In-Flight Performance of the Terminator Tape End-of-Life Deorbit Module

Harrison C. Stankey, Robert P. Hoyt,
Tethers Unlimited, Inc.
11711 N Creek Pkwy S Suite D-113, Bothell, WA 98011; +1 (425) 486-0100
hstankey@tethers.com

ABSTRACT

The Terminator Tape™ is a passive deorbit module that utilizes both electrodynamic and aerodynamic drag effects to reduce spacecraft deorbit time. To date, three satellites have deployed Terminator Tapes, accumulating a total flight time of approximately thirty months. The first two deployments, on the NPSAT-1 and PROX-1 satellites, are starting multi-year deorbit profiles that will characterize Terminator Tape performance over a full solar cycle as they descend from altitudes above 700km. Additionally, the DRAGRACER mission recently demonstrated performance at lower altitudes, where aerodynamic drag becomes the dominant effect and has given insight into late-stage performance of the tape. Analysis of the impact of the drag tape solution on the overall probability of collision with active satellites indicates the Terminator Tape can significantly reduce collision risks relative to an unaided passive decay approach.

INTRODUCTION

The Terminator Tape, developed by Tethers Unlimited, Inc. (TUI), is a passive deorbit module that leverages both electrodynamic and aerodynamic drag effects to rapidly deorbit spacecraft from orbit. The Terminator Tape is a readily scalable technology, and TUI has qualified and flown two configurations of the module, the NSTT, which deploys a 15cm wide x 70m long conductive tape, and the CSTT, which deploys a 7.5cm wide x 10m long conductive tape. Three NSTT units have been deployed in LEO and are currently deorbiting their spacecraft. This paper will present the flight data and perform analyses to compare the flight results with expected models. Basic theory will also be explored to provide physical explanations for the phenomena observed.

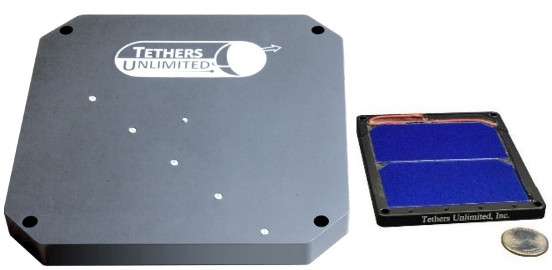

Figure 1: Terminator Tape Units; Right to Left, NSTT [180x180x18mm], CSTT [100x100x6.5mm].

THEORY

The Terminator Tape Deorbit Module is, essentially, a small, flat box that bolts onto any side of a spacecraft during pre-launch integration. The module consists of a cover plate, a restraint/release mechanism, a bottom mounting plate, and a length of metalized membrane tape folded up within the module and connected to both cover and mounting plates. At the completion of the spacecraft's mission, either the spacecraft or a separate timer/deadman activation circuit activates the module's release mechanism with a simple electrical signal. The module then releases and ejects its cover plate. The cover plate's momentum pulls the tape out, deploying it from the satellite. Regardless of what direction the tape is initially deployed in, gravity gradient forces will tend to orient the tape towards the local vertical direction, either above or below the spacecraft.

The Terminator Tape utilizes passive interactions with the space environment to hasten the deorbit of a spacecraft through two different physical phenomena: electrodynamic drag and aerodynamic (neutral particle) drag. The electrodynamic drag force generally is the dominant drag force at altitudes above 700km for low inclinations.[2] At lower altitudes and higher inclinations, aerodynamic drag enhancement due to added drag area of the thin-deployed tape, tends to dominate.

Electrodynamic Forces

As the conductive tape orbits the earth, its orbital motion across the Earth's magnetic field generates a Lorentz voltage along the length of the tape, represented by Equation 1. The voltage bias charges the ends of the tape relative to the ambient ionospheric plasma, attracting ionospheric ions at one end and ionospheric electrons at the other, resulting a small but significant flow of current along the tape. The current flow along the length of the tape interacts with the Earth's magnetic field, inducing a Lorentz force that opposes the velocity vector, regardless of the up-down orientation (see Equation 2). This process is also depicted in Figure 2.

$$\boldsymbol{V} = \vec{\boldsymbol{L}} \cdot (\vec{\boldsymbol{v}} \times \vec{\boldsymbol{B}}) \quad (1)$$

$$\vec{F} = \int_0^L (\vec{I} \times \vec{B})\, d\ell \quad (2)$$

where V is the induced voltage, $\vec{v}$ is the orbital velocity of the system, $\vec{L}$ is the length vector of the tape, $\vec{B}$ is the geomagnetic field vector, and $\vec{I}$ is the induced current.

In order to generate current, electron and ion exchange must occur, which is characterized by Orbital Motion Limit (OML) theory.[1] The equations for ion and electron exchange are shown in Equations 3 and 4.

$$\frac{dI_{electron}}{d\ell} = -(2w)e\frac{n_\infty}{\pi}\sqrt{\frac{2e(\Delta V)}{m_e}}, \quad (3)$$ [1]

$$\frac{dI_{ion}}{d\ell} = (2w)e\frac{n_\infty}{\pi}\sqrt{\frac{2e(-\Delta V)}{m_i}}, \quad (4)$$ [1]

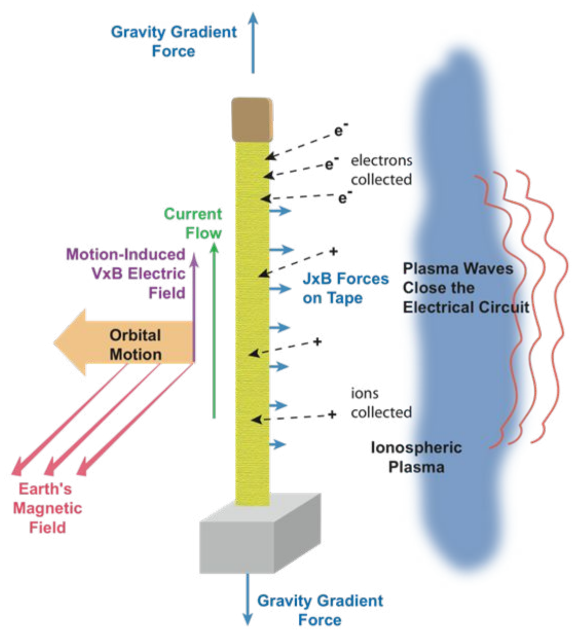

Figure 2: Terminator Tape Electrodynamic Effects

where w is the tape width, e is the elementary charge, n_∞ is the local plasma density, ΔV is the voltage differential between the metallized film and the local plasma, and m is the charged particle.

Aerodynamic Forces

As the tape orients itself along the local vertical, due to the gravity gradient, the thin film tape generates aerodynamic drag, which is represented in Equation 5.

$$A_{drag,tether} \cong {}^{2}/_{\pi}\, wL \quad (5)$$

where the factor of ${}^{2}/_{\pi}$ accounts for the likely random twist of the tape about its long axis.

Vertical Axis Stability

In order to generate maximum electrodynamic and aerodynamic drag, Terminator Tape relies on gravity gradient stabilization, also called tidal stabilization, represented by Equation 6.[5] This effect is dominant in higher altitudes, resulting in a stable orientation along the local vertical (nadir-zenith). At lower altitudes, aerodynamic torques (Equation 7) can alter the stable orientation of the tape and will partially reduce the effective drag demonstrated by the unit, as depicted in Figure 3. Since the duration of transit through lower altitudes is very short compared to the overall deorbit time, the reduced drag compared to the ideal case has a minimal impact on overall deorbit times, especially for missions that begin from higher altitudes.

$$\boldsymbol{T_g} = \frac{3\mu}{2R^3}\left|I_z - I_y\right| \sin(2\Theta) \quad (6)$$ [5]

$$\boldsymbol{T_a} = \frac{1}{2}\rho C_d A_r V^2 (cp_a - cm) \quad (7)$$ [5]

where T_g is the gravity gradient torque about the spacecraft's X principal axis, μ is the Earth's gravitational constant, R is the distance to the center of the Earth, Θ is the angle between the local vertical and the spacecraft z-axis, I_z and I_y are the moments of inertia about the Z and Y principal axes respectively, T_a is the atmospheric torque on the system (or element), ρ is the atmospheric density, C_d is the coefficient of drag, A_r is the ram area, V is the spacecraft velocity, cp_a is the center of pressure, and cm is the center of mass of the system.

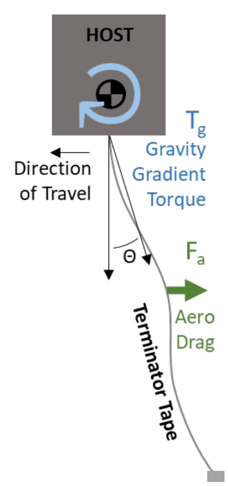

Figure 3: Gravity Gradient Stabilization and Aerodynamic Torque Disturbance

FLIGHT DATA

The three craft with deployed Terminator Tape units and associated mission data are listed in Table 1.

Table 1: Deployed Terminator Tape Missions

Craft (Mission)	Deploy Date	CAT ID
PROX-1 (STP-2)	09/23/2019	44339
NPSAT-1 (STP-2)	12/24/2020	44340
Alchemy (DRAGRACER)	11/21/2020	46954

NPSAT and PROX-1 (depicted in Figure 4) were launched on June 25th, 2019 to a shared orbit at an average altitude of approximately 720km. The two NanoSat Terminator Tape (NSTT) units, each mounted on one of the satellites along with timer units programmed to activate the NSTT deployment a pre-determined time after separation of the satellite from the launch adapter. The timer unit on PROX-1 was programmed to deploy after 90 days. The second unit, on NPSAT-1, was programmed to activate after 18 months. Tracking data from USSPACECOM, obtained through the Space-Track web portal, indicate that both units activated as intended and the Terminator Tapes are accelerating the orbital decay of these two spacecraft, as shown in Figure 5.

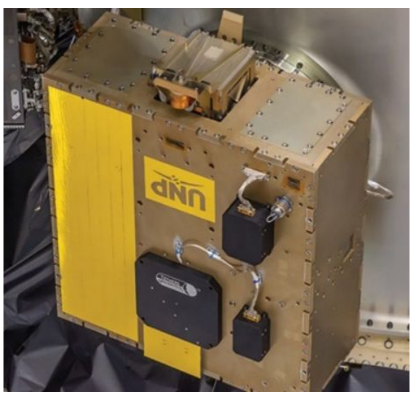

Figure 4: NSTT on PROX-1; Credit: SpaceX

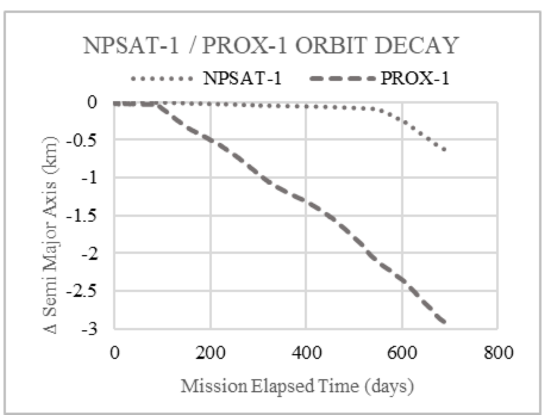

Figure 5: NSTT Effect on Orbital Decay of NPSAT-1 and PROX-1[3]

On November 19th, 2020, as a part of the DRAGRACER experiment, twin satellites with identical size and mass were launched to 500km, one named "Alchemy" with an NSTT and one named "Augury" without, to serve as a control.[4] Soon after launch, the Alchemy satellite deployed its NSTT and began deorbiting (see Figure 6).

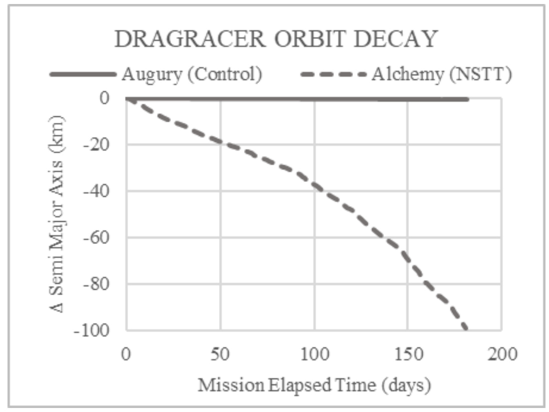

Figure 6: NSTT Effect on Orbital Decay of for DRAGRACER Satellites (500km)[3]

ANALYSIS OF FLIGHT DATA

PROX-1 & NPSAT-1 Missions

In both PROX-1, and NPSAT-1, a clear change in decay rate is seen after the onboard timers trigger the deployment of the NSTTs (T+90 and T+548 days respectively). The resulting decay rate curves are shown in Figure 7.

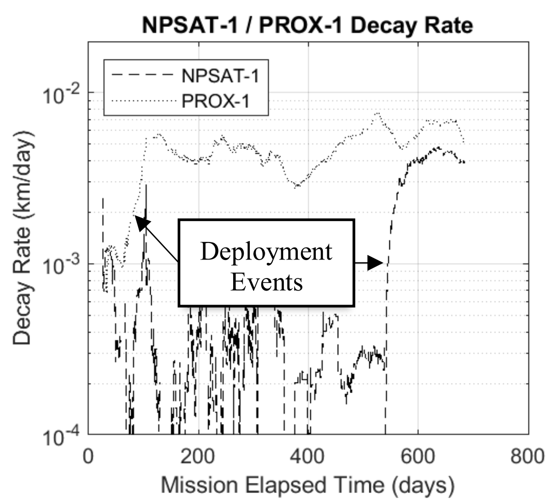

Figure 7: Orbital Decay Rate of NPSAT-1 and PROX-1 Satellites (Processed)[3]

As shown in Figure 7, in both cases the decay rate leaps more than an order of magnitude after deployment. The difference in the post-deployment orbital decay rate is due primarily to mass and satellite cross-sectional area variations between the two systems. It is also notable that the current deorbit rates are representative of solar minimum conditions. Deorbit rates depend strongly on solar activity levels, which drive both ionospheric plasma densities and neutral particle densities, and both NPSAT-1 and PROX-1 are expected to rapidly increase their decay rate in the next few years as the sun's activity rises with its 11-year cycle.

In pre-flight analysis, TUI used the TEMPEST code, a software developed by the University of Michigan, to predict the deorbit performance of the Terminator Tape. The TEMPEST code simulates electrodynamic interactions between an extended conductor and the Earth's ionosphere and magnetic field, as well as neutral particle drag. It does not, however, model detailed dynamic behavior of the tape, such as electrodynamic-induced swing or oscillations. Running the PROX-1 mission through TEMPEST yields a predicted decay rate of 7.79 m/day. The mean decay rate of PROX-1 shown in the flight data is 4.95 m/day (std = 1.43 m/day), or 63% of the predicted value. The discrepancy is hypothesized to be due to dynamic behavior of the tape that is not captured by the TEMPEST model. In future efforts, TUI will use its TetherSim code, which simulates tape oscillations and satellite dynamics, to determine if the variation in decay rate can be explained by tape dynamics.

DRAGRACER (Alchemy & Augury)

The DRAGRACER Mission offers a different view into the effect of Terminator Tape. Since the NSTT was deployed immediately upon arrival on orbit, Alchemy's orbit decay can be compared directly against that of Augury's, and environmental variations and spacecraft differences can be ignored, until sufficient altitude divergence occurs. Figure 8 shows a factor of 89 difference in decay rate between the two craft (for the first 90 days of flight) and a steady increase in this value as Alchemy falls further into the thicker atmosphere.

Since Alchemy is passing through the lower parts of LEO (<500km), the tape orientation is expected to start being pulled back by the aerodynamic torque on the system. As described in the Theory section, this results in a reduced drag compared to a case where the tape were to maintain vertical orientation all the way through the thickest portions of Earth's atmosphere. One of the key functions of this mission was to characterize this effect and to improve the accuracy of simulations of the expected drag at lower altitudes.

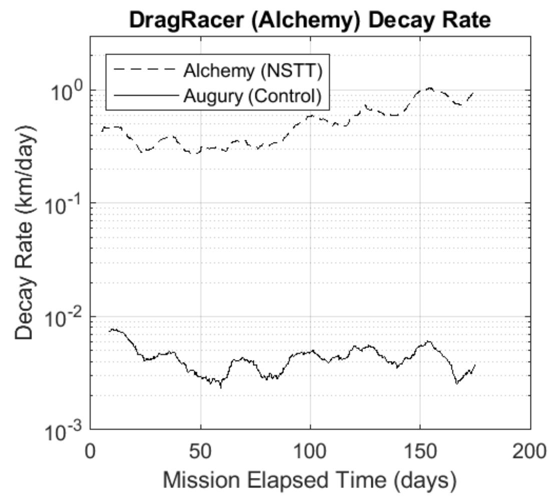

Figure 8: Orbital Decay Rate of DRAGRACER Satellites (Processed)[3]

TUI estimates that the NSTT on Alchemy is still maintaining 52% of its ideal drag case, where the tape is oriented perfectly with the local vertical. This is modeled in NASA's Debris Assessment Software (DAS) in Figure 9, where the output closely follows that of the flight data (shown in Figure 10).

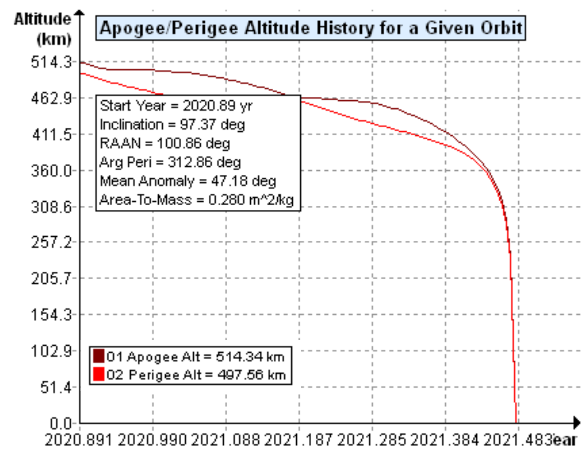

Figure 9: Alchemy Orbit Decay Simulation in NASA's Debris Assessment Software (DAS)

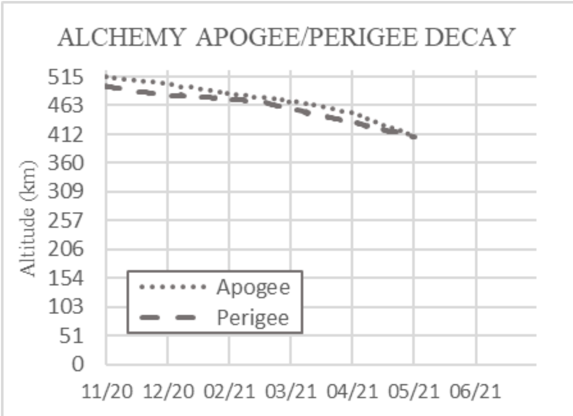

Figure 10: Alchemy Apogee and Perigee Time History Match DAS Model

COMMENTARY ON DEBRIS ENVIRONMENT

As the growing space debris problem becomes closer and closer to the Kessler Syndrome scenario, TUI recognizes the need to take rapid and radical approaches to cleaning up the orbital environment.

Time-Area Product

While there are several other passive deorbit modules on the market[6], most have seemingly minimal or no improvement on the key metric for addressing orbital debris mitigation, the "time-area product", the importance of which is captured in Equation 8.

$$\boldsymbol{Risk_{collision}} \propto (\boldsymbol{time_{deorbit}}) * (\boldsymbol{area}) \qquad (8)$$

While a drag sail decreases orbit time, it also increases its area, increasing the impact risk per unit time, essentially resulting in a near identical total risk of collision over the time on orbit. The parameters necessary to optimize a drag-only device are identified by a joint paper between the University of Milan, IFAC-CNR, LuxSpace, and ESA, which saw under certain cases up to a factor of 4.9 decrease in total collision risk.[7] Since Terminator Tape imposes an electrodynamic drag on the system, the time-area product is further reduced, giving it an advantage over drag-only devices.

Growing Debris Concentration

Since the debris environment is also changing, the time-area product cannot be the only consideration. Equation 8, along with many collision risk analyses, assumes present debris conditions to be representative of the future conditions. Because both the population of space debris in LEO is projected to continue to grow due to collisions, and the population of active satellites is projected to grow due to proliferation of LEO constellations, greater weight should be placed on future time on orbit than on near-present time on orbit. When accounting for this, the case for passive deorbit systems becomes clearer. **Error! Reference source not found.** compares the normalized collision risk for a deorbiting satellite that ends its mission early through the use of a passive system, compared to the case where it relies upon drag on the satellite to deorbit in 25 years, as required by the ODMSP.[8] For the modeled case, the Terminator Tape reduces the overall collision risk of the system by 86%. It should also be noted that the majority of the area-time-product of the TT-assisted case is a gossamer-thin membrane, which is highly unlikely to have sufficient kinetic energy to cause a catastrophic debris-generating collision. Consequently, the Terminator Tape can dramatically reduce the overall risks of catastrophic debris generating collisions that would contribute to the growth of the space debris population.

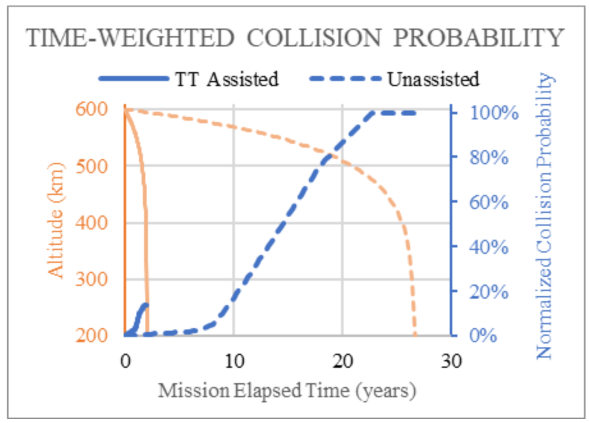

Figure 11: Collision Risk Analysis Accounting for Growth in Number of On-Orbit Objects

Because this effect is so pronounced, the time-area-product (Equation 8) should be re-written to include the function of the growth of the number of objects in LEO, as shown in Equation 9, when considering sufficiently long time-periods.

$$Risk_{collision} \propto area \int_0^T f_{growth}(t)dt \qquad (9)$$

CONCLUSION

Tethers Unlimited, Inc. (TUI) has performed three successful deployments of its Terminator Tape units on orbit. The NPSAT-1 and PROX-1 missions will be valuable for refining long-term models of Terminator Tape throughout the various phases of the solar cycle. As DRAGRACER ends its short seven-month mission, it has provided valuable metrics to inform proper modeling of the aerodynamically-dominated regime of low-altitudes. Terminator Tape has been demonstrated to be a valuable asset in the global effort to reduce orbital debris and will be a key technology for ensuring the sustainable use of space.

ACKNOWLEDGEMENTS

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