Exploring the Potential of Miniature Electrodynamic Tethers and Developments in the Miniature Tether Electrodynamics Experiment

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ABSTRACT

The success of nanospacecraft has spurred an interest in using even smaller satellites for longer-duration, constellation scale missions, requiring the use of a propulsion source on board to counteract the effects of drag and for coordination and maneuverability. Previous papers have shown that the use of short electrodynamic tethers (EDTs) has the potential to provide propellentless propulsion for drag make-up and the ability to change orbits of these small satellites. The Miniature Tether Electrodynamics Experiment (MiTEE) mission is a student-led technology demonstration mission by the University of Michigan to demonstrate the use of these short EDTs in a 1U CubeSat frame. This paper presents updates for the major MiTEE subsystems. The mission has progressed significantly with the use of a high-altitude balloon flight successfully demonstrating the communications subsystem and satellite integration. The paper concludes with an overview of the future plans for the MiTEE mission.

INTRODUCTION

The success of nanospacecraft-scale and millimeter-scale wireless sensor network concepts has furthered interest in the use of small, inexpensive “smartphone”-sized satellites for distributed, multi-point measurements as a part of constellations. These satellites, known as picosatellites (100 g – 1 kg) and femtosatellites (<100 g) have the potential to be launched into orbit on a scale of hundreds or thousands at a time.[1] However, satellites at this sub-kilogram scale often have high area-to-mass ratios, decreasing the orbital lifetime of the spacecraft due to atmospheric drag effects. These constellations of small satellites do not have the capability to achieve a high level of coordination and maneuverability due to their small size precluding on board use of traditional means of propulsion (chemical, EP thrusters etc.).[2] In order to improve the efficacy of such “satellite-on-a-chip”, or ChipSat, missions, an active means to provide thrust to the satellite must be provided and one such potential technology includes miniaturized electrodynamic tethers.

Previous studies have shown that electrodynamic tethers (EDTs) as short as a few meters can provide propellentless propulsions for these satellites.[3,4] The miniature EDT is a very short semi-rigid insulated-but-conducting tether connecting a pair of small satellites. By using electrical energy from solar cells, miniaturized EDTs offer a means to provide propellantless propulsion to organized fleets of picosatellites and femtosatellites. This thrust provides drag make-up capabilities, a means to actively de-orbit, thereby minimizing the risk of orbital debris collisions, and a means to change the inclination of a satellite.

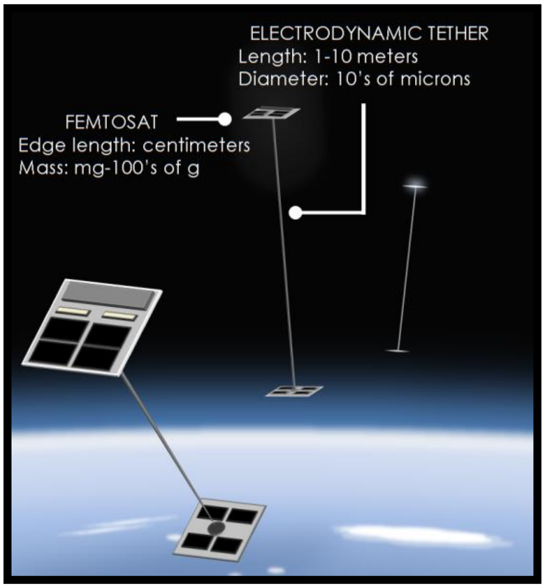

Figure 1: Visual Illustration of a Pair of Femtosat with EDTs Connecting Them[3]

The Miniature Tether Electrodynamics Experiment (MiTEE) is a technology demonstration mission to investigate the feasibility of using a 10-m long EDT for providing propulsion at the sub-CubeSat scale. The mission will assess the plasma interactions and the attitude dynamics of a tethered system. Additionally, the mission will also explore the use of the EDT as an antenna for spacecraft communication.

The MiTEE satellite will consist of an 8×8×2-cm "end body" with a mass between 100 g and 200 g that deploys from the main body of the 1U CubeSat upon detumbling and mimics a tethered picosatellite. The MiTEE mission has completed the Mission Definition Review (MDR) and is currently working towards a Preliminary Design Review (PDR) towards the end of this year.

The MiTEE student team consists of a diverse group of students ranging from undergraduate to doctoral students and comprises of many engineering disciplines, including aerospace, space systems, electrical, computer, and mechanical engineering. In the following sections, the paper describes the miniature tether concept and presents updates for the major MiTEE subsystems, including the results of the high-altitude balloon flight. The paper concludes with an overview of the next steps planned for the MiTEE mission.

SCIENTIFIC BACKGROUND

Electrodynamic Tethers

An electrodynamic tether is a conductor connecting a pair of satellites. EDTs, often ranging from meters to kilometers in length, exploit the force induced on a system due to a current conducting wire in a planetary magnetic field. This force, also known as the Lorentz force, is expressed as

$$\mathrm{F}_{\mathrm{Lorentz}} = \int_0^L \mathrm{I}_{\mathrm{tether}}\, \mathrm{d}\mathbf{L} \times \mathbf{B}\ , \tag{1}$$

where $\mathrm{I}_{\mathrm{tether}}$ is the tether current, $\mathrm{d}\mathbf{L}$ is the differential length along the tether, and $\mathbf{B}$ is the Earth's magnetic field.

In this system concept, electron current is collected from the ambient plasma at one end of the tether and emitted into the plasma at the other end, completing a closed circuit loop using the ionosphere.

Since the thrust generated by the Lorentz force of a miniature tether is estimated to be on the order of micro-Newtons and is difficult to directly measure, verification of the propulsion will occur through indirect methods such as change in altitude over multiple orbits or change in eccentricity.[4] In addition, measurement of the local magnetic field and verification of current passing through the tether would provide an estimate of thrust.

Gravity Gradient

One useful attribute of tethered systems is the gravity-gradient stabilization of the attitude of the system.[4] Gravity gradients occur when the mass distribution of the system is not isotropic, but rather a section of the spacecraft extends much longer than the rest. Since the force imparted by gravity reduces by the inverse square law, the parts of the spacecraft that are closer to the earth experience a larger force than the parts away from the earth. This imparts a torque on the system that causes it to stabilize along the minimum vertical moment of inertia axis, i.e. along the field gradient.

Long booms have been used in satellite missions to provide gravity-gradient stabilization. Similarly, a deployed tethered system will experience this gravity gradient, as shown by the Tethered Satellite System-1 Reflight (TSS-1R) mission.[5] The TSS-1R tether deployed 19.7 km, many times longer than the MiTEE tether. In order to better understand the effects of gravity-gradient torque at the miniature tether scale (in the presence of other torques, like atmospheric drag torque), the MiTEE CubeSat will study the attitude of the entire system relative to the local vertical.

HIGH-ALTITUDE BALLOON FLIGHT

The major milestone achieved over the past year was the successful launch and operation of a high-altitude balloon flight on April 30th. The balloon flight was intended to test the communications and sensor integration aspects in preparation for a future CubeSat launch.

A high-altitude balloon flight consisted of using a helium filled latex balloon to launch a payload about 80,000 feet into the atmosphere. At this altitude, the pressure is about 100 times lower than at sea-level, approximating the low-pressure environment of space.

The high-altitude balloon served to demonstrate key technologies of the MiTEE mission, including the use of the tether as an antenna. By successfully demonstrating the use of this technology in a space-like environment, the Technology Readiness Level (TRL) is raised. Throughout the paper, the various subsystems will describe the results of the balloon flight as it relates to the particular subsystem.

SUBSYSTEM OVERVIEW

Each of the subsystems have progressed significantly over the past year with the end goal of a high-altitude balloon flight realized.[6] The sections below outline the efforts and accomplishments of each subsystem over the past year, along with the plans for the future.

Tether Material Selection and Design

The EDT is a semi-rigid structure that will be made of multiple materials to ensure both structural rigidity, structural strength, and high conductivity. The rigidity is required to maintain a straight tether as the gravity gradient may not be strong enough at these lengths to keep the tether taut, while simultaneously having the flexibility to be enclosed in a small storage space.

In addition to semi-rigidity, maximum conductivity and structural strength are also desirable to ensure that the maximum efficiency of the propulsion and communications systems is achieved. The diameter of the tether is also a critical component as the drag of the tethered system increases with an increase in the cross-sectional area. A 200-µm diameter tether was found to be optimal for an end body of 100 cm^2 .[3] A trade study using the information above presented several possible candidates for the tether.

From Table 1, the Amberstrand cable is clearly the preferred option from a weight to strength ratio standpoint, with slightly high resistivity. The minimum Amberstrand fibers produced are too large for the purposes of the mission. The Liberator 20, however, can be produced in diameters of 34 AWG, which is ideal for this application.

Table 1: Properties of Possible Tether Materials

Material	Breaking Strength (kg)	Weight (g/m)	Resistivity (Ω m)
Copper Wire (34 AWG)	0.82	0.18	$1.68*10^{-8}$
Copper Clad Steel (34 AWG)	1.27	0.16	$4.40*10^{-8}$
Nitinol	1.83	0.13	$8.2*10^{-5}$
Amberstrand™	4.12	0.03	$1.08*10^{-7}$
Liberator 20 ™	2.59	0.06	$1.32*10^{-7}$

Nickel titanium, or nitinol, is also a viable candidate because it has superelastic properties. Superelasticity is a material property where the material maintains an elastic response (does not deform permanently) regardless of the deformation imposed upon it. As the tether will be coiled in a storage device prior to deployment, having a superelastic material in the tether ensures that upon deployment, the tether will maintain its original, straight shape.

In addition to the conductive and structurally supportive core materials, a protective insulating layer of material is required to provide electrical protection for the tether. This protection will be provided by a thin layer of Kapton due to its large dielectric strength and proven space heritage.

Plasma Electrodynamics System

The plasma electrodynamics system consists of the components that collect and emit the necessary current required to generate a Lorentz force in the Earth's magnetic field. This system includes the anode and cathode electrodes for generating and emitting the current, respectively, and a Langmuir probe for characterizing the ambient plasma.

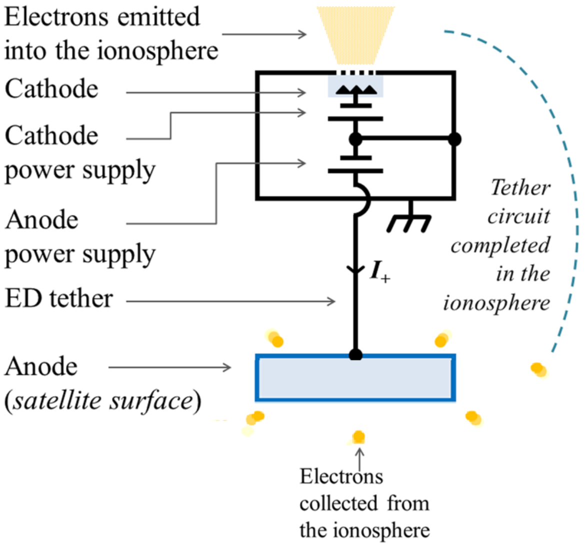

Figure 2. The System Concept Highlights the Primary Components of the EDT System .[2]

As shown in Figure 2, the deployed end body of the satellite will act as an anode biased positively with respect to the spacecraft and collect electrons that will be conducted through the tether to the power supply on the main MiTEE CubeSat.[2] The cathode will be located on the main CubeSat body and will be biased negatively with respect to spacecraft ground in order to emit electrons to complete the plasma circuit. For the MiTEE mission, both a thermionic and field emission array cathode will be flown, but only one of the two will be operating at a time.

Thermionic cathodes use the phenomenon of thermionic emission, wherein the cathode is heated to sufficiently high temperatures such that excited electrons overcome the work function of the material and are emitted in accordance to the Richardson-Dushman Equation.[7]Commonly used materials for thermionic cathodes include tungsten, thoriated tungsten, and oxide coated metals. In addition to the filament, a thermionic cathode also requires a focusing ring or accelerating grid structure in order to direct emitted electrons away from the spacecraft body.[8] For the purposes of the MiTEE mission, the thermionic cathode should be mechanically robust enough to withstand thermal stresses during emission and mechanical stresses incurred during launch. Figure 3 shows the test set-up of the thoriated tungsten filament prior to securing it in the vacuum chamber. The tungsten filament is in tied taut between the two pillars that are on each side of the aluminum deflector.

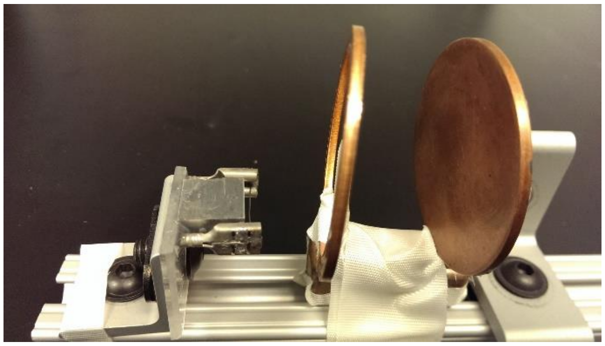

Figure 3. Ground Test Set-up of Tungsten Filament

Field emission array cathodes (FEACs) are “cold cathodes” that emit electrons through Fowler-Nordheim emission.[9] Emission occurs by applying a large voltage bias to an emitter surface covered in sharp tips and a gate surface consisting of apertures aligned directly above the tips. Due to their small size and mass, FEACs are inherently suited for CubeSat missions, however they are susceptible to atomic oxygen bombardment that severely reduces the emission capabilities of the technology. Additionally, FEACs are prone to inefficiencies where the gate structure collects electrons emitted from the tips and only a fraction of the current leaves the FEAC. The two variants of FEACs under consideration include Spindt-tip (usually with sharp molybdenum cones) and carbon nanotube cathodes.[10]

Both the thermionic and FEA cathode technologies have limited heritage at the CubeSat scale. Among others, a series of thermionic cathodes were flown on the SENSE satellite (launched November, 2013) as a part of the WINCS scientific package.[11] Recent missions with FEACs include the ALICE mission (launched December 2013) and ESTCube (launched May 2013**)**.[12,13] However, in all three cases, the corresponding data has not been published or the satellite has not entered the scientific phase of its mission. Thus, thorough verification and ground testing of both cathode technologies must be conducted, including current-voltage characterization, lifetime degradation, vibration, and oxygen exposure tests.

The system integration of the anode and cathode systems in the EDT has also been considered. The electrical configuration chosen for the MiTEE mission is the grounded gate, isolated tether configuration. As explored by Morris, the grounded gate, isolated tether configuration for a FEAC consists of the gate structure held at spacecraft ground potential and the emitter surface held negatively with respect to the gate structure.[8] For the thermionic cathode, the filament is biased negatively with respect to a grounded focusing ring or accelerating grid structure and a negatively biased repeller structure may also be included.[11]

A Langmuir probe will be used on the MiTEE mission for measurements of the electron temperature, density and plasma potential with respect to the spacecraft.[14] The probe will consist of a single, cylindrical tip deployed beyond the end of the primary antenna in order to extend the probe beyond the influence of the plasma sheath surrounding the spacecraft, as shown in Figure 4. Because of the low satellite surface area to Langmuir probe surface area ratio, the spacecraft will not have a 1000:1 area ratio that is typically required to maintain the spacecraft floating potential. The effect of this low surface area ratio is an active area of exploration.[14]

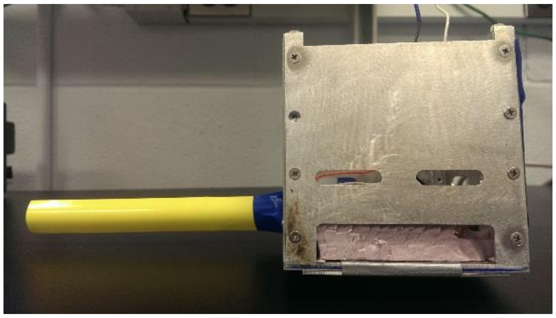

Figure 4. **The Primary Antenna (Yellow) to be used as a Boom for the Langmuir Probe**

Electrical Power System

The MiTEE electrical power system (EPS) is composed of two major subsystems: a low voltage EPS and a high voltage EPS. The low voltage EPS is designed for power generation, storage and distribution, while the high voltage EPS is designed for precisely biasing the on board plasma electrodes.

The low-voltage EPS consists of solar panels for power generation, a load balancing circuit for interfacing the solar panels with an on board battery, a lithium-polymer battery for power storage, and a power distribution board designed to provide regulated low voltage power output for all on board systems.

The high voltage EPS biases the plasma electrodes, anode and cathode systems, with two load regulated voltage high voltage outputs. The high voltage EPS consists of a switched-mode flyback converter used to convert the low voltage power input from the EPS distribution board to a high voltage power output. This converter is accompanied by a digital control circuit allowing for independent control of each output, one positive and one negative relative to spacecraft ground, over a range from ~0 to +250 volts on the positive output and ~0 to -250 Volts on the negative output.

The MiTEE EPS has undergone significant development over the 2013–2014 academic year. Work has focused primarily on two tasks: defining subsystem requirements and specifications based on mission objectives and developing the high voltage converter, novel for a CubeSat mission, required for precisely biasing the anode and cathode systems. Efficiency, overall power consumption, and volume have been major challenges for this task, but a preliminary design based on the LT3751 flyback converter controller IC is currently under development. Near term future work on the MiTEE EPS entails characterization of the current high voltage converter design, selection of a power distribution board solution, and determination of the cost-benefit trades associated with the use of deployable solar panels for increased power generation.

Communications Architecture

The secondary goal of MiTEE is to verify the functionality of the EDT as an antenna for space operations. Raising the TRL of this aspect of the experiment was the focus of the communications subsystem early in 2014. In addition to designing and characterizing the EDT as an antenna, designing a traditional monopole antenna to serve as a primary mode of communication was required. Therefore, a minimum of two antennas are required for this mission: a quarter-wave monopole which would perform the function of being the primary communications antenna and the tether itself as a secondary antenna.

Simulations performed using ANSYS HFSS™ software showed that the tether behaves as a travelling wave antenna. The simulations results are shown in Figure 5. The radiation pattern is an annular ring, propagating forward, with a null at the center.

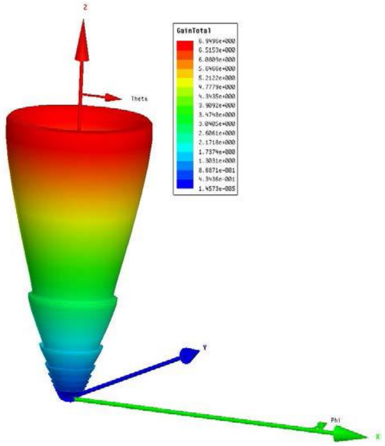

Figure 5: ANSYS HFSS™ Simulation Results for Tether

In order to verify the simulation results, empirical data was obtained through a number of tests. These were conducted by transmitting from the roof of one building to a receiving antenna on the roof of another building a large distance away to collect far-field transmission data. The results conformed to the simulations for angles where interference from surrounding objects was expected to be a minimum. The empirical test results in Figure 6. For other angles, the results were not sufficiently conclusive, ostensibly due to non-line-of-sight paths and multi-path effects.

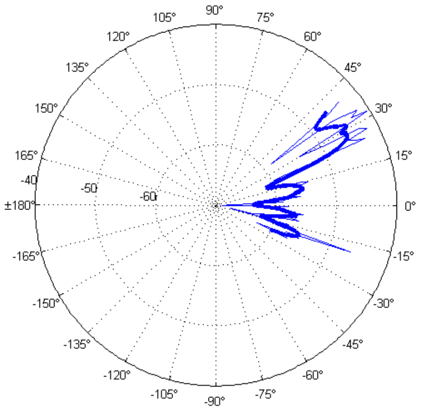

Figure 6: Experimental Results for Tether

Three different materials were used with similar setups: Monel™, copper-clad steel, and Litz wire. Copper-clad steel was found to be the best candidate for higher gain, efficiency and showing high conformity to the predicted radiation pattern. Further simulations were also carried out to understand the best length of the tether such that it will have a high value for the transmission gain along with providing propulsion for the satellite. This is an ongoing, slow process due to the frequency of operation and the physical properties of the tether.

A monopole antenna attached to one of the orthogonal faces of the CubeSat will be the primary antenna for communication of data since the tether as an antenna is still in a proof-of-concept stage. Such an antenna was designed and tested in isolation previously. Understanding the coupling effects from having two antennas, designing a switching circuit and building on the architecture for such a system that interacts with other subsystems was carried out in 2014.

The critical factor in designing the RF switching circuit was impedance matching for different terminals. The input signal was the modulated data signal transmitted by the radio and control logic from the on board computer determined which antenna would transmit at the given time. Various tests were carried out using this circuit, the two antennas, and the CubeSat structure to determine the optimal configuration that reduced the loss due to coupling. Due to a much broader beam pattern, thus lesser gain from the primary, the received power levels from the two antennas during the rooftop tests were found to be much closer to each other than expected.

The primary antenna performed to a high degree on the high-altitude balloon flight test. The received signal on the ground showed minimal noticeable attenuation in power levels or distortion up to the maximum distance between the balloon and the receiver stations on the ground. These results are encouraging given the fact that the transmission power provided to the antenna was much lower than the required power for the space mission. Thus, there is confidence within the team that the architecture developed for the communications subsystem will show good performance in the future.

The high-altitude balloon flight was conducted as a test mainly for verification of the tether's use as an antenna. While the deployment was unsuccessful, there is cause for optimism that signals transmitted from the tether could have been observed. The tether transmitted at similar power levels as the primary antenna during each of the ground tests, thus should have transmitted at similar levels on the balloon flight. Future balloon flights will need to be conducted to determine if this claim is true.

Command and Data Handling

The Command and Data Handling team is responsible for determining the orientation, interfacing with sensors on board, collecting data, executing the mission states, and telemetering the data back to the ground stations. Over the last year the subsystem focused on methods that can be used to determine orientation as well as practicing integration and data collection using the balloon flight.

The two body architecture required for EDT testing requires a more complex understanding of the CubeSat orientation than a traditional CubeSat. The force generated by the tether is a function of the current perpendicular to the magnetic field and the effective length of the tether. The effective length can be determined by thoroughly understanding the positioning of the main body and the end body in relation to the earth. As in most CubeSats, the MiTEE system requirements necessitate the knowledge of the position of the main body in relation to the Earth. More specifically, knowledge of the distance between the main body and the end body (within 10 cm accuracy), orientation of the end body and main body, and the alignment of the main body and end body are required. In order to acquire this information, the team evaluated various methods that are commonly used as well as some newly developed theoretical methods.

The most promising methods that were identified by the team are high megapixel camera, Bluetooth pinging, and a combination of sun sensors and high accuracy GPS. Using a high megapixel camera, the location as well as the distance of the end body can be determined. Further testing and review with other CubeSat teams at The University of Michigan highlighted several drawbacks associated with this method. While using markers to distinguish the end body, the task of locating the end body against the background of the Earth is difficult, especially at further distances. Detecting the orientation of the end body also becomes considerably more challenging as the end body gets further away. As such, the camera cannot be used exclusively to fulfill the requirements, however the camera is a feasible method for completing the given objectives at closer distance and may still be used to verify the deployment of the end body and provide images for promotional purposes.

The second method evaluated was a combination of Bluetooth pinging device and GPS. The pinger would be used to gauge the distance between the end body and the main body, while the GPS will be used to determine the position of the main body. The time required for the pinger to return the pinging signal as well as the processing time will be characterized on earth and by measuring the time between the initial ping and the return ping, the time of flight of the signal can be calculated. Although this method has been used in many other applications, due to the speed of electromagnetic waves and the close proximity between the end body and main body, this method requires a very high clock rate. Furthermore, orientation and alignment cannot be acquired using this information.

The most promising method identified was a combination of sun sensors and high-accuracy GPS. The high-accuracy GPS, possibly placed on both the end body and main body, provides positioning data within centimeter level precision. An illustration of this concept is given in Figure 7. The GPS uses real time kinematics to enhance the accuracy of a traditional GPS. This methodology provides us with alignment information and position information. Solar panels can also be used as sun sensors to provide the orientation of the bodies in relation to the sun. Using known flight models, this information can be correlated with the orientation of the bodies in relation to the Earth. This multi-sensor approach will be developed over the summer and the upcoming term.

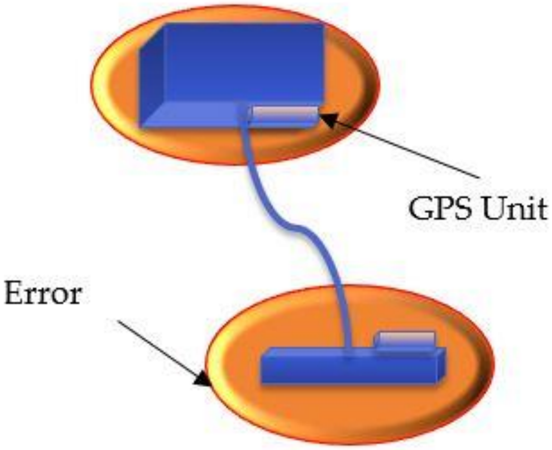

Figure 7: Illustration of Using GPS Units to Determine Distance of Two Satellites

The second major objective of the CDH subsystem was to practice integration, data collection, and support other systems through the high-altitude balloon flight. The system developed a state diagram with the other subsystems and executed it using an Arduino Mega. Environmental and housekeeping data was collected as expected on the balloon flight. This flight gave the team real world experience in developing state diagrams, working with other subsystems, and interfacing with sensors. The lessons learned in the balloon flight will be beneficial as the subsystem works with other subsystems to develop the CubeSat.

Orbits and Attitude Control

The Orbits and Attitude Control Subsystem is responsible for running relevant simulations, characterizing system dynamics, and implementing an active attitude control system for de-tumble. This semester, the team arrived at significant conclusions with regard to both thrust detection and attitude control systems.

One of the lingering questions for MiTEE is how to detect thrust on the scale of micro-Newtons. A direct thrust measurement system was not found to be feasible by the CDH team, so a different method of indirectly measuring thrust was needed. Previous simulations suggested that altitude decay differences between thrusting and non-thrusting modes may provide an indirect method to measure thrust. Some of the assumptions, however, such as seven days of continuous thrust, are no longer valid for this system. After accounting for more realistic drag parameters and thrust durations, the altitude decay difference between thrusting and non-thrusting modes was calculated to be 1.8 meters. This study was completed using Satellite Tool Kit (STK) to simulate orbits with and without thrusting. An illustration, completed in STK, of the path the orbit takes over time is given in Figure 8. The tether was modeled as an engine with an extremely high Isp and a constant thrust, which was applied for the first fifteen minutes of each orbit.

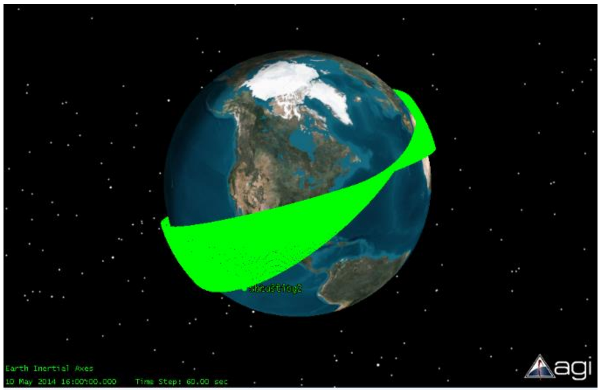

Figure 8: Path of Satellite as it Orbits

OACS has also worked on characterizing the potential noise in thrust detection measurements due to variations in drag throughout each orbit and has concluded that altitude fluctuations due to drag could easily dwarf the altitude variation due to thrust. Drag variations in the atmosphere can cause an altitude difference peak-to-peak of up to 4 meters per orbit (and can potentially be higher if solar activity continues to increase until launch), so it will not be possible to determine if altitude decay per orbit is influenced by thrust or variations of drag (due to density variations).

OACS also conducted a successful trade study on attitude control methods. The results of this study can be seen in Table 2. Since an active control system is required for de-tumble, gravity gradient was ruled out. Magnetic torque rods (or magnetorquers) were the only truly feasible option for MiTEE, since reaction wheels require far too much power and Hysteresis rods would create permanent local magnetic fields which would interfere with the tether experiment. Magnetorquers also create local magnetic fields, but are not intended to operate during thrusting; the active control system is only to be used during de-tumble and other circumstances when the tether is not in operation. OACS has started exploring magnetometer calibration in a cooperative effort with CDH and is also exploring B-dot control methods.

Table 2: Attitude Control Methods Trade Study

Control Method	Mass (g)	Volume (cm^3)	Power (mW)	Accuracy
Magnetorquer	< 9	2.0	140	±1 deg
Reaction Wheel	~12	5.3	720	±0.1 deg
Gravity Gradient	-	-	-	±5 deg
Hysteresis Rod and Perm Magnet	~9	0.3	-	±5 deg

FUTURE PLANS

The next few months for the MiTEE mission are critical, as the team moves into the Preliminary Design Review phase. In preparation for this, several initiatives are underway to raise the TRL of several key technologies.

Another high-altitude balloon flight testing the communications and sensors in a space-like environment is planned, along with a micro-gravity flight.

The high-altitude balloon will test the use of the tether as an antenna, similar to what was anticipated in the high-altitude balloon flight that flew the past summer. As the use of tether as an antenna is a secondary objective for this mission, raising the TRL of this concept through a successful test in a similar environment would greatly enhance confidence in this technology. In addition, the balloon flight will act as an exercise in the systems engineering and integration aspects of the mission as several subsystems will be involved to ensure a successful launch.

The micro-gravity flight serves as a testing environment for the deployment mechanism of the tether. The micro-gravity flight mimics the low gravity environment of space, where the unique dynamics of a tethered system can be observed. This helps to better understand the stresses imparted onto the tether, as well as any motion of the end body due to the deployment.

Acknowledgments

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