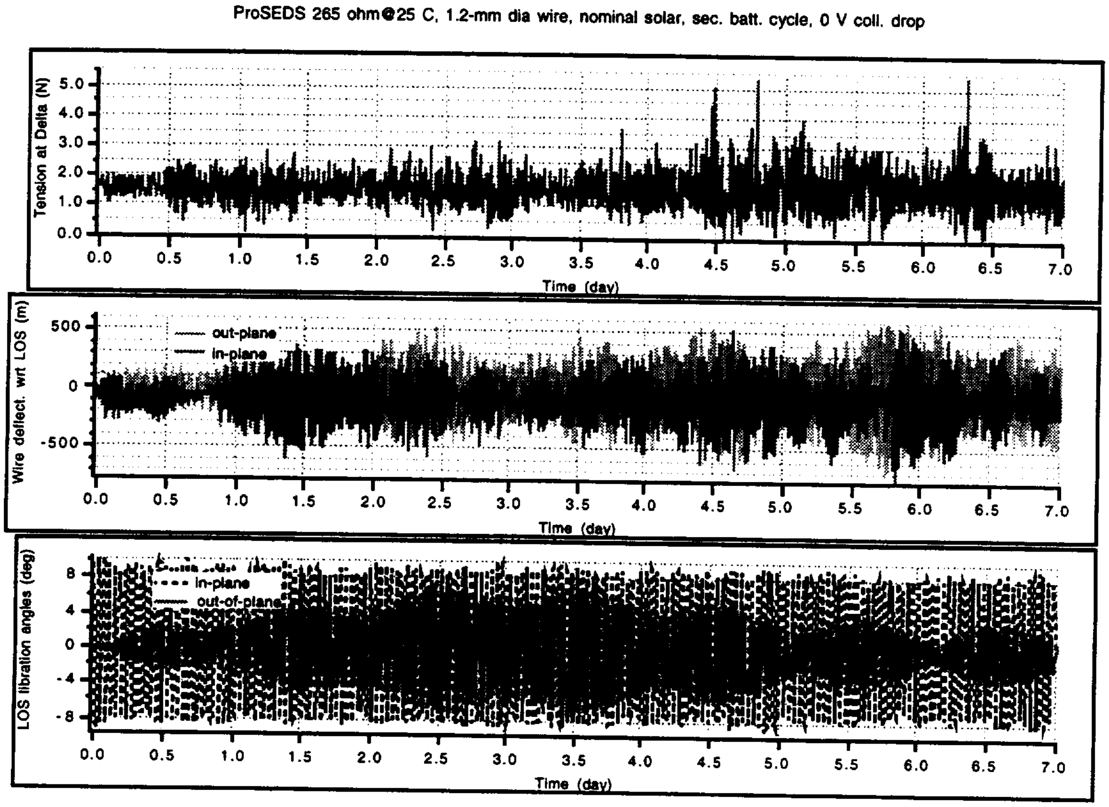


Fig. 2.2(c). Simulation of ProSEDS with 265-ohm (at 20°C) aluminum tether coated with a 100% PANi without collection losses.

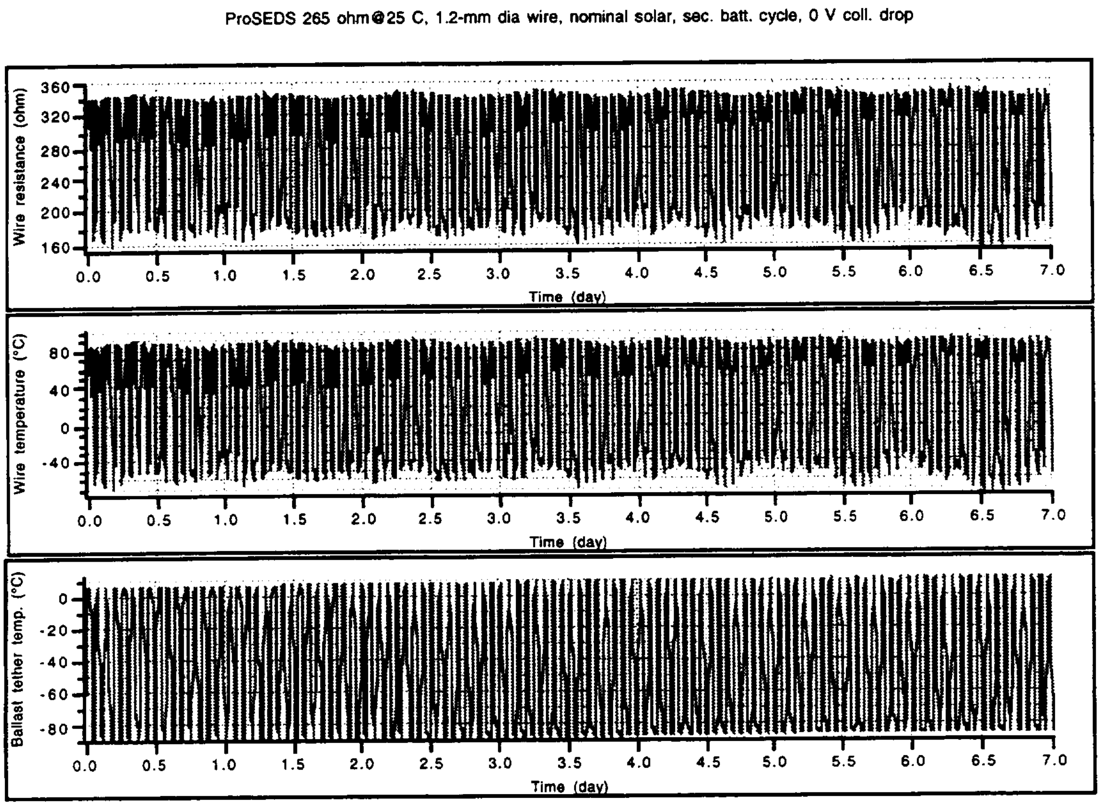


Fig. 2.2(d). Simulation of ProSEDS with 265-ohm (at 20°C) aluminum tether coated with a 100% PANi without collection losses.

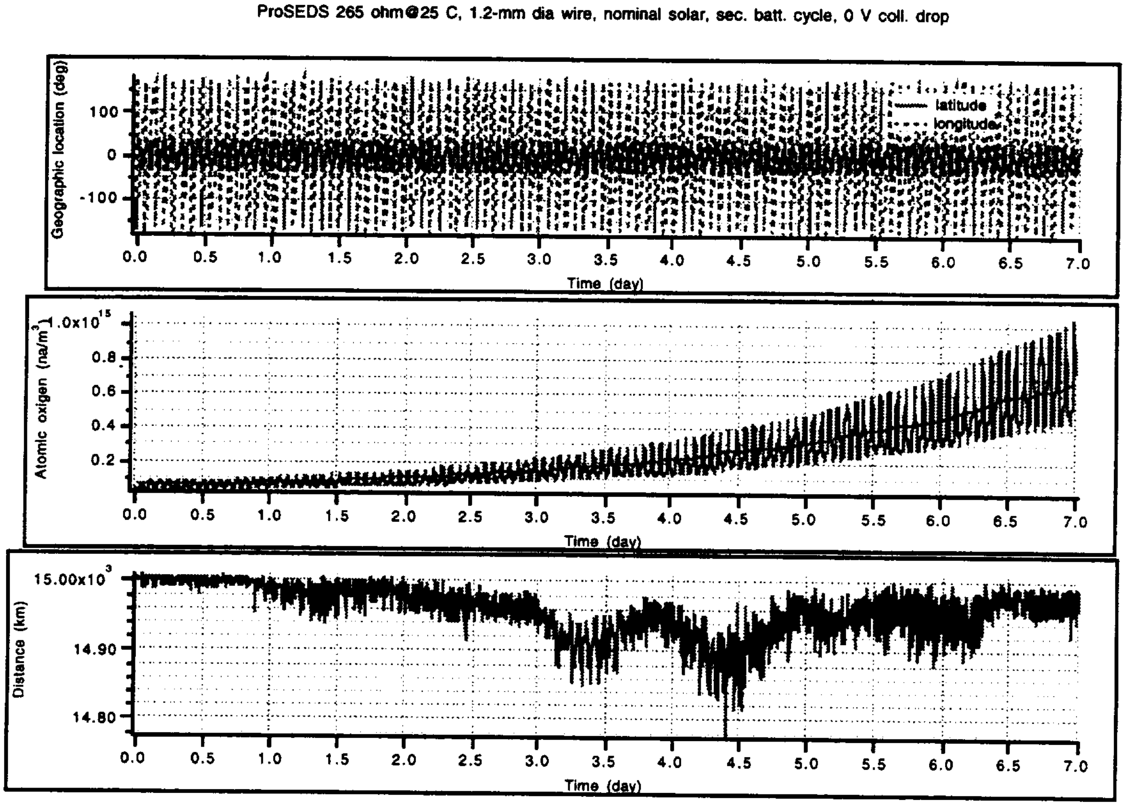


Fig. 2.2(e). Simulation of ProSEDS with 265-ohm (at 20°C) aluminum tether coated with a 100% PANi without collection losses

The following Figures 2.3(a)-2.3(e) are a detailed view of the previous simulation over a period of only 3 orbits in order to show the phase relationships among the various variables involved.

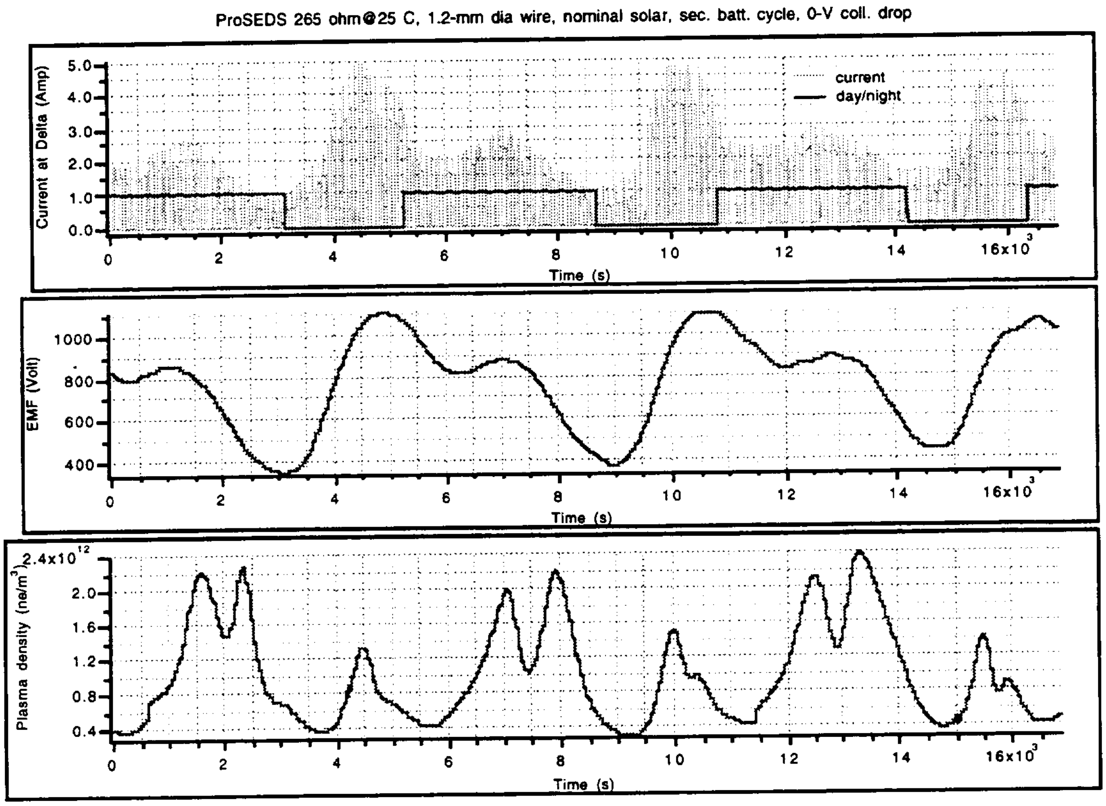


Fig. 2.3(a). Detail of previous simulation with 265-ohm (at 20°C) aluminum tether coated with a 100% PANi without collection losses.

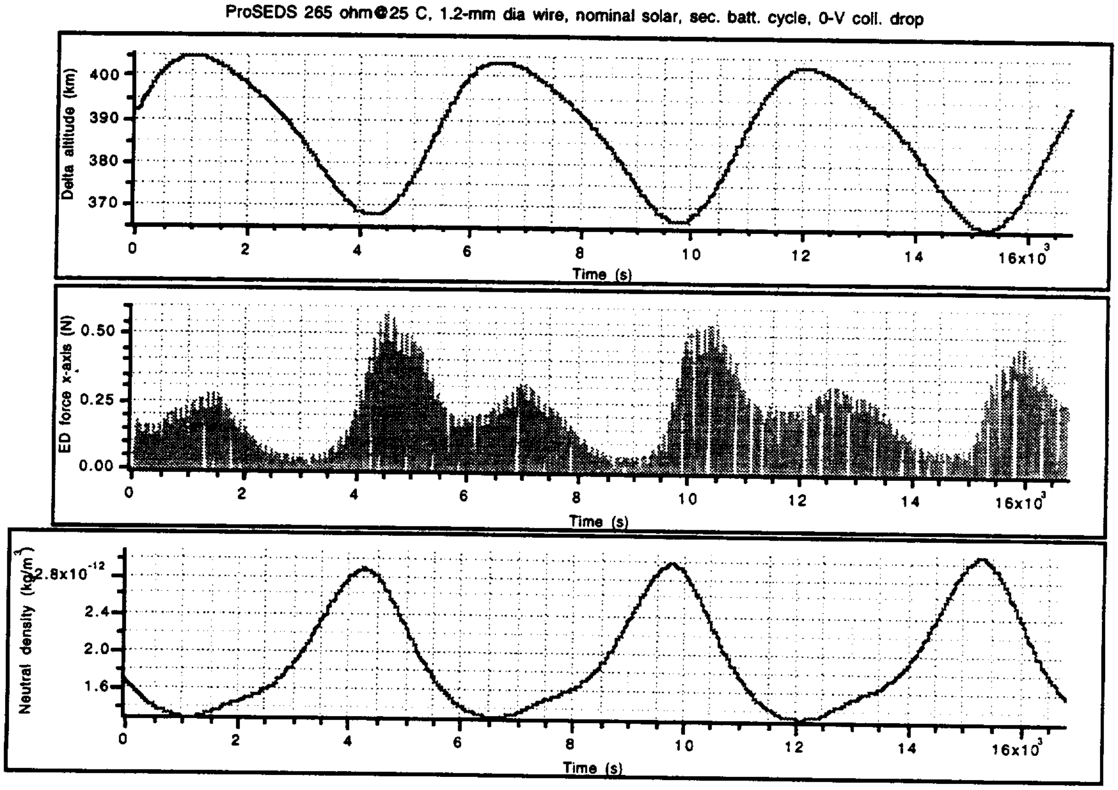

ProSEDS 265 ohm@25 C, 1.2-mm dia wire, nominal solar, sec. batt. cycle, 0-V coll. drop

Fig. 2.3(b). Detail of previous simulation with 265-ohm (at 20°C) aluminum tether coated with a 100% PANi without collection losses.

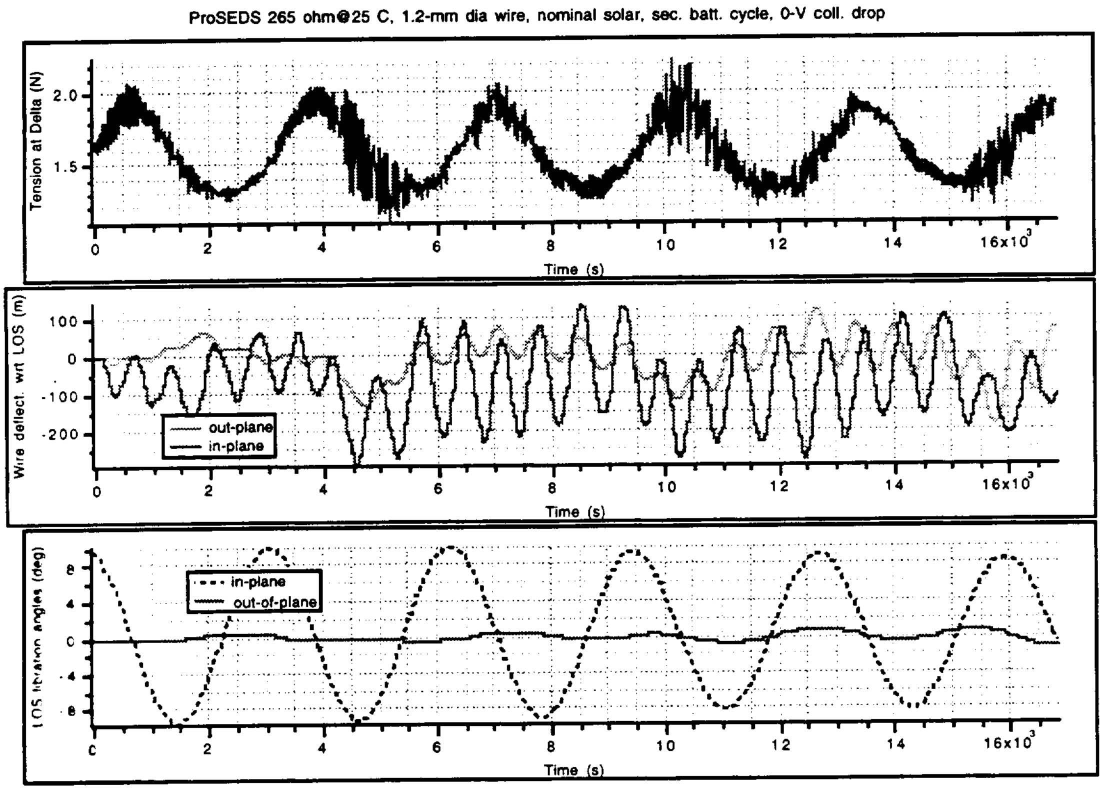


Fig. 2.3(c). Detail of previous simulation with 265-ohm (at 20°C) aluminum tether coated with a 100% PANi without collection losses.

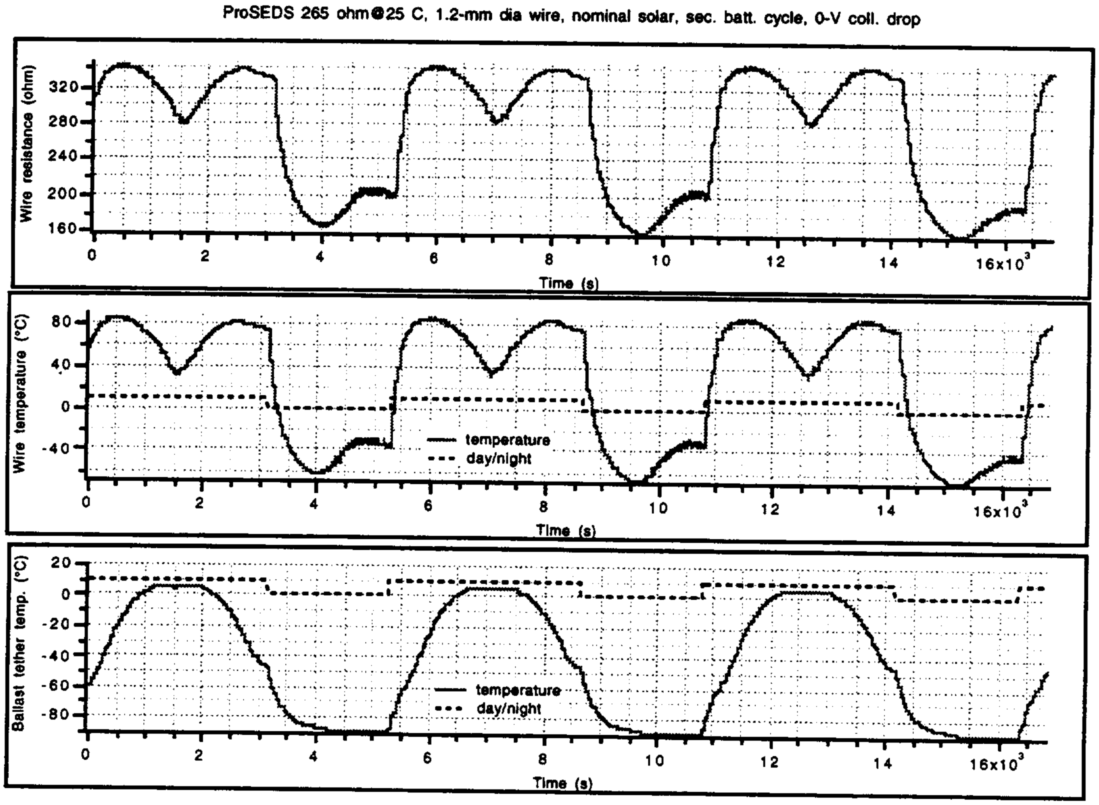

ProSEDS 265 ohm@25 C, 1.2-mm dia wire, nominal solar, sec. batt. cycle, 0-V coll. drop

Fig. 2.3(d). Detail of previous simulation with 265-ohm (at 20°C) aluminum tether coated with a 100% PANi without collection losses.

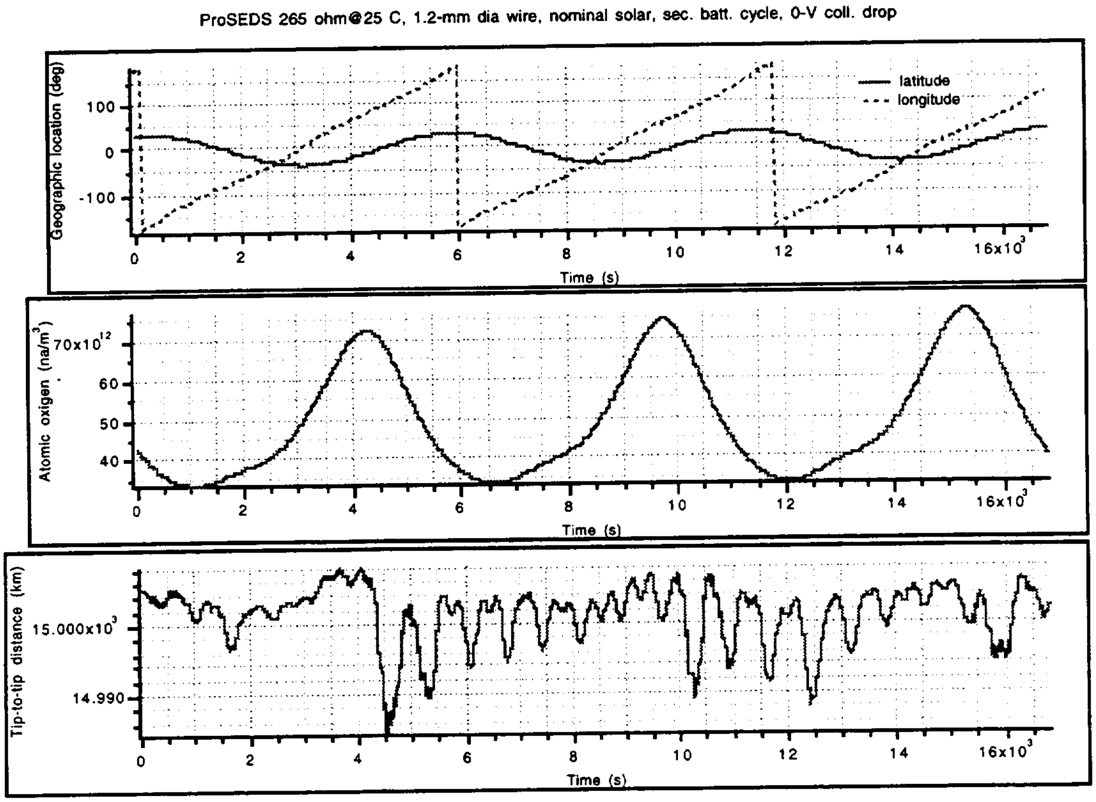


Fig. 2.3(e). Detail of previous simulation with 265-ohm (at 20°C) aluminum tether coated with a 100% PANi without collection losses.

At this point, it is interesting to isolate the effect of the changing tether temperature upon the tether current and the system dynamics. To this aim, we ran a simulation with the same system parameters adopted to derive Figs. 2.2 but assuming (unrealistically) that the tether temperature stays constant at 20 °C. The results of this simulation are shown in Figs. 2.4(a)-2.4(e).

After comparing Figs. 2.4 (tether with constant temperature) to Figs. 2.2 (tether with variable temperature), we can conclude that the system thermodynamics and its interaction with the current can not be neglected in the analysis of ProSEDS. The inclusion of the thermal model of the tether has actually a beneficial effect on the system dynamics. The tether current, in fact, becomes more uniform during the day/night cycles thanks to the decrease of temperature and electrical resistance during the night that compensates for the decrease in plasma density. Consequently, the 1-Ω (with Ω = orbital rate) spectral component of the tether current (related to the plasma density variation in the day/night cycle) is reduced and the dynamic stability of the system increases. This effect is apparent after comparing the plots of the tether tension and tip-to-tip distance in Figs. 2.2 and 2.4. A strong reduction of the tip-to-tip distance (of the order of a km or more) is a clear indication of a significant tether skip-rope which can produce sizable tension spikes when it grows too large forcing a series of tether slacks and rebounds.

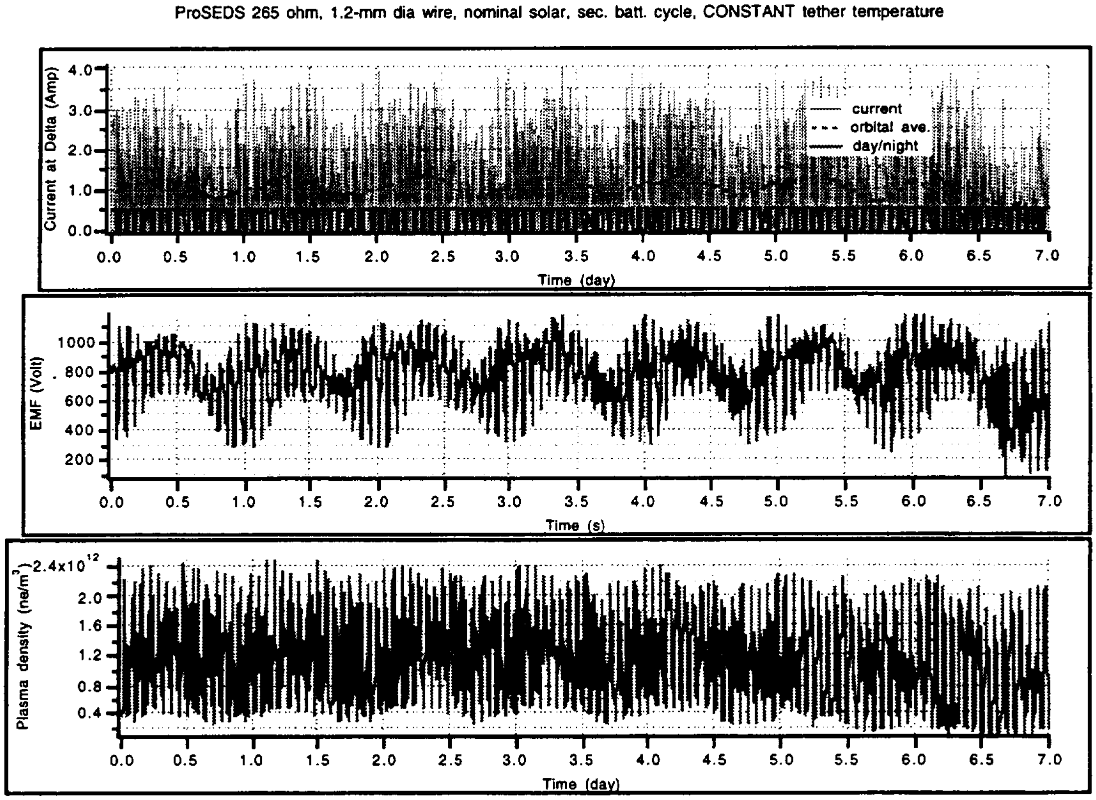

ProSEDS 265 ohm, 1.2-mm dia wire, nominal solar, sec. batt. cycle, CONSTANT tether temperature

Fig. 2.4(a). Simulation of ProSEDS with a CONSTANT 265-ohm aluminum tether coated with a 100% PANi without collection losses.

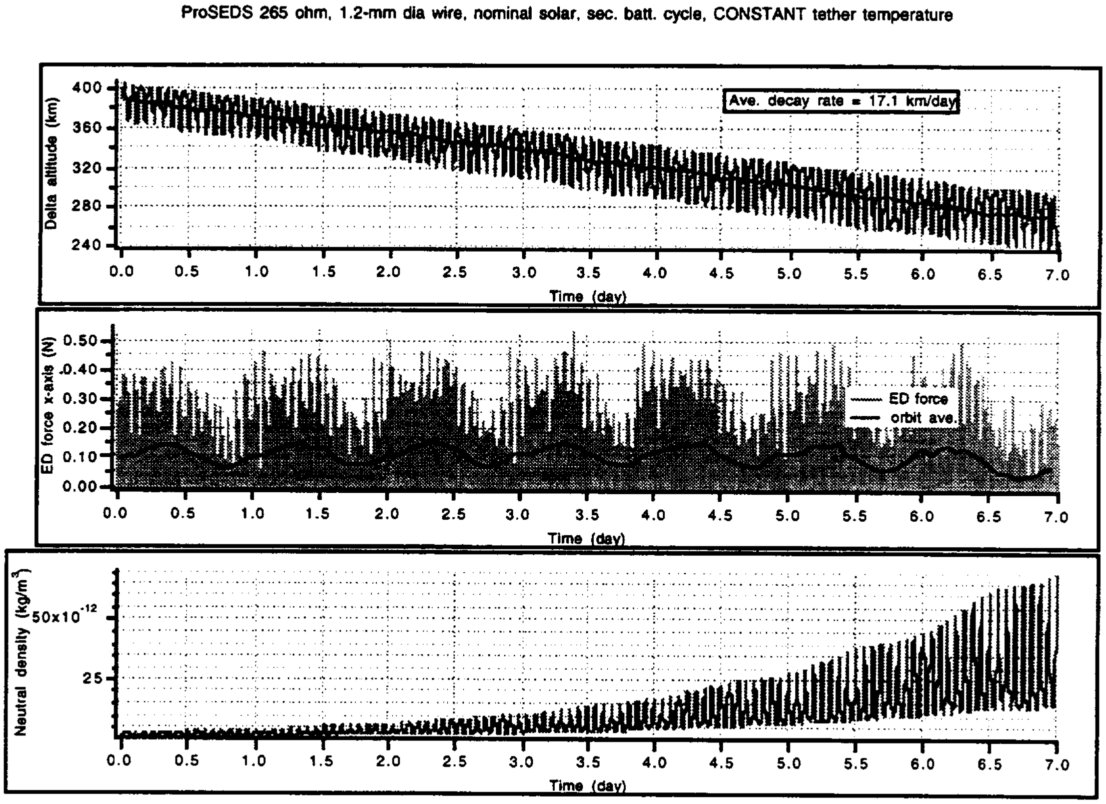


Fig. 2.4(b). Simulation of ProSEDS with a CONSTANT 265-ohm aluminum tether coated with a 100% PANi without collection losses.

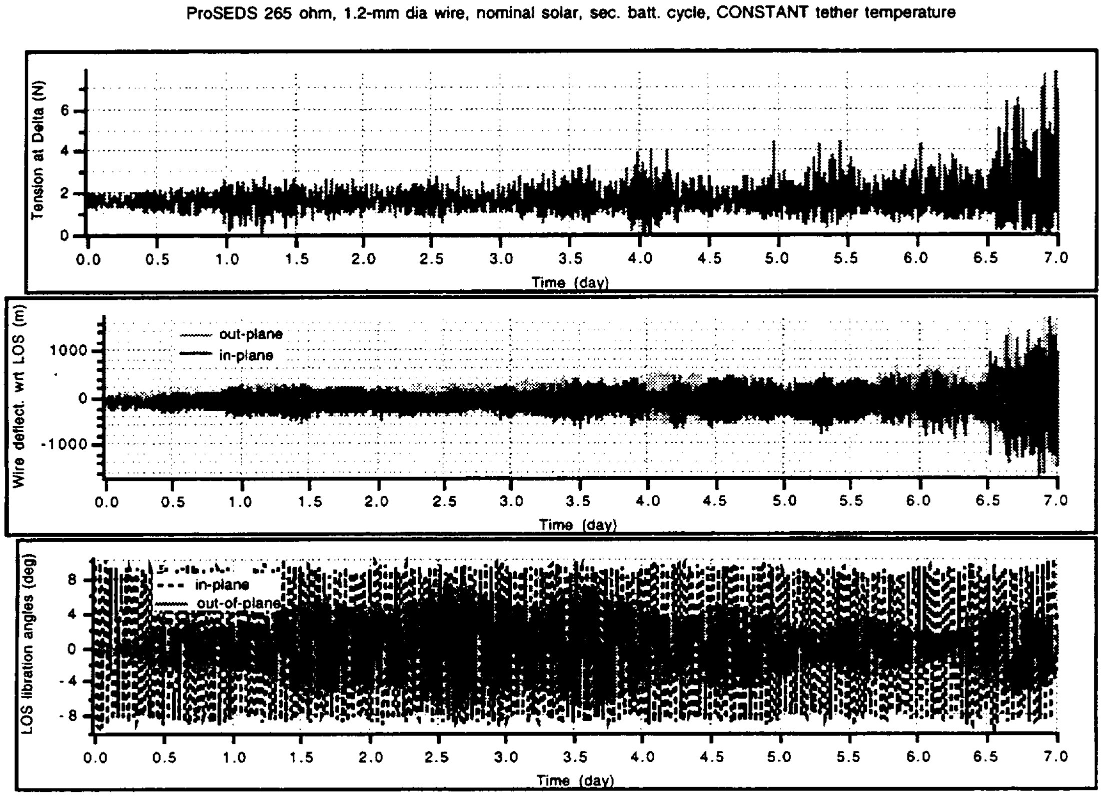

ProSEDS 265 ohm, 1.2-mm dia wire, nominal solar, sec. batt. cycle, CONSTANT tether temperature

Fig. 2.4(c). Simulation of ProSEDS with a CONSTANT 265-ohm aluminum tether coated with a 100% PANi without collection losses.

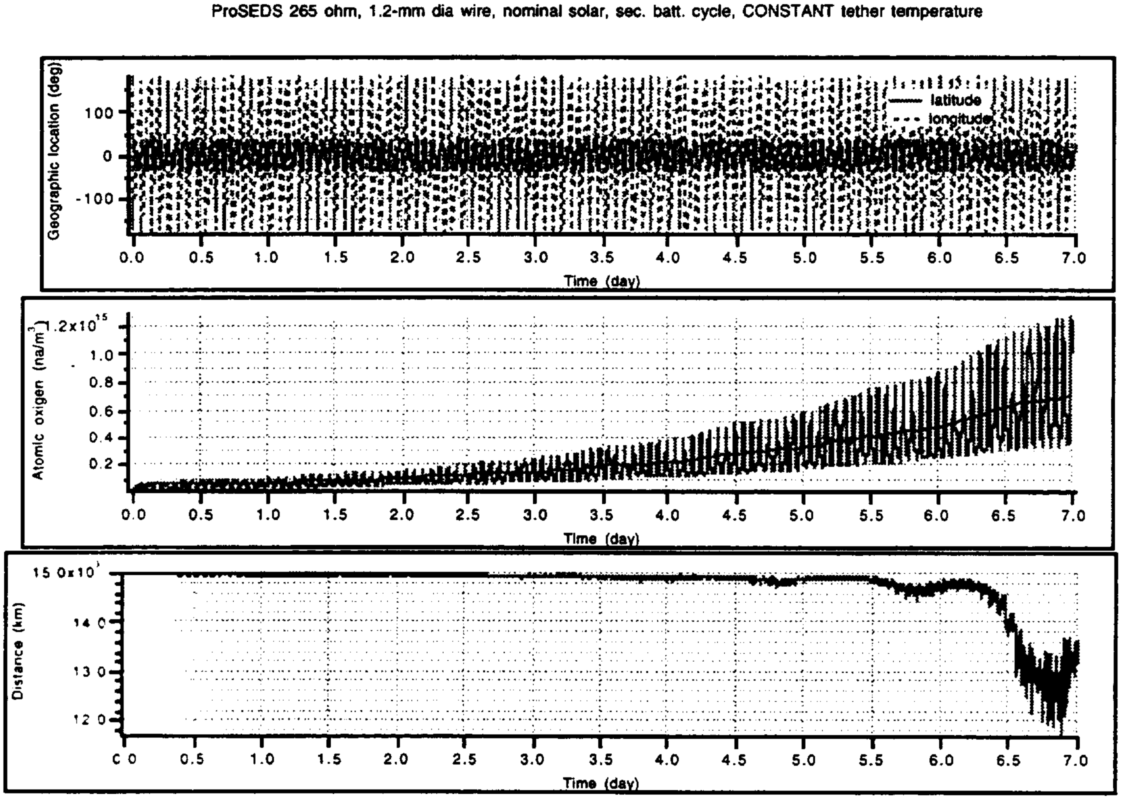


Fig. 2.4(d). Simulation of ProSEDS with a CONSTANT 265-ohm aluminum tether coated with a 100% PANi without collection losses.

2.3 Concluding Remarks

The accurate simulation of ProSEDS requires the combination of dynamics, electrodynamics and thermal models of the tether. The interplay among dynamics, electrodynamics and thermodynamics is crucial in explaining the performance of a system like ProSEDS. The changing tether temperature and, consequently, electrical resistance of the wire has a positive effect on the current profile over the day/night cycles and ultimately on the dynamics stability of the system.

Another important conclusion of the analysis conducted above is that an uncoated metal wire would attain high maximum temperatures that are strongly undesirable from the points of view of system performance and mechanical strength of the tether. Consequently, the α/ε (absorptance/emittance) ratio of the metal wire must be decreased (while preserving its ability to collect electrons) by using appropriate coatings or other suitable techniques with the final goal of keeping the temperature of the wire below roughly-speaking 100 °C.

The present estimate of the orbital decay rate during the first week of the mission is about 15.4 km/day (after correcting for the overestimate) with the present wire configuration coated with the 100% PANi coating (no collection losses). Coatings with collection losses different from zero will produce decay rates smaller than indicated above.

3.0 ProSEDS Tether Development and Testing

3.1 Introduction

The tether development and testing has been conducted with a team of people whose expertise covers the broad range of skills required for this task.

The following documents show the testing plan of the tether candidates, preliminary requirements of the ProSEDS tether, results from the measurements of tether properties and early results from the deployment tests.

Members of the ProSEDS Development and Testing Group are shown in the following.

Tether Development and Deployment Tests Group (June 1998)

Name	Organization	Area of expertise
Ken Welzyn	NASA/MSFC	Tether Dynamics
Chris Rupp	NASA/MSFC	System
Jonathan Lee	NASA/MSFC	Materials
Andrew Hodge	NASA/MSFC	Materials
Ken Wright	MSFC/UAH	Plasma physics
Judy Ballance	NASA/MSFC	System (Chief Engineer)
Neil Rainwater	NASA/MSFC	System requirements
Jason Vaughn	NASA/MSFC	Materials
Keith Presson	NASA/MSFC	Thermal analysis
Linda Neergaard	Sverdrup	Space environment
Robert Estes	SAO	Bare tether physics
Enrico Lorenzini	SAO	Dynamics/Testing
Manuel Martinez-Sanchez	MIT	Bare tether physics
Rob Hoyt	Tether Unlimited	Fail-safe tethers
Joe Carroll	Tether Applications	Tether deployer

3.2 ProSEDS Tether Development Status (as of April 1998)

The tether development status as of April 1998 is summarized in the presentation shown in Appendix B. After extensive measurements conducted on the tether for atomic oxygen resistance, optical properties, electron collection (in plasma chamber) and estimation of survivability to micrometeoroid and orbital debris (MO/D) impacts, the ProSEDS mission has been subdivided in different phases: 3 orbits of continuos data taking for meeting the success criteria on the primary mission objectives; 13 additional orbits with periodic data taking for strengthening the science return on the primary mission objectives; and up to system destruction (by natural causes) for an extended mission phase.

The presentation shows the summary of the tether testing, preliminary tether requirements and the present tether configuration. This configuration has been used to carry the first deployment tests as shown later on in this report.

Results from atomic oxygen (AO) tests on ProSEDS tether materials indicate that AO erosion is severe for AO concentrations encountered below about 250 km of altitude (with spectra being the most sensitive material followed by kevlar). Given the initial orbit of 375x414 km and the presently estimated decay rate, ProSEDS will approach the altitude of 250 km after a week when the tether integrity will start to be seriously jeopardized.

The estimation of the survival probability of the ProSEDS tether to micrometeoroid and orbital debris (MO/D) impacts is difficult and the results inaccurate because of the complex geometry of the ProSEDS tether. Preliminary results points to a rough estimate of a 90% survival probability at *only a few days* MO/D exposure.

Measurements of optical properties on bare, surface-treated and coated tethers indicate the following. Copper and aluminum bare tethers reach temperatures in space that are too high for providing good electrical conductivity and mechanical strength. Surface treatment, like alodine, worsen this situation even further. The conductive coating C-COR provides good optical characteristics at the expense of an acceptable loss in electron collection. This coating, however, must still be tested for its deployability characteristics. Alternative techniques to reduce the wire temperature with a high-emissivity overwarp have been proposed but sufficient data are not yet available to assess the validity of these techniques.

3.3 ProSEDS Present Tether Configuration

The design of ProSEDS tether is driven by the severe mass and volume constraints of this mission. The present tether configuration tries to achieve a low electrical resistance by using aluminum with passive thermal control (conductive coating) and high mechanical resistance by using a kevlar core for the wire and spectra for the ballast tether.

The present tether configuration is shown in the following.

Overall length = 15 km of which

Non-conductive portion

non-conductive ballast tether (Spectra-2000) = 10 km

Conductive portion

conductive wires (Aluminum) with non-conductive core (Kevlar-29) = 5 km

Overall mass = 11.75 kg of which

Conductive portion = 9.85 kg (8.15 kg Aluminum + 1.7 kg Kevlar-29 core)

Non-conductive portion = 1.9 kg (Spectra-2000)

Configuration

Non-conductive portion

Flat tether (Spectra-2000): 1.2-mm x 0.15-mm (11x135 denier)

Conductive portion

Cylindrical tether with 1.2-mm outer diameter.

The inner Kevlar-29 core diameter is about 0.6 mm (2000 denier);

7x28 gauge aluminum wires are wrapped around the inner core (to reach an outer diameter of 1.2 mm); the aluminum wires cover most of the core.

Ultimate mechanical strength

Non-conductive portion (Spectra-2000) ≈ 450 N (estimated)

Conductive portion (Kevlar-29 core) ≈ 320 N (estimated)

The strength of aluminum at our max temperature of 100 °C is negligible with respect to the Kevlar core strength.

3.4 Tether Testing

Teleconference: April 22, 1997

Deployment test plan

A test plan for ProSEDS deployments is presented in the following. This plan will be updated and refined as time progresses and test results are acquired.

Test facilities

The two test facilities (full-up deployment test facility and brake test equipment) at NASA/MSFC must be reassembled and refurbished as soon as personnel and financial resources are available. The full-up test facility needs upgrading especially with regards to the tether tension measurements. The running tensiometer adopted for the SEDS-II Spectra tether is not suitable to run experiments on the Copper wire of ProSEDS. Chris Rupp has a valid suggestion for measuring the tether tension, without the running tensiometer, by suspending the deployer horizontally on a trapeze and by measuring the horizontal pull on the deployer. This modification of the test facility should be implemented.

The test facilities, once in operation, can be used for both the ProSEDS program and the ISS tether towing program.

The present estimate for reassembling both test facilities at NASA/MSFC is 2 months.

Availability of test items

The present availability of tethers and deployers suitable for testing is as follows:
a) 100 km of Spectra tether from the SEDSAT mission and the SEDS-II flight tether;
b) 3 deployers (from a total of 5) from SEDSAT and 1 spare deployer from SEDS-II;
c) Spectra fail-safe tether from Tether Unlimited to be made available in June 1997;
d) Copper fail-safe tether from Tether Unlimited likely to be available in Summer 1997;
e) Baseline Copper wire to be purchased by NASA/MSFC.

Development tests

Development tests are for defining the system performance during deployment in order to: (a) allow key decisions to be made on flight tether types; (b) finalize deployment strategies; and (c) refine models to be used for predicting deployment dynamics.

Development tests must be conducted on the following tethers listed in terms of (time wise) priorities:

1) Baseline Copper wire

2) Fail-safe Spectra tether

3) Fail-safe Copper wire

4) Baseline Spectra tether (SEDS-type).

Key quantities/information to be obtained from the test results are:

level of deployability without entanglements and hang-ups, minimum tension, inertia multiplier, friction coefficient, brake response, tether tension variations when going through the Spectra/Copper junction, location and intensity of the sling/scrub transition.

Development tests should proceed on a learn-as-we-go basis. Some early tests on the Copper wire should be carried out in vacuum as the friction coefficient of metals may change substantially in vacuum conditions. Development tests on Spectra tethers can be run in air.

Verification tests

Verification tests are for checking the complete deployment of ProSEDS in close-to-flight conditions. These tests must be run in vacuum and will be carried out after the development tests are completed. At least two full deployment test should be conducted on flight-configured ProSEDS tethers.

General concerns

Deployment testing of the Copper wire will require changing or refinishing those parts of the test hardware that are in contact with the running Copper. Non-flight hardware must be used for deployment tests of the Copper wire. Time intervals between successive tests on the Copper tether will be required for refurbishing or replacing the relevant test articles and components.

Scheduling

It is strongly desirable to have some preliminary test results before the ProSEDS PDR at the end of FY1997. Given the time necessary for reactivating the NASA/MSFC test facilities, it is recommended that early development tests be run at Tether Applications on test articles provided by NASA/MSFC and utilizing test facilities available at Tether Applications. The priority list indicated above for the development tests applies to these preliminary tests. Later in the test program, Tether Applications could also run additional tests for backing up the results obtained at NASA/MSFC.

Teleconference: June 3, 1997

Deployment Tests List

Tests to preselect tether candidates for the conductive (wire) and non-conductive portion of the ProSEDS tether will be conducted at Tether Application (TA) during the Summer 1997. About 4 conductive tethers and 3 non-conductive tethers will be tested during this pre-selection process at TA. These tethers will include conventional braided tethers, Hoyt tethers and caduseus tethers. Copper and aluminum wires will be tested. At the end of this pre-selection process two valid candidates for the conductive and two for the non-conductive tether will be selected and subsequently tested at NASA/MSFC to define the tether characteristics (development tests), the brake response (brake tests) and to validate performance of the flight and spare tethers in their flight configurations for the planned deployment profile (verification tests).

The following is a preliminary list of tests to be conducted at NASA/MSFC. Considering that there is no past experience to draw from for the testing of bare wires, this list will be subjected to modifications and updates as more data is acquired.

Deployment tests matrix

	Development tests	Brake tests	Verification tests
Tether W1	3*[¥]	3*[¥]	0
Tether W2	3*[¥]	3*[¥]	0
Tether NC1	3*	3*	0
Tether NC2	3*	3*	0
Tether FT1	0	0	2[¶]
Tether FT2	0	0	2[¶]

Nomenclature

W1 = conductive wire 1
W2 = conductive wire 2
NC1 = non-conductive tether 1
NC2 = non-conductive tether 2
FT1 = flight tether 1
FT2 = flight tether 2

The two flight tethers (flight, FT1 and spare, FT2) consist of the splicing of a non-conductive and a conductive tether in flight configurations. FT1 and FT2 will result from the best combinations of the four tether candidates listed in the deployment test matrix (two wires and two non-conductive tethers) after the development and brake tests are complete.

Footnotes

* One test for each temperature value: minimum, nominal, and maximum;

[¥] Initial tests to be conducted in vacuum;

[¶] One test for minimum and one for maximum temperature.

Test facilities used

Full-up test facility for:	development tests and verification tests;
Brake-only test facility for:	brake tests.

Data to be extracted

From development tests:

- minimum tension, friction coefficient, inertia multiplier for the three temperature values;
- location and intensity of the sling/scrub transition.

From brake tests:

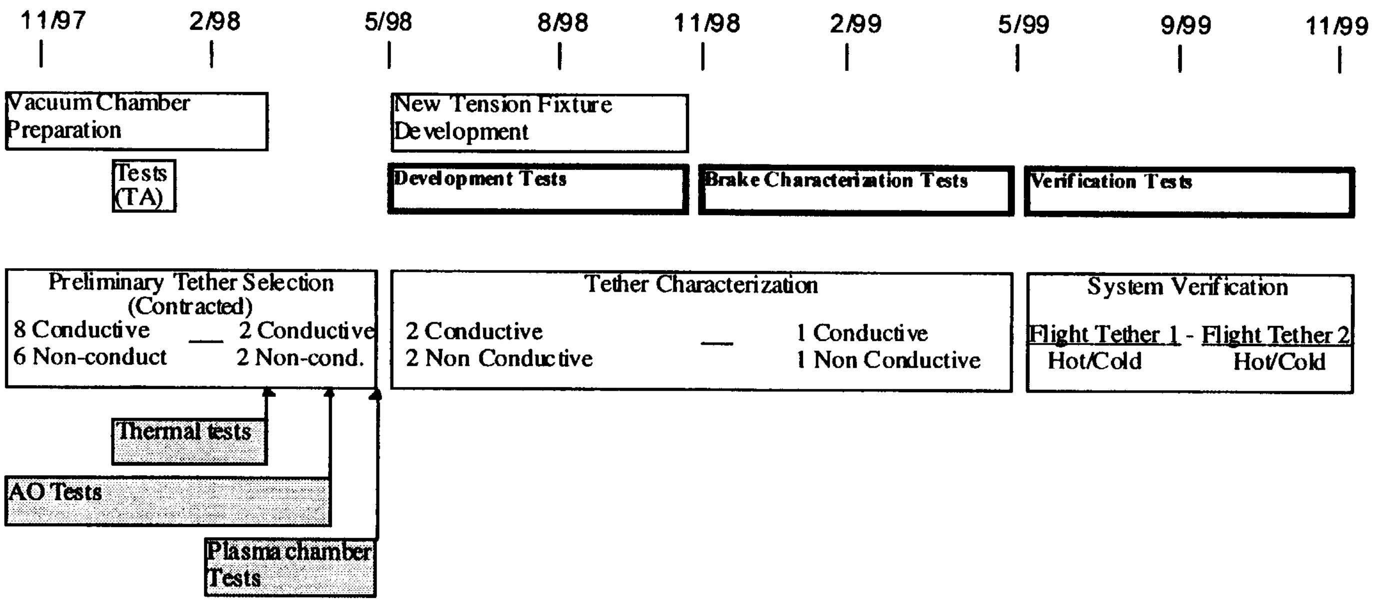
- brake response as a function of brake turns for the three temperature values.

From verification tests

- validate results for the planned deployment profile on the flight and spare tethers for the minimum and maximum temperature values.

General concerns

Deployment testing of the wires will require changing or refinishing those parts of the test hardware that are in contact with the running metal. Non-flight hardware must be used for deployment tests of the wires. Tests of the wires will require more time allocated to refurbishing or replacing the relevant test articles and components than tests of the non-conductive tethers.



ProSEDS Tether Testing Schedule (updated in April 1998)

Teleconference: August 14, 1997

Deployment Tests Status

Pre Development Tests (contracted to Tether Applications)

Deployability tests on the non-conductive, fail-safe, Hoyt tether will be conducted at Tether Applications during the next two weeks and early results (if available by that time) will be presented to the group at the next Deployment Tests teleconference.

Procurement of Conductive Tether Samples

The procurement by Tether Applications of conductive tether samples from Cortland has been put on hold pending the resolution of the appropriate surface coating to be used. The tether samples considered for procurement from Cortland have a Kevlar core with the conductor on the outside. The samples will be made into single-line tethers and two-line Caduceus by Tether Applications.

The surface coating of the aluminum conductor must provide not only good electron collection but also relatively high thermal emissivity that implies a lower tether temperature. A thin anodization is now been considered for increasing the surface emissivity at the expense of a decrease of the surface electrical conductivity.

Lewis will run tests on anodized aluminum to measure the surface conductivity for various coating thickness. Joe Carroll will receive the results of those tests.

Regarding the conductive fail-safe Hoyt tethers, Rob Hoyt is supervising the manufacturing of new conductive tether samples of this kind.

Plasma Chamber Tests

Plasma chamber tests to measure the electron collection of aluminum tether samples with different coatings will be conducted at NASA/MSFC before the end of September.

Teleconference: November 5, 1997

Changes of Mission Requirements Affecting Tether Development

The rescoping of the ProSEDS mission had important effects on the tether design. The present baseline configurations for the two tether portions are as follows:

– Single-line, spectra tether for the non-conductive portion;

– Single-line, copper or aluminum tether for the conductive portion.

The rescoping, however, did not rule out the possible use of fail-safe tethers if such tethers prove to be deployable and resistant to AO (atomic oxygen) deterioration for the mission duration. Consequently, tether tests will be run for the baseline configuration and for the fail-safe configurations as originally planned. However, the higher priority will be given to the baseline configuration while the other tether configurations will be tested on a non-interference basis.

The rescoping also affected the tether size (length and diameter) as a shorter and fatter tether is preferable from the AO degradation and micrometeoroid survivability point of view. Total tether length and diameter are yet to be finalized. However, preliminary results point toward the following preliminary conclusions:

a) Tether length of the conductive tether portion = 5 km;

b) Tether length of the non-conductive tether portion = 10 km or slightly less;

c) Equal diameters for the conductive and non-conductive tethers;

d) Tether diameter ≈ 0.8-0.9 mm and, as a general rule, the maximum diameter that can be accommodated in the SEDS deployer in its current configuration.

Tether Samples Procurement

Procurement of a new Spectra tether (slightly fatter than the SEDS-II flight tether) will take about 1 month and 2000 $ for a 20-km sample.

A 30-40 feet sample of TOR tether (resistant to AO) is available from Triton. Longer samples (of a few hundreds feet) have to be made to order and the braiding takes about two weeks at a cost of 5 $ per foot.

Actions

Enrico to find out from Joe the minimum length of a tether sample needed for running a meaningful deployment test.

Joe Carroll to report to the group the results of the deployment test on the non-conductive Hoytether at the next Tether Development teleconference.

Teleconference: February 13, 1998

Optical Characteristics of Tether Candidates

Previous emissivity and absorptivity tests concluded that bare aluminum and bare copper would reach maximum temperatures that are too high and undesirable because of reduced mechanical strength, increased electrical resistance and incompatibility with the temperature requirements of the non-conductive tether core.

Consequently, a new conductive-polymer coating (called C-COR), developed by Triton, was used to coat an aluminum sample and tested by Jason Vaughn at NASA/MSFC for emissivity and absorptivity characteristics.

The measured characteristics are as follows:

emissivity, $\varepsilon = 0.9$

absorptivity, $\alpha = 0.8$

These values will provide a maximum tether temperature in space which has been estimated with a simplified thermal model to be about 60 °C. This temperature estimate will be checked with a more accurate thermal model. The temperature, however, is low enough to be attractive for solving the problems mentioned above regarding bare aluminum and bare copper.

The same conductive coating will be tested on a sample of copper for emissivity and absorptivity. These tests will be followed by measurements of electrical conductivity and plasma chamber tests for both the coated aluminum and a coated copper in order to determine whether the electrical properties of the coating are suitable for electron collection.

Actions

Jason Vaughn to arrange for having a sample of copper coated with the Triton's coating and tested for thermal characteristics.

Joe Carroll to provide data that will help in making the material selection between aluminum and copper.

Jim Sorensen to compute the steady state tether temperature under worst case conditions of high plasma density and maximum solar illumination for aluminum and copper tethers coated with the Triton's coating.

Enrico Lorenzini to contact Jonathan Lee and evaluate the mechanical strength of all-aluminum and all-copper tethers at the newly estimated tether temperatures.

3.5 Results of early deployment tests

Date: Sunday, 19 Jul 1998 19:13:21 -0700
From: Joe Carroll <tether@home.com>

Report on the Deployment Test of the First Baseline Conductive Tether carried out at Tether Applications[2]

I was finally able to finish setting up for the deployment test and run the test today. The results indicate that, as I suspected, deployment is far less of a problem than winding. There were problems, including 2 hard jams, but the fixes appear straightforward.

I first deployed the 11x215 flat Spectra braid that served as a partial "ballast tether" winding. This was intended both to get experience with flat braids, and also to compress the underlying wire so its deployment properties are more representative of a full winding. There were no obvious surprises in deploying this. (I add the "obvious" qualifier because I haven't yet looked at the test data in great detail.) I deployed this at rates of 1 to 7 m/s, with 0 to 4 turns brake on the brake.

I went through the Spectra/wire transition at 5 m/s with no brake, to mimic an actual deployment which might start deploying wire at a speed near this. I thought that transition might cause a problem that would require a very gradual change in tether mass and stiffness. However the transition deployed with no problem. Wire deployment tension after the transition was about 0.9 newton, at 5.1 m/s.

I stopped the deployment, added one turn brake, and then deployed at 5.1 m/s. The average tension was about 2.4 newtons. I then added another turn of brake. This raised the average tension to 7.5 newtons. (This data is based on 1/30 second averages that go off-scale at 8.2 newtons, and so the actual may be a bit higher due to truncated values going into the average.)

I found that every time I came to a stop, or deployed at low speed, some wire would "pre-deploy" inside the can. I was concerned that this would cinch up on itself, but when a jam actually occurred, it turned out to be due to something else.

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[2] This section contributed by Joe Carroll of Tether Applications

After deploying for a few seconds at 0.5 m/s, with two turns of brake, a hard jam occurred, at the entrance to the brake. I got some close-up video of the jam. It involves a significant kink in the tether somehow wrapping partway around the outer barrel of the entrance side of the orbiting guide. There were no broken or loose wires at all associated with the kink: it just developed during winding and/or deployment, managed to wrap around the outside of the orbiting guide, & cinched up.

After I inspected and videotaped the jam, I fed it through the brake, straightened the kink out, and continued the deployment. But I moved the camcorder to view the brake rather than the deployer after that, until late in deployment when I moved it back to look at the sling/scrub transition speed.

I continued the deployment with 2 turns, then 1, then no brake, at about 2.5 m/s. I noticed that every ~3 meters (which corresponds to one axial cycle deploying from the criss-cross pattern inside the deployer), there was a pronounced transient skiprope oscillation between the deployer and brake. I could not verify that it occurred at the same time as the top turnaround but I suspect that is the case. This led me to suspect that the jam may have occurred during a worse-than-usual skiprope.

This led me to increase the deployer-brake distance about 5 cm and put a pigtail guide between the deployer and brake. The idea was to force the wire to come out of the deployer straighter, so it would be less likely to skiprope and wrap around and cinch up on the orbiting guide. There were no problems with the brake after that.

For the future, I suggest making the same change I have made with the Mini-SEDS deployer, which has a separate heavily anodized "cork" that fits inside a 1.5" diameter neck in the canister. This "cork" can be as long as needed to ensure the wire deploys without significant skiprope between it & the brake orbiting guide. I don't think the deployer/brake distance needs to be changed from what it is now on SEDS, but if it does need to be increased, 2-3 cm should be enough. This can be obtained by changing the brake adapter plate that goes between the computer and the brake.

I also recommend a shape change for the orbiting guide: round the outside near the bottom, to make it harder to catch the wire. We might also reverse the guide, but I would want to test the ballast tether with the guide reversed and up to 4-5 turns of brake on it first. We would also need to lock the retention clip against rotation, so it doesn't jam against the brake post and prevent brake rotation.

For the remainder of the test I used this configuration with the added pigtail guide. I positioned the the video to cover the region from the deployer exit to the brake exit. There were no further jams until the last few layers of insulated wire deployment, when the wire cinched up around the core as it sometimes does even with Spectra.

I deployed the criss-cross portion of the wire at up to 6.8 m/s (and that had 1 turn of brake on it!). The faster the deployment, the smoother the wire deployed. The sound was loud enough to be audible above the takeup motor.

The criss-cross/parallel wind transition deployed at 4.4 m/s. There was a tension spike very near the transition (probably after it, since the very end of the parallel winding caused me some trouble and was somewhat uneven), but due to the setup for this test, and the truncation of the data to 8.2 newtons max tension (which I can fix with a software change for future tests), I can't get a good estimate of the magnitude of the spike.

I deployed much of the parallel winding at speeds of 2-3 m/s to explore the sling/scrub transition and to determine the minimum speed at which the tension inside the deployer due to inertia is enough to keep the wire in place until deployment, despite its springiness. The sling-scrub transition early in the parallel winding deployment was about 2 m/s, but up near the top of the core some scrubbing occurred even at 2.3 m/s.

The minimum speed to guarantee no "pre-deployment" of the tether appears to be around 2.6 m/s. In a zero-gee environment this speed might be a bit higher, since gravity may help the wire to stay in place on a horizontal spool. If we use wire somewhat stiffer than the dead-soft 28 AWG aluminum used in this test, the transition speed will increase further. As a result, I suggest we try to keep the deployment rate above ~3.5 m/s until VERY late in deployment (ie, until we've deployed some of the insulated wire).

After establishing the sling/scrub and predeploy/no-predeploy transition speeds, I stepped up to 5.8 m/s for 100 m or so, then down to 5.0, 4.0, and 3.6 m/s. The Hi-Wire/PMG wire splice deployed at 3.6 m/s. The tension roughly tripled when the PMG wire started to deploy, from 1.8 to 5.4 newtons. I then slowed down to 2.6 m/s and found that the PMG wire continued to deploy in the sling mode, without any pre-deployment, at about 40%

lower tension than at 3.6 m/s. I then added one turn brake for ~7 seconds. This took the tension off-scale, but the wire deployed smoothly. I removed half the brake, waited 3 seconds, and then removed the rest.

When I slowed down and stopped, in the last few "partial" layers of the PMG wire, the turns spread apart into a helix covering the bare part of the core. Thereafter the wire was hard to deploy: it would cinch up against the top flange. I would grab the wire between the can and the pigtail and wiggle it, and then deployment would start (not a feasible scenario in orbit!).

I will try to get the tension, length, and length-rate data sent out tonight, in ascii form (1 second summaries).

Lessons learned and other recommendations:

A. SEDS hardware design

1. Force the wire to exit the deployer axially, either with a guide ~1" away or by extending the exit guide (the "cork" option).

2. Taper the OD of the orbiting guide and round the edge to make it harder for the wire to wrap around it and cinch up.

3. Use the modified should screw developed for YES (put a conical taper on it to make it harder to catch on something.

4. Maybe alter the core shape (reduce top flange OD, and/or increase core ID.

5. If we plan to use 7075 for some deployer components, we should have them made now, so if there is any difference in the anodize properties due to the alloy, our future tests are as relevant as possible.

6. Try to get a decent simulant of the exit guide we plan to use on ProSEDS: a section of a 7/8" radius cylinder would be good. This will be far more representative than the LVDT

guide we now use, which has a bend radius near 0.25". I used a 1/2" radius cylinder, with a 30 degree wrap angle.

B. Winding design

1. Eliminate the partial layers at the beginning (do them later, or not at all). This will make the insulated wire wind more smoothly, and possibly deploy better.

2. Take care to keep the reversal areas smooth near the end of the parallel winding to try to eliminate tension spikes.

3. Do several full windings to determine how much the edges of a full package slump. We want the package either lightly in contact with the base (so it doesn't slump during combined axial acceleration plus high vibration), or at least nearly in contact (so pre-deployed wire cannot get into the gap between package and baseplate). Because of the higher stiffness and friction of the wire, we should not use high force during assembly to squash the winding against the baseplate. Finding the right package shape may take several full windings, with vibration tests on each to see how they hold up.

C. Tether design

1. The flat braid winds and deploys well. It seems to have a slightly lower sling/scrub transition speed than round tethers, despite the larger area/mass ratio.

2. Copper-covered-aluminum wire may generate considerably less debris than the aluminum wire does, and MAY have better surface properties for plasma contact. We should probably get some copper-covered aluminum wire as a backup to the C-COR coating, and test it as soon as feasible.

3. We should also get some Kevlar-overbraided wire (perhaps 7 strands of 28 AWG aluminum) to see how that winds and deploys. Kevlar on the outside could provide strength, protection for the wire, high emittance, and a modest absorptance. We could get this with low coverage (30-50%) for the upper ~1/2 of the wire, and high coverage (60-

90%) for the lower half or so, to reduce temperature. But note that this construction would NOT have good AO tolerance.

4. The innermost layer of insulated wire might have a Kevlar overbraid, both to increase deployment tension at the very end and also to provide protection to the wire that ends up stopping in the exit guide, because that wire will be forced to flex more than the rest of the wire is.

D. Test hardware setup

1. Limit the unsupported wire length, especially upstream of the first tensioning device. At MSFC, it may make sense to move the squeegee tensioner towards the "lab" LVDT guide.

2. Be prepared for considerable generation of aluminum powder debris. It is possible that the powder could damage the turbo-molecular pumps or the roughing pumps.

3. Use thick hard anodize or Tiodize coatings on all guides. The thin coatings wear through too quickly.

4. To limit damage to the wire, it may be best to use a very light squeegee tension, followed by a turn around one or more pulleys with modest drag to increase the tension. It may be useful to use a squeegee that slowly rotates due to vibration when in use, so it does not accumulate wear in a small area. For accuracy of the 3" diameter metering wheel, do not add drag to that; use another wheel upstream of it to increase the tension before the metering wheel.

5. Try to use pigtail or donut guides only as guides upstream of pulleys, and use pulleys (at least ~2" in diameter) to change the wire direction. This should greatly reduce damage to the wire. It is hard to do this with the existing takeup assembly. You will probably have to move the level-wind assembly further away from the spool to make room for a pulley. I know this is a pain, but I can't think of alternatives right now.

6. MSFC should get a clear plastic baseplate and do some tests in air. You'll learn a lot from them. Note that "antiglare" plastic sheets are usually lightly frosted rather than anti-reflection coated, so they're not a good choice for making a clear plastic baseplate.

7. When you do tests in air, definitely videotape both the deployer (through a plastic base) and the nipple/brake/exit area. For vacuum tests, consider taping some sort of contact-mike to the canister, and connecting the mike to any camcorder used during the tests. I could clearly hear the difference between the criss-cross & parallel windings deploying, and between the Spectra, bare wire, and insulated wire deployments.

8. I did not tip the deployer upright during the test, but was able to establish that deployment with the deployer upright is likely to cause problems if deployment of the wire ever slows down below ~2.6 m/s, since the wire tends to move around on the package even if the deployer is horizontal. So lest we get into a situation analogous to that shown in the movie "Speed", let's plan on being able to do deployments with the deployer horizontal or tilted, rather than vertical.

E. Test Software

1. Modify program so the scale factor for the 30 Hz averaged data can be scaled as desired, so it does not go offscale at 8.2 new. (The data is now 14 bits of integer data, plus 2 LSBs that indicate whether any of the 16 datapoints averaged in it were offscale high or low. Each count of the 14 MSB tension data is now fixed at one millinewton.)

F. Deployment strategies

1. We want to keep the deployment speed up above ~3.5 m/s as long as possible during deployment, preferably until all but the last layer of insulated wire has deployed. The proposed Kevlar overbraid (Kevlar rather than Spectra for added friction) could help. If we reach the end of the wire at speeds near 3.5 m/s, we need to ensure that the resulting peak "bungee jump" tension is acceptable to the wire.

2. It is possible that we may want to deploy the wire with a modest amount of brake (<1 turn) to keep the speed near the end from being excessive (>>3.5 m/s). Because of the potential problems with braking, however, I only recommend this if it is clear based on deployment tests with the final tether design that it is necessary.

Addendum to the Report on Deployment Test by Tether Applications[3]

There are 4 important things I left out from my summary.

1. Based on data collected during the winding of the Kevlar/aluminum crisscross pattern, the winding density is a bit higher than I expected. My best estimate is that we could get about 6.5 km of the current tether design onto the package while not taking the OD beyond 8.0 inches, or use a tether with up to ~30% larger cross-sectional area. That leaves about 22% of the volume for ballast tether outboard of 8.0 inches, if we limit the package OD to 9.2 inches and taper the upper end of the package as we have done in the past. (We did one SEDS winding with 22.5 km of tether. This gave a package OD of 9.18 inches. It deployed fine, despite there being only 0.35 inch radial clearance with the canister. I don't want WIRE wound that close to the can, but Spectra is ok there.)

2. The jam at the entrance to the brake occurred with the copper wire, not the aluminum/Kevlar hiwire. It was not obvious that it was the copper at the time, because the copper strands are individually silver plated and look like aluminum. But the jam did indeed occur with the copper, not with the aluminum. The copper/aluminum transition was later and can be seen in the camcorder side-view of the brake. Deployment rate at the time was ~0.5 m/s, far slower than I think we should deploy the wire (even at the very end!).

3. The copper (19x34 AWG copper, with silver plating on the individual strands) has a mass of 3.8 grams/meter, while the aluminum/Kevlar has a mass of only 1.8 grams/meter. However at the transition from the copper to the aluminum, the tension went up ~23%, from .39 to .48 newton (with no brake, at a deployment rate of 2.4 m/s). This means the aluminum deploys at about 2.5X higher tension per unit mass than the copper. I presume that both the strand diameters (320 vs 160 microns) and the surface properties (here, aluminum vs SILVER) affect the tension.

4. The transient skiprope behavior that I noted in the summary was far more pronounced after the copper/aluminum transition, so it's not clear what triggered the jam of the copper wire. This suggests that we should videotape both the inside of the canister and the exit-brake area throughout all future deployment tests.

---

[3] This section contributed by Joe Carroll of Tether Applications

Note that both the copper and the aluminum were deployed at high speed with brake at one time or another: the copper at 5 m/s with 0, 1, and 2 turns, and the aluminum at 6.8 m/s with one turn brake.

3.6 Concluding Remarks

Results from atomic oxygen (AO) tests on ProSEDS tether materials indicate that AO erosion is severe for AO concentrations encountered below about 250 km of altitude (with spectra being the most sensitive material followed by kevlar). Given the initial orbit of 375x414 km and the presently estimated decay rate *(corrected for the 14% overestimate)*, ProSEDS will approach the altitude of 250 km after nine days when the tether integrity will start to be seriously jeopardized.

The estimation of the survival probability of the ProSEDS tether to micrometeoroid and orbital debris (MO/D) impacts is difficult and the results are inaccurate because of the complex geometry of the ProSEDS tether. Preliminary results points to a rough estimate of a 90% survival probability at *only a few days* MO/D exposure.

Measurements of optical properties on bare, surface-treated and coated tethers indicate the following. Copper and aluminum bare tethers reach temperatures in space that are too high for providing good electrical conductivity and mechanical strength. Surface treatment, like alodine, worsen this situation even further. The conductive coating C-COR provides good optical characteristics at the expense of an acceptable loss in electron collection. This coating, however, must still be tested for its deployability characteristics. Alternative techniques to reduce the wire temperature with a high-emissivity overwarp have been proposed but sufficient data are not yet available to assess the validity of these techniques.

The design of ProSEDS tether is driven by the severe mass and volume constraints of this mission. The present tether configuration tries to achieve a low electrical resistance by using aluminum with passive thermal control (conductive coating) and high mechanical resistance by using a kevlar core for the wire and spectra for the ballast tether.

Preliminary results from the spooling of the ProSEDS tether (in its present configuration but without the conductive coating) and deployment tests indicate that:

(1) deployment characteristic of the ballast (spectra) tether are good and those of the metallic wire are satisfactory and less problematic than expected;

(2) the spooling of the metallic wire with non-metallic core is more difficult than expected and adjustments have to be made to the tether design and spooling technique in order to make this procedure more reliable.

4.0 Tethers for Reboosting the Space Based Laser

Results of the study carried out for the space-based laser (SBL) are shown in Appendix A. Appendix A is the final presentation of the SBL study carried out jointly by NASA/MSFC and SAO. The SAO contributions to this study were focused on: (1) electron collection computations; (2) parametric analysis of the system performance; (3) airdrag evaluation during the whole mission phase; (4) comparison between drag make up with an electrodynamic tether system and a conventional chemical system; and (4) analysis of the attitude torque produced by the tether and acting on the spacecraft.

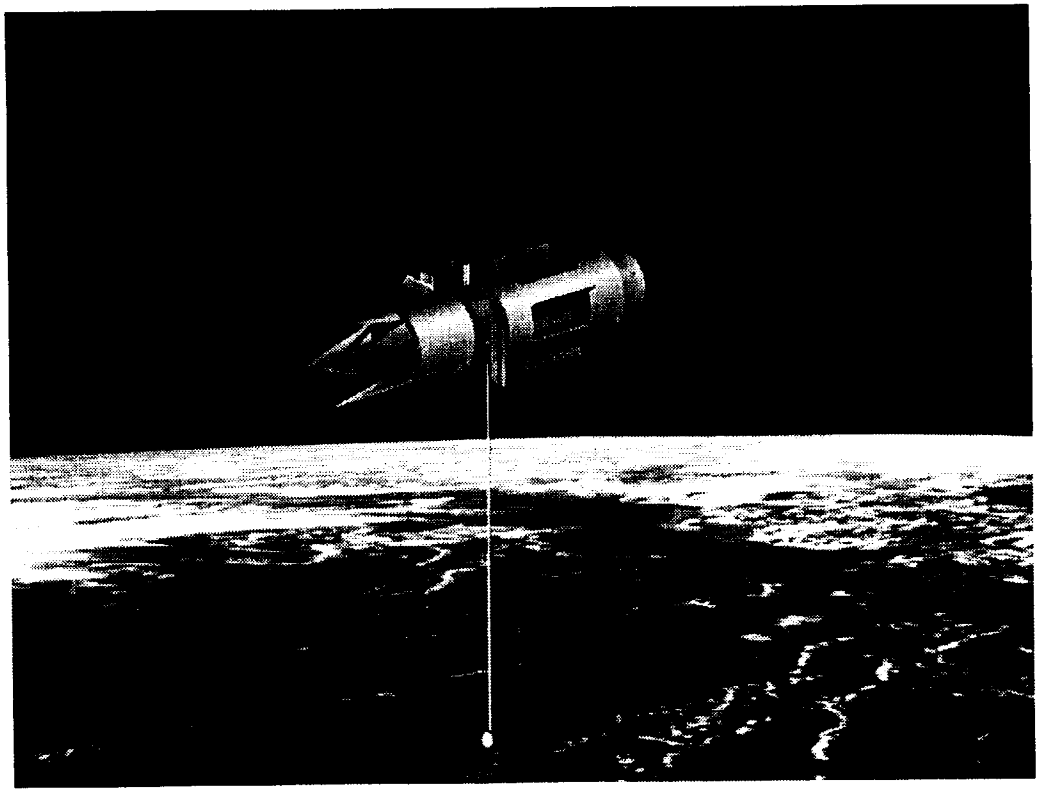
Appendix A

Final presentation on the Space Based Laser study

Space Based Laser

Electrodynamic Tether Reboost Feasbility Assessment

June 29, 1998



NASA MSFC

Smithsonian
Astrophysical
Observatory

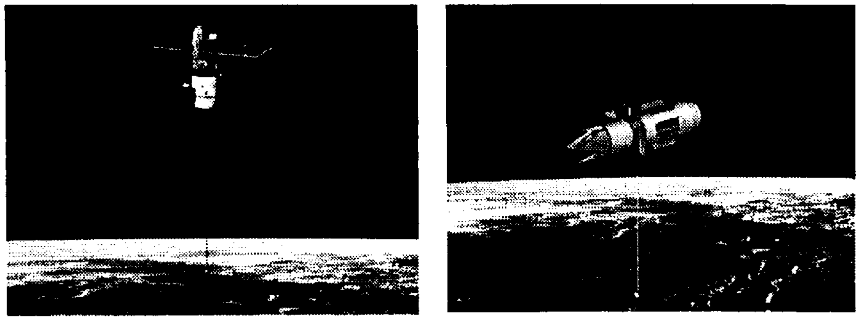
Presentation Overview

- Study Objectives and Guidelines
- Tether Technology Status
- Electrodynamic Tether Reboost Principles
- Recommended System
  - Performance
  - Tether
  - Deployer
  - Dynamics
  - Environmental Effects
- Comparison to Competing Systems
- Recommendations

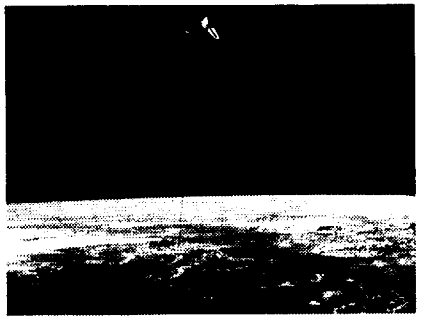
SBL Reboost Assessment Objectives

- Assess the applicability and feasibility of using electrodynamic tether propulsion for altitude maintenance of the Demonstrator Vehicle and/or the Operational SBL System
- If deemed both applicable and feasible, develop a concept appropriate for maintaining Demonstrator Vehicle altitude for 3 years
- Compare performance of the tether reboost system with the current reboost approach and quantify differences
  - Support requirements on-orbit (weight, power, volume)
  - Risk (technical and programmatic)

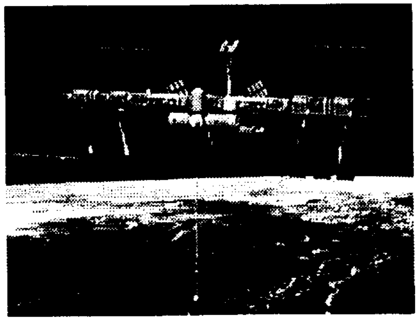
Tether Technology Supports Multiple Space Missions and Applications



Advanced Space Propulsion



Science



International Space Station

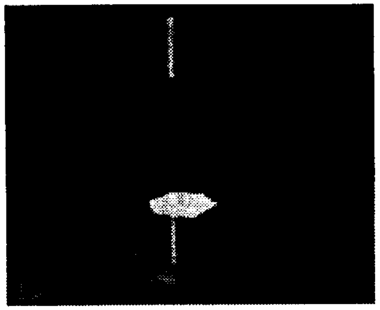
16 Tether Missions Have Flown Since 1967

NAME	DATE	ORBIT	LENGTH	COMMENTS
Gemini 11	1967	LEO	30 m	spin stable 0.15 rpm
Gemini 12	1967	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	?	magnetic field aligned
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 & 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 science and power
TiPS	1996	LEO	4 km	long life tether on-orbit (approaching 2 yrs)

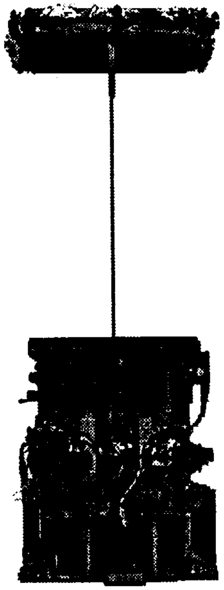
Significant activity since 1992

Current & Planned Tether Missions

- Tether Physics & Survivability Experiment
  - NRL mission using NASA-developed SEDS deployer
  - On orbit since June 1996

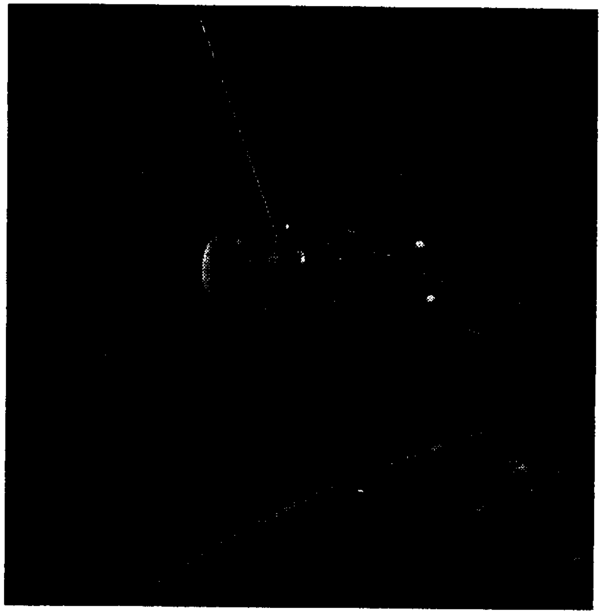


- Advanced Safety Tether Operations and Reliability (ASTOR) Experiment
  - Orbiter ejected payload to test new tether safety system
  - Planned for flight in 2001
  - Funded by SBIR Program (MSFC)



- Advanced Tether Experiment (ATEX)
  - Classified NRL mission to be launched in fall 1998

ProSEDS Experiment Is Precursor to Electrodynamic Tether Propulsion Applications



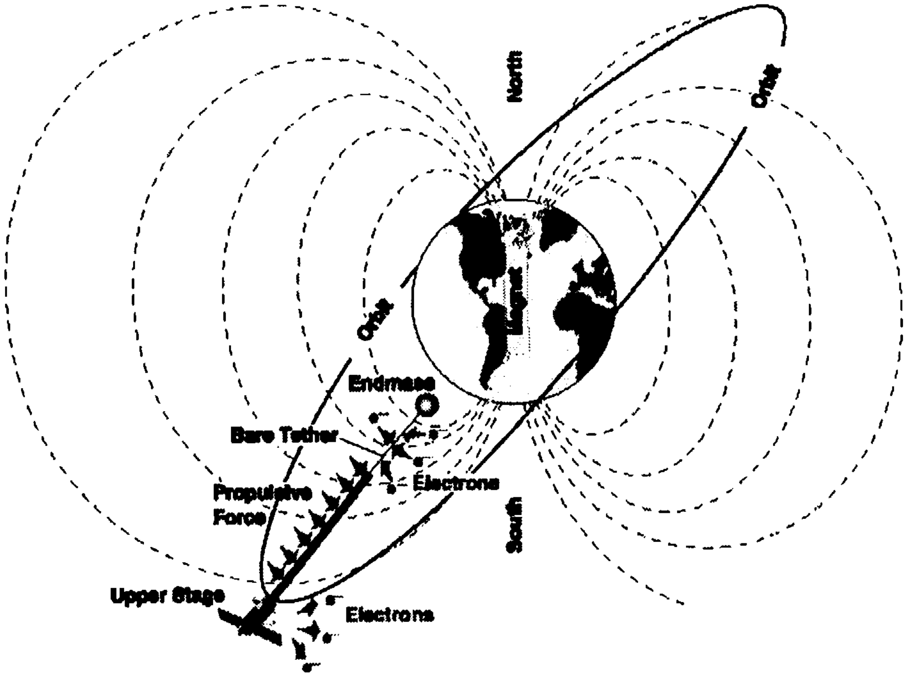
Artist Concept Of ProSEDS

- Objective
  - Demonstrate the use of a 'bare' electrodynamic tether for propulsion in low earth orbit

- Scope
  - Secondary payload on Delta II rocket
- Status
  - Proposed for flight in 2000
    - $6.0M experiment cost*
    - $1M FY98 funding from Advanced Space Transportation Program
    - FY99 funding contingent upon winning upcoming NASA Research Announcement
  - Deployer 80% complete
  - Tether development and testing underway

*excluding integration costs

Electrodynamic Tether Thrust Principles

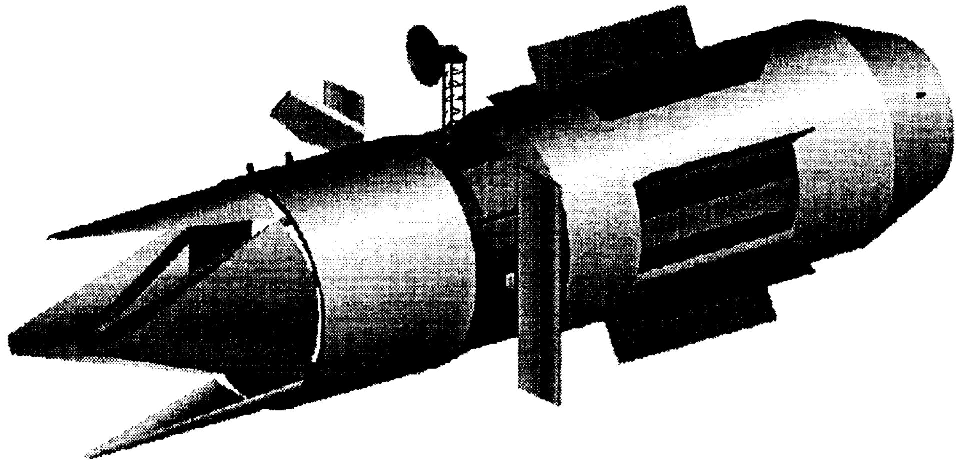


- Only propulsion method to use both solar energy and no conventional propellant
- Power applied at spacecraft to force a positive tether potential and current down the tether
- Return current is through the surrounding plasma
- Downward current **I** produces a thrust force **F** in the reboost direction along the orbit
  - Magnetic force **F** from current **I** through insulated tether of length ℓ. $\mathbf{F} = \ell \mathbf{I} \times \mathbf{B}_{North}$

The Tethered Satellite System Mission (TSS-1R) Produced Electrodynamic (Drag) Thrust

- Space Shuttle Orbiter based demonstration of electrodynamic tethers
- Prior to the break, TSS system generated ~3.5 kW power
- Electrodynamic drag on TSS tether/ Orbiter system calculated to be ~0.4N
- New technology approach to current collection could significantly reduce system weight, cost and complexity

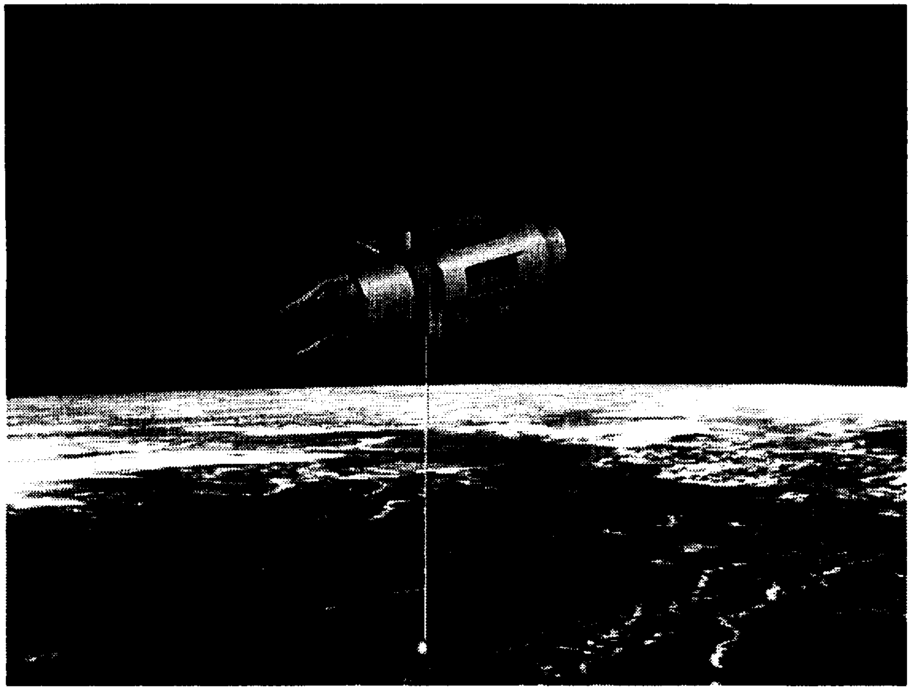
SBL Guidelines For Tether Reboost Study



Artist Concept of the Space Based Laser Demonstrator Vehicle

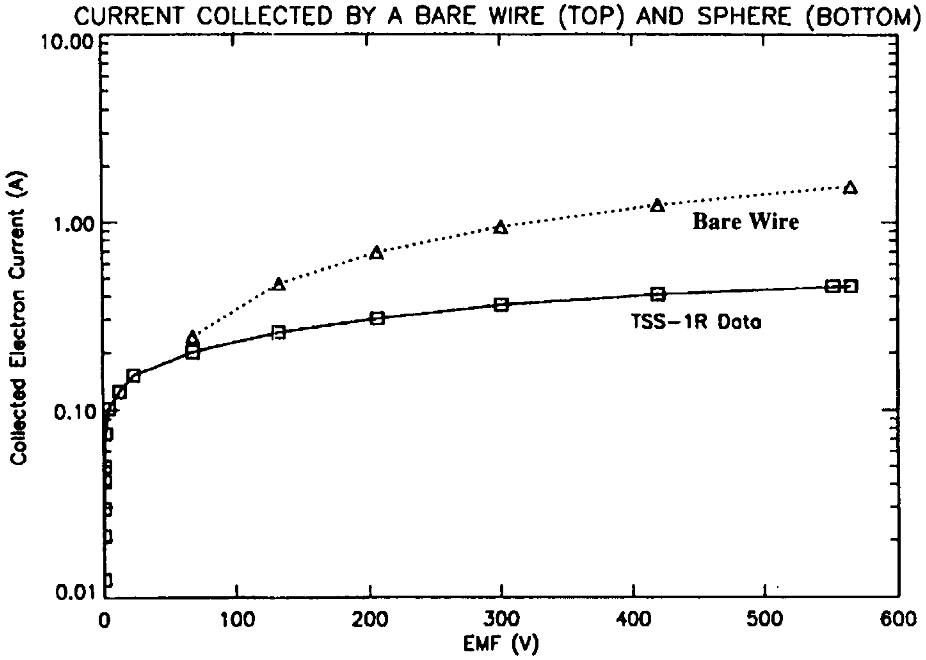
- Demonstrator
  - 4.5 x 20 meters
  - 18,200 kg (~40,000 lb.)
  - 400 km circular orbit, 28.5°
  - 3 year life (desired)
- Operational System
  - 9 x 32 meters
  - 36,400 kg (~80,000 lb.)
  - 1300 km circular orbit, 40°
  - 16 year life (desired)

SBL Tether Reboost Concept Overview



- 2-km aluminum tape tether deployed downward
  - 0.6 mm x 5 mm
- 150 W tether input power
  - 300 W from SBL power system
- Small Expendable Deployer (SEDS) derived system to be used in the endmass
- >450 kg fuel savings possible over three years

New ‘Bare’ Tether Technology

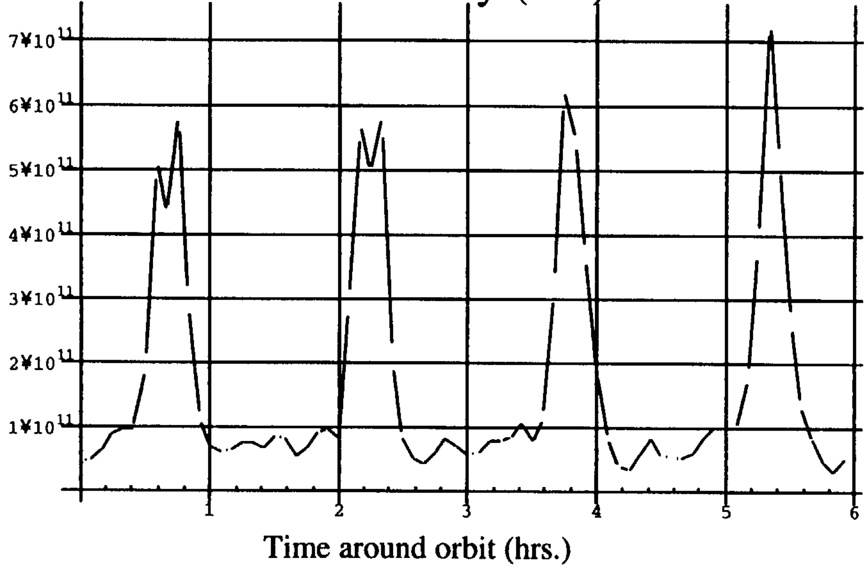


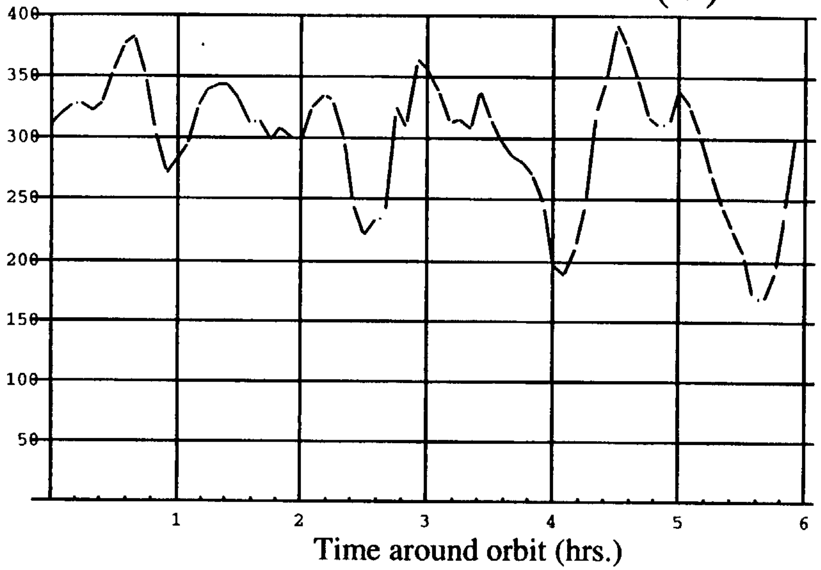
Plasma density of 8.1 x $10^{11}/m^3$
0.7 mm diameter (tether)
~4 km tether length
0.8 m sphere radius

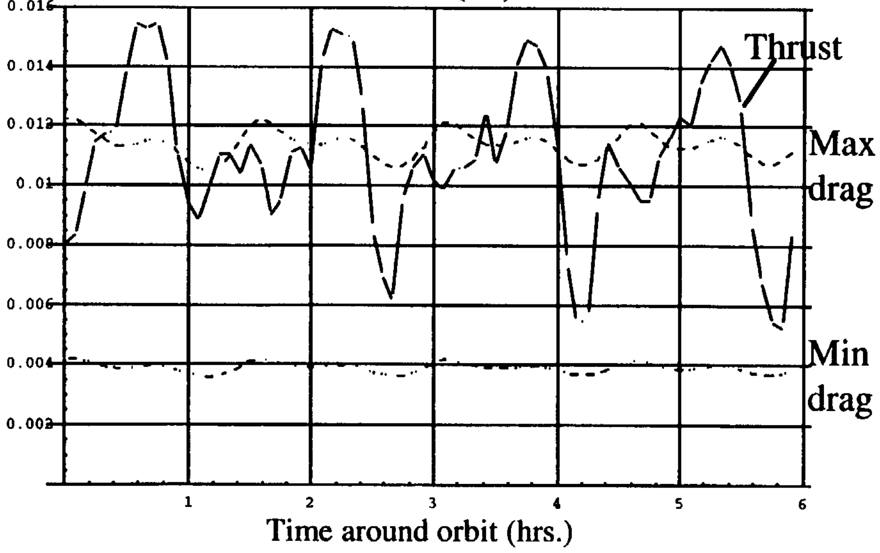
- Long, small diameter wire collects electrons much more effectively than large sphere of equal area (as was used on TSS)
- Collecting area of bare wire is self-adjusting; tends to maintain fairly constant current collection over a wide range of densities
- MSFC tests validate model predictions
- Recommended approach

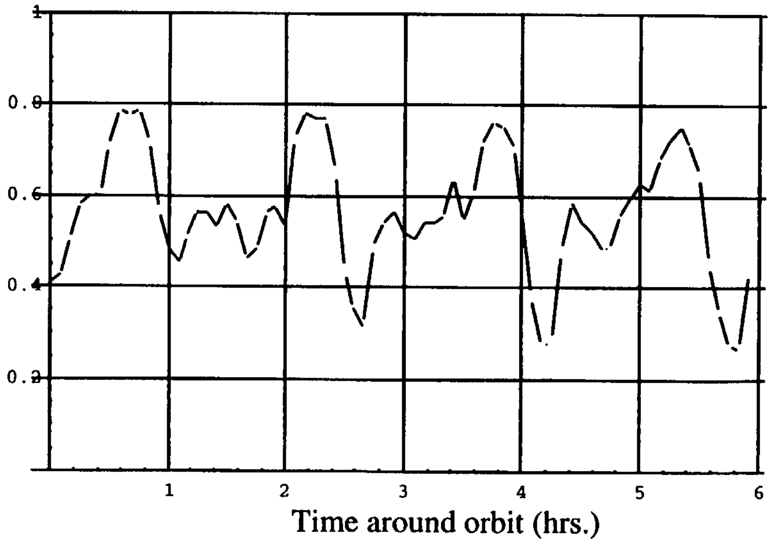
Marshall Space Flight Center

150 W, 2 km (.6mm X 5mm) Tether System


Plasma Density (m^{-3})


End-to-end motional emf (V)

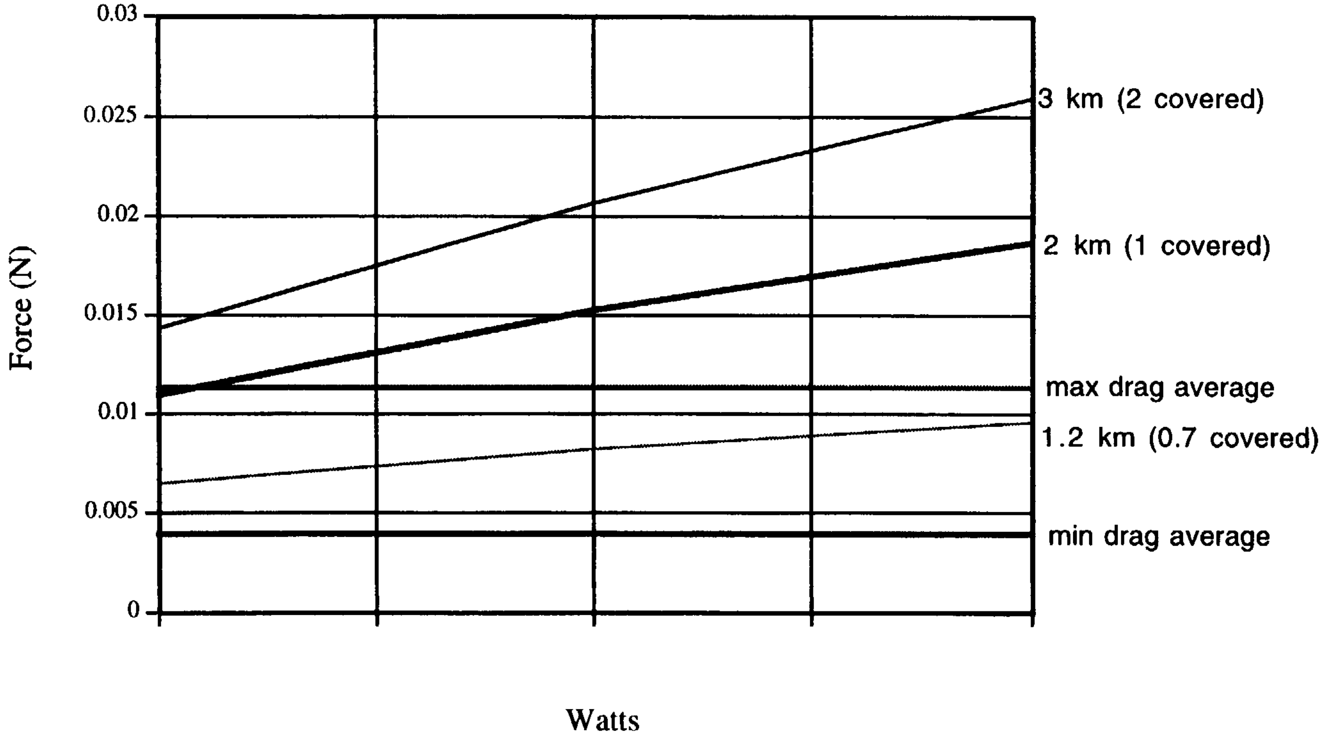

Thrust (N)


Thruster Efficiency

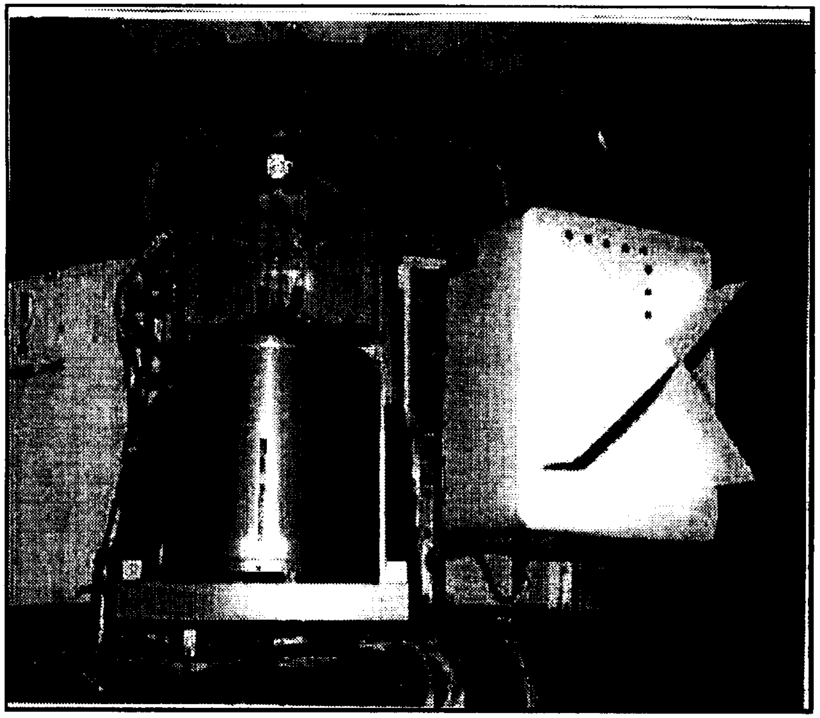
Reboost Performance Sensitivity

All tethers 0.6 mm X 5.0 mm. Ionosphere for year 2005 assumed.

Average Thrust as a function of input power for three tethered systems



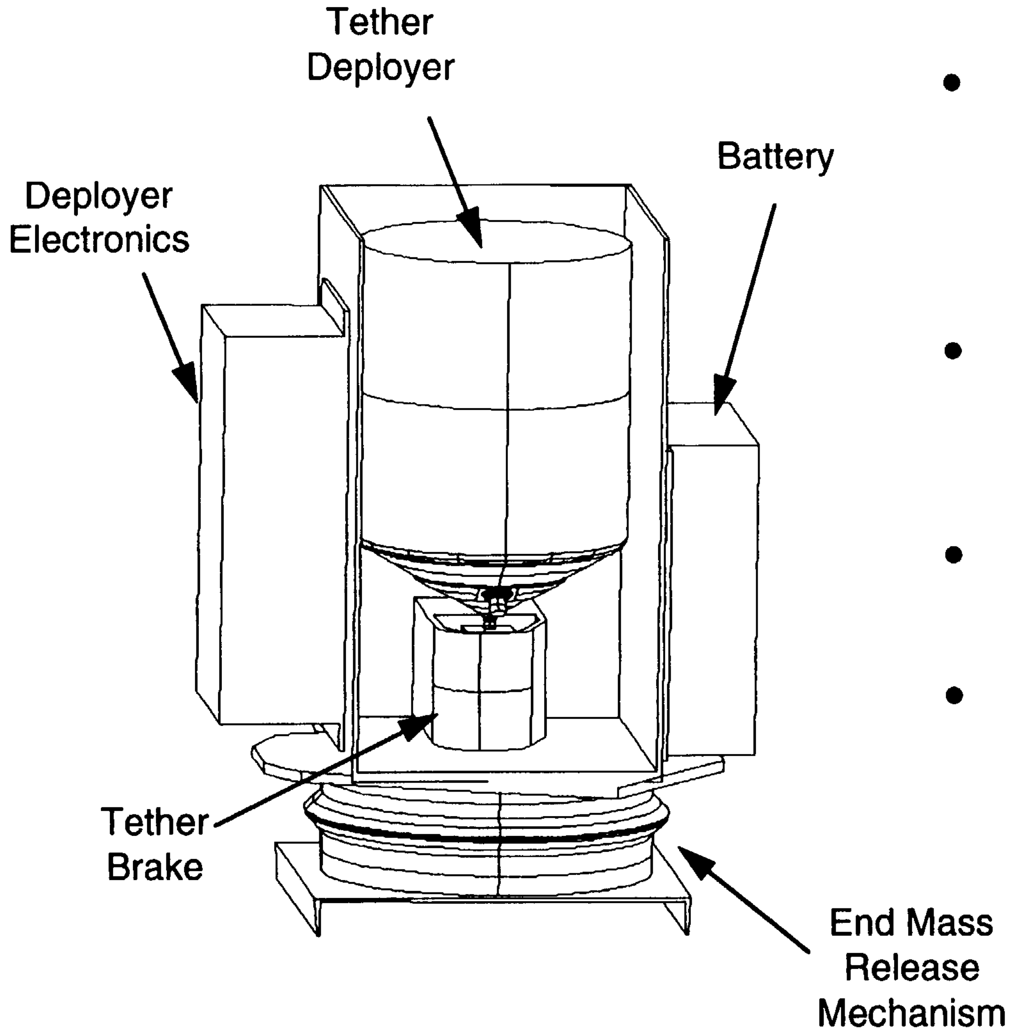
Propose to Build Upon the Successful Small Expendable Deployer System (SEDS)



Small Expendable Deployer System as flown on Delta II

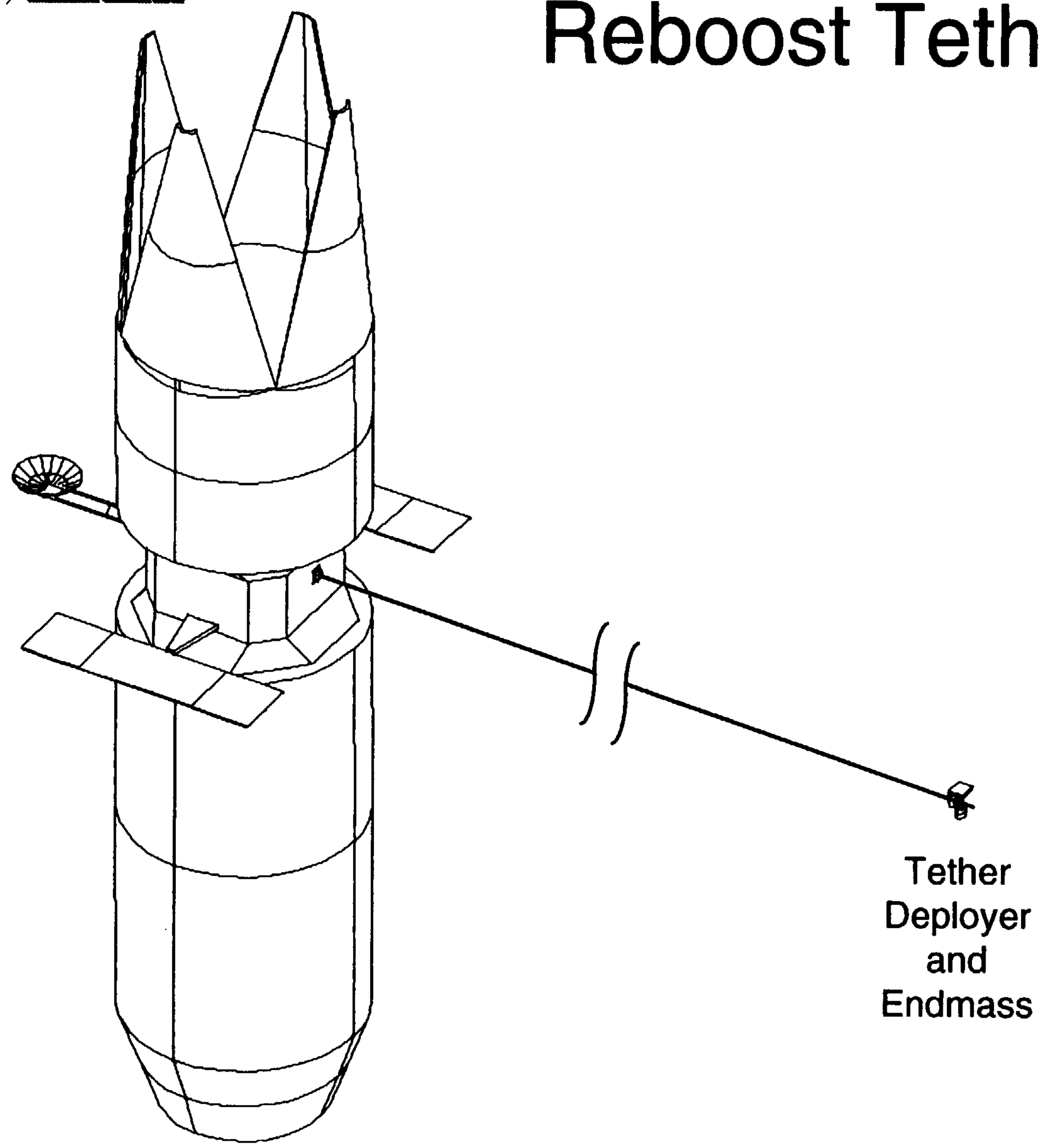
- Deployer has flown successfully four times
- Deployment initiated by spring ejection
- Mini-SEDS being developed for payload return applications
  - Smaller than the 2’ x 2’ SEDS
  - SEDS missions (incl. deployer, tether & endmass) weighed < 175 lb.

Expendable Self Deployer



- Deployer is on endmass and 'deploys itself'
    - Allows insulated portion of tether near the spacecraft
- Should accommodate both baseline and Hoytether configurations
- Deployment initiated by spring ejection
- Derivative of proven Small Expendable Deployer System (SEDS)

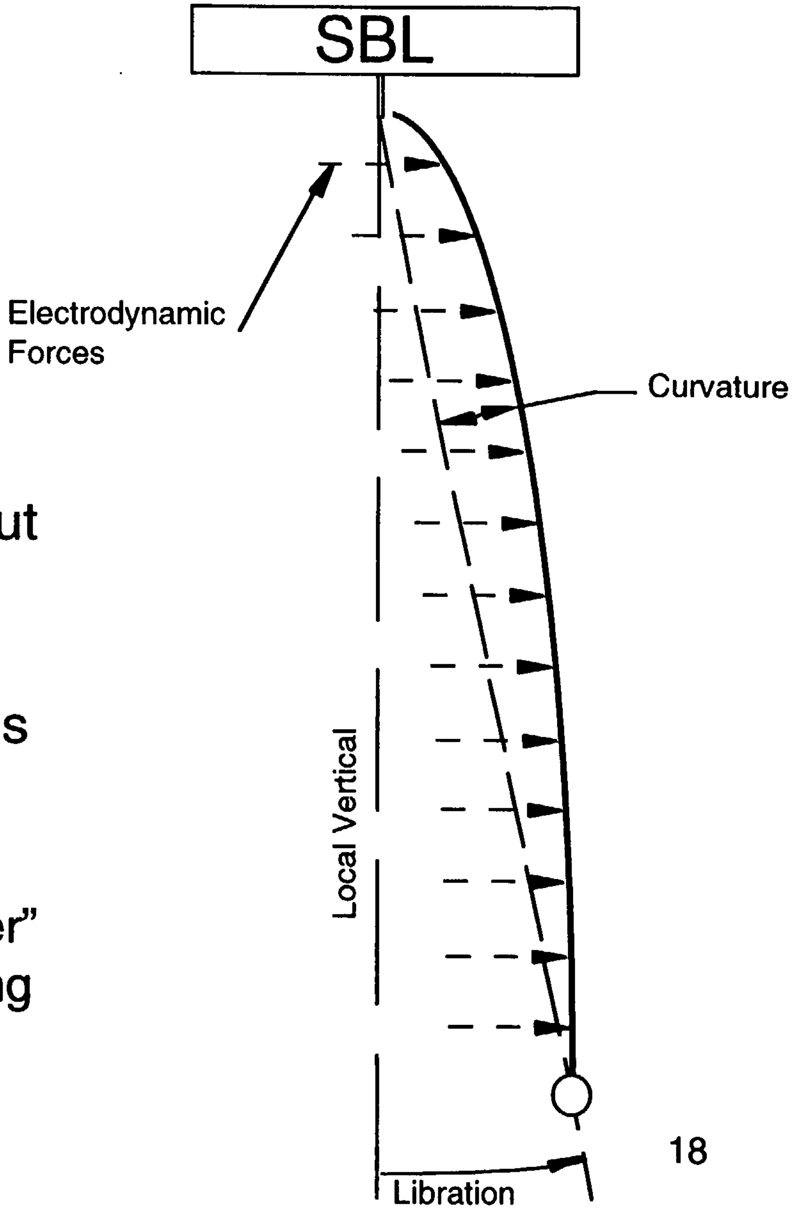
Reboost Tether Deployment



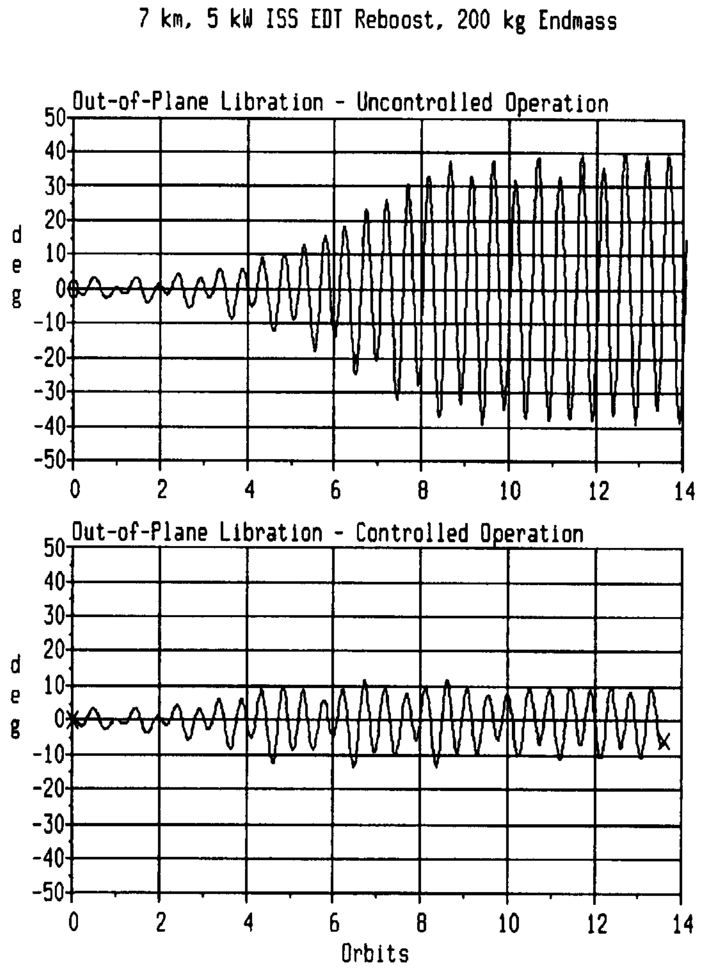
- Deployer is located near the Center of Mass
- Tether deploys toward the Earth

Reboost Dynamics

- Electrodynamic forces acting upon the tether will result in tether "deflections"
  - Libration and curvature
  - Some deflection is required to transmit propulsive force to SBL
  - The deflections occur both in and out of (perpendicular to) the orbit plane
  - The tether tension (proportional to tether length and endmass) provides the restoring force to oppose the electrodynamic force
    - Keeps the system from rotating "over" (excessive libration) and from "folding up" (excessive curvature)



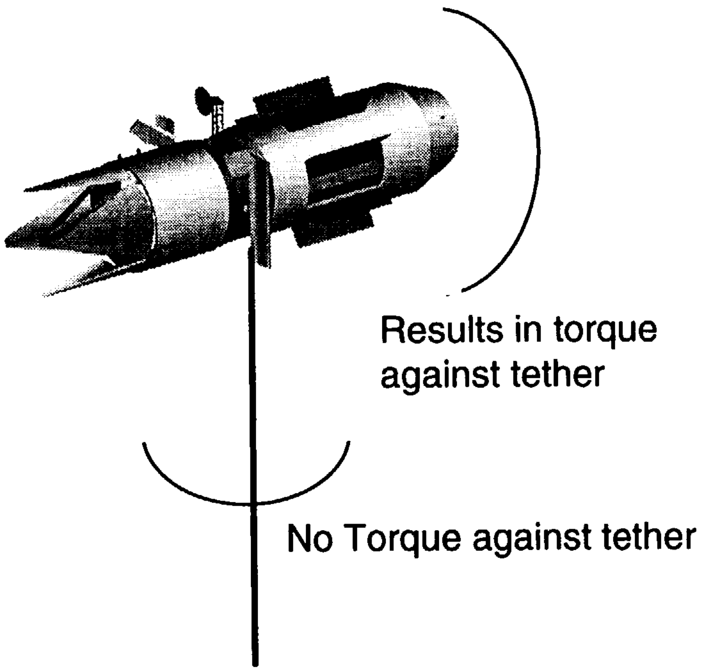
Tether Dynamics Drive Need For Active Feedback Control System



- ‘Libration Limiting’ control system required to maintain tether libration angles less than 10°
  - SBL will operate at much lower power, thus simplifying the active control requirement.
- Deployer provides endmas
  - Provides reasonable time constant (for amplitude growth)
  - Limits tether curvature

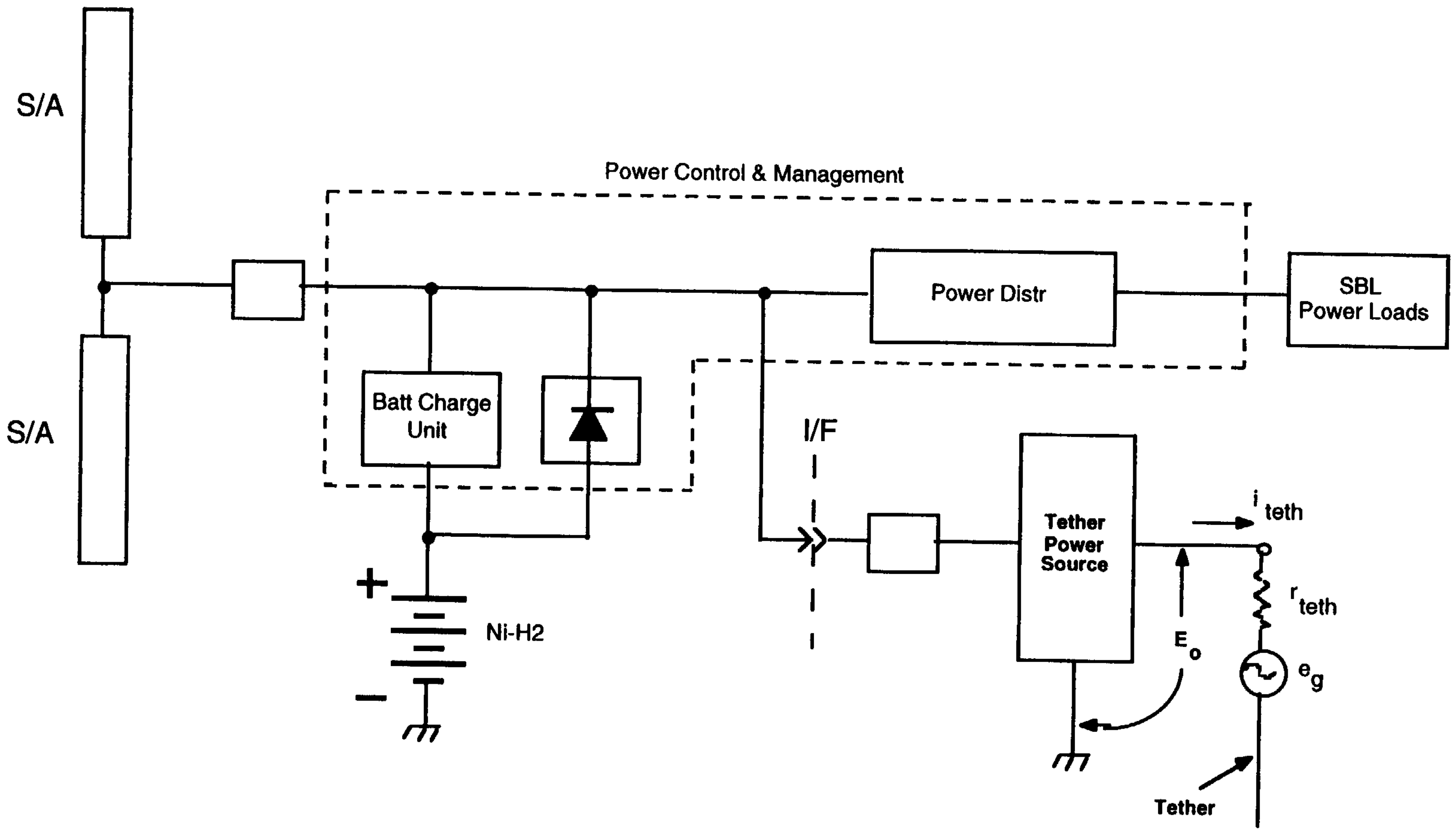
Example libration for a multiple kilometer tether on the ISS.

Impact of Tether on Slewing Dynamics

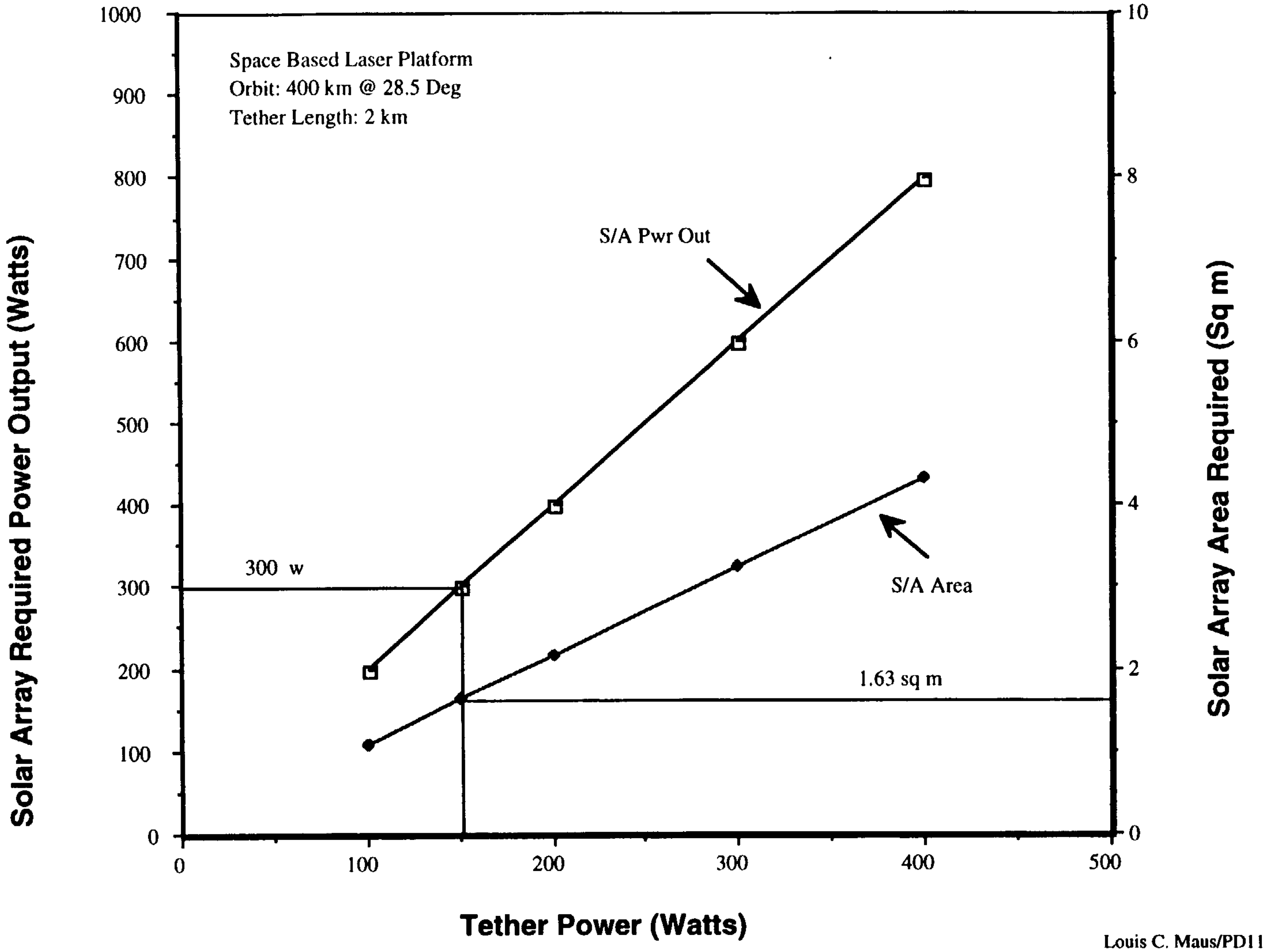


- Gravity gradient torques from tether tends to align system CM with tether line
- Spacecraft slews about this line do not generate any torque; slews orthogonal to this line result in a torque against the tether
- The torques are relatively small for the tether design proposed, i.e., a maximum value of 0.005 Nm/deg
- As an example, torqueing 45° about an axis perpendicular to the tether for 1 hr would require only 0.16 kg of propellant

SBL Tether System EPS Block Diagram



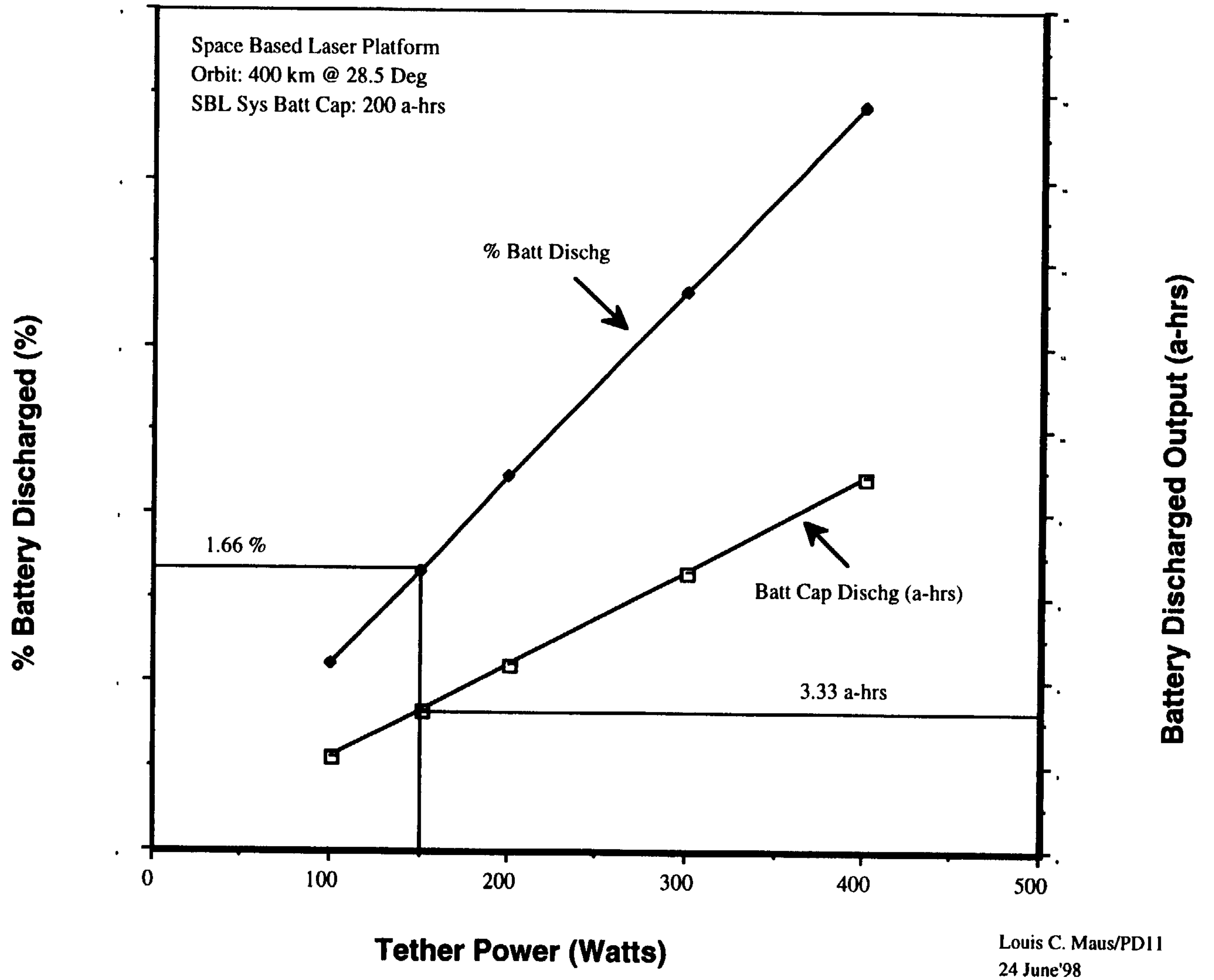
Solar Array Power Versus Tether Power



Louis C. Maus/PD11
24 June'98

Existing solar array can provide sufficient power during non-test periods

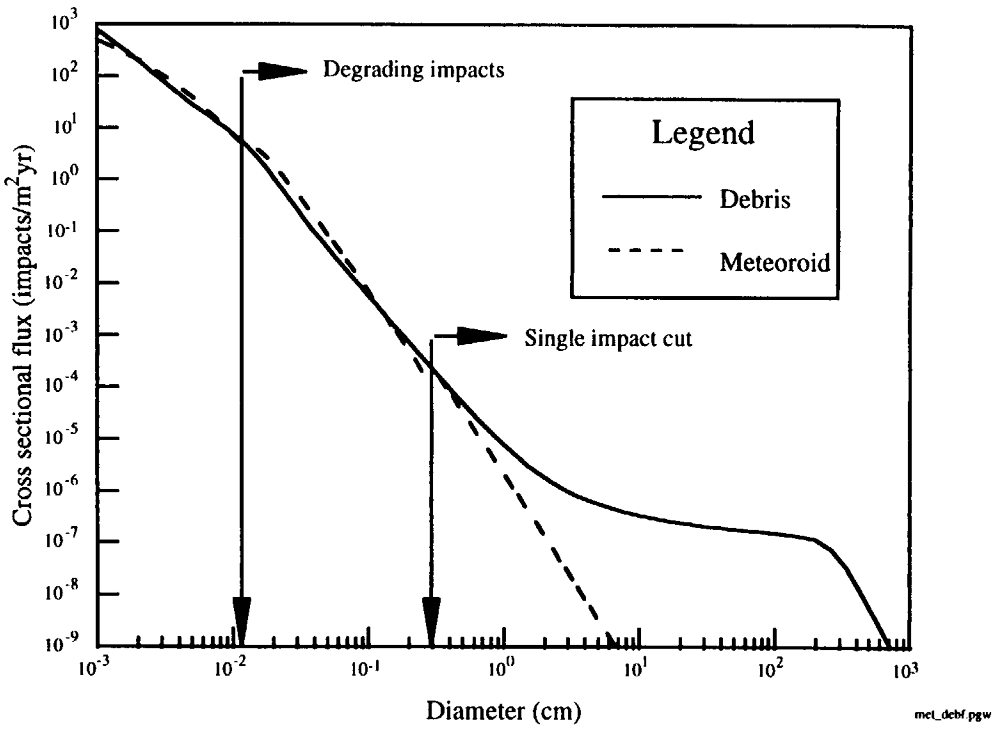
Battery Usage Versus Tether Power



Debris Threat to the Tether

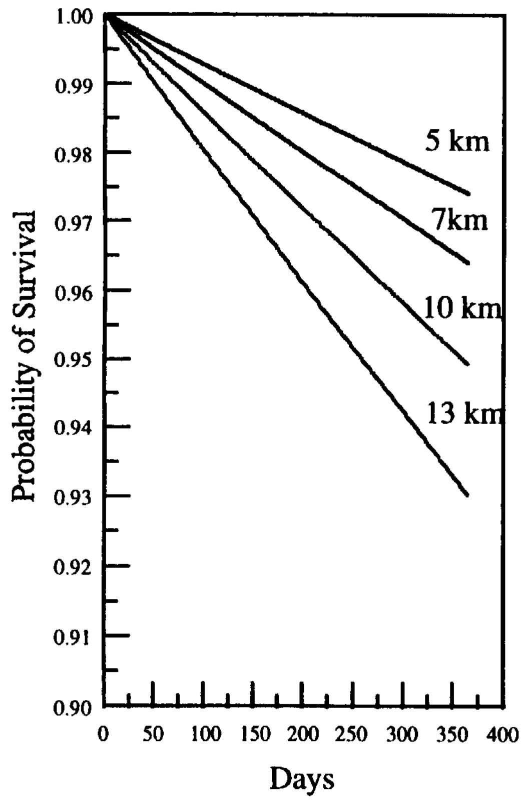
- Degrading impactor diameters are 0.12 mm (1/5 tether thickness)
- Single cutting impactor diameter is 3 mm (1/3 tether width)
- Various techniques are available to mitigate risk to tether

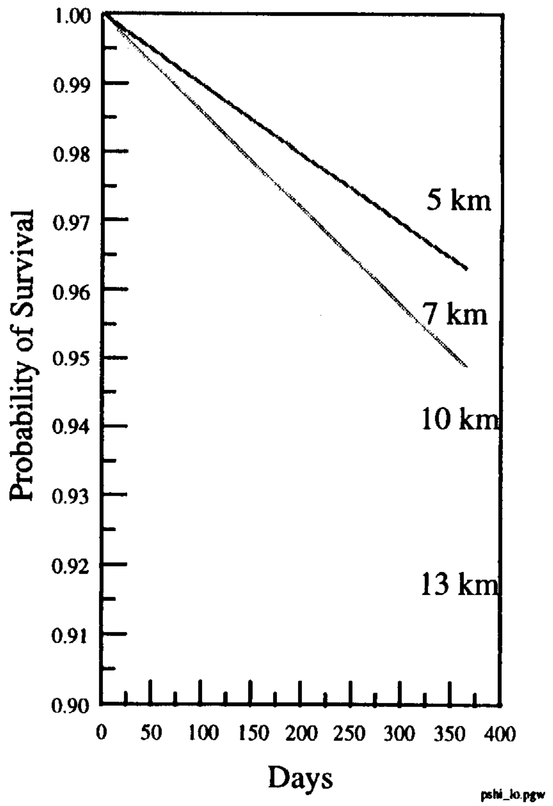
Comparison of Meteoroid and Orbital Debris Flux: 400 km, 51.6 deg, 2005



Meteoroids and Orbital Debris Contribute to Risk

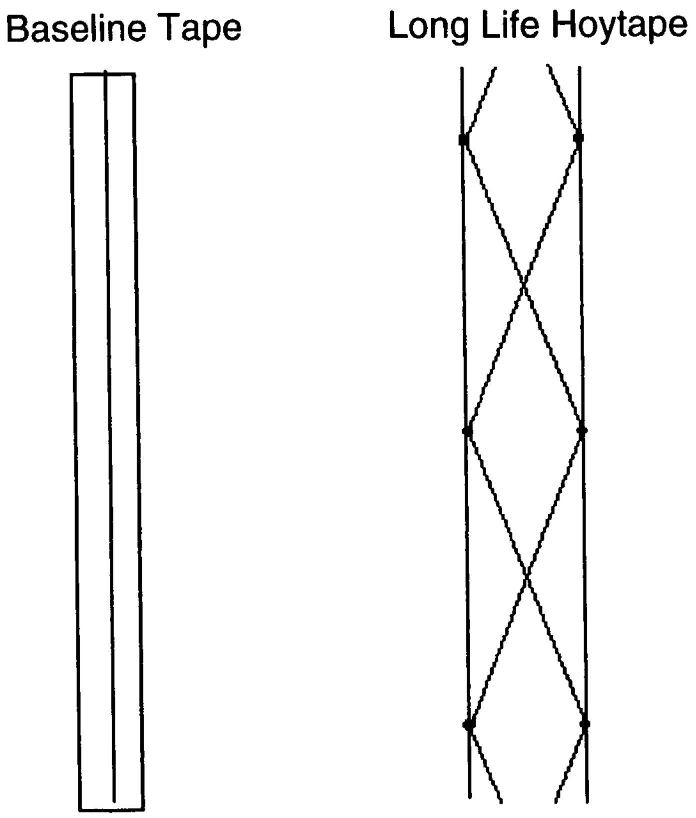
Single-Line Tether Probability of Survival for a Single Cutting Impact


350 km Altitude Environment


460 km Altitude Environment

- Single line tethers have non-trivial probability of being severed when operated for long periods (up to 3 years)
- Baseline 2 km tether has estimated survivability probability of >0.98 for one year of operation
- An alternative tether is being developed which has a dramatically longer lifetime

Long Life Tethers: The Hoytape



~ 2 mm

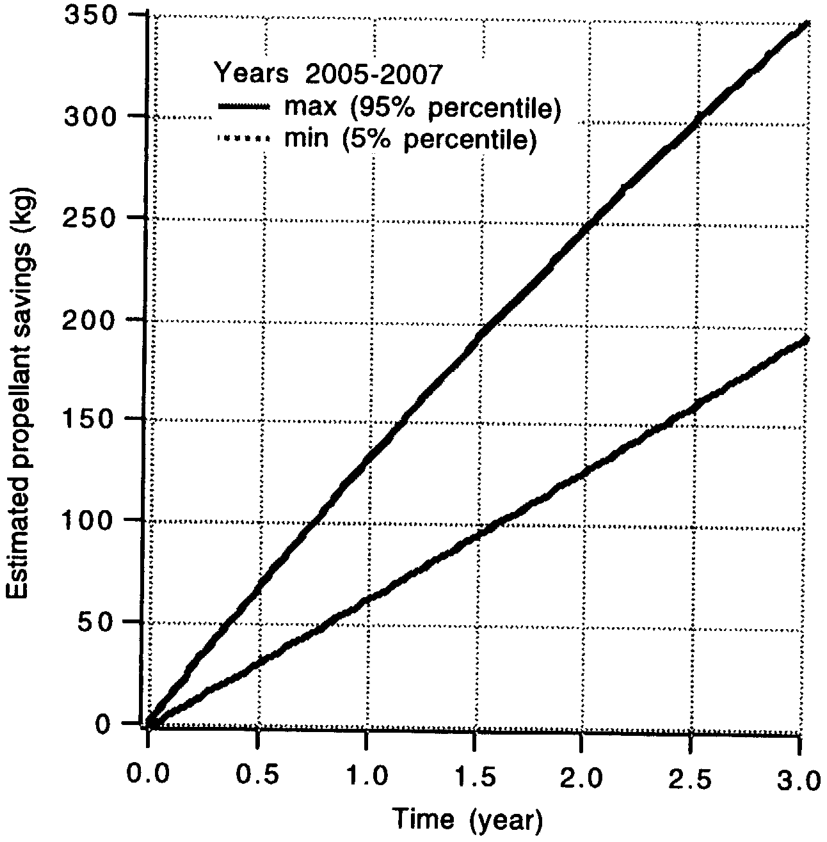
Aluminum tape with
Spectra strength members

4 x 0.54 mm

Aluminum wires
separated by >1 cm

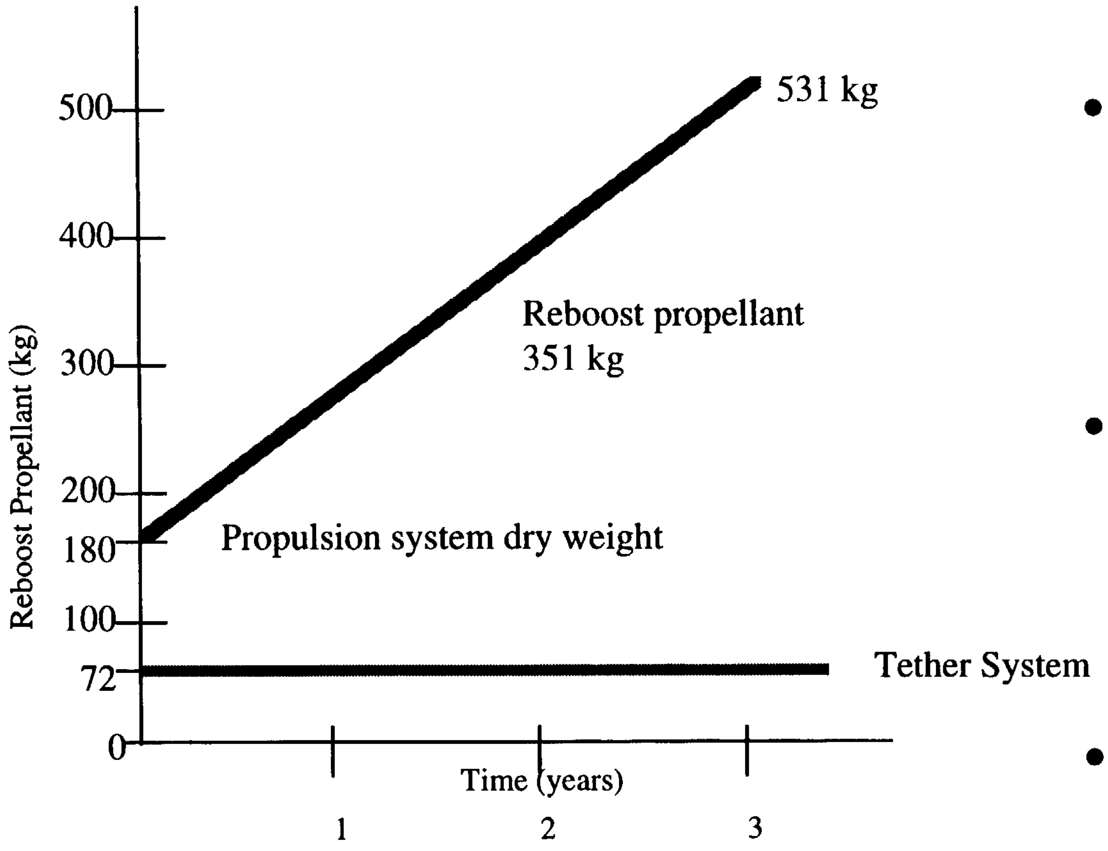
- A Hoytape tether is made from much smaller individual tether strands widely separated from one another to increase the overall tether's likelihood of surviving a given impact.
  - During such an impact, one strand might break but several would remain to pick up the load
- Hoytapes are being developed under Phase 2 SBIR
- ProSEDS is developing a Hoytether as an alternative to the baseline tether
  - If no development problems are encountered, the multiline tether will fly instead of the baseline

Electrodynamic Tether Reboost Performance



- Preliminary analysis indicates that the SBL Demonstrator can maintain its 400 km circular altitude (28.5° inclination) with a 2-km (0.6 mm x 5 mm), 150 W electrodynamic tether reboost system
  - No reboost propellant would be required during the lifetime of the experiment
- If system were designed for ED tether use, total weight would come down (no propellant need be carried) and improve reboost performance or allow a shorter, lower-power reboost system

Tether Reboost Provides Substantial Benefit to SBL Demonstrator



- Estimated propellant weight
  - 1223 kg total
  - 67-117 kg/year for reboost

- Baseline Propulsion System
  - Mono-propellant hydrazine used for Δ Velocity and attitude control system functions
- Tether Reboost System
  - ~390 Kg propellant saved over 3 years
  - Or significant increase in on-orbit life
- 16-year life of operational system would realize even bigger savings

Benefits of ED Tether Reboost

- PRIMARY
  - Lower spacecraft weight (elimination or significant reduction of traditional propulsion system and propellant)
  - Extended lifetime (no propellant is expended; solar arrays and tether can last for many years)
- SECONDARY
  - Ability to change orbit slightly *per orbit* to ‘confound’ orbit predicts (if desired)
  - Electrodynamic tether gives a large spread on RADAR signature
- POTENTIAL
  - Modification of baseline orbit to improve system performance (allows long-life system operation at lower altitudes without a propulsion system weight penalty)

Conclusions and Recommendations

- Electrodynamic tether reboost appears to provide significant savings and/or performance enhancement to SBL demonstrator vehicle
- Recommend more detailed analysis of approach
  - Detailed system trades and impacts assessment
  - Cost/Benefit analysis
  - Development of alternative architecture(s) using tether reboost
- Need Program contacts to obtain additional data and to review the concept
  - SBLRD Estimates
    - Propellant reboost and reserves
    - Number of reboost maneuvers in mission lifetime

Recommendations, continued

- Propose assessment of tether reboost on operational system
  - System performance estimates
  - Comparison to baseline reboost approach
  - Cost/Benefit assessment
- Recommend consideration of tether reboost by CDS contractors

Appendix B

Status of ProSEDS tether development and testing as of April 1998

Tether Development Status

presented by

Enrico Lorenzini

ProSEDS Team Design Review
29-30 April 1998

ProSEDS Tether

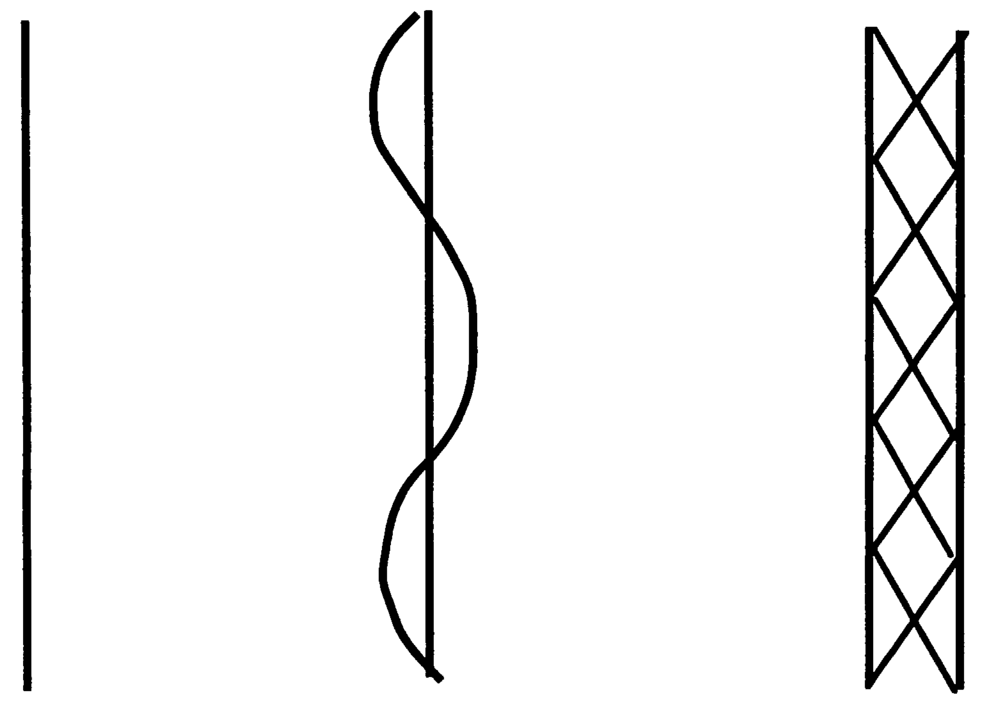
- Tether length
  5-km conductive + 10-km non-conductive
- Present tether requirements
  - Physical -> mass < 15 kg
    available spool volume = 10160 cc
  - Mechanical -> max static load = 4 N with sf ≥ 5 at $T = T_{max}$
    max impulsive load = ?? N during deployment
  - Thermal -> temperature < 100 °C
  - Electrical -> wire resistance < 400 ohm at $T = T_{max}$
    surface resistance << wire resistance
  - Survivability -> survive 1-day exposure to AO;
    survive M/OD impacts with > 90% probability
  - Deployability -> match deployability req's of SEDS
  - Other -> smooth splicing, low level of sizing agents

ProSEDS vs TSS tether

	TSS-1R tether	ProSEDS tether
Mass	**167 kg**	**< 15 kg**
Max. tether current	**0.5 Amp**	**> 2.5 Amp**
Electric resistance	**1700 ohm**	**< 400 ohm**
Max joule heating	**425 W**	**> 2500 W**
Mission duration	**2 days**	**1 days**
Max load	**45 N**	**4 N static** **?? N impulsive**
Spool volume	**150,400 cc**	**10,160 cc**
Tether e^- collection & bombardment	**no**	**yes**

Non-conductive Tether Configurations

Baseline



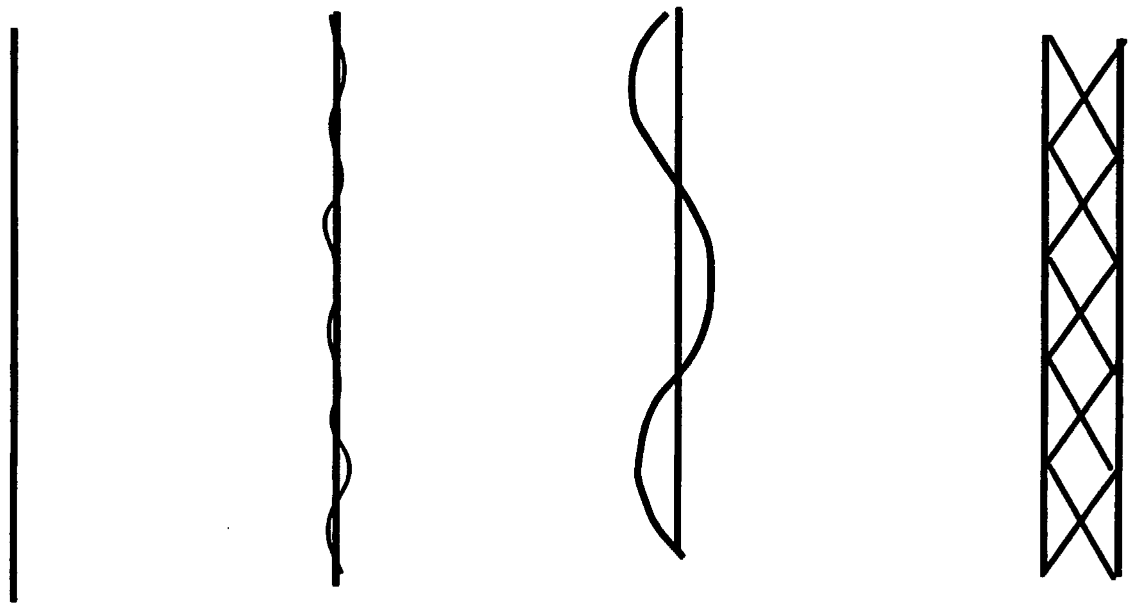
Single line
(multi-strand)

Caduceus

Hoyt tether

Conductive Wires

Baseline



Single line
multi-strand
conductor

Single line
core mostly
covered by
wrapped
conductor

Two-line
caduceus;
two cores with
wrapped
conductors

Multi-line
Hoytether

Conductive Tether Candidates

- Conductive candidates
  1. Single-line multistrand aluminum
  2. Single-line multistrand copper

  → 3. Single-line kevlar core with wrapped aluminum*
  4. Single-line kevlar core with wrapped copper*
  5. Caduceus kevlar/aluminum
  6. Caduceus kevlar/copper
  7. Aluminum Hoytether + PTFE
  8. Aluminum core with wrapped TOR

→ presently selected tether candidate

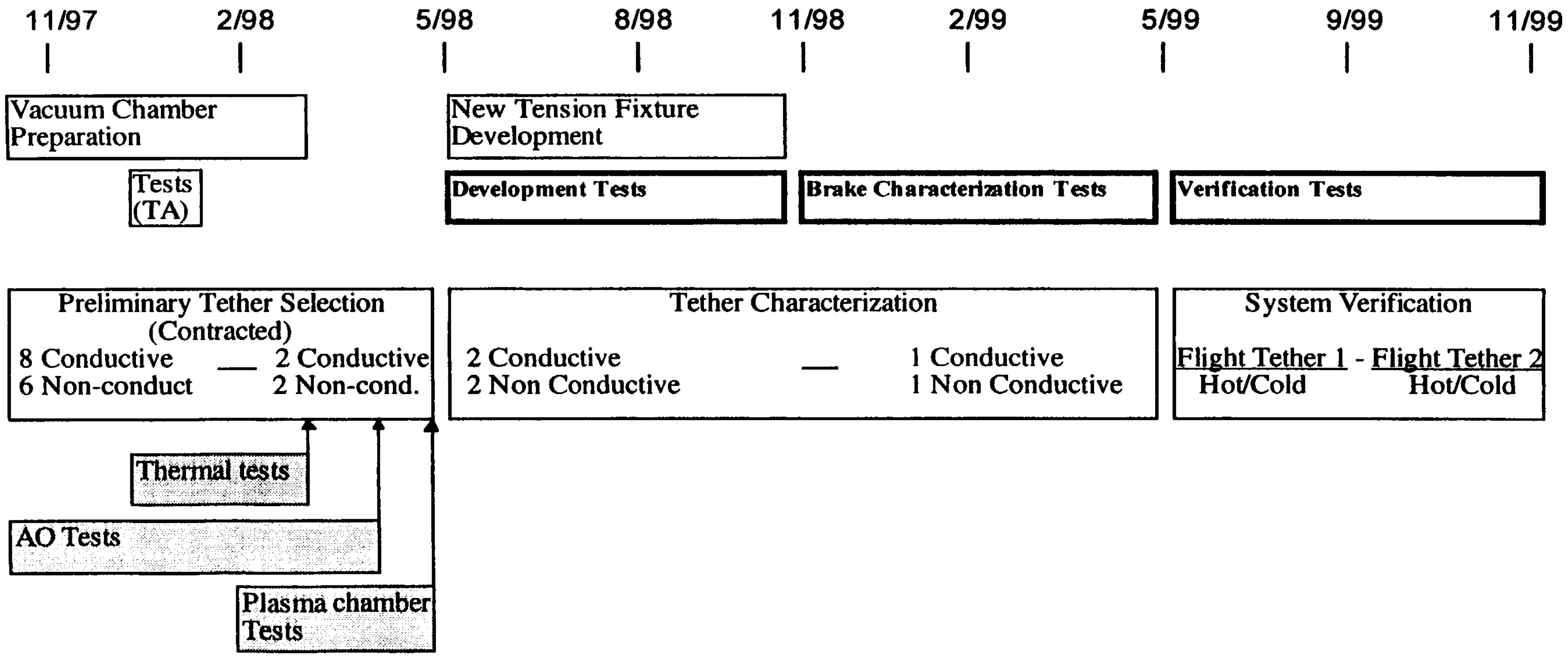
* coated with C-COR

Non-conductive tether candidates

- Non-conductive tether candidates
  → 1. Single-line multistrand Spectra*
  2. Spectra Hoytether**
  3. PTFE Hoytether
  4. Spectra/Kevlar Caduceus
  5. Oriented PTFE Caduceus
  6. TOR/Spectra Caduceus

→ presently selected tether candidate
* already tested
** prototype sample available

Present Tests Schedule



Thermal tests

- **Items tested**
  1. Aluminum foil, dull/shiny (1856 alloy)
  2. Alodined aluminum foil, dull/shiny (1856 alloy)
  3. Copper foil (99.998% pure)
  4. C-COR coating
  5. Polyaniline coating

- Ratios α/ε too high for items 1-3 which imply max temperatures well above 250 °C that result in
  too high electrical resistance and low mechanical strength
- Good α/ε ratio (0.8/0.9) for item 4 which results in
  maximum wire temperature < 100 °C
- Adequate α/ε ratio for item 5; tether equilibrium temperature under evaluation

AO tests (MSFC EH Lab)

- **Materials and coatings tested for AO**
  - TOR/Kevlar braid
  - Spectra-1000
  - Kevlar-29
  - Kapton
  - Oriented PTFE
  - C-COR (coating)
  - Polyaniline (coating)

- Strong mass losses for mission duration well above 5 days for all materials except TOR/Kevlar and C-COR
- Low mass losses for all samples if duration ≤ 5 days
- Negligible mass losses for mission duration ≤ 1 day

Percent Mass Loss Data for October 97 Test
Scaled for Decay Rates with Initial Orbit 415 km x 375 km

	Percent Mass Loss for Kevlar	Percent Mass Loss for Spectra 1000	Percent Mass Loss for Kevlar/TOR	Percent Mass Loss for Gore PTFE
Test Data (10-7-98) 400x400 km initial orbit 20-day mission, 20 km/day **($2.4x10^{21}$ atoms/cm^2)**	**44%**	**20%**	**5%**	**26%**
10-day mission **20 km/day Decay** **($1.5x10^{21}$ atoms/cm^2)**	**27%**	**12%**	**3%**	**16%**
10-day mission **10 km/day Decay** **($4.2x10^{20}$ atoms/cm^2)**	**8%**	**3%**	**1%**	**5%**
5-day mission **20 km/day Decay** **($2.2x10^{20}$ atoms/cm^2)**	**4%**	**2%**	**0.5%**	**2%**
5-day mission **10 km/day Decay** **($1.3x10^{20}$ atoms/cm^2)**	**2%**	**1%**	**0.3%**	**1%**

Plasma chamber tests (MSFC ES Lab)

- **Items tested**
  - Bare stainless steel
  - 0.5-mil/13%-doped C-COR coated stainless steel
  - 0.2-mil/13%-doped C-COR coated aluminum
  - 0.2-mil/100% dopant (Polyaniline) coated aluminum

  13%-doped C-COR coatings non conductive enough

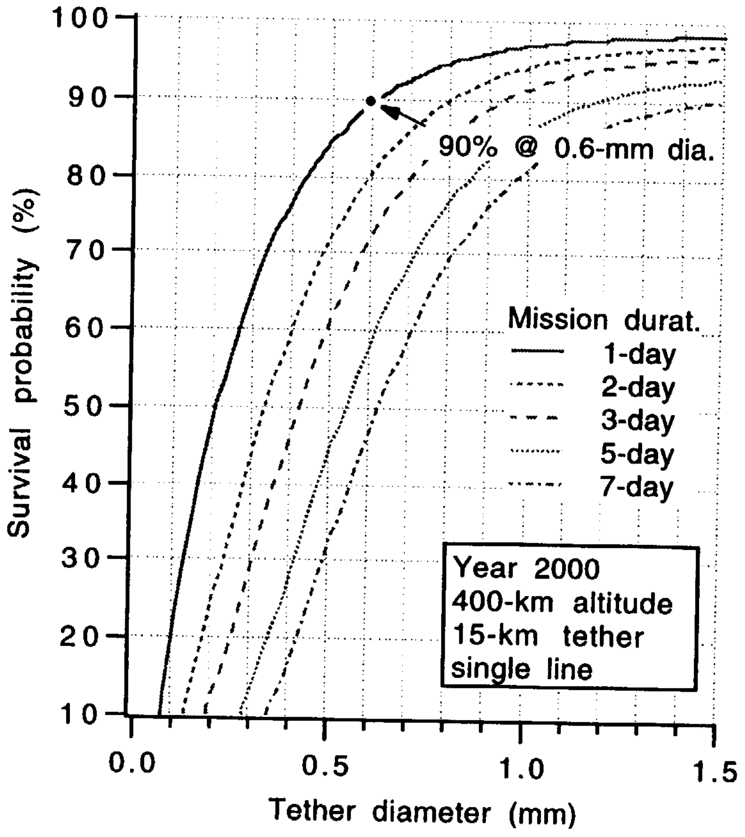
  100% Polyaniline has good surface conductivity and e^- collection
- **Items to be tested**
  - 0.5-mil Polyaniline coated aluminum
  - 50%-doped C-COR coated aluminum
  - 80%-doped C-COR coated aluminum
  - Bare aluminum
  - Bare copper*

* Only if tether mass allowed to increase above 15 kg

Micrometeoroid and orbital debris risk

- survival probability > 90% for single-line tethers with diameter > 0.6 mm and a 1-day mission duration

- fail safe tethers would strongly increase the survival probability but require 1.5-2 times the volume of single-line tethers for equal mechanical strength



Baseline Tether Configuration

- *Single-line tether*

  Conductive portion (5 km)
  Conductor: 7X28 AWG Al wires wrapped around core
  Core: 0.6-mm-dia (3000 denier) Kevlar-29 or PBO
  Mass: 8.15 kg (Al wires) + 1.7 kg core = 9.85 kg
  Tether outer diameter ≈ 1.2 mm
  C-COR wire coating or tether partial Teflon overwrap

  Non-conductive portion (10-km ballast tether)
  Configuration: 1.2-mmX0.15-mm (11X130 denier) flat braid
  Material: Spectra-2000
  Mass ≈ 1.9 kg

Electrical resistance & tether mass

Wire type	Resistance at 90 °C (resistance at 20 °C)	Metal wire mass
7x28 AWG, Aluminum	**340 ohm** **(265 ohm)**	**8.15 kg**
7x28 AWG, Cu equal volume	**215 ohm** **(167 ohm)**	**26.9 kg**
3x28 AWG, Cu max allowed mass	**502 ohm** **(392 ohm)**	**11.5 kg**

- Al preferable to Cu in terms of electrical resistance with present tether requirement mass ≤ 15 kg

- Cu would be preferable if tether mass allowed to be > 15 kg

Mechanical Strength

- Estimated mechanical strengths (preliminary data):
  - Non-conductive portion:
    1.2-mmx0.15-mm Spectra: $F_{break} \approx 450$ N
  - Core of conductive portion:
    0.6-mm-dia Kevlar-29: $F_{break} \approx 320$ N
    0.6-mm-dia PBO: $F_{break} \approx 570$ N

Outstanding Issues

- Fine tuning of C-COR electrical characteristics;
  Wire coating techniques;
  Thermal characteristics of tether with Teflon overwrap

- Deployability of conductive tether:
  friction, flexibility, abrasion, coating integrity

- Design of high-voltage insulation of lower part of tether

Next Actions

- Deployment tests at NASA/MSFC and TA:
  - preliminary tests of bare wires
  - tests of baseline tether configurations

- Evaluation of equilibrium temperature for the latest tether resistance and thermal characteristics

- Thermal and plasma chamber tests:
  - C-COR coatings with high-dopant content
  - Wire with Teflon overwrap

Concluding Remarks

- The shortening of the mission duration to 1 day has relaxed substantially several tether requirements
- Much more likely to meet the requirements with a tether that fits strict volume and mass constraints of ProSEDS
- Deployability issues of the conductive aluminum wire are still open but deployment tests will start shortly