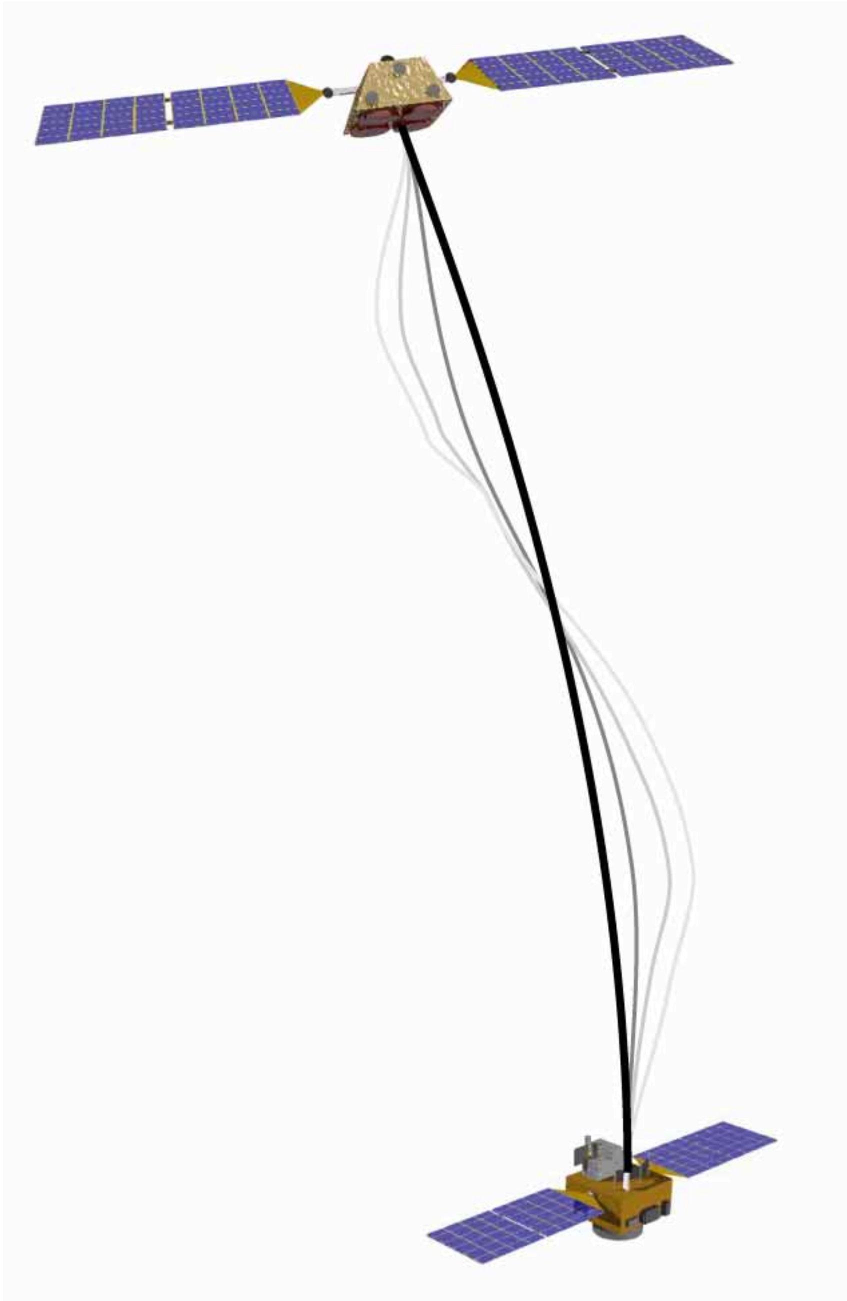
STABILIZATION OF ELECTRODYNAMIC SPACE TETHERS



ROBERT P. HOYT
TETHERS UNLIMITED, INC.
19011 36th Ave W, Suite F, Lynnwood, WA 98036-5752
Phone: (425) 744-0400 Fax: -0407 email: TU@tethers.com
www.tethers.com

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Abstract. Electrodynamic tethers are susceptible to instabilities in a number of different modes, including pendulum librations, transverse wave oscillations, and "skip rope" oscillations. We have developed two simple feedback algorithms for controlling these oscillations. The first algorithm requires knowledge of the motion of several points along the length of the tether, and control is achieved by varying the tether current. Detailed simulations of electrodynamic tethers indicate that this feedback control algorithm is successful in stabilizing the dynamics of electrodynamic tethers during extended periods of operation. The second algorithm requires only knowledge of the motion of the tether endmass. Simulations indicate that this simpler algorithm is also successful in stabilizing the dynamics of the tether, although it stabilizes the oscillations at a higher quasi-steady state level.

INTRODUCTION

Electrodynamic tethers have strong potential for providing propellantless propulsion to spacecraft in low-Earth orbit for applications such as satellite deorbit (Forward, 1998) orbit boosting, and stationkeeping (Johnson, 1998). Unfortunately, however, electrodynamic tethers are inherently unstable (Beletskii, 1993, Levin 1987, Pelaez, 2000) When a tether in orbit carries a current along its length, the interaction of the tether with the geomagnetic field creates a force on the tether that is directed perpendicular to the tether. The summation of this force along the length of the tether can produce a net pro pulsive force on the tether system, raising or lowering its orbit. The tether, however, is not a rigid rod held above or below the spacecraft. It is a very long, thin cable, and has little or no flexural rigidity. The transverse electrodynamic forces therefore cause the tether to bow and to swing away from the local vertical. Gravity gradient forces produce a restoring force that pulls the tether back towards the local vertical, but this results in a pendulum-like motion. Because the direction of the geomagnetic field varies as the tether orbits the Earth, the direction and magnitude of the electrodynamic forces also varies, and so this pendulum motion develops into complex librations in both the in-plane and out-of-plane directions. Due to coupling between the in-plane motion and longitudinal elastic oscillations, as well as coupling between in-plane and out-of-plane motions, an electrodynamic tether operated at a constant current will continually add energy to the libration motions, causing the libration amplitudes to build until the tether begins rotating or oscillating wildly. In addition, orbital variations in the strength and magnitude of the electrodynamic force will drive transverse, higher-order oscillations in the tether which can lead to the unstable growth of "skip-rope" modes.

In this paper, we present the performance of two new control schemes that provide the ability to prevent the unstable growth of librations, transverse oscillations, and skip-rope modes. These feedback control schemes requires as input periodic measurements of the locations of the tether endmass and/or several points along the tether. The feedback algorithm calculates a gain factor based upon the net work that the electrodynamic forces will perform on the tether dynamics. The feedback is performed by varying the current in the tether system

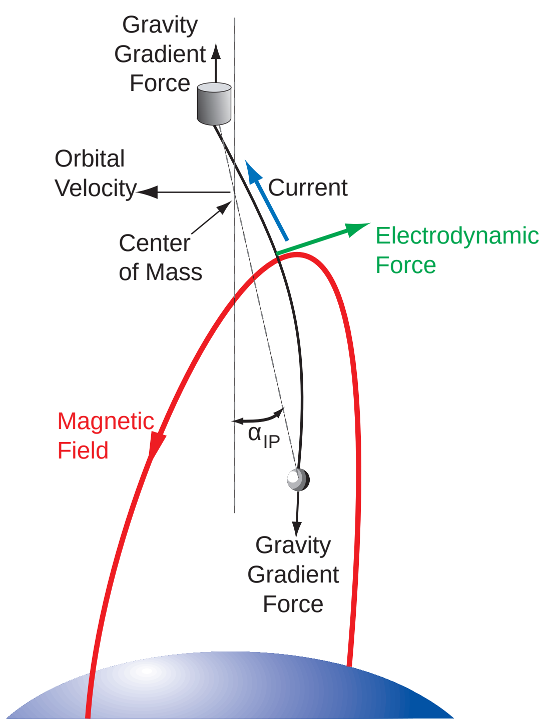

Figure 1. Electrodynamic tether, in drag mode.

slightly according to the calculated gain factor.

We will begin by reviewing the fundamental nature of electrodynamic tether instabilities and discussing prior work on understanding and controlling tether dynamics. Next, we will present the new feedback control algorithms, and describe the results of detailed numerical simulations conducted to test the performance of these algorithms.

ELECTRODYNAMIC TETHER INSTABILITIES

A tether system deployed in orbit around the Earth will be pulled by gravity gradient forces towards an equilibrium configuration oriented along the local vertical. In an electrodynamic tether system, illustrated conceptually in Figure 1, currents in the tether flowing across the planetary magnetic field will generate **J**x**B** forces acting in a direction perpendicular to both the magnetic field and the tether. These forces will push the tether away from the local vertical orientation, and the tether will have a new equilibrium configuration roughly like that shown in the figure. Because the strength and relative direction of the geomagnetic field will vary as the tether orbits the Earth, however, this "equilibrium" configuration is really only an instantaneous equilibrium configuration, and it changes constantly during the orbit. The tether will thus naturally develop oscillations as it seeks to follow its changing "equilibrium" configuration.

The first criteria for electrodynamic tether stability is that the tether libration angles cannot exceed 45°. If the tether librations exceed this level, the tether will begin to go slack at the peak of its librations, much like the cables on a child's swing will go slack as the angle approaches 90°. If the tether goes slack, it will generate complex, difficult-to-predict higher-order oscillations and large tension excursions when the tether re-where μ=GM$_e$, R_A and φ are the polar coordinates of the tether system's center of mass in the Earth-centered frame , G is the tether system impedance, α is angle between the tether and the local vertical, and *a* and *g* are feedback coefficients.

Unfortunately, this control algorithm only works under the assumptions of equatorial orbit in a non-tilted magnetic field. In reality, any electrodynamic tether will experience forces perpendicular to the orbit plane, resulting in out-of-plane motions. This is true even for equatorial orbits, because the Earth's magnetic field is tilted relative to its spin axis, and is not a perfect dipole. Because the out-of-plane librations and higher order modes can couple energy into the in-plane librations, the feedback algorithm expressed in Eqn (2) breaks down when out-of-plane forces are present.

bounds. The "first critical current", the current at which the tether's swing will exceed 45°, is given by (Beletskii, 1981):

$$I_{crit} \approx \frac{3\omega^2}{B_o}\left(m_{endmass} + \tfrac{1}{2} m_{tether}\right) \qquad (1)$$

Levin studied the stability of a flexible tether under the assumptions that the tether is in a circular equatorial orbit in a perfect, spin-axis oriented dipole field, and thus experiences forces only in the plane of the orbit (Levin, 1987). Under even these simplifying assumptions, he found that the equilibrium configuration of the tether is unstable if the tether current is held constant. This fundamental instability results from the fact that if the tether endmass swings incrementally away from the equilibrium configuration, the resulting "restoring forces" due to the imbalance between the gravity-gradient induced tether tension and the electrodynamic forces do not push the tether directly back to its equilibrium configuration. Rather, because of the gyroscopic (or coriolis) forces inherent in relative motion in orbit, the restoring forces will push the endmass along a path in which net energy is added to the tether system.

To stabilize the tether system, Levin suggested varying the tether current according to

$$\delta E = \frac{\mu}{R_A^{\,2}}\left(a\omega\delta R_A\right) + \frac{g}{G-g}\left[\frac{\mu}{R_A^{\,2}}\left(\left(a+1\right)\omega\delta R_A\right) + \int_0^l \frac{\mu\gamma}{R_A^{\,3}}\left(R\sin\left(\alpha\delta\dot{\varphi}\right) - \cos\left(\alpha\delta\dot{R}\right)\right)ds\right], \qquad (2)$$

Columbo *et al.*, used a rigid-rod model to study control of electrodynamic tether behavior (Columbo, 1981). Their study assumed that the tether orbited in a perfect, non-tilted, non-spinning dipole field. Under these assumptions, they found that the tether's in-plane motion exhibited periodic behavior, but the out-of-plane motion grew unstably. They showed that by applying current to the tether only while the electrodynamic forces opposed the out-of-plane motion of the tether they could damp the out-of-plane librations of the tether.

In reality, however, the Earth's magnetic field rotates along with the Earth. Consequently, the out-of-plane forces that a tether experiences during a particular potion of its orbit will change directions once per day. This means that the instability that Columbo observed in the out-of-plane librations is only a concern if the tether current is large enough that the out-of-plane libration exceeds 45° within twelve hours. If the libration does not go unstable that quickly, then as the Earth rotates inside the tether's orbit, the electrodynamic forces will later damp the out-of-plane oscillations, resulting in periodic growth and decay of the out-of-plane oscillations.

Hoyt investigated the dynamics of a flexible electrodynamic drag tether in a non-ideal, spinning magnetic field using a numerical simulation of a flexible tether in orbit, and found that the primary instability of concern was the growth of in-plane-librations (Hoyt, 1998). He observed that during some portions of the motion of the tether, the electrodynamic forces were performing net positive work on the in-plane libration, and during other portions of the libration they were doing net negative work on the libration. Using the simulation code, he demonstrated that by slightly reducing the tether current when the electrodynamic forces are doing net work on the in-plane libration, and allowing the current to flow unimpeded when the forces were reducing the energy in the librations, was sufficient to stabilize the in-plane libration instability long enough to permit an electrodynamic tether to deorbit a spacecraft from Low Earth Orbit. These simulations showed, however, that the simple feedback on the in-plane libration tended to drive growth of transverse and skip-rope oscillations. This was acceptable for the spacecraft deorbit application, because the spacecraft and tether deorbited before the oscillations became unmanageable, but for longer duration propulsion missions, such as satellite stationkeeping, satellite orbital maneuvering, and Space Station reboost, the instability of these higher-order modes could pose a significant problem.

Peláez *et al*. have investigated the dynamics of an electrodynamic tether in an inclined orbit by modeling the tether as a rigid, inextensible rod (Peláez, 2000). They found that in inclined orbits, there are components of the magnetic field oriented along the local vertical. These magnetic field components result in coupling between in-plane and out-of-plane motions. This coupling allows electrodynamic interactions with the horizontal components of the magnetic field to drive the net flow of energy into the librations of the system, resulting in instabilities of the pendulum librations of the tether system.

The utility of the analyses and results of these prior studies, however, are limited by the simplifying assumptions that each study used. In reality, the Earth's magnetic field is tilted relative to the Earth's spin axis, the field is not a perfect dipole, and it rotates with the Earth. Consequently, any electrodynamic tether will experience forces perpendicular to the orbit plane, resulting in out-of-plane motions, which can in turn feed energy into the in-plane motions. Because the density of the Earth's ionosphere changes dramatically from sunlit to eclipse conditions, and changes with the solar conditions, tether currents in real systems will likely vary over each orbit. Moreover, space tethers are not rigid bodies, but cables that can bend, go slack, display temperature dependent behaviors, and exhibit other non-linear behavior. As a result, real tether dynamic behavior is significantly more complex than can be captures in the analytical treatments reviewed above. Moreover, a control method for stabilizing the tether dynamics must be designed to handle these many non-ideal behaviors, and must be tested within a numerical simulation that includes the flexural dynamics, orbital mechanics, non-linear strain characteristics, and other important physics of the tethered system.

FEEDBACK CONTROL TO STABILIZE ELECTRODYNAMIC TETHERS

A simple feedback control algorithm may stabilize the dynamics of the transverse and skip-rope modes of electrodynamic tethers. The control method is based upon the fact that as the tether librates, oscillates, and orbits the Earth, the electrodynamic forces on the tether will at some times be performing net positive work on the modes of the tether motion, and at other times they will be performing net negative work on the tether modes. The algorithm does not seek to eliminate tether librations; some libration is an inevitable fact of life in an electrodynamic tether. It does, however, seek to limit the growth of the librations, and to prevent the growth of higher-order oscillatory modes.

Under a NASA/MSFC Phase I SBIR contract, TUI has developed two new feedback algorithms that evaluate the work being performed on the tether oscillations and calculate a feedback modulation that is applied to the tether current to achieve net damping of the unstable tether modes. The first algorithm requires periodic measurements of the location of several points along the tether; this algorithm is referred to as the “Tether Configuration” feedback method. The second algorithm requires only periodic measurements of the acceleration of the tether endmass; this algorithm is referred to as the "Endmass Acceleration" feedback method. These algorithms are proprietary, and are the subject of current patent applications, so they will not be detailed in this paper. They are, however, detailed in the final report on the Phase I SBIR contract (Hoyt, 2001).

These stabilization algorithms form the heart of the Electrodynamic Tether Stabilization (EDTS) System, illustrated in Figure 2, which will enable electrodynamic tethers to provide long-term propellantless propulsion while maintaining tether stability and efficiency.

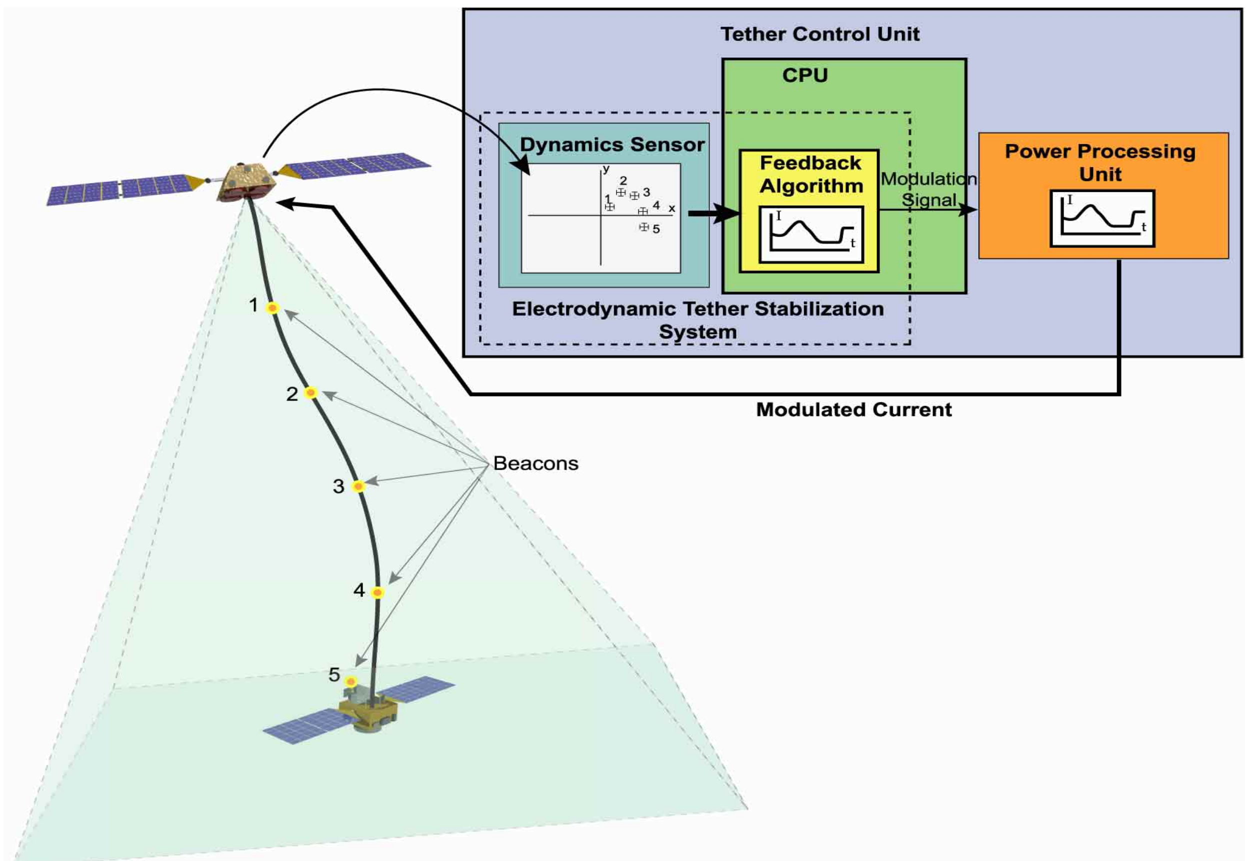

Figure 2. The Electrodynamic Tether Stabilization (EDTS) System.

TESTING THE FEEDBACK CONTROL METHODS

To test this new feedback control algorithm, we have utilized the TetherSim™ code to simulate the behavior of electrodynamic tethers with and without various forms of feedback control. TetherSim™ is a numerical simulation tool that includes models for:

- tether dynamics, including both an implicit propagator and an explicit (4^{th} order Runge Kutta) propagator
- orbital mechanics, using a 4^{th} order Runge-Kutta in either Cartesian or spherical coordinates
- IGRF magnetic field,
- IRI plasma density field,
- MSIS90 neutral density field,
- tether thermal characteristics,
- bare wire electrodynamic interactions with the ionosphere,
- endmass dynamics.

In the simulations, the tether was modeled with 20 discrete segments, and the work summation in Eqn (5) was calculated using 10 points along the tether. Perfect knowledge of the velocities of those 10 points was assumed. The feedback control was performed once every 10 seconds. Furthermore, to prevent the possible development of short-wavelength oscillations that can be driven by rapid cycling of the tether current, we limited the rate of change of the tether current to 100 mA/min. Note also that in these simulations, the tether was modeled as having no longitudinal damping.

Test Case: GLAST Deorbit For testing the control algorithm, we chose to utilize a test case involving the end-of-mission deorbit of the GLAST spacecraft. The GLAST spacecraft is planned to be a 3360 kg (drymass) space telescope that will be placed in a 550 km circular orbit at 28.5° inclination. Deorbit of this spacecraft should represent a relatively challenging scenario, because a tether system can generate larger currents in deorbit mode than in boost mode, leading to faster instability growth, and because the tethered system will pass though the range of altitudes where magnetic field and ionospheric density are greatest. The tether system modeled was a Terminator Tether™ device with a 10 km long, 15 kg tether constructed of aluminum wire, with a 15 kg endmass containing the tether deployer and the control electronics.

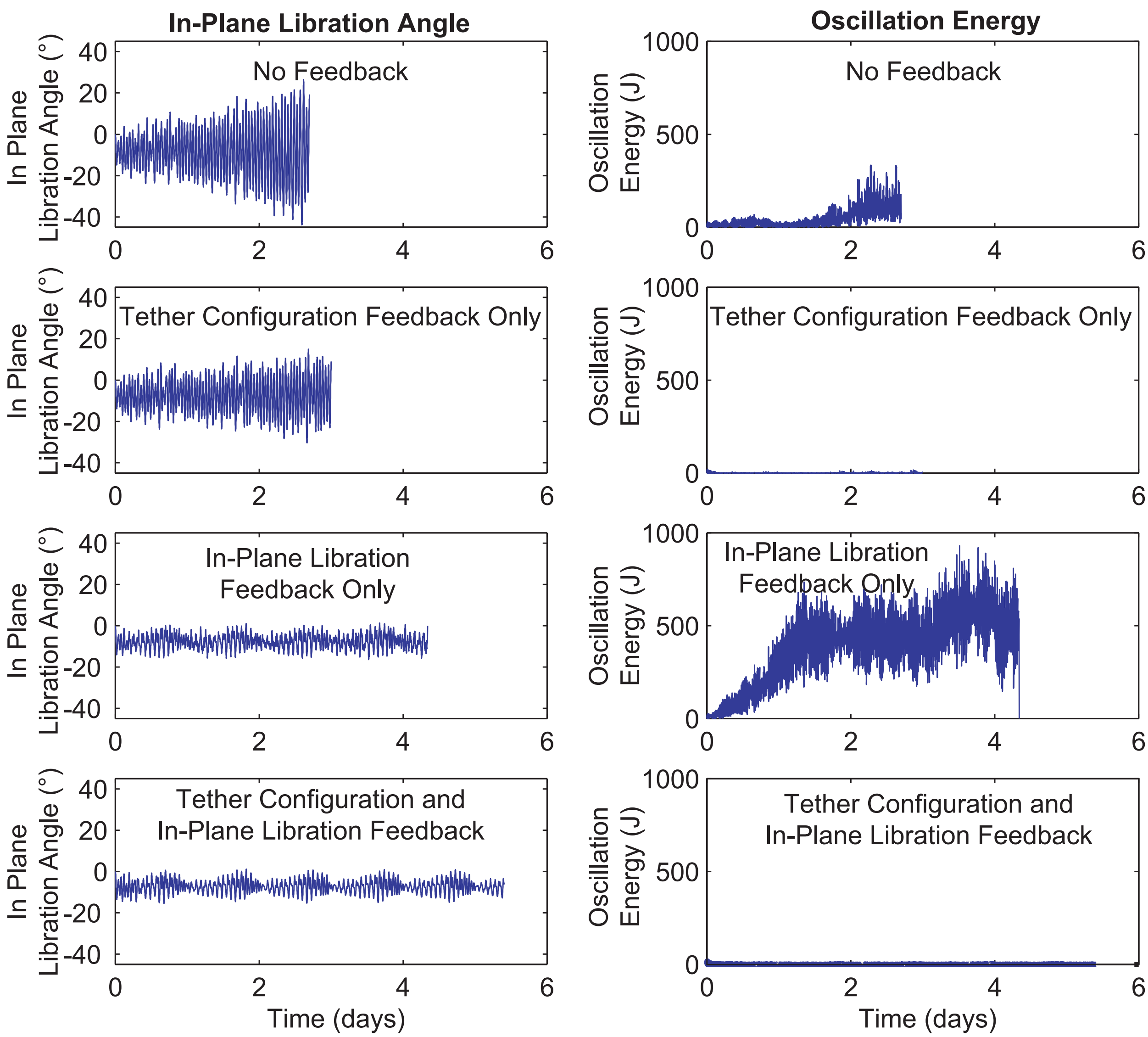

Figure 3. Comparison of simulation results for deorbit of a 3360 kg GLAST spacecraft by a Terminator Tether™ device with a 15 kg, 10 km tether and a 15 kg endmass, with no feedback, tether configuration feedback, in-plane libration feedback, and both tether configuration and in-plane libration feedback.

Results

Tether Configuration Feedback: Figure 3 compares results for the tether in-plane libration angle and the total kinetic energy in the tether oscillations for simulations with and without the feedback control. The top two traces show that, with no feedback control, the in-plane libration grows rapidly, exceeding the critical angle of 45° within three days. Simulations using only the tether configuration feedback demonstrated that it performed very well for stabilizing the transverse and skip-rope modes, but it did not prevent a slow growth of the in-plane libration. Conversely, use of the in-plane feedback only, shown in the third pair of traces, stabilizes the libration mode, but excites the higher order modes. To address this, we combined the tether configuration feedback with the in-plane libration feedback by simply superimposing the modulation gains. The bottom pair of traces show that this combination is very successful at stabilizing both the libration and the transverse oscillation instabilities.

Endmass Acceleration Feedback: Figure 4 shows a comparison of simulation results with no feedback, with only the endmass acceleration feedback, and with both endmass acceleration and in-plane libration feedback. The results indicate that when this method is used by itself, the tether system successfully damps the transverse and skip-rope oscillations, but the in-plane librations still grow to instability. By superimposing this endmass acceleration-based modulation with current modulation based upon the in-plane libration angle, however, we were able to stabilize both the in-plane librations and the higher-order modes for durations in excess of 30 days.

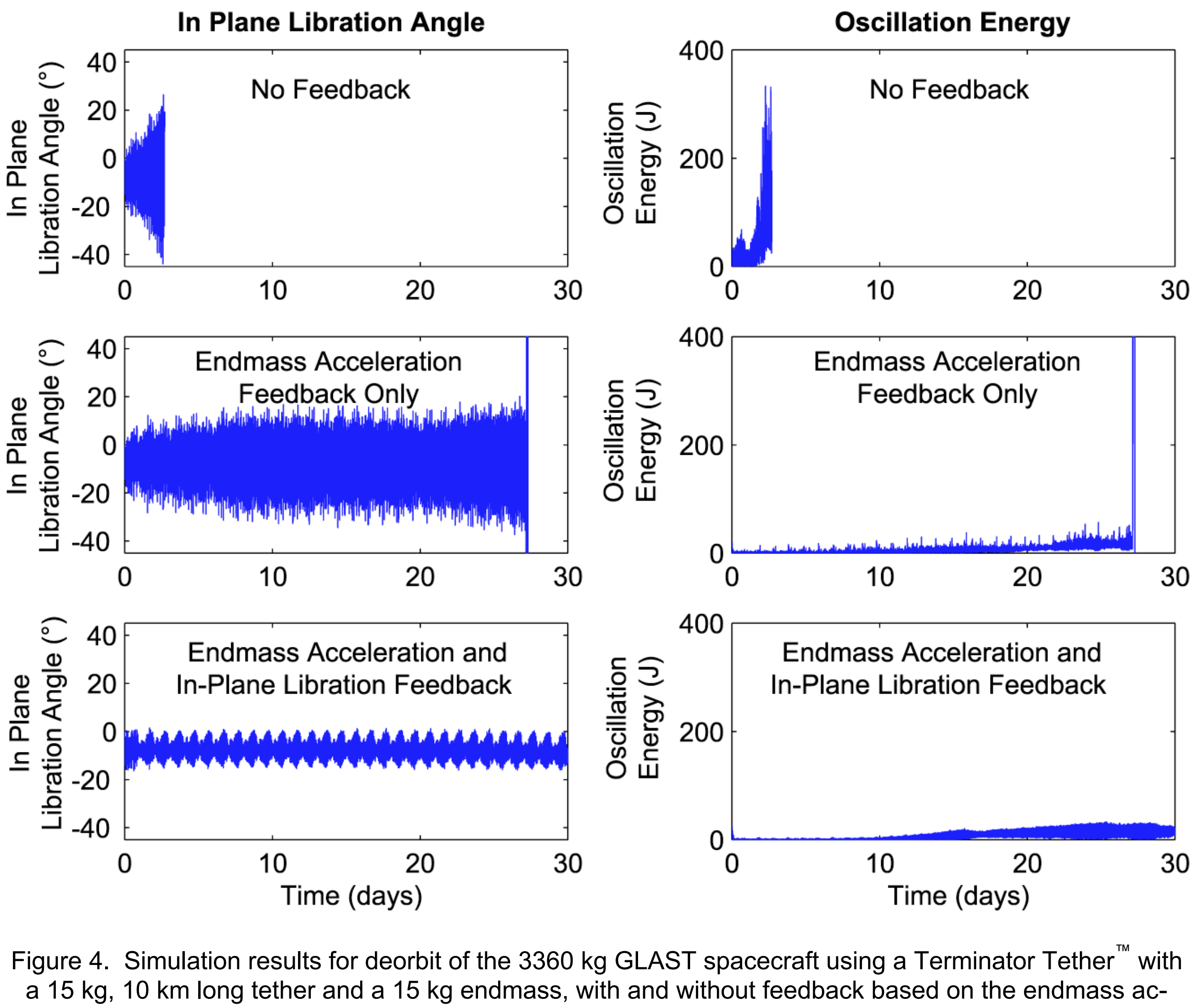

Figure 4. Simulation results for deorbit of the 3360 kg GLAST spacecraft using a Terminator Tether™ with a 15 kg, 10 km long tether and a 15 kg endmass, with and without feedback based on the endmass acceleration.

Figure 5 shows a simulation of a full deorbit of the GLAST spacecraft using the tether configuration feedback method. The feedback method succeeds in stabilizing both the in-plane and oscillation instabilities, and the tether librations show a stable, periodic behavior that is maintained until the tether enters the upper atmosphere.

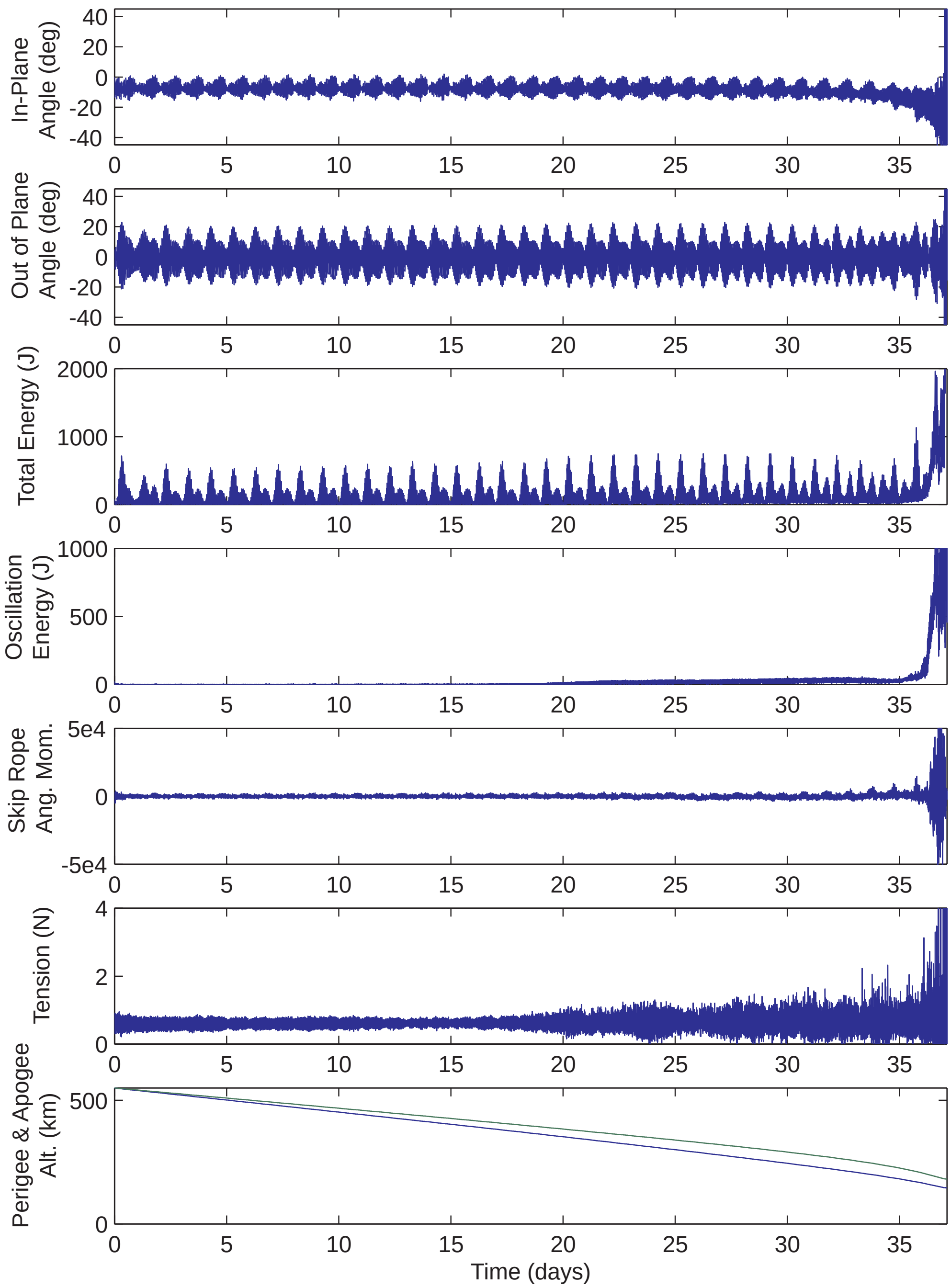

Figure 5. Simulation of deorbit of the GLAST spacecraft, with feedback control on both oscillation modes and in-plane libration. Tether only loses stability after it enters the upper atmosphere.

CONCLUSIONS

The tests conducted using the TetherSim™ numerical simulation tool have demonstrated that both of the new feedback control algorithms can succeed in stabilizing the long-term dynamics of electrodynamic tethers. Without any feedback control on the tether dynamics, an electrodynamic tether will exhibit steady growth of the in-plane libration amplitude and skip-rope oscillations. When the in-plane libration amplitude nears 45°, the tether will begin to experience slack behavior, which results in more violent motions and larger tension excursions when the tether rebounds. While the previously proposed method of performing damping on the in-plane libration only does succeed in pre venting the growth of in-plane libration amplitude, it also tends to exacerbate the instability of transverse and skip-rope modes. The new control methods performs subtle feedback to "drain" energy from the skip-rope, transverse, and in-plane librations. The simulations indicate that it can succeed in maintaining oscillation energies at a low level and prevent growth of skip-rope modes, without significantly degrading the performance of the tether system.

ACKNOWLEDGMENTS

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