The Propulsive Small Expendable Deployer System (ProSEDS)

NASA Grant NAG8-1605

Annual Report #4

For the period 1 August 2002 through 31 July 2003

Principal Investigator

Enrico C. Lorenzini

August 2003

Prepared for

National Aeronautics and Space Administration

Marshall Space Flight Center, Alabama 35812

Smithsonian Institution

Astrophysical Observatory

Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The Propulsive Small Expendable Deployer System (ProSEDS)

NASA Grant NAG8-1605

Annual Report #4

For the period 1 August 2002 through 31 July 2003

Principal Investigator

Enrico C. Lorenzini

Co-Investigators

Mario L. Cosmo

August 2003

Prepared for

National Aeronautics and Space Administration

Marshall Space Flight Center, Alabama 35812

Smithsonian Institution

Astrophysical Observatory

Cambridge, Massachusetts 02138

TABLE OF CONTENTS

LIST OF FIGURES

SCOPE

This is the Annual Report #4 for Grant NAG8-1605 entitled "The Propulsive Small Expendable Deployer System (ProSEDS)" prepared by the Smithsonian Astrophysical Observatory for NASA Marshall Space Flight Center. This report covers the period from 1 August 2002 through 31 July 2003. The level of activity during this reporting period has been strongly reduced because *the grant has been under a no-cost extension since September 30, 2002*. The technical officer for this grant is Leslie Curtis at NASA MSFC.

SUMMARY

The summary of activity during this reporting period, most of which was covered by a *no-cost extension* of the grant, is as follows:

1) Participation in remote and in-situ (at MSFC EDAC facility) mission operation simulations;

2) Analysis of the decay rate of ProSEDS when starting the mission at a lower altitude;

3) Analysis of the deployment control law performance when deploying at a lower altitude.

1. ProSEDS Mission Brief Overview

We recall in the following a few general information about the Propulsive Small Expendable Deployment System (ProSEDS)for the benefit of the readers.

ProSEDS will carry out a demonstration of a bare electrodynamic tether for propulsion. The system will fly as a secondary payload on a Delta II and it will be deployed from and remain attached to the 2nd stage of the rocket (see Fig. 1). The electrodynamic forces generated by the current flowing in the conductive tether are expected to strongly increase the decay rate of the Delta stage. The reader should consult references[1 2 3 4 5] for a more detailed description of ProSEDS and the principles of operation of bare-tether anodes.

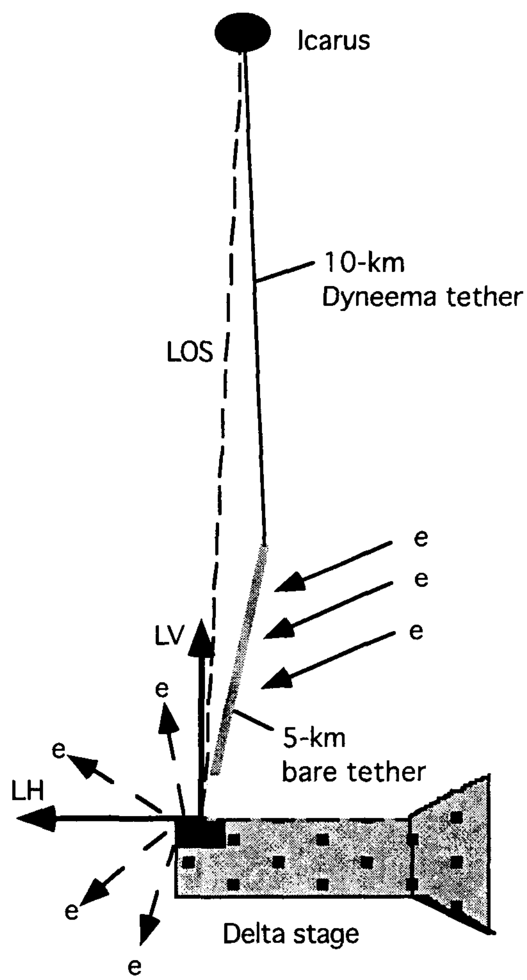

Figure 1 Schematic of ProSEDS on Delta 2nd stage

Electrons are collected along the upper portion of the bare and conductive tether which is positively biased with respect to the surrounding plasma. They are then reemitted into the ionosphere at the Delta stage by an active hollow cathode device. The (electronic) current flowing along the tether from its top to the bottom interacts with the Earth's magnetic field to produce an electrodynamic drag force which decreases the orbit of the Delta stage.

The performance of ProSEDS will be assessed on the basis of the decay rate of the Delta stage which is affected (for a given tether design) by the plasma conditions at mission time and, consequently by the initial altitude. Because of the launch postponement and the need to reduce the orbit altitude from the present 360 km, the orbital decay and the deployment performance of ProSEDS were reevaluated to see whether they meet the mission requirements.

2. Mission Operation Simulations

During this reporting period our team participated in the following mission simulations:

1) Remote simulation (nominal conditions) - January 21, 2003. Summary of activity: downloaded simulated deployment data from server; analyzed turn counter data to reconstruct deployment trajectory; uploaded results and plots to the server.

2) In-situ simulation at EDAC (off-nominal conditions) – February 25-26, 2003. Summary of activity: loaded updated data analysis software onto the computer at EDAC. Phase 1 of sim; downloaded simulated data; spotted the first off-nominal condition (absence of turn counters data); after analysis of GPS-data and discussion with team members working on electrical data, we concluded that the end mass had deployed notwithstanding the malfunctioning of the turn counters; evaluated the tether length from GPS data to be the full tether length. Phase 2 of sim: spotted a divergent increase of the distance between Delta stage and end mass that was correctly attributed to a tether breakage; confirmed results with team members who saw anomalous behavior in the electrical data.

3. Dynamics Analysis for Mission Starting at Lower Altitude

Dynamic Analysis

The results of simulations for ProSEDS starting from a 260-km orbital altitude are shown in the following. Nominal values of the ionosphere and atmospheric densities were assumed as predicted by the IRI95 and MSIS86 models for a launch at 22:00:00 GMT on March 29, 2003. Figure 2 shows the orbital decay of the Delta stage of ProSEDS with ED and atmospheric drag while Figure 3 shows the decay for atmospheric drag only (with the tether fully deployed but not generating current). In summary, the atmospheric drag plays a rather significant role in this altitude region. In fact, the atmospheric drag is comparable to the ED drag (see Figure 4). The instantaneous value of the ED drag can exceed the value of the atmospheric drag but its orbital average is mostly lower than the atmospheric drag with the exception of a brief period of time (see Figure 5).

Finally, Figures 6 and 7 show the neutral density of the atmosphere and the atomic oxygen (AO) vs. time during ProSEDS decay when both ED and atmospheric drag are present. One issue that needs to be evaluated is the time needed for the AO to erode the Dyneema tether during this orbital decay profile.

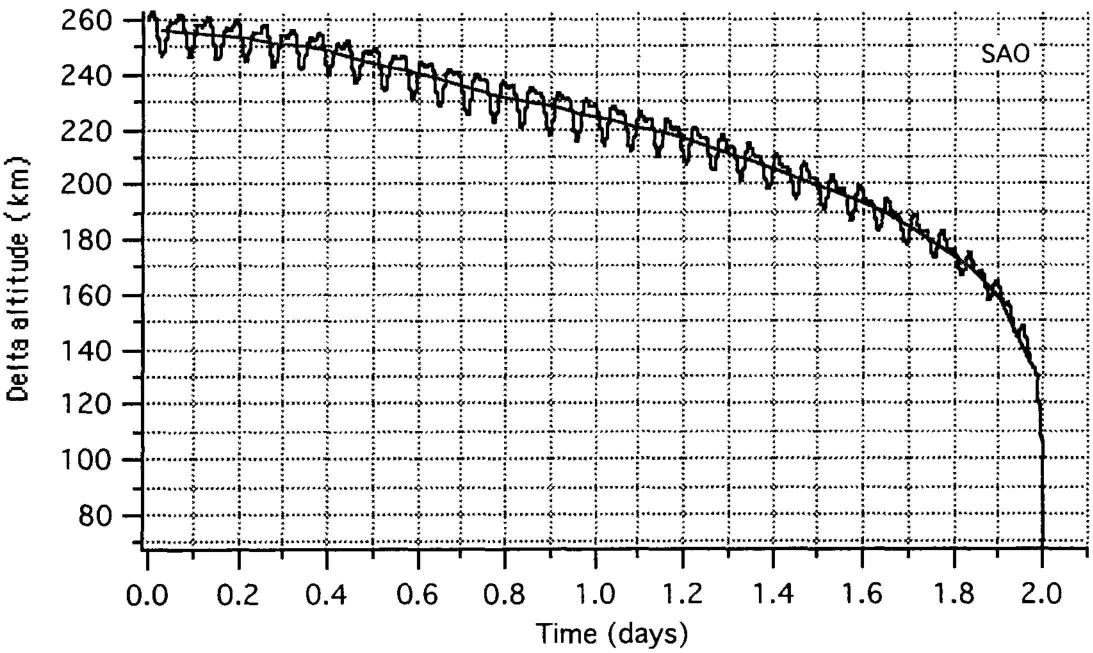

Figure 2 ProSEDS decay with atmospheric and ED drag

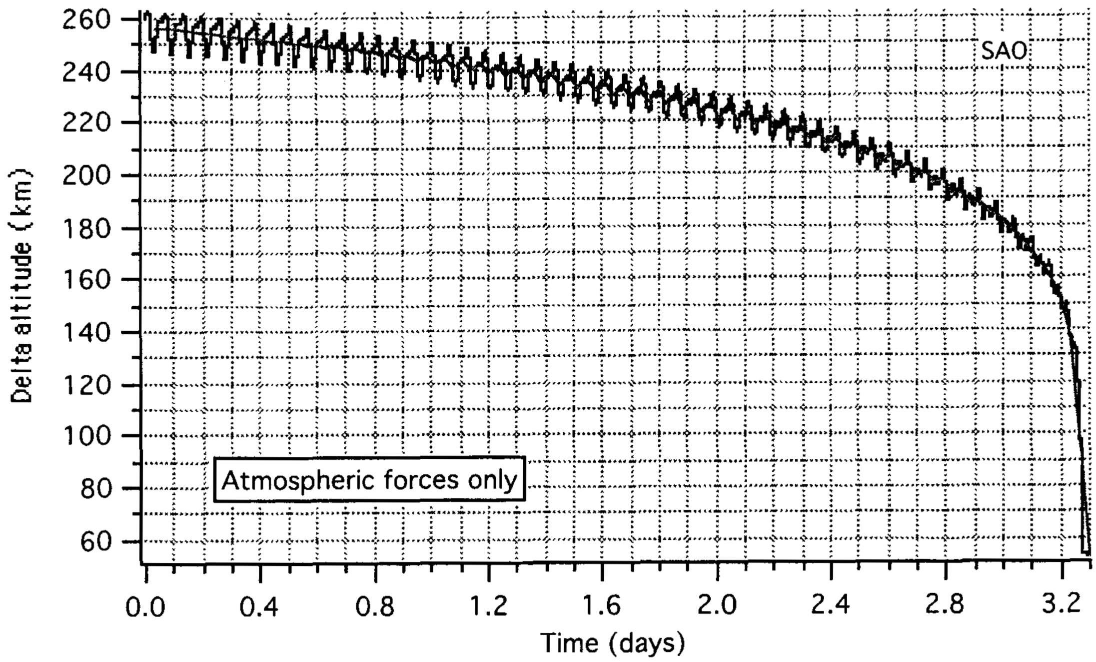

Figure 3 ProSEDS decay with atmospheric drag only

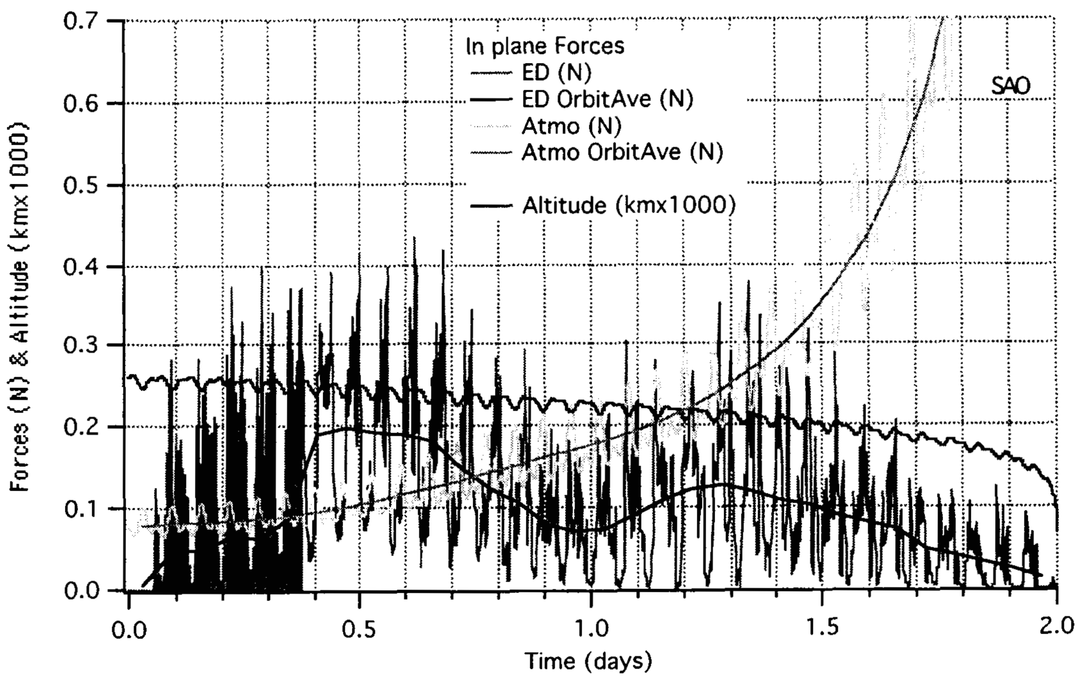

Figure 4 Comparison of atmospheric and ED forces acting on ProSEDS

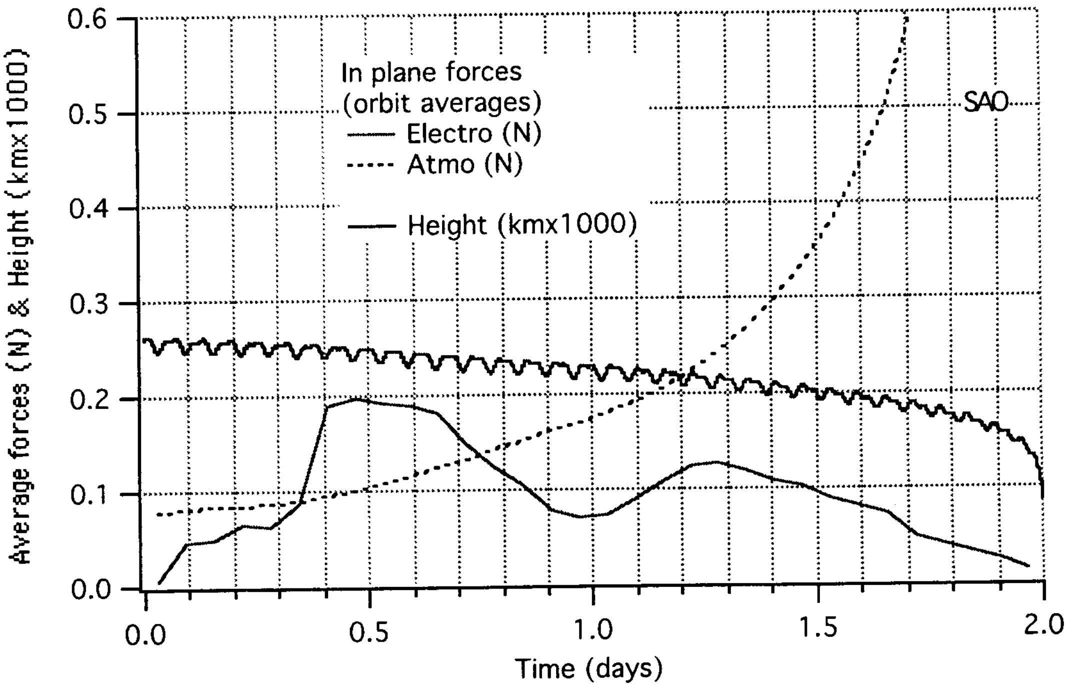

Figure 5 Comparison of orbit-average atmospheric and ED forces on ProSEDS

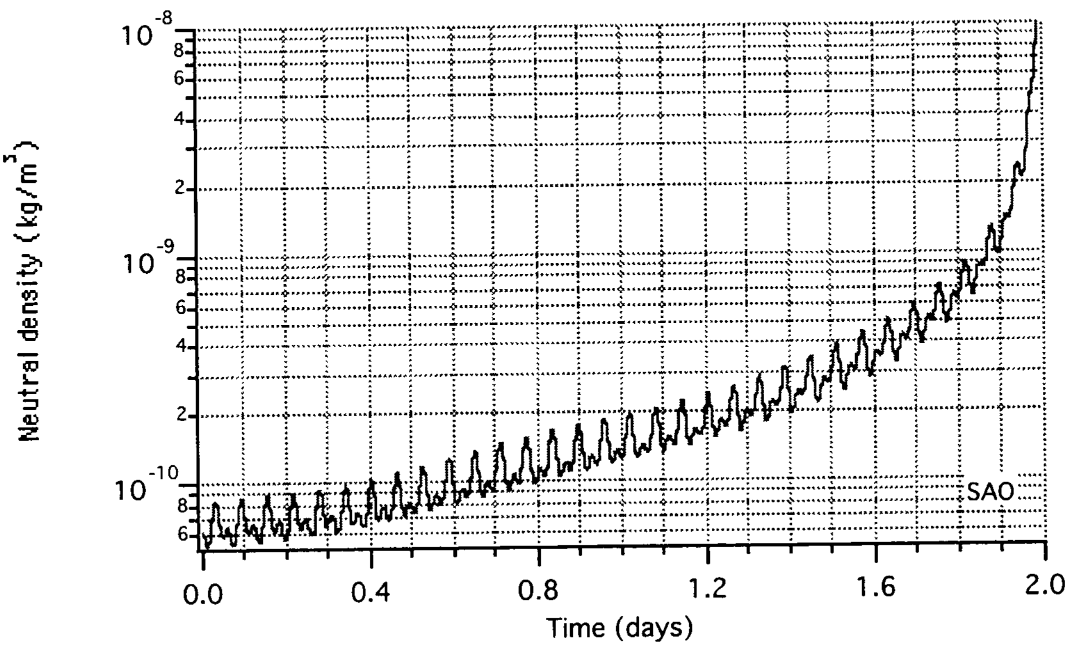

Figure 6 Neutral density vs. time

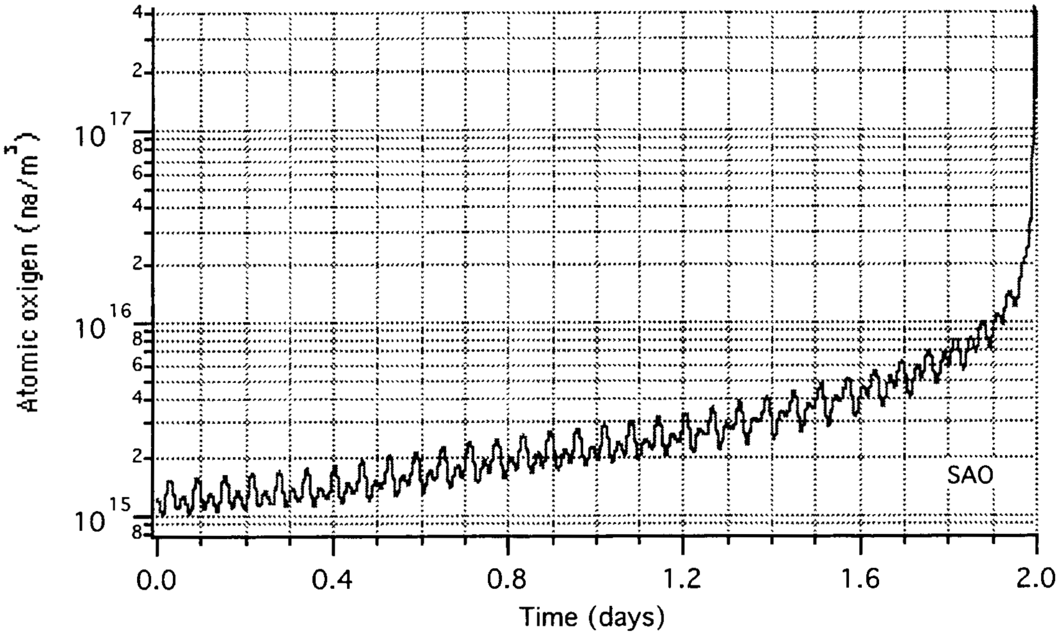

Figure 7 Atomic oxygen vs. time

Concluding Remarks

A reduction of the starting orbital altitude from 360 km to 260 km will change the relative contributions of electrodynamic and neutral drag forces to the decay rate. The overall decay rate will be still substantial and well above the value established in the mission success criteria. However, about half of the decay rate can be attributed to neutral drag at this low altitudes.

4. Deployment Performance At a Lower Altitude

Deployment Analysis

We have analyzed the impact of a starting altitude at 260 km on the deployment of ProSEDS. The control law and control parameters are those utilized for the original starting altitude at 360 km. Simulations have been run to estimate the impact of the lower altitude on the performance of ProSEDS deployment control law without any modification to the control law.

The final libration amplitude at the end of ProSEDS deployment is required to be less than 20 deg with respect to the local vertical. This goal is attained by utilizing a feedback control law that controls the tether during the 10-km-long Dyneema tether. The brake is then kept constant at half a turn during the CCOR deployment in order not to damage the CCOR coating while limiting the deployment velocity. Before the end of deployment, when the insulated portion starts deploying, the brake is ramped up to decrease the deployment speed. Finally, the brake is slowly removed to let any remaining tether coils out of the deployer canister. The control law is derived from the law successfully utilized to deploy SEDS-II[6]. As it was investigated for SEDS-II the deployment final libration is mostly sensitive to the shape of the exit velocity profile during the early part of deployment, that is, for ProSEDS during the deployment of the Dyneema portion. The libration amplitude is insensitive to changes in the profile during the latter part of deployment (i.e., the CCOR portion). The deployment control law adjusts the brake in order to force the tether length and velocity to follow pre-computed reference profiles that would provide a very small final libration amplitude under reference conditions. The actual deployment velocity depends on the frictional force acting on the tether as it moves through the deployer. This force is analytically modeled by a tension law which depends on a set of parameters described in Refs. [7] and [8]. The values of these parameters are measured during the deployment ground tests under different temperature conditions and for tethers of different batches.

The most uncertain and also influential parameter (during the early and critical phase of deployment) of the tension model is the minimum tension T_{min}. The minimum tension of the ProSEDS non-conductive tether has been measured throughout the many deployment tests on the ground to vary between 5 mN and 30 mN depending on temperature and cleanliness of the tether. Consequently, the control law must provide a residual libration at the end of deployment of less than 20° (as specified by the mission requirements) within the expected range of variability of the minimum tension.

Figure 8 shows the amplitude of the residual libration at the end of deployment vs. the minimum tension T_{min} of the Dyneema tether for the flight profile of Ref. #78 and starting altitudes of 360 km and 260 km. Figure 1 also shows the final libration that ProSEDS would attain without control and the representative points from the SEDS-I and SEDS-II flights. The final libration amplitude is sensitive to the Dyneema tether T_{min} and it is insensitive to the value of the wire T_{wire}.

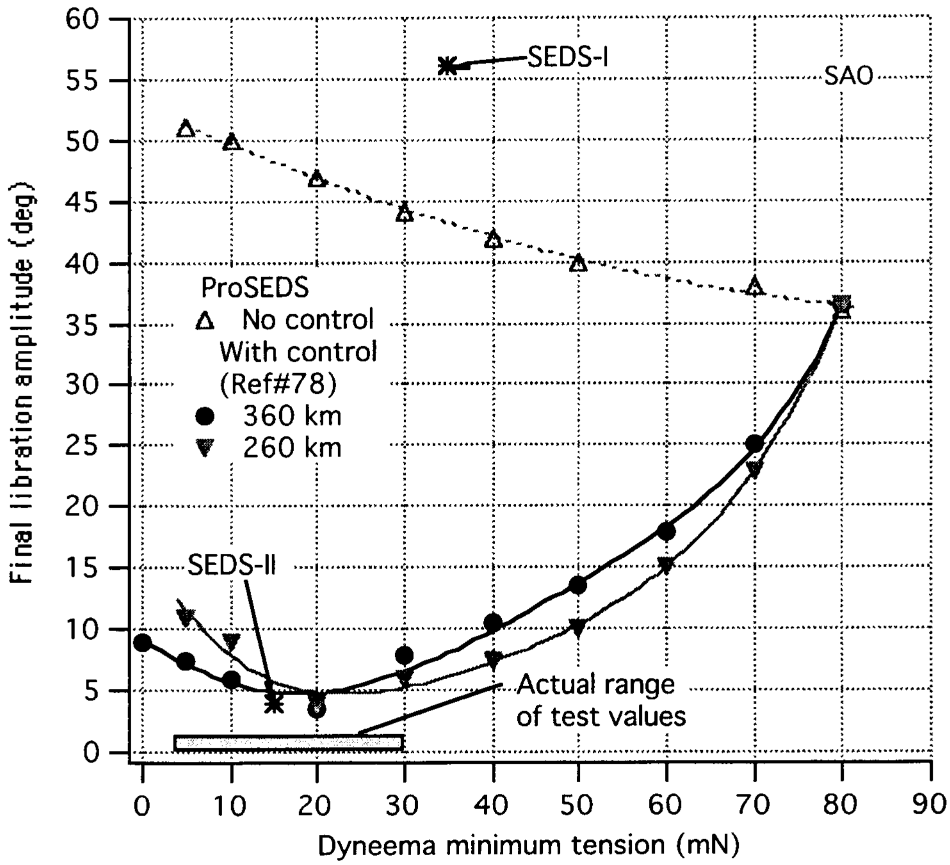

Figure 8 Final libration amplitude vs. Dyneema minimum tension

The differences in performance between starting altitudes of 360 km and 260 km are not substantial. A starting altitude of 260 km implies a somewhat larger final amplitude (than starting at 360 km) for $T_{min} < 20$ mN (the reference value for the control law) and somewhat smaller values of the final libration amplitude for $T_{min} > 20$ mN.

Concluding Remarks

The deployment control law meets the requirement of a final libration amplitude of less than 20 deg over the experimentally-measured range of the Dyneema minimum tension of 5 mN and 30 mN with a substantial margin even for a starting altitude of 260 km. The performance decays substantially only for values of T_{min} above 60 mN. For $T_{min} \geq 80$ mN, the deployment stops prematurely because of excessive tether friction and without any role being played by the control law.

Papers Published or Presented at Conferences

During this reporting period we co-authored the following three papers presented at the 2003 Joint Propulsion Conference, 20-23 July, Huntsville, Alabama:

Johnson, L., Gilchrist, B., Lorenzini, E., Stone, N. and Wright, K. "Propulsive Small Expendable Deployer System (ProSEDS) experiment: Mission Overview and Status." 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Huntsville, Alabama, 20-23 July 2003, Paper AIAA-2003-5094.

Lorenzini, E.C., Welzyn, K. and Cosmo, M.L. "Expected Deployment Dynamics of ProSEDS." 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Huntsville, Alabama, 20-23 July 2003, Paper AIAA-2003-5095.

Sanmartin, J.R., Charro, M. Lorenzini, E.C., Cosmo, M.L., and Estes, R.D. "Analysis of ProSEDS Test of Bare-Tether Collection" 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Huntsville, Alabama, 20-23 July 2003, Paper AIAA-2003-5097.

REFERENCES

1 J.R. Sanmartin, M. Manuel-Martinez, and E. Ahedo, "Bare Wire Anodes for Electrodynamic Tethers." *J. of Propulsion and Power*, Vol. 9, No. 3, 353-360, 1993.

2 R.D. Estes, J.R. Sanmartin, and M. Martinez-Sanchez, "Performance of Bare-Tethers Systems Under Varying magnetic and Plasma Conditions." *J. of Spacecraft and Rockets*, Vol. 37, No. 2, 197-204, 2000.

3 Estes, R.D., E.C. Lorenzini, J.R. Sanmartin, M. Martinez-Sanchez and N.A. Savich, "New High-Current Tethers: A Viable Power Source for the Space Station?," Smithsonian Astrophysical Observatory, White Paper, December 1995.

4 L. Johnson, R.D. Estes, E. Lorenzini, M. Martinez-Sanchez and J. Sanmartin "Propulsive Small Expendable Deployer System Experiment." *J. of Spacecraft and Rockets*, Vol. 37, No. 2, 173-176, 2000.

5 E.C. Lorenzini et al., "The Propulsive Small Expendable Deployer System (ProSEDS)." Annual Report#1 on NASA Grant NAG8-1605, September 2001.

6 E.C. Lorenzini, S.B. Bortolami, C.C. Rupp and F. Angrilli, "Control and Flight Performance of Tethered satellite Small Expendable Deployment System-II." Journal of Guidance, Control and Dynamics, Vol. 19, No. 5, 1148-1156, 1996.

7 E.C. Lorenzini et al., "The Propulsive Small Expendable Deployer System (ProSEDS)." Annual Report #1 on NASA Grant NAG8-1605, September 2000.

8 E.C. Lorenzini et al., "The Propulsive Small Expendable Deployer System (ProSEDS)." Annual Report #2 on NASA Grant NAG8-1605, July 2001.