Integration of Geophysical Parameters for Electrodynamic Tether Propulsion Modeling Environment

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Abstract - Electrodynamic tether propulsion enables a future for very small satellites to operate over theoretically infinite orbital lifetimes, subjected to material lifetimes in the space environment. The advantage of electrodynamic tethers relying on the in-situ collection of electrons for propulsion from the ionosphere makes this an attractive alternative to consumable propulsion systems. However, the extremely complex electrodynamics and mechanical dynamics of operating this system in the space environment requires a robust modeling environment. This report explores the recent developments to integrate updated geophysical parameters into the TEMPEST modeling software to support this goal. The discussion is introduced by a detailed exploration of the fundamental tradeoffs of a CubeSat versus traditional satellite system and how electrodynamic tethers can bridge this gap. The report is then concluded by a summary of the motivations of the MiTEE CubeSat Program and the progress into this modeling endeavor.

I. INTRODUCTION

The rapid adoption and proliferation of CubeSat class satellites since the mid-2000s has provided the space community with an attractive alternative to traditional satellite buses. CubeSats offer specific pros and cons compared to their traditional counterparts, but are best described in terms of comparative advantages and disadvantages. The following subsections describe the fundamental tradeoffs between traditional satellite buses and CubeSats from both an economical and physical environment standpoint. The final subsection will describe recent efforts from the University of Michigan to develop a novel CubeSat propulsion technique to limit the tradeoffs associated with the space environment.

A. Spacecraft Economic Tradeoffs

It is no industry secret that space programs tend to be extremely expensive and technologically complex. Although highly dependent on the launch vehicle, typical launch and deployment costs for a spacecraft run on the order of tens-of-thousands of dollars per kilogram of mass [1]. Thus, it is extremely advantageous to limit the size and mass of your spacecraft as to limit costs as much as possible. This has led to two different schools of thought with regards to satellite and spacecraft development.

From a traditional standpoint, this steep price tag is countered by creating a massive spacecraft which hosts several instruments and experiments at a time. Spacecrafts of this type can weigh on the order of several thousand kilograms and can be the size of an SUV car or greater [2]. Obviously this leads to massive launch costs, but is justified by making it a multipurpose platform. For example, NOAA's GOES-R satellite contains at least six individual instrument suites including Earth observatories, solar observatories, and radiation hazard detectors for human spaceflight applications [3]. This large number and diverse profile of instruments justifies the massive cost of production and launch as only one satellite has to be created with only one launch. However, this generally has a negative impact on instrument science. Each experiment will have its own optimal orbital parameters and it is rare for each instrument to have the same parameters. Thus, certain instruments may have to trade off performance to accommodate other instruments and be able to fly the experiment. Additionally, the larger the number of experiments, the greater the complexity necessary to produce the spacecraft which consequently increases development costs.

Figure 1: GOES-R satellite compared to the size of a person [3]. Traditional satellite buses are massive in size to accommodate several instruments, but are also extremely expensive to develop and launch.

The development of traditional satellite buses dominated the space industry for several decades until the rise of popularity of CubeSats in the 2000s. A CubeSat is defined by a foundational unit size called a "U" where one U is a 10cm x 10cm x 10cm cubic volume with a mass no greater than 1.33kg per U. The greatest characteristic of a CubeSat is its extremely compact design and low mass intended to minimize launch costs. A typical CubeSat ranges between 0.25U to 12U, or roughly between the size of a smartphone and a microwave. Analogous to the volume reduction of computers going from the size of a room down to a smartphone, CubeSat technology has been made possible and driven by the miniaturization of commercial electronic components.

Additionally, most CubeSats are designed using primarily industry grade and commercial off-the-shelf (COTS) components from electronics stores and websites. This, in tandem with the very low mass architecture of CubeSats, makes it possible to develop and launch a satellite for a cost on the order of magnitude betweens tens- to hundreds-of-thousands of dollars. As a direct comparison, traditional satellite systems typically cost on the order between tens- to hundreds-of-millions of dollars. This greatly reduces the barrier of entry for scientific investigators and enables academic institutions, such as universities and even high schools, to design, develop, and fly their own space programs.

Figure 2: MiTEE-1 spacecraft developed by the University of Michigan. MiTEE-1 is a 3U CubeSat and weighs less than 4kg which greatly reduces launch and development costs.

Of significant operational consideration also is the benefit that CubeSats allow for an economic avenue to establish satellite constellations. Constellations have been rising in popularity and typically consist of a fleet of identical spacecraft orbiting at the same time. Famous examples of constellations currently in operation include SpaceX's Starlink communications constellation and NASA's CYGNSS hurricane tracking constellation (PI Prof. Chris Ruf, University of Michigan), both of which utilize CubeSat or smallsat satellites. Constellations are an attractive mission architecture as they allow for simultaneous measurements, rapid repeat measurements of a single location, wide global coverage, and backup systems in the event of an anomaly in one spacecraft. This is especially important for physical science experiments which need multiple, simultaneous data points to differentiate between temporal or spatial phenomena. However, as described earlier, this is only practical to perform when using CubeSats or smallsats from a cost perspective.

Thus, from a cost and flexibility standpoint, CubeSats have become a highly attractive and popular alternative to traditional satellite systems.

B. Physical Space Environment Tradeoffs

Additional constraints arise from the complex nature of the space environment itself. Although typically thought about as a pure vacuum, space is actually composed of a low-density mixture of electrically neutral and electrically charged particles. This is especially true in Low-Earth Orbit (LEO) between roughly 300km to 1,000km where the majority of satellites operate and Earth's ionosphere is a major factor.

The ionosphere is the region of Earth's atmosphere characterized by complex interactions with the solar wind and Earth's magnetosphere that generates a significant plasma environment. Its composition is colloquially thought of as a low-density soup of electrons and positively charged ions. Visually, it manifests itself as the region responsible for producing Earth's auroras in tandem with the magnetosphere.

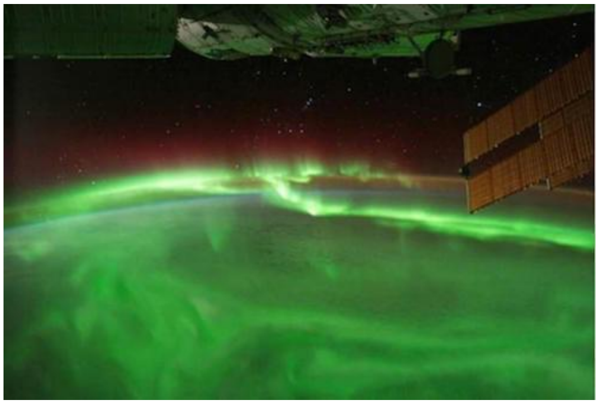

Figure 3: Earth's auroras as visible from the International Space Station [4]. The solar wind collides with the upper atmosphere of Earth to strip neutrally charged particles into free electrons and positively charged ions. These charged particles are then electromagnetically transported by Earth's magnetic field to the North and South Poles which cause high energy interactions, again, with the neutral atmosphere to cause the Northern and Southern Lights.

Although very low in density, orbital drag is a significant issue due to the drag force's squared dependence on velocity and the extremely fast orbital velocities of LEO. The net effect on spacecrafts is that energy is progressively removed from the system which causes a deterioration of orbital altitude. Specifically, an object that does not correct for drag will see its orbit slowly spiral down to Earth until it disintegrates as it interacts with ever greater atmospheric density. Obviously, this is undesirable for a spacecraft which hopes to operate for a mission lifespan on the order of years.

There is a strong dependence on the orbital deterioration caused by drag and the surface area to mass ratio of a spacecraft, which disportionately affects CubeSats over traditional satellites. An analogy can be drawn between the space environment and throwing a leaf out of the window of a car on the freeway. When driving, the car sees a large drag force applied to it from moving through the atmosphere and air, but it can be easily overcome and controllable. Yet, when the leaf is tossed out the window, the leaf feels this exact same drag force but its speed rapidly falls and even becomes uncontrollable compared to the car. This is a result from the fact that the leaf has a significantly higher surface area to mass ratio compared to the car and is thus much more greatly impacted by atmospheric drag. Similarly, CubeSats have a high surface area to mass ratio and typically have orbital lifespans between 6-18 months, depending on initial orbit altitude, and traditional satellites have a low surface area to mass ratio and are able to remain in orbit for several years.

Thus, a fundamental tradeoff between mission lifetime and cost is struck when choosing between a CubeSat or traditional spacecraft system.

C. Electrodynamic Tether (EDT) Theory

Technology can be employed to attempt to mitigate the negative effects of atmospheric drag while continuing to use a CubeSat platform for the cost benefits. Most commonly, CubeSats integrate a propulsion system into their design to compensate for drag losses. For this architecture design decision, cold gas thrusters and electric propulsion systems tend to be the most popular choice as a result of their extentensive flight heritage. However, there is a massive drawback associated with this decision as the thrusters use a consumable propellant and propellant storage tends to be extremely volume expensive in a CubeSat. A positive feedback loop is established where adding a propulsion system increases the spacecraft size, which then increases the surface area to drag ratio, which ultimately requires a greater amount of propellant and greater spacecraft volume. As a result, CubeSats using propulsion systems must have a fundamental minimum size to be able to accommodate propellant storage while balancing expected orbital drag and mission lifetimes. Additionally, once the propellants are entirely consumed, then the spacecraft is subjected to the same orbital degradation as a spacecraft designed without a propulsion system.

To combat this, the University of Michigan's Miniature Tether Electrodynamics Experiment (MiTEE) CubeSat Program is attempting to develop a novel propulsion system operating on the principle of electrodynamic tether (EDT) theory which avoids the negatives of cold gas thrusters and electric propulsion entirely. This principle revolves around the manipulation of the space environment itself to our advantage versus accepting orbital atmosphere as a fundamental negative.

As explained earlier, most satellites orbit in a region called the ionosphere which is a mixture of electrons and positively charged ions. It is theoretically possible to harvest electrons from the ionosphere by setting the spacecraft's electrical potential to a high, positive voltage bias relative to the surrounding plasma. If the spacecraft system is designed as two independent spacecrafts connected by an electrically conductive tether, as seen in Figure 4, then the harvested electrons can be transported through the tether and ejected out of the second spacecraft to complete an electrical circuit back into the ionosphere. Importantly, this generates a current running through the length of the tether which electromagnetically interacts with Earth's magnetic field to produce a Lorentz Force.

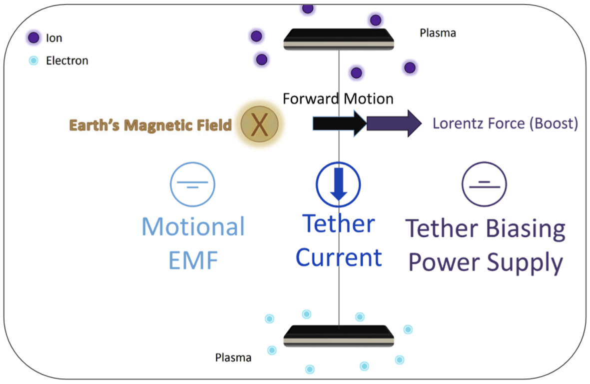

Figure 4: Theoretical demonstration of an electrodynamic tether for propulsion in a spacecraft system of two tether picosats [5].

As a highlighted advantage over cold gas thrusters and electric propulsion, an EDT propulsion system is fully propellantless. Thus, no extra storage, other than the storage needed for the tether, must be allocated on the spacecraft. Additionally, the system can theoretically operate indefinitely without the risk of ever running out of propulsion capabilities. This enables spacecrafts to fundamentally reduce their size and mass even further down to picosat classifications, or roughly the size of a modern smartphone, while keeping the full functionalities of a satellite.

It is also important to highlight the mechanical advantages of a tethered spacecraft system over an untethered system. The optimal tether length for a CubeSat EDT is within the range of 10-30m which balances the proportional dependence of the Lorentz Force on tether length versus the increased drag force and storage constraints associated with a longer tether [5]. This gives rise to a significant gravity gradient force due to the nature of the extremely long spacecraft. As a result, the spacecraft system has a passive restoration force to align the spacecraft nadir to Earth without having to expend any additional energy or power. This, in theory, eases attitude control constraints as no extra hardware is needed to properly align the spacecraft for science and communications purposes.

Overall, electrodynamic tethers give rise to the opportunity to mitigate all the negatives associated with operating a consumable propulsion system, addresses orbital drag concerns associated with CubeSats, and continues to take advantage of the low cost and high flexibility properties of a CubeSat platform over a traditional satellite system.

II. MOTIVATION

Despite the strong advantages electrodynamic tethers afford CubeSat missions, the technology is relatively unexplored and thus has a very low technology readiness level (TRL) score. The MiTEE Program is attempting to raise this TRL by demonstrating the EDT technology in orbit to establish a flight heritage for future missions.

The MiTEE Program is split between two distinct spacecraft, MiTEE-1 and MiTEE-2, with both being 3U CubeSats. MiTEE-1 was deployed to orbit in January 2021 and is performing preliminary science measurements and proof-of-concept activities for the MiTEE-2 spacecraft, which is currently in the mission concept review and preliminary design phases. The primary distinction between both spacecraft is that the MiTEE-2 satellite will implement, fly, and deploy a full EDT system, whereas the MiTEE-1 spacecraft has a simplified design using a deployable, but rigid, 1m long boom to act as a pseudo EDT.

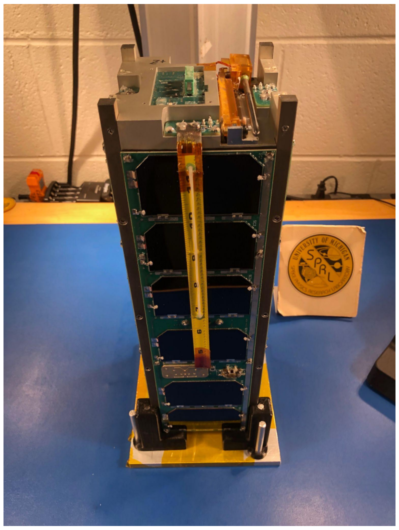

Figure 5: MiTEE-1 spacecraft fully integrated prior to deployment to orbit in January 2021.

The main motivation behind this design decision is the extremely complex electrodynamics and mechanical dynamics associated with a nonrigid tether. As opposed to a 1m rigid boom, the planned 30m long EDT for MiTEE-2 will be unconstrained during deployment and mechanical vibrations may cause significant disturbing forces on the spacecraft. Thus, MiTEE-1 is designed to be the pathfinder mission and to develop flight heritage and experience before designing the significantly more complicated MiTEE-2 satellite.

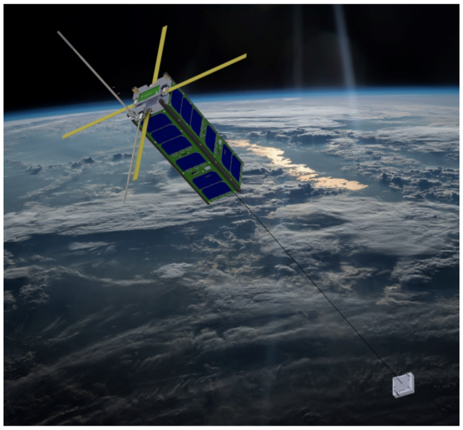

Figure 6: MiTEE-2 spacecraft rendering. A significant focus will be placed on expanding on MiTEE-1 lessons learned and flight heritage while implementing a full EDT system.

To help alleviate the risk associated with flying an EDT propulsion system for the first time, it was determined necessary to develop a robust modeling environment. The first major purpose was to understand the constraints we would be facing in orbit and to identify unwanted surprises early. It is expected that a much more complicated attitude control system will be necessary to stabilize MiTEE-2 over MiTEE-1 and only first order calculation can be performed by hand. Thus, a simulation framework will aid in accurately representing the actual space environment and how the spacecraft will react to operating an EDT.

Secondly, there are significant regulatory concerns from the Federal Communications Commision (FCC), which is the government body that grants flight licenses to spacecraft operators, for operating a satellite on an unproven propulsion system. Thus it is necessary to demonstrate to the FCC via simulation results that the risk of the spacecraft will operate in a controllable way.

III. METHODS

It is the objective for the rest of this report to present the progress in activities designed to address the problems and concerns discussed in the Motivation section. For the purposes of this project, the TEMPEST modeling software was identified as a suitable backbone to build the modeling environment upon. TEMPEST was originally designed in the 1990s specifically for modeling the electrodynamics of an EDT spacecraft system and thus has heritage in this endeavor. However, its last major update occurred in the early 2000s and was operating on outdated geophysical parameters.

It was my goal to update this program to 2020s standards and to integrate updated and reevaluated geophysical parameters. Updated models will be generated using data from

NASA's Earthdata database as well as its available models based on solar-terrestrial interactions [6].

DISCUSSION

It is important to note that this is an ongoing project and investigation towards creating a final modeling environment. Unforeseen technical issues associated with updated computer operating systems now being incompatible with the original TEMPEST source code has slowed progress. Therefore, this project has been extended into future months for the foreseeable future. Despite this, it is important to discuss the next steps and plan of action to arrive at our end goal:

A. Model Verification and Validation

Once the model is updated and complete, it will be necessary to verify and validate its accuracy. This will be a two pronged activity led by comparing against other simulation environments and against real data.

There exist other simulation environments for modeling EDTs, however there has not yet been a study to compare them all against each other. Thus there is a collaboration beginning to be formed between researchers at the University of Michigan, Pennsylvania State University, York University of Canada, and University Carlos III de Madrid of Spain to spearhead the study. This will be the opportunity to compare the updated TEMPEST model against the other models in circulation. The hope is to be able to understand any discrepancies between the models and to evaluate their strengths and weaknesses. As a result, we hope to validate TEMPEST at this stage to move into the next stage of testing.

Secondly, it is our hope to validate TEMPEST against real spacecraft data. Primarily, we are hoping to use the data from MiTEE-1 to complete this effort. Information gained about the plasma environment and the geophysical parameters at that time will be invaluable to ensure that the model is accurately representing legitimate space conditions. Additionally, we have access to historical data from early EDT missions intended for power generation on traditional spacecraft systems to additionally use to validate the TEMPEST updates.

Once extensively tested, the updated TEMPEST version will be cleared to move forward with use on preliminary design activities for the MiTEE-2 spacecraft.

B. Integration with Multibody Dynamics Models

Since the TEMPEST software primarily covers only the electrodynamics aspect on an EDT, it will still be necessary to integrate the model with a nonrigid, multibody dynamics modeling simulation framework. For this, we are planning on integrating with NASA JPL's Dynamics and Real-Time Simulation (DARTS) modeling software. DARTS has extensive usage in spacecraft missions and is one of NASA's primary modeling environments. Within it, we will have access to an environment that succinctly integrates extremely complex mechanical dynamics and that is flexible enough to add TEMPEST and our preliminary MiTEE-2 attitude control software as plugins into the model. Additionally, the MiTEE team has been working with NASA JPL on these preliminary steps for at least two years and has obtained a licensing agreement to use DARTS on MiTEE-2 modeling efforts.

CONCLUSIONS

Electrodynamic tethers provide an exciting alternative to consumable propulsion systems and have the potential to elevate the CubeSat revolution to a new level. The ability to perform drag makeup maneuvers theoretically indefinitely while retaining a low mass and low cost architecture is an important innovation that may continue to greatly expand access to space. The efforts led by the University of Michigan's MiTEE CubeSat Program will continue to push these boundaries of raising the technology readiness level of EDTs until they are proven as a viable propulsion method for any CubeSat platform.

However, to accomplish this goal there exists the need to develop a modeling environment that can integrate the complex electrodynamic and mechanical dynamics as influenced by the space environment into a single application. These efforts are continuing at the University of Michigan as we prepare for the upcoming MiTEE-2 EDT demonstration mission. The primary modeling backbone is TEMPEST as it becomes updated to the standards of the 2020s. Additionally, the steps for verifying and validating the model remain a planned future activity over the near future. Once verified, progress can move forward with integrating the TEMPEST electrodynamics model within NASA JPL's DARTS non-rigid body modeling environment. The final tool will be invaluable in modeling EDT spacecraft systems throughout the preliminary design phase and will be used extensively over the development of the MiTEE-2 CubeSat spacecraft.

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