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The Terminator Tape™: A Cost-Effective De-Orbit Module for End-of-Life Disposal of LEO Satellites

Robert P. Hoyt*, Ian M. Barnes†, Nestor R. Voronka‡, Jeffrey T. Slostad§
Tethers Unlimited, Inc., Bothell, WA, 98011

The rapid growth of the orbital debris population poses an increasing threat to military, commercial, and civilian science spacecraft in Earth orbit. NASA, the DoD, ESA, and other organizations have begun to respond to this problem by imposing requirements for debris mitigation upon new space systems. These requirements specify that spacecraft at end-of-life be disposed of by either atmospheric re-entry within 25 years, maneuver to a higher storage orbit, or direct retrieval. For most satellites operating in low Earth orbit (LEO), atmospheric re-entry is the most viable option. To provide a cost-effective means for satellite operators to comply with the 25-year post-mission orbital lifetime restriction, Tethers Unlimited is developing a lightweight de-orbit module called the “Terminator Tape™”. The Terminator Tape is a small module that bolts onto any side of a spacecraft during satellite integration. At the completion of the satellite’s mission, the satellite will activate the Terminator Tape module. The module will then deploy a several-hundred-meter length of thin conducting tape. This tape will not only significantly enhance the aerodynamic drag experienced by the system, but will also generate electrodynamic drag forces through passive interactions with the Earth’s magnetic field and conducting ionospheric plasma, de-orbiting the satellite within 25 years. Two modules are currently in development, one sized for microsatellites operating at altitudes of less than 900 km, and the other sized for CubeSats. In this paper, we will present design overviews and concept of operations for both modules, as well as analyses of deorbit of satellites using these modules.

Nomenclature

\vec{B}	= magnetic field vector
\vec{I}	= current vector
L	= tether length
$m_{e,i}$	= electron/ion mass
n_{∞}	= ambient plasma density
\vec{v}	= orbital velocity vector
V	= tether voltage
w	= tape width

I. Introduction

THE orbital debris population and its potential for continued rapid growth pose a significant threat to both DoD space assets and civilian space systems. Studies of the interaction of satellite systems with the space debris environment have concluded that unless debris mitigation measures are adopted, “the debris environment cannot sustain the long-term operation of [large constellations but].... could sustain the long term operation of medium sized constellations of up to 100.... provided that the constellations implement strict mitigation measures such as explosion prevention and immediate satellite de-orbiting upon end-of-life and failure. These findings have proven that low Earth orbit is not a limitless resource and must be managed carefully in the future.”¹ Recent studies at NASA/JSC have indicated that the population of debris in LEO is now so large that it will continue to increase for over 50 years

* President, CEO, & Chief Scientist, 11711 N. Creek Pkwy S., Bothell WA 98011, hoyt@tethers.com, Member AIAA.

† Lead Mechanisms Engineer.

‡ Chief Technologist, Member AIAA.

§ Chief Engineer.

even if no new objects were to be launched into orbit.² Other studies have indicated that unless strong mitigation measures are adopted, the density of orbital debris particles in LEO will soon become large enough that collisions between them will lead to exponential growth of the number of debris particles, which would pose a severe threat to DoD and commercial space assets.³

Fortunately, NASA, the DoD, FCC, and other relevant authorities have begun to respond to the orbital debris problem by placing requirements for debris mitigation upon new space systems. Examples of these requirements are the DoD Instruction 3100.12, Sec. 6.4, “Spacecraft End-of-Life” and NASA’s Safety Standard (NSS) 1740.14, “Guidelines and Assessment Procedures for Limiting Orbital Debris,” which specify that stages, spacecraft, and other payloads should be disposed of at the end of mission life by one of three methods: atmospheric re-entry, maneuver to a designated storage orbit, or direct retrieval. If these mitigation measures are implemented and adhered to over the coming decades, the growth of the debris flux can be reduced from an exponential growth curve down to a logarithmic growth curve.³ If more aggressive actions such as active removal of existing large debris objects are undertaken, the growth of the debris population could be halted and reversed within several decades.

A challenge to universal compliance with these regulations is the cost of meeting orbital lifetime restrictions using current technologies. Relying upon chemical rocket-based propulsion to accomplish de-orbit will require a propellant mass equal to 5-20% of the spacecraft mass, adding significantly to the satellite hardware and launch costs. Even if higher specific impulse electric propulsion systems are used, many of the spacecraft’s systems, including command and data handling, attitude control, guidance, telemetry, power, and the thruster systems themselves must be designed with the robustness and redundancy needed to ensure operation at the satellite’s end-of-life. This additional redundancy can dramatically increase the cost of the satellite hardware, and even then the satellite operators will eventually be forced into the unpleasant situation of having to de-orbit their spacecraft while they are still capable of performing revenue-generating operations.

1. Lessons Learned from Prior Work: The Terminator Tether™

Over a dozen years ago, Tethers Unlimited began working to address the orbital debris problem by developing a device called the “Terminator Tether™,” which utilizes electrodynamic drag generated by a several-kilometer-long conducting tether to deorbit a spacecraft.^{4,5} Several lessons learned from developing and marketing the Terminator Tether have guided our more recent efforts to develop the Terminator Tape, resulting in a very different end product.

The Terminator Tether module incorporated a tether deployment mechanism, a multi-kilometer, multi-strand conducting tether, an active electron emission device such as a Hollow Cathode Plasma Contactor (HCPC) or Field Emission Array Cathode (FEAC), and control and power conversion avionics. Under a NASA SBIR effort, we designed and built a Terminator Tether brassboard prototype sized to deorbit 3-metric ton satellites from mid-LEO altitudes with a deorbit time of less than a year. The prototype is shown in Figure 1. The Terminator Tether unit would be integrated onto a spacecraft prior to launch, and during the mission of the spacecraft the unit would remain dormant. When the host spacecraft completed its mission, or in the event of an unrecoverable malfunction of the host, the Terminator Tether unit would activate itself, ejecting away from the host and deploying its conducting tether below the spacecraft. Voltages generated by the motion of the conducting tether across the geomagnetic field would enable the tether to collect electrons from the conducting ionospheric plasma. These electrons would flow down the tether to the Terminator unit, where they would be emitted back into the ionosphere. The flow of current along the tether would generate a drag force through electrodynamic interactions with the geomagnetic field, and this drag force would deorbit the tether and its host spacecraft over a period of several months.



Figure 1. The Terminator Tether brassboard prototype developed in prior efforts.

Several design objectives chosen early in the development of the Terminator Tether technology drove the system’s complexity and cost. The first objective was to minimize the deorbit time achievable within a mass allocation of 2% of the host spacecraft mass. This objective drove the system design to a very high-performance electrodynamic tether system, requiring a relatively long tether length of 5-10 kilometers, as well as requiring active electron emission at one end of the tether. Both HCPC and FEAC electron emission devices have significant power, mass, and cost impacts. A second objective was to enable the device to be autonomous, requiring no input power from the

host spacecraft, and enabling the device to deorbit the host spacecraft even if the host had malfunctioned and lost all control and power. This autonomy requirement drove the design to incorporate power conversion electronics to enable the system to power itself using the voltage and current generated by the electrodynamic tether. Furthermore, it required inclusion of avionics to implement the autonomy. The need to ensure that these systems would all function with high reliability after up to a decade on-orbit resulted in system costs beyond that desired by spacecraft integrators.

2. Design Objectives for a Next Generation Deorbit Module

Recently, the DoD, NASA, FCC, and other agencies that regulate space activities have become more diligent about enforcing end-of-mission disposal guidelines, driving a market need for a cost-effective satellite disposal technology. Based upon the results of our prior work, we chose to develop a new generation of deorbit technologies, focusing on a design approach that would seek to minimize complexity, technical risk, cost, and mass while enabling spacecraft operators to comply with the 25-year orbital lifetime restriction. This design focus has resulted in a rather different system concept.

The Terminator Tape Deorbit Module

To provide a significantly more cost-effective means for satellite operators to comply with the 25-year post-mission orbital lifetime restriction, Tethers Unlimited is developing a lightweight de-orbit module called the “Terminator Tape”. The Terminator Tape Deorbit Module is, essentially, a small, flat box that bolts onto any side of a spacecraft during pre-launch integration. At the completion of the spacecraft’s mission, the spacecraft will activate the module with a simple pyro signal. The module will then deploy a several-hundred meter length of thin conducting tape. Regardless of what direction the tape is initially deployed in, gravity gradient forces will (eventually) orient the tape along the local vertical direction, either above or below the spacecraft. This tape will not only significantly increase the aerodynamic drag experienced by the system, reducing its ballistic coefficient, but will also generate electrodynamic drag forces through passive interactions with the Earth’s magnetic field and conducting ionospheric plasma. With proper selection of tape length, width, and conductivity, the enhanced aerodynamic drag and passive electrodynamic drag will be sufficient to de-orbit the satellite from orbits up to 900 km within 25 years. The Terminator Tape technology is highly scalable to accommodate different satellite sizes. Tethers Unlimited is currently developing two Terminator Tape modules, one sized for 180-kg ESPA-secondary-payload class satellites, and the other sized for 1-5 kg CubeSats and other pico- and nano-satellites.

Aerodynamic Drag Enhancement

Once the gravity gradient forces orient the tape roughly along the local vertical direction, the tape will increase the system’s aerodynamic drag cross section by an amount approximately equal to

$$A_{drag, tether} \approx \frac{2}{\pi} wL, \quad (1)$$

where the factor of $2/\pi$ results from the assumption that the tape either has some twist along its length, or that the system rotates around the tape’s long axis.

Passive Electrodynamic Drag

The principal of passive electrodynamic drag generation by the Terminator Tape is illustrated in Figure 2. The orbital motion of the conducting tape across the Earth’s magnetic field will induce a voltage along the tape, equal to

$$V = \vec{L} \cdot (\vec{v} \times \vec{B}), \quad (2)$$

where V is the induced voltage, \vec{v} is the orbital velocity of the system, \vec{L} is the vector from one end of the tape to the other, and \vec{B} is the geomagnetic field vector. In a direct orbit, this voltage will bias the top of the tape positive relative to the ambient environment, and the bottom of the tape negative. This voltage bias will enable the top portion of the conducting tape to collect electrons from the ionospheric plasma, and the bottom portion of the tape will collect ions, resulting in a small but significant flow of current up the tape. Note that this ‘passive’ current collection works regardless of whether the tape is deployed above or below the host spacecraft, and so the Terminator Tape does not require specific placement on the spacecraft or deployment in a particular direction.

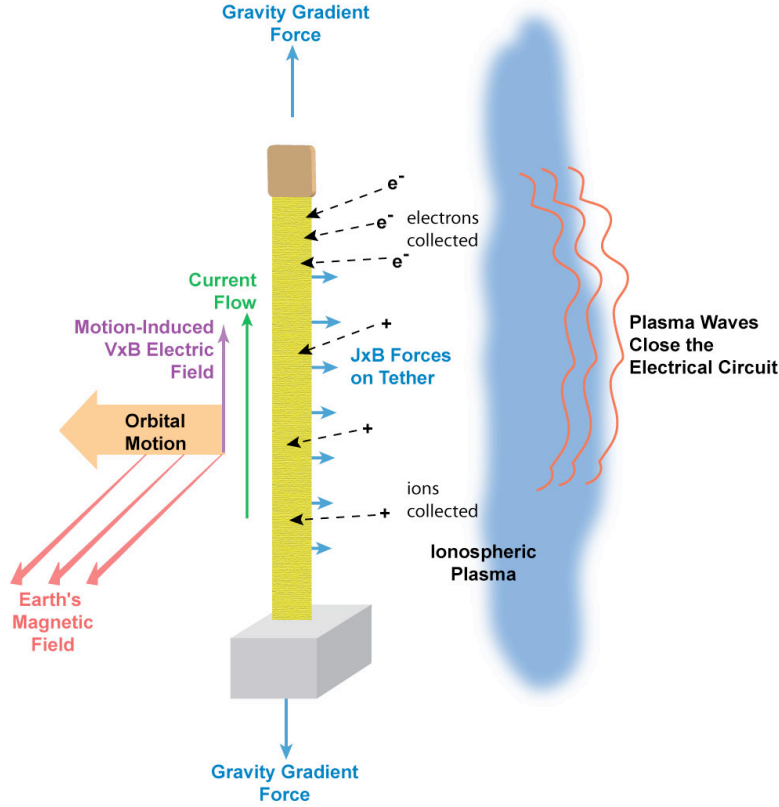


Figure 2. Illustration of the physics of passive electrodynamic drag on the Terminator Tape.

This current exchange with the conducting plasma will result in a flow of current \vec{I} up the tape, and this current will interact back with the Earth's magnetic field to induce a Lorentz force that will oppose the orbital motion of the spacecraft, lowering its orbit:

$$\vec{F} = \int_0^L (\vec{I} \times \vec{B}) d\ell, \quad (3)$$

where the integral is performed along the length of the tape to account for variations in the current density along the tape. Because ions are heavier and thus much less mobile than electrons, most of the length of the tape will be collecting ions, balanced by a short electron-collecting length at the top of the tape. The collection of electron and ion currents by the biased tape of width w can be approximated using the Orbit Motion Limit theory,⁶

$$\frac{dI_{electron}}{d\ell} = -(2w) e \frac{n_{\infty}}{\pi} \sqrt{\frac{2e(\Delta V)}{m_e}}, \quad \frac{dI_{ion}}{d\ell} = (2w) e \frac{n_{\infty}}{\pi} \sqrt{\frac{2e(-\Delta V)}{m_i}}, \quad (4)$$

where ΔV is the voltage difference between the metalized film and the local plasma potential, m_e and m_i are the electron and ion masses, and n_{∞} is the local plasma density. At an altitude of 700 km, where the plasma density is on the order of $1.2 \times 10^{11} \text{ m}^{-3}$ at local noon, a 250 m long, 0.28 m wide Terminator Tape will collect an ion current density of approximately 68 $\mu\text{A/m}$ over most of its length, resulting in peak currents of approximately 10 mA. While this is a small current, it will result in a drag force of approximately 15 μN . Thus at 700 km altitude, the passive electrodynamic drag will roughly double the net drag on the tape. Because the ionospheric plasma density drops more slowly with altitude than the neutral density, above about 700 km altitude the electrodynamic drag will exceed the neutral density drag. Thus the Terminator Tape module will provide significantly lower deorbit times than aerodynamic-drag-only systems, thereby dramatically increasing the altitude range over which satellites can meet the 25-year orbital lifetime requirement.

Terminator Tape for ESPA-Class Microsatellites

Hardware Implementation

Under funding from the Air Force Research Laboratory Space Vehicles Directorate at Kirtland AFB, NM, Tethers Unlimited is developing a Terminator Tape Module sized for ESPA-Class Microsatellites. The module's configuration is shown in Figure 3. The module has a square 8"x8" footprint, sized so that it will fit inside the Mark II Lightband release clamp used for ESPA payloads, as shown in Figure 4. The module is designed to deploy a conducting tape with a width of 17 cm and a length of 100-250 meters. Actuation of the Terminator Tape Module is accomplished using a single NEA Model 800 actuator, fired by a standard pyro signal from the host vehicle. If desired, the module is designed to accommodate an additional NEA Model 800 actuator that can serve as a 'safety' to provide redundant restraint of the module, ensuring the module deploys only when desired. An initial engineering model prototype is shown in Figure 5. The mass of the module with a 150 m long, 17 cm wide tape is 1.5 kg.

The design of the tape must ensure that it will maintain electrical conductivity and tensile integrity over 25 years deployed on orbit while minimizing the mass required for the tape. To accomplish these objectives, the tape will be constructed of thin metalized films commonly used in multi-layer insulation with the addition of embedded metalized aramid fibers intended to provide rip-stop characteristics, enhanced conductivity, and increased M/OD survivability.

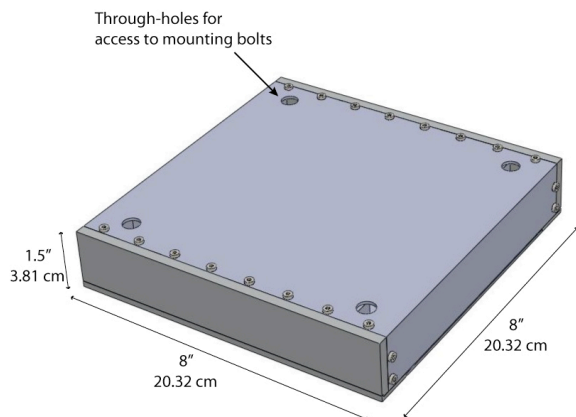


Figure 3. Terminator Tape Deorbit Module design for ESPA-class microsatellites.

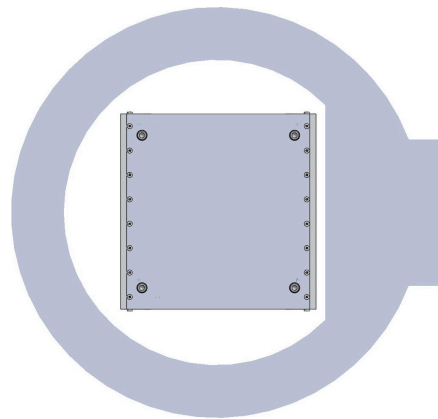


Figure 4. The Terminator Tape Deorbit Module fits within the keep-out zone of the motorized 15" Mark II Lightband used for ESPA microsatellite payloads.

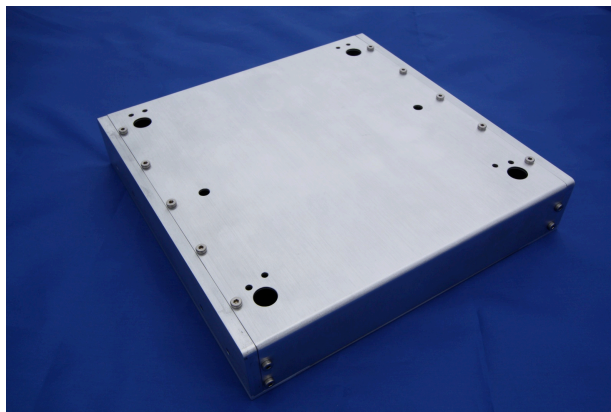


Figure 5. Engineering model prototype of the Terminator Tape module for ESPA-class microsatellites.

Predicted Performance

The amount of time required for a Terminator Tape Module to de-orbit a spacecraft will depend upon the spacecraft mass, initial altitude and inclination, tape width, tape length, and tape linear resistivity. To evaluate these dependencies, we utilized the TEMPEST code, an electrodynamic tether simulation code developed by the University of

Michigan. TEMPEST includes models for electrodynamic drag, aerodynamic drag, and orbital mechanics, and utilizes NASA-standard environment model codes such as the IRI-90 ionospheric plasma model and MSIS90 and MSIS86 neutral density models. The TEMPEST code does not model tether dynamic behavior, but because the electrodynamic forces in the Terminator Tape are very small compared to the gravity gradient forces, tether dynamics can be neglected for this application, and simulations of several decades of operation can be conducted in a matter of hours.

Figure 6 shows plots of time versus altitude for four different several tape lengths. The four curves were generated by simulating systems deorbiting from an initial altitude of 900 km, and plotting the resultant data with the time on the y axis and the altitude on the x-axis. The higher-order oscillations on the curves at altitudes greater than 670 km are the result of variations in aerodynamic and electrodynamic drag due to solar cycle impacts on neutral and ionospheric plasma densities during the deorbit period. Thus the deorbit time from a given altitude will vary depending upon when in the solar cycle the Terminator Tape is deployed, with the longest deorbit times occurring when the system is activated a few years after solar max. The figure indicates that for ESPA-class microsatellite payloads, a 150 meter long, 17 cm wide tape will suffice to deorbit satellites from orbits up to about 850 km within 25 years.

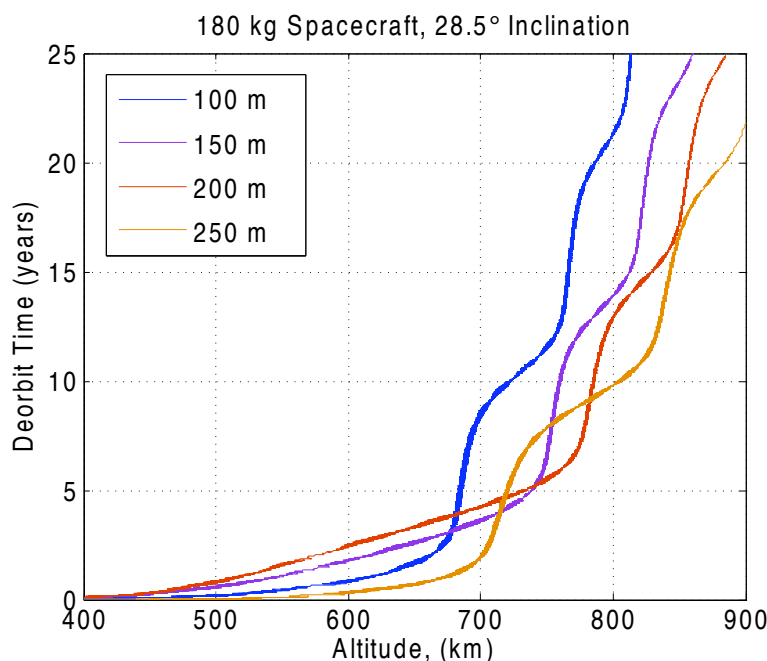


Figure 6. Deorbit time versus altitude for a 180 kg spacecraft in a 28.5 degree orbit, as a function of tape length, for a 17 cm wide tape.

Figure 7 shows plots of deorbit time versus altitude for four different orbit inclinations. For initial altitudes above about 670 km, deorbit times from polar and sun-synchronous orbits will be approximately 10 years longer than from low-inclination orbits due to weaker electrodynamic coupling between the orbital motion and the geomagnetic field. However, even in near-polar orbits, a 150 m long, 17 cm wide tape will suffice to deorbit ESPA-class microsatellites from altitudes up to 850 km.

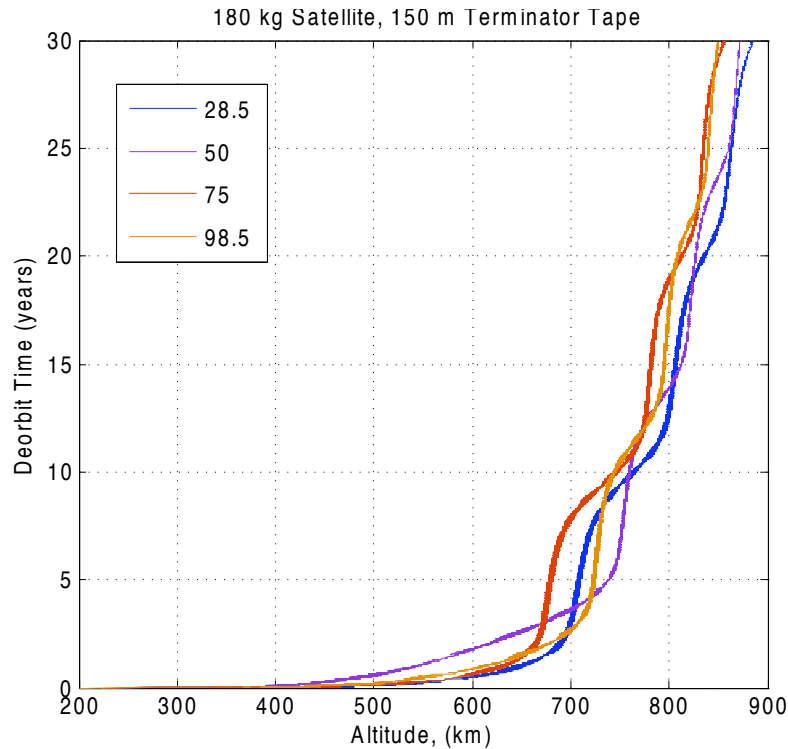


Figure 7. Deorbit time versus altitude for a 180 kg spacecraft with a 150 m Terminator Tape, as a function of inclination, for a 17 cm wide tape.

AREA TIME PRODUCT

To minimize the chances that a satellite will fragment and contribute to the growth of the space debris population, it is necessary to not only reduce the orbital lifetime of the satellite, but also reduce its area-time-product, which determines its probability of experiencing a collision with another space object. Deorbit devices which rely exclusively upon drag enhancement may reduce the orbital lifetime of a system, but for these systems the orbit lifetime scales as the inverse of the deployed area, so they offer little or no improvement in area-time-product. Because the Terminator Tape induces both aerodynamic and electrodynamic drag to accelerate the deorbit of a spacecraft, it can achieve a net reduction in area-time-product, and thus a reduction in the probability the object will experience a collision. Figure 8 shows plots of deorbit time and area-time-product for 17 cm wide tapes of varying length. The plot

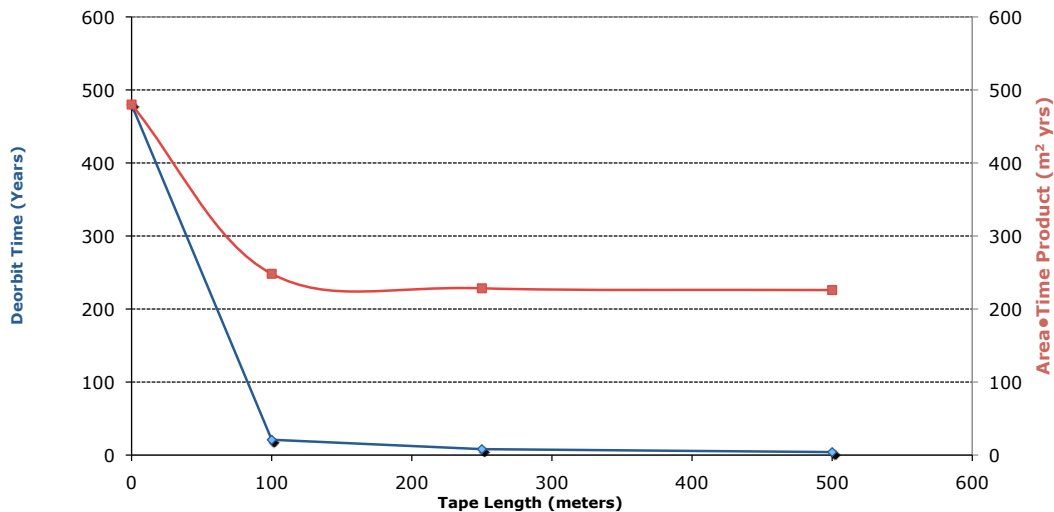


Figure 8. Variation of deorbit time and area-time-product with tape length, for a 180 kg spacecraft with a 1m² cross section, deorbiting from an 800 km initial orbit.

indicates that the Terminator Tape module can roughly halve the area-time-product of the satellite. There appears to be little advantage to using tape lengths in excess of 150 meters in terms of reducing area-time-product, so in designing a Terminator Tape module for a given spacecraft, the tape length should be chosen as the minimum length at which the system will meet the 25-year lifetime restriction.

nanoTerminator Tape for CubeSats

Nano- and pico-satellites such as CubeSats have developed as an attractive platform for conducting space flight missions rapidly and at low cost. A large number of organizations, including government agencies, universities, and commercial companies, are taking advantage of the lower cost barrier to spaceflight afforded by the CubeSat program, and even if only a small fractions of these programs make it all the way to flight they will contribute dozens of new objects to the space catalogue per year. Because these spacecraft typically fly as secondary payloads, their operational orbit is determined by the launch vehicle's primary payload orbit, and as a result, most opportunities to fly CubeSats are in orbits where the CubeSat will not meet the 25 year orbital lifetime restriction without use of a drag enhancement device. Fortunately, the Terminator Tape technology is highly scalable, and so we have also implemented the technology in a device suitable for use on CubeSats and other pico- and nano-satellites, shown in Figure 9. This “nanoTerminator Tape for CubeSats” is sized to mount on one face of a CubeSat. It can be mounted so that it projects out into the ‘extra volume’ beyond the rail faces, as permitted by the CalPoly P-POD payload specification, as illustrated in Figure 10. The module contains a 30-m length of conducting tape. The lid of the module is restrained by a burn wire actuator, which can be activated by a small circuit board that must be integrated into the CubeSat. The module design includes electrical feed-throughs so that solar cells can be mounted on the face of the module. The mass of the module, including circuit board, but not including battery, is 80 grams.

Hardware Implementation

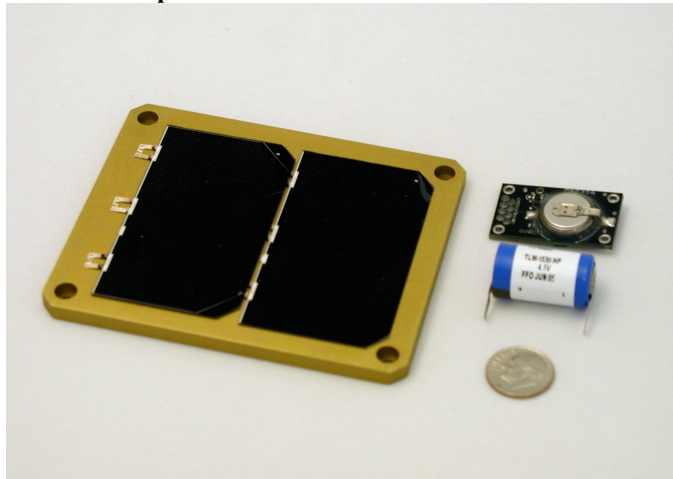


Figure 9. Photograph of a preliminary engineering model of the nanoTerminator Tape for CubeSats.

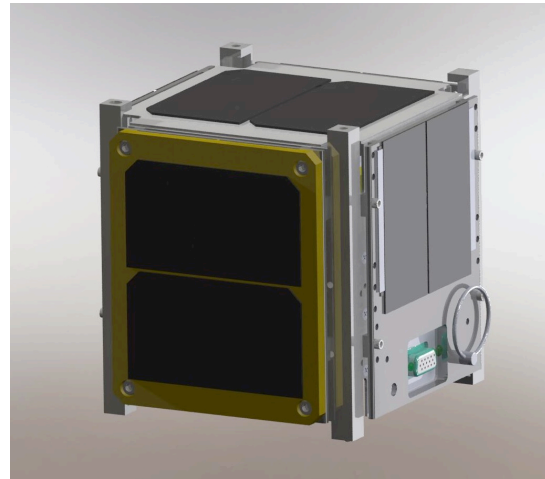


Figure 10. Rendering of a nanoTerminator Tape module integrated onto a 1U CubeSat.

Predicted Performance

Figure 11 shows graphs of deorbit time versus initial altitude for CubeSats with and without nanoTerminator Deorbit Modules. With no drag device, 1U CubeSats will exceed the 25 year orbital lifetime restriction if they are deployed above about 650 km. The nanoTerminator Tape module, however, will enable even 3U CubeSats to meet the 25 year lifetime restriction in orbits up to 1000 km.

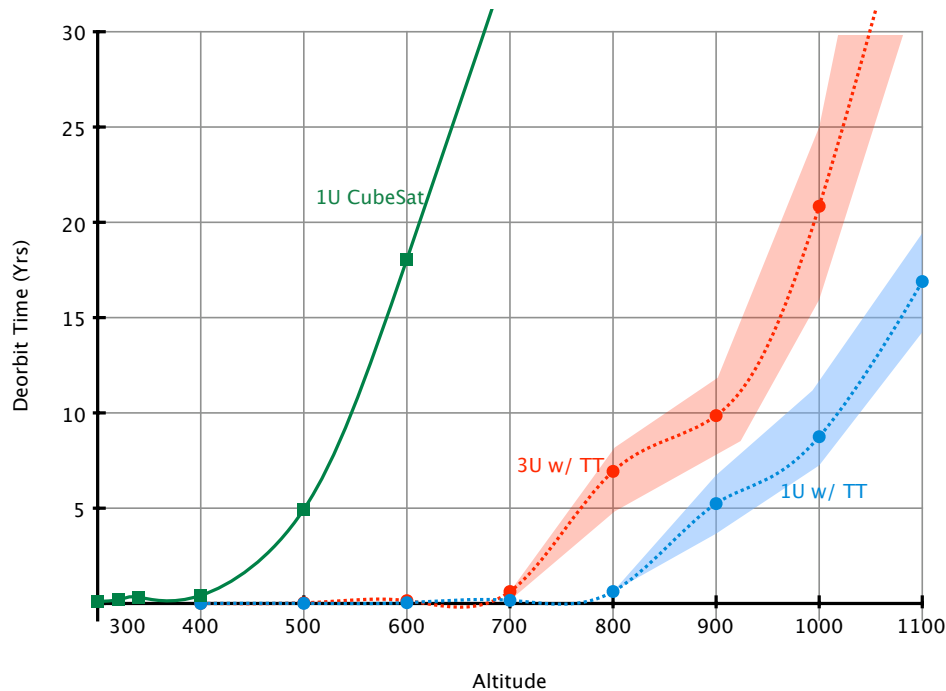


Figure 11. Deorbit Time for 3U, 3kg CubeSats and 1U, 1 kg CubeSats, with nanoTerminator Tape modules, as a function of initial orbit altitude. Deorbit times for a 1U CubeSat without a drag device is also shown. The shaded regions illustrate (approximately) the variability of deorbit time as the tape deployment time is varied relative to the phase of the solar cycle.

Conclusions

The Terminator Tape Deorbit Module has been developed to provide a means to enable satellite programs to comply with orbital lifetime restrictions with minimum mass, cost, and risk impacts to the program. The technology is highly scalable, and Tethers Unlimited is currently developing two modules, one sized for ESPA-class microsattel- lites and the second sized for CubeSats. Analyses of the system’s performance indicate that this technology can enable ESPA-class micosatellites to meet 25-year orbital lifetime restrictions in operational orbits as high as 850- 900 km, and CubeSats as high as 1000 km.

Acknowledgments

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