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Technology Demonstrator of a Standardized Deorbit Module Designed for CubeSat and RocketPod Applications

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ABSTRACT: The population of man-made orbital debris is growing rapidly, dominating the meteoroid environment in all but the micrometer size range. Objects between 1 cm and 10 cm - referred to as the *lethal* population are of most concern, as they are difficult to track and can cause catastrophic damage when colliding with a satellite. Many nanosatellites are launched as secondary payloads meaning that the initial orbit can be very constrained and have an expected post-mission lifetime exceeding the recommended 25 years. To address this problem, TUI has designed a standard tether module that can be used to reduce the expected lifetime of a nanosatellite by increasing its aerodynamic and electrodynamic drag. Most of this module's design is leveraged from TUI's Multi-Application Survivable Tether (MAST) experiment. The module itself is designed to accommodate tether lengths ranging from up to a few kilometers, and can be readily integrated with a CubeSat, RocketPod™ and other larger spacecraft. As a proof-of-concept demonstrator mission, this module is integrated with standard components from other CubeSat mission, and packaged as a RocketPod™ payload. Additional components from the MAST mission are also utilized in this technology demonstration mission.

Introduction

The population of man-made orbital debris is growing rapidly, dominating the meteoroid environment in all but the micrometer size range. Objects between 1 cm and 10 cm - referred to as the lethal population – are of most concern for space system safety, as they are difficult or impossible to track and can cause catastrophic damage when colliding with a satellite. To limit future debris generation, NASA and other government agencies have published policies and recommendations that require the satellite owners to either move the satellite into a disposal orbit at the end of its mission, or limit the post-mission orbital lifetime of the satellite to less than 25 years. Tethers Unlimited previously developed the Terminator Tether™, a lightweight low-cost device that utilizes electrodynamic drag generated by a bare conducting tether to remove satellites and upper stages from low to medium earth orbit when they have complete their mission. The Terminator Tether™ device consists of a bare conducting tether, a tether deployer, an electron emitter, and avionics to control the deployment and operation of the tether. This system was designed for large spacecraft that required high levels of drag in order to achieve a short orbital lifetime.

To date, all of the past and proposed bare tether electrodynamic missions have relied upon plasma contactors at the cathodic and anodic ends of tether to maximize current draw through the tether and thereby maximize thrust. For applications where system drivers of size, mass, power and cost overwhelm the performance goals, we propose to utilize bare tethers that do not use plasma contactors, and in particular do not rely on electron emitters (e.g. hollow cathodes, field emissive array cathodes) at the cathodic end. This type of system is particularly attractive when used to deorbit a launch vehicle third or upper stage simply to meet the 25 year lifetime requirements for debris mitigation. A system configuration for nanosatellites, its performance analysis and simulation results will be discussed.

Bare electrodynamic tethers have been studied previously for propulsion in high power systems where the bare tether acts as an anode, and current closure is achieved primarily through active cathodes. For systems where module volume, mass and budget are very constrained, such as nanosatellites in the 1-10 kg range, simplification of the tether system through the omission of the plasma contactors (field emission cathodes, hollow cathodes, grid anodes) may enable an electrodynamic tether system to meet performance requirements while fitting within cost and size constraints. A contactor-less tether electrodynamic system does not function well in the thruster mode where the power sources are used to reverse the natural direction of current flow due to the high impedance contacts to the ambient plasma. Such a system does function sufficiently well to be used in the generator mode to accomplish the deorbit of a satellite system, and in particular can enable nanosatellite systems and rocket upper stages to meet disposal guidelines for mitigation of space debris.

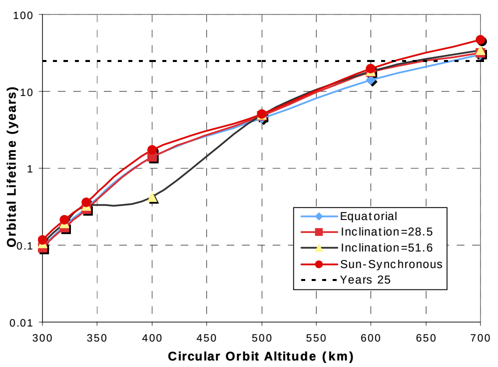


Figure 2. Simulated orbital Lifetime for a CubeSat satellite without deployables from a given initial circular orbital altitude.

Recently, nanosatellites have become a viable platform for low-cost scientific research, and significant numbers of these 1-10 kg spacecraft are being launched as secondary payloads each year. Their role as a secondary payload means that usually the selection of their initial orbit can be quite constrained by the requirements of the primary payload. For most nanosatellite secondary flight opportunities, the initial orbit is such that the nanosatellite will have an expected post-mission lifetime exceeding the recommended 25 years. To address this problem while fitting within the extreme constraints on subsystem mass and volume, TUI has developed a very small, standardized tether module that can be used to reduce the expected lifetime of a nanosatellite by increasing its electrodynamic and aerodynamic drag. In essence this device is a scaled down implementation of the Terminator Tether™, with the significant omission of the electron emission device and control electronics. The module itself is designed to accommodate variable tether lengths, and can be readily integrated with a CubeSat and RocketPod™ payload. as well as upper stages and inter-stage structures and other larger spacecraft. As many of the nanosatellites have diameters close to 10 cm, this module is key to reducing the orbital debris growth due to long-orbiting non-functional nanosatellites. While the deorbit time of such as system is significantly greater than that for a Terminator Tether™ device with an active cathode, analyses will show that the system works sufficiently well for nanosatellite applications to enable them to meet debris mitigation guidelines.

Deorbit Tethers with Cathodic Electron Emitters

Electrodynamic tether deorbit systems function by converting orbital energy to electrical energy, which is then dissipated as heat, thereby causing the altitude reduction of the satellite system. The motion of the conducting tether through the Earth's magnetic field generates a voltage along the length of the tether; in a direct orbit, the top of the tether will be charged positively relative to the ambient ionospheric plasma (Figure 1) Most of the tether length will be left uninsulated, so that the bare wires can efficiently collect electrons from the ionosphere.[2] These electrons will flow down to the bottom of the tether, and in an active system such as the Terminator Tether™ an electron emission device such as a hollow cathode plasma contactor (HCPC) or field emission array cathode (FEAC) located at the bottom tether endmass will expel the electrons back in to the ionosphere. Thus a current will flow up the tether, and the current "loop" will be closed by plasma waves in the ionosphere.[3,4] The current flowing through the tether will then interact with the Earth's magnetic field to generate a Lorentz **J**x**B** force on the tether, which opposes the orbital motion of the tether. Through its mechanical connection to the host spacecraft, the tether will thus drain the orbital energy of the spacecraft, lowering its orbit until it disintegrates in the upper atmosphere.

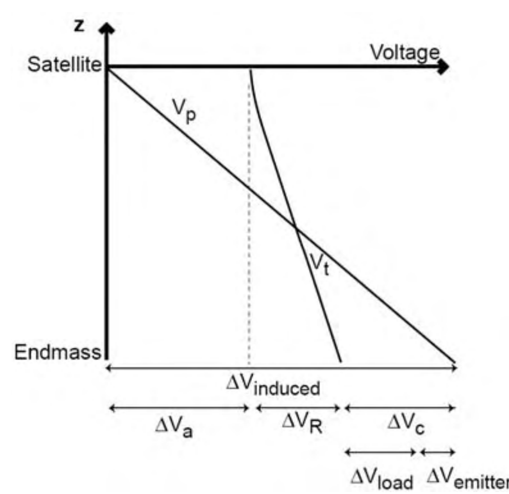


Figure 1. Tether voltage and plasma voltage along the tether length.

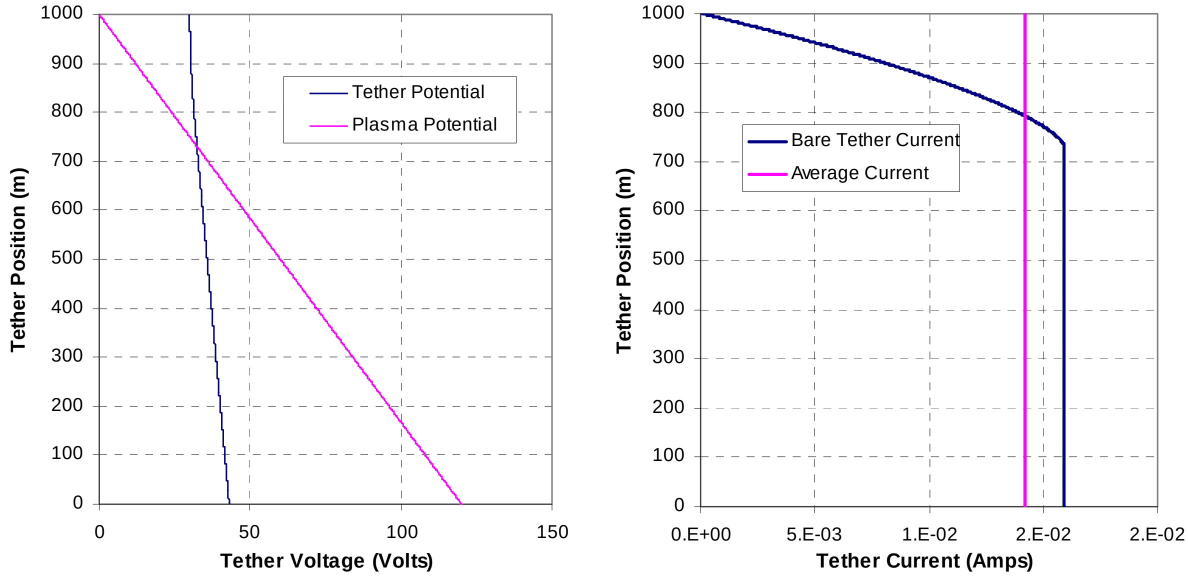


Figure 3. Voltage and current profiles of a 1km fully bare electrodynamic tether operating in generator mode with a 10Ω load and a cathodic emitter with a ΔV_c= -75 volts.

A representative current and voltage profile for an electrodynamic tether system that is comprised of a fully bare tether and a cathodic plasma contactor is depicted in Figure 3. The parameters are as follow: a 1 kilometer tether with a resistance of 918Ω, connected to a 10Ω load, and an emitter with a ΔV_c=-75 volts. It should be noted that this system's performance, as measured by average current, is most significantly dominated by the system's ability to collect electrons, which is in turn is primarily driven by the cost of the voltage drop at the cathode. Some performance gains can be had by reducing the resistance of the tether and by partially insulating the tether so as to minimize ion collection in the lower segment of the tether.

The advantage of this configuration is that the current levels and thrust (drag) are reasonably high and will affect orbital change of the system quite rapidly. The tradeoff here is that one needs a robust cathode with sufficient consumables to last the period of operation (if required), and an avionics stack to modulate the current levels in the tether to minimize undesired libration modes. Ultimately, this is a system that requires control.

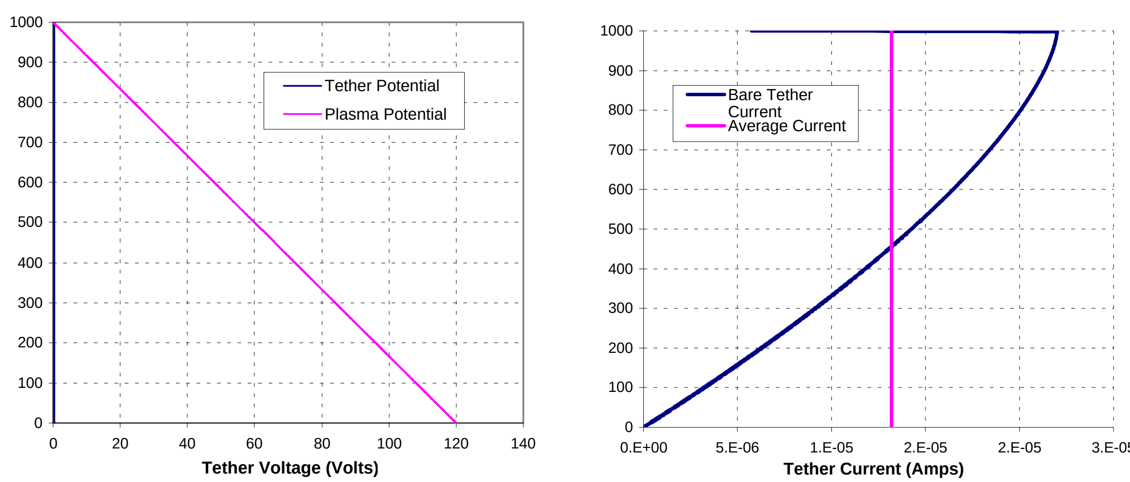


Figure 4. Voltage and current profiles for 1km fully bare contactor-less tether in low-earth orbit operating in deorbit (generator) mode.

Deorbit Tethers WITHOUT Cathodic Electron Emitters

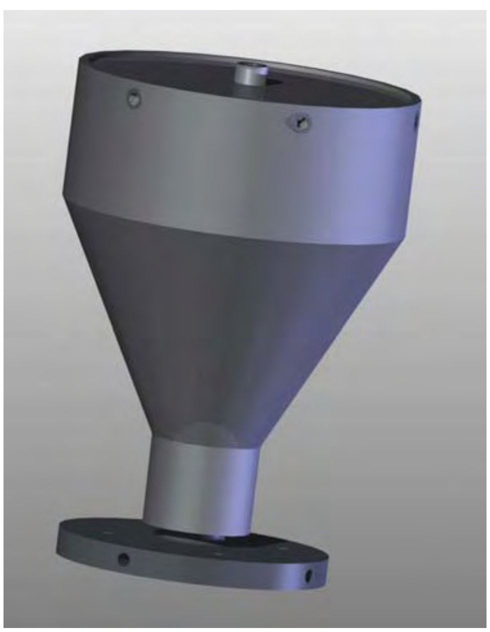
In an effort to simplify the system and minimize required spacecraft resources, we propose to remove the cathodic contactor from the electrodynamic tether system. While this greatly reduces the performance of the system, the complexity is also significantly reduced. For those spacecraft operators that are simply looking to meet the 25 post-mission orbit lifetime of their satellite with minimal expenditure of resources this type of system can be very attractive. Although it seems somewhat counterintuitive, the absence of any avionics and resultant lack of control over the system can actually be a significant benefit for potential users. When a satellite is intentionally deorbited under operator control, as is commonly done with chemical propulsion, the operator is assuming responsibility for the debris that survives reentry and where it falls. When a satellite deorbits naturally without control, reentry is an Act of God with minimal responsibility to the operator. From an operational perspective, at the end of mission life, the tether is deployed, and the operator simply walks away.

From a performance perspective, the average current along the tether is drastically reduced compared to a system with an active electron emitter. For comparison, the voltage and current profiles for the same 1 kilometer, 918Ω bare tether system are depicted in Figure 4. Most notably, the average current and therefore thrust (drag) is reduced by three orders of magnitude. As a bare tether system with no contactors, the tether must collect a net current of zero, so it is not unexpected that the majority of the tether is collecting ions. As the current levels are quite low, the resistance of the tether itself, as well as the addition of a load resistor, has very little effect on the current capabilities of the tether. It is also interesting to note that at these low current levels, the energy available to add energy to undesirable libration modes is also greatly reduced and typically well below the gravity gradient force.

One possible way to enhance performance of the system may be to coat the lower portion of the tether with a low work function metal to enhance the emission of secondary electrons as well as the photoemission currents from the cathodic end of the tether.

The nanoTerminator™ Device

Due to the relatively low per satellite costs associated with launching nanosatellites in the 1-10 kilogram class, the number of nanosatellites being launched is growing. This growth is being enhanced by the development and availability of standardized nanosatellite classes such as the CubeSat (http://www.cubesat.org) and Ecliptic Corporation’s RocketPod™. Should a nanosatellite developer build a spacecraft that conforms to one of these well-specified nanosatellite standards, the satellite can be readily deployed as a secondary payload from a number of upper stages. As noted previously, the orbit into which the nanosatellite is deployed is typically determined by the requirements of the



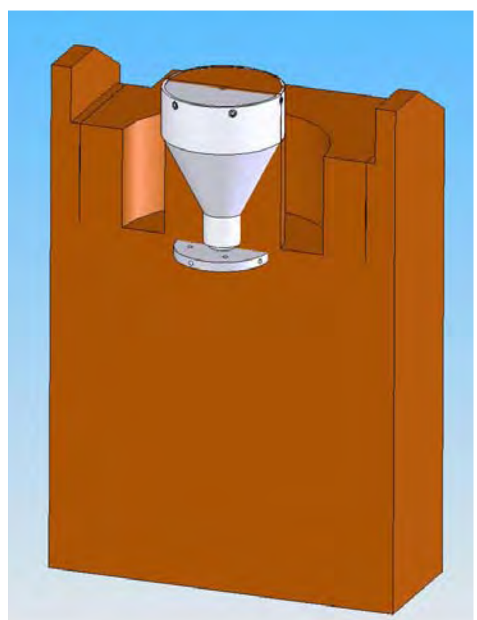


Figure 5. Rendered drawing of a CubeSat/RocketPod class nanoTerminator™ module. The device requires a 54.5mm by 38 mm diameter envelope, with a mass of less than 100 grams. This module fits nicely within the extended ‘neck’ volume of a standard RocketPod satellite, which is shown on the right.

launch vehicle's primary payload, not the desires of the nanosatellite developer. The challenge here is that a single CubeSat satellite weighing 1 kg with a cross sectional area of 0.01m^2 (or a triple CubeSat with a mass of 3 kg and an area of 0.03 m^2) has a ballistic coefficient in the range of 45 kg/m^2, which when launched to an initial circular orbital altitude greater than 620-680 km has a lifetime exceeding the 25 years specified by the NASA Debris Mitigation Guidelines. In Figure 2Figure 9 we see that the deorbit times are higher at high inclination orbits, however this dependency on inclination is quite low when atmospheric drag is the mechanism of deorbit.

At the scale of these satellites, there is not much mass or volume available for a deorbit system that would be needed to allow the satellite operator to take advantage of a launch should it place secondary payloads in an orbit higher than 620 km. In addition, many nanosatellites do not have sophisticated attitude stabilization and control, making it difficult if not impossible to generate thrust in a specific desired direction.

To enable developers of nanosatellites as small as the CubeSat or RocketPod to take advantage of more launch opportunities while complying with debris mitigation guidelines (and potential future requirements), TUI has developed the nanoTerminator™ deorbit module. The nanoTerminator™ module consists of a multi-strand conductive Hoytether™,a tether spool/endmass, and a mounting/ejection post that remains with the host spacecraft. To reasonably fit within the constraints of a single CubeSat or RocketPod satellite, the module was designed to fit within a 54.5mm long by 38mm diameter envelope with a total mass less than 100 grams (comparable to a D-cell battery.)

The tether for the nanoTerminator™ is made of Dupont's Aracon™ and DSM Dyneema™ yarns. Aracon™ is a copper and nickel clad Kevlar™ yarn used as the conductive element of the tether. The Aracon™ yarn has a resistance of 9180Ω/kilometer. To increase the probability of tether survivability, additional yarns are braided with the Aracon™ to create a failure-resistant multi-strand Hoytether™ structure. As the strength re-

Figure 6. nanoTerminator™ tether with 2 primary and 1 secondary lines.

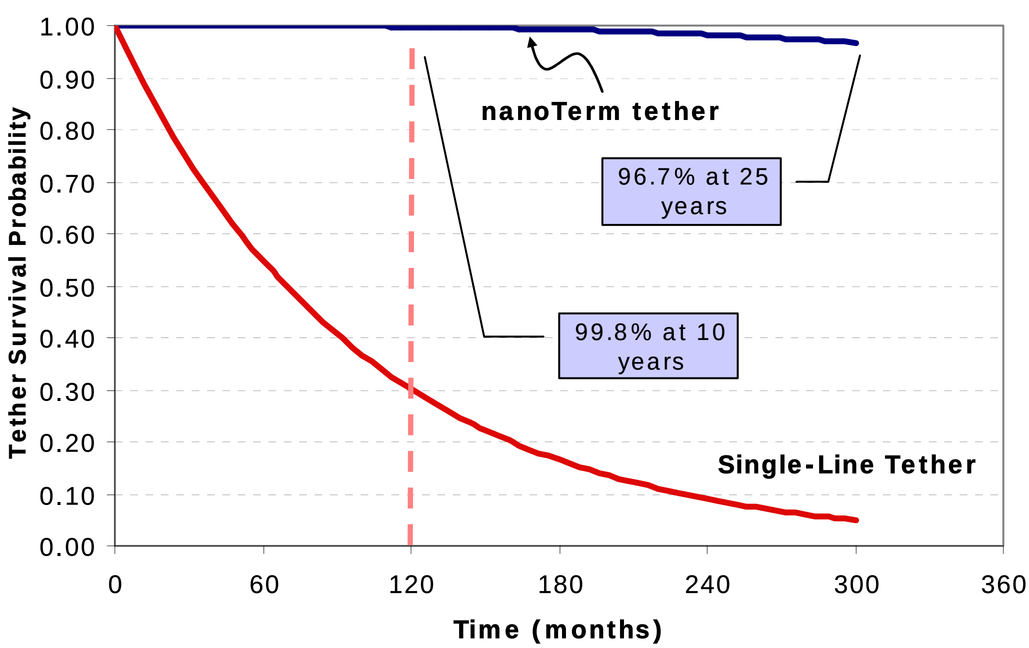


Figure 7. The predicted tether survivability of the nanoTerminator's tether and of an equivalent-diameter single-line tether over a 25 year MEO orbital lifetime.

quirements of this tether are negligible compared to the strength of a single yarn or aramid fiber, to minimize the mass and packed volume of this tether, a very fine denier Dyneema™ yarn was used. This structure was constructed on TUI's computer controlled braiding machine which produces the structure photographed in Figure 6. The nanoTerminator™ tether has 2 primary lines nominally separated by 25 mm, and a single secondary line that interconnects the two primaries every 0.5 meters providing redundant load paths should one of the primaries be cut. To cause a failure and separation of the tether, all three lines must be cut by micrometeoroids, or by a single large debris object, both which have a low probability. Over 25 years, the probability of the tether remaining intact exceeds 99%.

The nanoTerminator™ tether module nominally has 100 meters of multi-strand conductive tether wound onto the spindle. During fabrication, the tether is wound in such a way as to survive launch intact without wind slippage, yet deploy with minimal drag and zero net twist. After winding the tether spool is shrouded, connected to the ejection mechanism and secured with a 'remove before flight' screw to prevent inadvertent deployment. The nanoTerminator™ module is then installed by bolting the base of the module to the structure of the satellite. For maximum flexibility, the nanoTerminator™ module does not an include integral spool retention and release mechanism. It is up to the user to specify and select this mechanism.

Cathodeless nanoTerminator™ Deorbit Times

After the nominal mission operations are complete, the nanoTerminator™ tether deployment is initiated. Based on a number of mission requirements, this deployment can be initiated either by operator command or through the expiration of a watchdog timer. The use of a watchdog timer can be quite advantageous as should the satellite experience a failure and become inoperative and unresponsive to commands, the remove of the satellite from its operation orbit shall commence. Care would have to be taken to prevent premature activation and loss of a functional satellite. The activation command for the nanoTerminator™ simply needs to effect release the tether spool by actuating the release mechanism. The spring energy contained in the ejection mechanisms would then deploy the nanoTerminator™ tether to its full length at which point the electrodynamic drag starts reducing the orbital energy of the satellite. In addition, the ballistic coefficient is drastically reduced through the significant increase in total cross sectional area significantly increasing the atmospheric drag. The simulated orbital decay profile of a single CubeSat with a 100 meter tether from a 550 kilometer circular sun-synchronous orbit is shown in Figure 9.

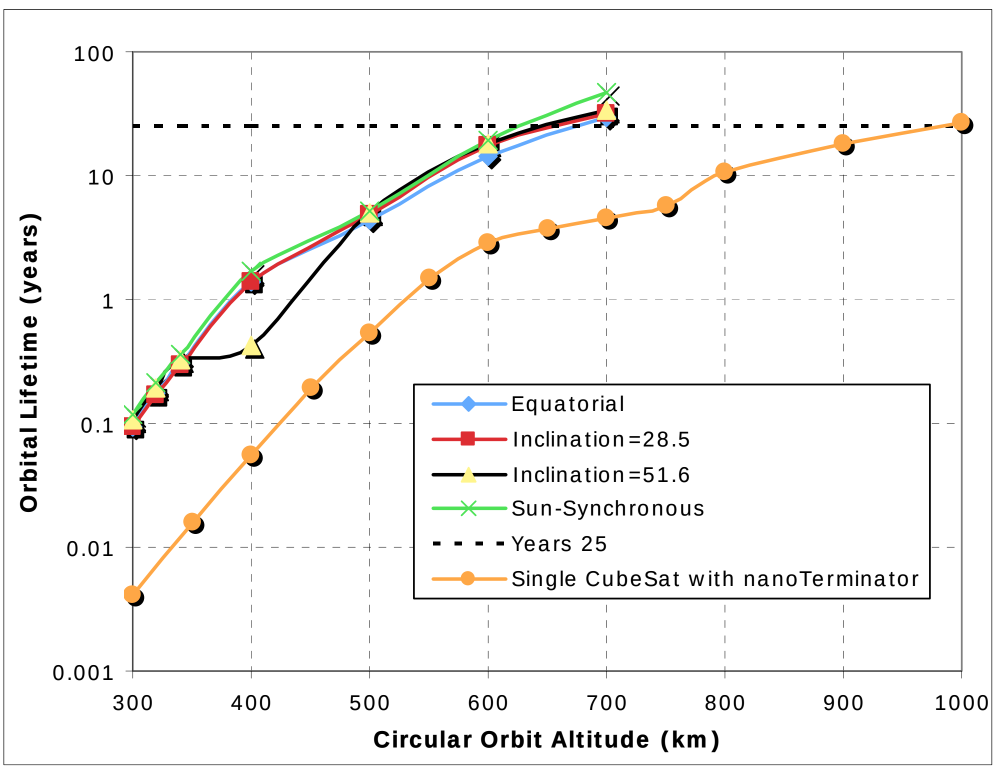


Figure 8. Simulated orbital Lifetime for a single CubeSat satellite without deployables from a given initial circular orbital altitude, as compared to a single CubeSat with a 100m nanoTerminator™ contactorless deorbit tether system.

The combination of electrodynamic and atmospheric drag from the 100 meter tether then significantly reduces the orbital lifetime of the nanosatellite – by approximately an order of magnitude (Figure 8). The inclusion of the nanoTerminator™ module into the design of a nanosatellite will raise the ceiling of the initial secondary payload orbit from 620-680 kilometers to nearly 1000 kilometers. The deorbit lifetimes depicted in Figure 8 showed surprisingly little variation in orbital inclination and can readily be approximated by the single plot. Should an increase or decrease in orbital lifetime be desired, the length of the tether can be readily adjusted (within reason and available volume) to accommodate varied requirements. Ultimately if a longer tether is needed, a larger tether spool and shroud would be required.

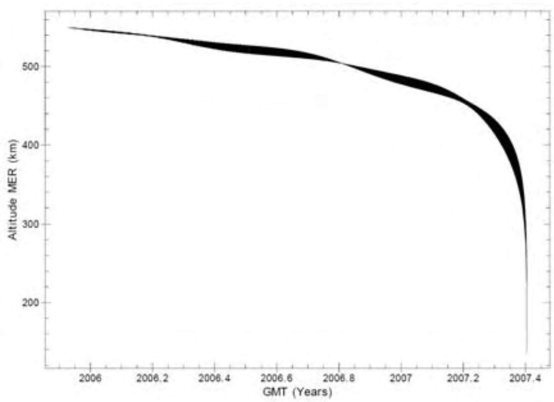


Figure 9. Simulated decay profile for a initial 550km sun-synchronous orbit (97.58° inclination) orbit.

TechnologyDemonstrator Mission – BarnacleSat

Montana State University's **S**pace **S**cience and **E**ngineering **L**aboratory (SSEL) is currently developing a CubeSat-type spacecraft, BarnacleSat (BSat) in collaboration with Tether's Unlimited, Inc. (TUI) and Ecliptic Enterprises. The BarnacleSat mission is currently supported by the Montana NASA Space Grant Consortium (MSGC), whose mission requirements are defined by the aforementioned entities. SSEL is entirely a student-based organization with the philosophy of exposing students to all aspects of satellite design, manufacture and operation. The BarnacleSat Program is a product of the internationally recognized CubeSat Program, and the vision of both academic and industry participants.

BarnacleSat Mission Statement and Objectives

The objective of the BarnacleSat mission is to demonstrate the capabilities of a bare electrodynamic tether to increase the deorbit rate of a booster or satellite at the end of its operational mission. The form factor for BarnacleSat will be the RocketPod™ Plus form factor, which is similar to the CubeSat form. The RocketPod™ Plus form factor was selected here as it provided the

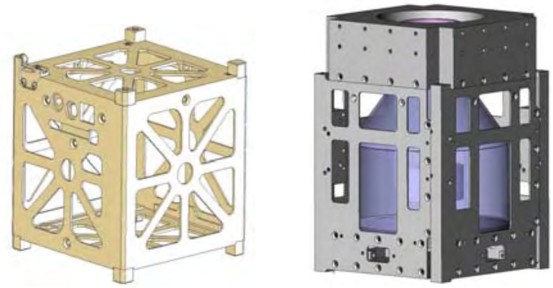


Figure 10. P-POD (CubeSat Kit by Pumpkin) and RocketPod™ Plus example payloads.

additional volume required for the tether required to significantly increase the deorbit rate of a spent Delta II upper stage.

In addition to preparing a deployable payload for the RocketPod™'s first flight, BarnacleSat will also accommodate a TUI tether payload to demonstrate the utility of a one-kilometer tether. Whereas nominally the RocketPod™ will be ejecting a free flying satellite, here the tether will connect the BarnacleSat deployed satellite to the spent orbital booster. BarnacleSat's primary mission goal will be to increase the natural-orbital decay rate of the booster following the completion of its primary mission. Under this pretense the design of BarncleSat is governed by the following requirements:

1. Monitor the increase orbital decay rate of the booster;
2. Obtain *in-situ* GPS position data to gain insight on the deployment dynamics of a TUI furnished tether deployer system;
3. To verify the survivability of a TUI conductive

Figure 11: BarnacleSat deployed from Delta II upper stage.

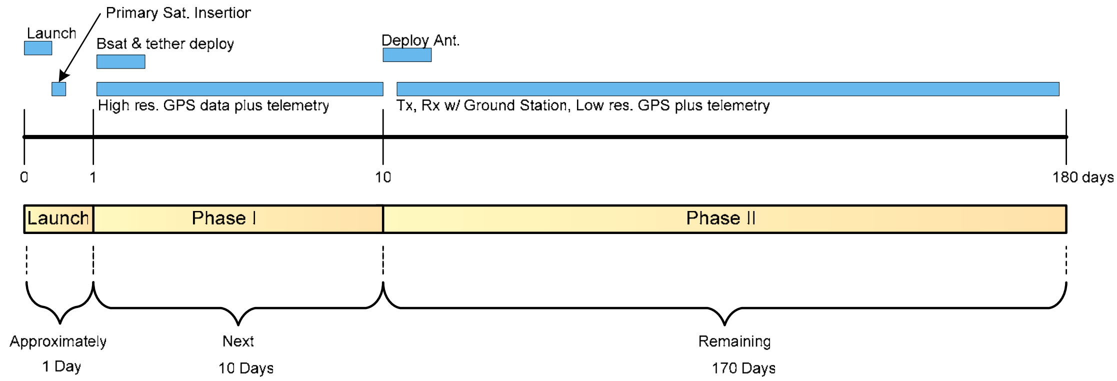


Figure 12: BarnacleSat Mission Timeline

tether and the variety of COTS subsystem components in the harsh realities of LEO.

BarnacleSat Mission

The BarnacleSat Mission will fly as a Class-D secondary payload ejected from the RocketPod™ deployer. The RocketPod™ will remaining externally attached to the orbit insertion stage of an ELV, and await command for BarnacleSat deployment only after the completion of the booster's primary mission. The separation speed of BarnacleSat is tunable between the limits of 1 m/s - 3 m/s prior to launch; to satisfy the requirements above it is anticipated that a slower ejection velocity will be chosen to aid in achieving the highest resolution of GPS data possible. Position and velocity data will then be recorder *in-situ* by BarnacleSat as a 1 km long conductive tether is deployed. The study of the dynamics of gossamer flexible structures is space is a complex problem that has been extensively studied and modeled however could greatly benefit from space flight data, as adequate ground simulation is not possible. The secondary objective of the BarnacleSat mission is to provide an accurate tether dynamics data set by which to validate such tether dynamics as incorporated in simulation packages such as TUI's TetherSim™.

Phase I of this mission encompasses the successful deployment of BarnacleSat; defined as that which ends with the tether unwound to its full length and gravity-gradient stabilized. The time scale on which gravity-gradient stabilization will occur is not predefined, and will only be determined once the data has been retrieved and analyzed. As a result of this uncertainty Phase I is currently defined to last ten days (upon deployment). Phase II then consists of the remaining 170 days where discretionary GPS data will be recorded in low resolution while the decay rate of the booster is monitored via radar here on Earth.

BarnacleSat CONOPS

The concept of operations (CONOPS) for the BarnacleSat experiment is subject to change, but currently based on philosophies of the Terminator™ demonstrator Mission along with heritage from the successful XSS-10 Mission. [3]

1. RocketPod™ will attach to a Delta II ELV as a secondary payload with BarnacleSat stowed within.
2. Once the second stage separates from the primary satellite RocketPod™ will await command to initiate the deployment of BarnacleSat.
3. After a period of time sufficient to ensure that the booster is oriented in a manner that will deploy the tether toward the preferred direction, a command will activate the RocketPod™'s separation mechanism to eject BarnacleSat. The initial ejection momentum will be sufficient to pull the tether out of the deployer to its full 1-km length. Passive braking will be used to halt the deployment in a gradual manner to prevent rebound of BarnacleSat.
4. Phase I is the time-sensitive, absolutely critical period which will define mission success. This period is currently defined to last 10 days beginning on deployment and encompassing the acquisition of high-resolution spatial and velocity measurements.
5. BarnacleSat's antennas will be deployed on completion of Phase I so that chances of entanglement with the tether are at a minimum.
6. Phase II begins with the antenna deployment and will encompass the remaining orbital mission lifetime up to 170 days. During this period BarnacleSat will transmit data at least once per day to the SSEL ground station. While continuing to monitor telemetry and GPS data at discretionary rates, data from both phases will be downloaded and processed.

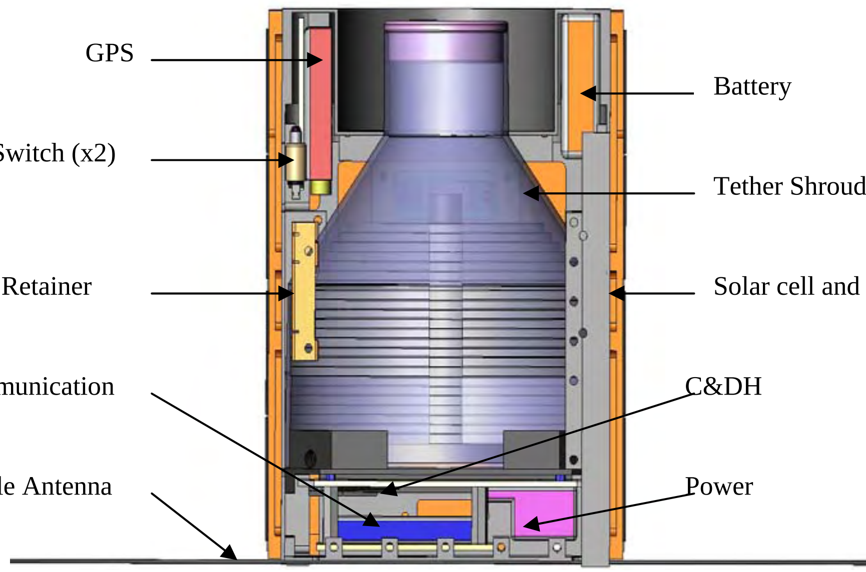


Figure 14: BarnacleSat Architecture and Subsystems.

BarnacleSat Mission Philosophy
BarnacleSat is the third satellite being built at SSEL, MSU-Bozeman. The SSEL is an academic institution which is managed by students who are responsible for a variety of high altitude and space deliverable platforms. That is to say that first and foremost, BarnacleSat is an educational project. Students are involved with every aspect of the satellite's design, fabrication, testing, communications, etc. The current constraints under which BarnacleSat is being constructed dictates it be constructed using mostly commercial off the shelf (COTS) hardware wherever possible and reasonable.

Subsystem Development and Systems Engineering
Detailed progress on BarnacleSat has been made and prototype construction and subsystem development is under way. The primary challenges in the satellite design have been to reduce the volume of spacecraft support systems within a bus that is only 30% larger that a standard CubeSat to accommodate a payload volume approaching 70% of the total spacecraft volume. An overview of some of the subsystems of note follows.

Structure
The RocketPod™ ICD dictates the physical structure of BarnacleSat so that the two entities will interface properly. Along with requirements from the ICD, the structure must withstand the specific g-loads, acoustic and vibration loads, and the thermal environment of space. The chassis of BarnacleSat consists of machined 6061 or 7075 aluminum sides fastened together with countersunk machine screws. Launch rails are provided in the satellite to successfully interface with the RocketPod™. A tether shroud bracket that interfaces the tether payload within the confines of BarnacleSat's interior is in fabrication. Aluminum solar panels have also been designed for securing solar cells to BarnacleSat's exterior. The estimated mass of the chassis is 670 g which is contributes significantly to the overall mass of the satellite which cannot exceed 2 kilograms. The antenna deployment mechanism will consist of a Delrin® housing where the antenna is attached, curled up and kept in place by a nylon string wrapped around a resistor. Current will be sent through the resistor causing it to heat

Figure 13: BarnacleSat Structure Engineering Model

the line, and the antenna to unfurl. Three printed circuit boards (PCBs) will carry the required BarnacleSat subsystems: a command and data handling (C&DH) board, a power management board, and a communications board. The GPS payload, batteries, and antennas will be mounted directly to the chassis.

Command and Data Handling (C&DH)

The C&DH subsystem is tasked with controlling most aspects of the internal electronics: communications uplink (Rx) and downlink (Tx), and organizing payload and telemetry data for transfer to the ground station. The choice of processors was driven primarily by SSEL's MEROPE mission heritage, power usage, processing speed, and adequate interfaces. The Motorola MC68HC812A4 (HC12) microcontroller is the heart of the C&DH board and was chosen for its speed, processing power, and integral features which include 8 channel 8-bit analog to digital converter (ADC) , watchdog timer, 1Kbyte random access memory (RAM), 4Kbyte programming space, external memory mapping, two serial interfaces, and a sufficient number of software and hardware interrupts. Also mounted to the C&DH board is a 128 Mbyte flash memory chip for data storage and additional A/D converters for capturing housekeeping and telemetry data.

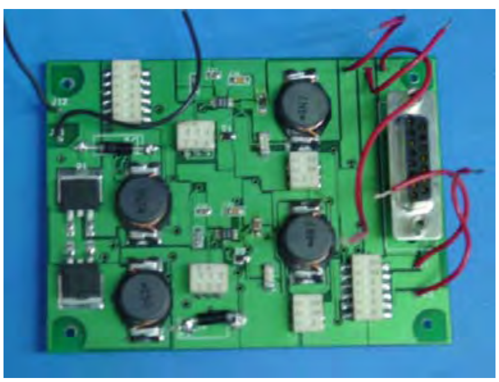


Figure 16: 5V Regulator, Test Board

Power

The power subsystem consists of one 3.6V lithium-ion cell for energy storage, diode protected double-junction solar cells, and a 5V and 3V regulator. The double-junction solar cells from Spectrolab measure 3.1 x 7 cm and are 21.5% efficient. Solar cells will encompass all four sides of the satellite in such a manner that three sides will have four cells in two strings, and the fourth side only having a string of two cells. The solar cells will provide 4.0 volts at a nominal 2.14 watts. The power budget reveals that the power system is required to generate a maximum 50 watt-hrs of energy per day.

Communications

The communications subsystem hardware consists of a Chipcon CC1000 ultra-high frequency (UHF) transceiver, and a Melexis TH1722 very high frequency (VHF) transceiver. Following in the footsteps of the MEROPE Mission the communications system onboard the satellite will be programmed to receive commands at a frequency in the 437 MHz band, and transmit data in the 145 MHz band. These decisions were based upon characteristics of SSEL's ground station and to minimize the amount of work required to prepare the ground station for the BarnacleSat Mission. Thus, the CC1000 Transceiver will serve as the RF receiver onboard the satellite while the Melexis chip will serve as the transmitter. The CC1000 transceiver chip has many favorable features including low quiescent power, programmable between 300-1000 MHz, operating from the 3.3V bus, built-in frequency shift keying (FSK) modulation with Manchester encoding, and 9600 KBaud data rate with an average current consumption of 9.3 mA. The TH1722 chip is less elegant than the CC1000, but will appropriately serve the transmission needs of BarnacleSat. The TH1722 runs on a 3.3V bus, has an adjustable transmit output power range from -20 dBm to +10 dBm, and is compatible with a 9600 KBaud data rate with NRZ encoding. The major constraint with a radio-on-a-chip is the limitations on the output power, therefore the integration Linx BBA-332-A amplifier is being considered. A subsystem requirement defines a minimum output power of 1W for transmission which means that the amplifier would need to produce a 30 dBm signal. The antenna consists of a half-wave dipole

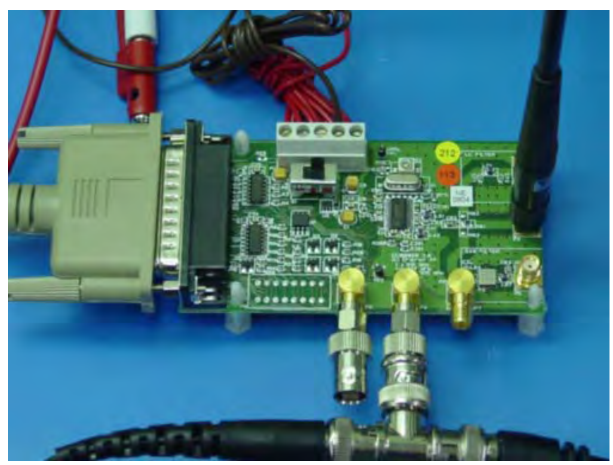


Figure 15: Communication System Prototype - Chipcon CC1000 Development Board.

with two separate elements on opposing sides of the spacecraft. A single dipole antenna will be tuned to the 2 m transmissions while the 3rd harmonic will remain sufficient for reception.

GPS Payload

The essence of the BarnacleSat Mission as well as one of the most challenging aspects is the selection of a GPS receiver along with its operation in a low earth orbital environment. A GPS unit is required to record position and velocity data in order to verify the performance of the tethered-satellite deployment. Currently, the Surrey Satellite Technology LTF SGR-05 GPS receiver is the leading choice due to its micro-satellite form factor.

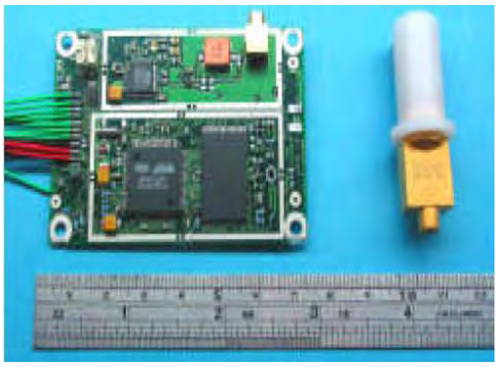


Figure 17: Surrey SGR-05 GPS Receiver

Tether Deployer

The tether subsystem which includes the tether, the spindle it is wound on, along with a shroud has been leveraged from TUI's Multi-Application Survivable Tether (MAST) experiment. This subsystems is fundamentally a scaled up version of the nanoTerminator™ module as required to deorbit a significantly larger spacecraft than a CubeSat or a RocketPod™ payload.

Figure 18. Rendering of the external view of BarnacleSat.

Ground Station

Communication with BarnacleSat will be done through a preexisting ground station located in Cobleigh Hall on the MSU campus. This same station is also responsible for ground-satellite communications between two other SSEL satellites: MEROPE and Maia. The ground station is made up of three main components. An Icom IC-910H satellite transceiver, a LabJack U12 interface to control the rotors on the roof, and a computer with satellite tracking software (Nova for Windows), to control the movement of the antenna array and to also handle communications and handshaking with the satellite.

The antenna array is located on the roof of the same building with two Yagi-Uda antennas tuned to the 70 cm and 2 m bands. The 70 cm antenna will be used for transmitting commands to BarnacleSat, and 2m antenna will be used to receive data from BarnacleSat.

Summary

In this paper, the concept of a bare electrodynamic tether system that does not utilize any cathodic plasma contactors was proposed for used in low-cost, low-mass and low-volume deorbit systems such as CubeSats and RocketPod™ payloads. A system based on this concept is ideal for applications where the satellite operator's key requirement is to simply meet the 25 year orbital lifetime limit after mission operations. In particular, this concept meets a number of key requirements for nanosatellite applications where the satellite developer/operator does not have any inputs into orbits as a secondary payload, and simply can choose whether or not take advantage of a particular launch opportunity. The nanoTerminator™ system targeted at CubeSat and RocketPod™ class payloads (1-3 kg mass, < 0.1 m^2 cross sectional areas) enables nanosatellite developers to consider a broader range or rideshare opportunities while still meeting the orbital debris mitigation guidelines. In addition, a larger scale technology demonstrator mission is currently under development and will demonstrate the increased orbital decay rate by deploying a 1 kilometer tether housed in a RocketPod™ end-body from a Delta II upper stage. Ultimately the deorbiting of satellites after their mission operations will help control the growth of the orbital debris population, thereby reducing the probability of on-orbit conjunctions, collisions, and the number of required maneuvers that other spacecraft must perform to avoid collision with orbital debris.

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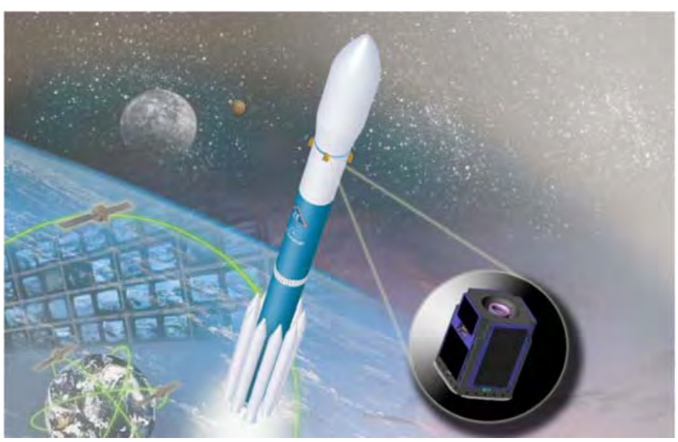

Figure 19: BarnacleSat as Secondary Payload