Maneuver Planning for Demonstration of a Low-Thrust Electric Propulsion System

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ABSTRACT

As the testing and implementation of CubeSat technologies on-orbit becomes more prolific, the need for high-efficiency, low-mass propulsion systems continues to grow. Ionic propulsion systems have emerged as a potential technology to fill the niche of CubeSat propulsion. BeaverCube, a student-built 3U CubeSat from the Massachusetts Institute of Technology, will host an ionic propulsion system demonstration in low Earth orbit. Slated to launch no earlier than October 2020, BeaverCube seeks to demonstrate the Accion Systems Inc. Tiled Ionic Liquid Electrospray propulsion system. This system utilizes an ionic liquid as propellant, giving BeaverCube the ability to make high-efficiency, low-thrust maneuvers. A successful system demonstration will be able to detect a translational maneuver using the NovAtel OEM-719 Global Positioning System receiver onboard BeaverCube. Detectability requires the altitude change of a maneuver to be at least 9 meters, which is 3 standard deviations above the expected GPS altitude error. The goal of this work is to determine the duration of translational maneuver that will result in the highest probability of detection while producing the smallest error in thrust calculation. From simulations performed in Systems Tool Kit, a 3.5 hour maneuver was determined to be optimal, resulting in an altitude change of 280.6 meters.

INTRODUCTION

CubeSats are an increasingly important platform for early stage, small-scale space technology development due to their small form factor and standardized launch and deployment procedures. While CubeSats provide a low-complexity, low-cost way to test novel technologies in space, their use in larger missions, including multi-satellite constellations and space exploration, is limited by their reliance on launch vehicles for delivery into their final orbit. The primary barrier for the use of propulsion on CubeSats is the lack of high-efficiency, low-mass, low-power propulsion systems. In response to the lack of CubeSat appropriate propulsion, engineers at Accion Systems Inc. (Accion) developed the novel Tiled Ionic Liquid Electrospray (TILE 2) thruster system, which utilizes an ionic liquid as propellant.[1] While some forms of electrospray propulsion have been extensively characterized in lab settings, most have not yet been demonstrated on orbit.[2,3] As a result, the demonstration of the TILE 2 is one of the mission objectives of BeaverCube, a 3U CubeSat designed and built by the Massachusetts Institute of Technology (MIT).

BeaverCube provides an opportunity to test the TILE 2 propulsion system in space, validating performance of the thruster on orbit. The NovAtel OEM-719 Global Positioning System (GPS) receiver onboard BeaverCube will be utilized to detect any changes in its orbit resulting from maneuvers produced by the TILE 2 thruster. These changes will be compared to orbital simulations in Systems Tool Kit (STK) to confirm that the system is functioning as anticipated. In addition to demonstrating the TILE 2 system, the BeaverCube mission is required to prove that the thruster does not pose a risk to the International Space Station (ISS), other satellites, or to its own payloads. This will be ensured by continuously monitoring BeaverCube's location and preventing thruster firing until consent has been given by both the ISS and the Combined Space Operations Center (CSpOC). The system parameters of BeaverCube can be found in Table 1.

Maneuver planning must be completed to determine the maneuver duration required to meet the primary propulsion demonstration objective. Altitude change for a given maneuver duration is subject to maneuver starting altitude along with uncertainties in the Attitude Determination and Control System (ADCS). Errors in thrust calculation are subject to errors in ADCS capabilities in addition to GPS errors. The goal of this work is to determine the duration of translational maneuver that will result in the highest probability of detection while producing the smallest error in thrust calculation.

BACKGROUND

BeaverCube Project Overview

BeaverCube, shown in Figure 1, is being built by students as part of the Space Systems Development capstone course at MIT. Students are responsible for designing, assembling, testing, and integrating all components of BeaverCube. BeaverCube carries two payloads: a visible and long-wave infrared camera array to perform sea surface and cloud top temperature measurements, and the TILE 2 propulsion technology from Accion for orbital maneuvering.

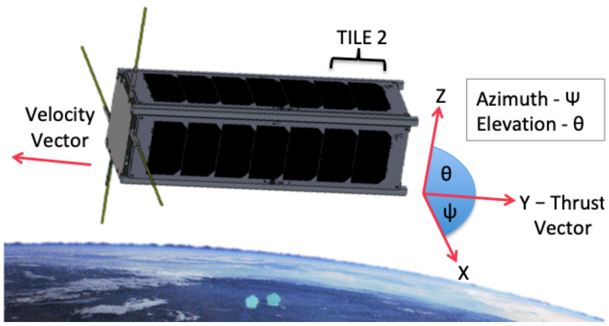

Figure 1: Reproduction of BeaverCube.

BeaverCube is currently scheduled to launch on NG-14 as early as September 2020 and will be deployed into low Earth orbit (LEO) from the ISS. Following the activation of the imaging payload and approval to fire, the propulsion demonstration will be performed. This will most likely occur between 1 and 3 months after deployment. The ADCS onboard BeaverCube is the iMTQ MagneTorQuer Board by Innovative Solutions in Space (ISISPACE). To power all onboard systems, BeaverCube has 10 units (3x 2U and 2x 2U) of solar panels fixed on the outer surfaces and a battery with a capacity of 40 Watt hours.

Table 1: BeaverCube System Parameters

Parameter	**Quantity/Type**
Mass	4 kg
Size	10 cm x 10 cm x 30 cm
Imaging Payload	1 Matrix Vision BlueFOX camera 2 FLIR Boson IR cameras
Propulsion Payload	Accion TILE 2 Thruster
GPS Receiver	NovAtel OEM-719
ADCS	ISISPACE MagneTorQuer
Battery	Clyde Space 40 Wh
Solar Panels	Clyde Space 10U
IMU	TDK MPU-6000

Electrospray Propulsion

An electrospray propulsion system produces thrust by applying voltage between an extractor grid and a porous emitter chip of sharp tips wetted with propellant. The resulting electric field causes ions to evaporate from the tips and accelerates them through holes in the extractor. Electrospray propulsion is particularly suited to small satellites due to the high thrust density and high specific impulse of the design.[2,3] Electrospray characteristics make it well suited for widely varying mission requirements including attitude control for imaging missions, station keeping for constellations, and large orbital maneuvers for space exploration.[4,5]

The TILE 2 system, shown in Figure 2, is suitable for demonstration of the electrospray propulsion concept on a 3U CubeSat. Table 2 lists the important characteristics of the TILE 2 system.

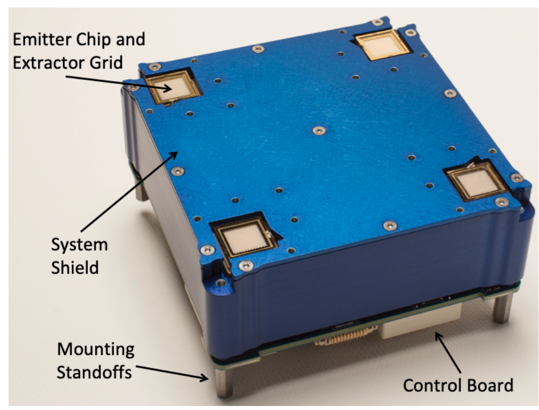

Figure 2: Image of Accion TILE 2 propulsion system.

Table 2: Accion TILE 2 System Parameters

Parameter	**Value**
Thrust	50 μN
Specific Impulse	1800 s
Mass	0.48 kg
Size	0.5U

Low-Thrust Maneuvers

The demonstration of the Accion Systems TILE 2 propulsion system will be considered successful if the firing of the system results in a detectable maneuver. The two main types of maneuvers used to demonstrate the function of propulsion systems on orbit are rotational and translational maneuvers. Rotational maneuvers cause a rotation of the satellite about the center of mass by generating torque via off-axis thrusting. Although rotational maneuvers may require a lower maneuver duration to achieve results detectable by most gyroscopes, spinning up the satellite has drawbacks. In particular, it is possible to spin the satellite to a rate at which the solar panels are not able to supply enough energy for the ADCS to detumble. Although the risk of this failure mode is low, it could result in an end to the mission. As such, rotational maneuvers were ruled out as a way to demonstrate the TILE 2 system on BeaverCube.

The propulsion demonstration will be achieved through the completion of multiple translational, or orbit-raising, maneuvers. In this type of maneuver, all four emitter chips on the TILE 2 system will fire simultaneously with the thrust vector antiparallel to the orbital velocity vector. The ΔV, a measure of the impulse per unit spacecraft mass, from the propulsion system adds energy to the orbit of the satellite. This energy addition results in an altitude increase.

The thrust produced by the TILE 2 system is small enough to make the assumption that the satellite orbit will remain nearly circular throughout the course of any maneuvers.[6] This allows for ΔV to be approximated as the difference in velocities between the initial orbit and the orbit after firing:

$$\Delta V \approx \sqrt{\frac{\mu}{R_0}} - \sqrt{\frac{\mu}{R}} \tag{1}$$

where μ = Earth gravitational constant; R_0 = initial altitude; R = altitude after maneuver.

The maximum ΔV achievable by the TILE 2 system is 8.8 m/s, which results from a burn of approximately 8 days in duration at the expected thrust of 50 μN. Thrust can be calculated by dividing Eq. (1) by the maneuver duration. Utilizing the low-thrust approximation, Eq. (1), this ΔV results in an altitude change of 14.2 km. However, due to the altitude of the orbit of BeaverCube, atmospheric drag effects must be considered as well. Drag decreases the altitude change for a maneuver. The drag force is given by:

$$F_D = \frac{1}{2} C_D A \rho v^2 \tag{2}$$

where C_D = drag coefficient; A = drag area; ρ = atmospheric density; and v = orbital velocity.

The drag coefficient and drag area of BeaverCube are provided in Table 5. Atmospheric density varies with altitude, leading to varying drag forces. Drag is not only dependent on the altitude of the satellite, but is also dependent on the velocity, drag area, and pointing error.

ADCS and Pointing

In order for the satellite to complete a translational maneuver, the propulsion system requires coordination with the ADCS. The ADCS ensures the satellite is in the correct pointing orientation to guarantee thrusting will occur along the intended vector. If a satellite were to orbit the Earth without force input from the ADCS or elsewhere, the satellite would always point in the same direction with reference to the stars. In this example, the thruster would only be in the optimal position to maneuver for a single moment each orbit. To maneuver the satellite in an optimal position for the entire orbit, the ADCS will slew the satellite to the desired, corrected position to keep all thrust pointed in the anti-velocity direction as the satellite orbits the Earth. Assuming all thrust is antiparallel to the direction of orbital velocity, Eq. (1) describes how the altitude will change for a given ΔV.

BeaverCube utilizes the 3-axis iMTQ board for attitude control. Magnetorquers work by creating a localized magnetic field that interacts with the magnetic field surrounding the Earth. This interaction causes the satellite to change orientation depending on the direction and the strength of the field generated by the magnetorquer.[7]

While the magnetorquer can adjust BeaverCube's orientation as desired, there may still be errors in the pointing that result in thrusting in an off-nominal direction. Pointing error is expected in both azimuth (Az) and elevation (El). 0 degrees of error is optimal, 5 degrees of error is assumed for realistic off-nominal pointing, and 15 degrees is assumed for conservative worst-case off-nominal pointing. Thrust in an off-nominal orientation will result in a lower change in altitude, and therefore semi-major axis, than thrusting in the nominal orientation. The proportion of on-axis thrust can be determined by rotating the thrust vector by the pointing error and projecting it onto the satellite velocity vector. Additionally, because the CubeSat is pointed in an off-nominal direction, the ram-facing surface area with respect to orbital velocity direction may increase. Drag area is determined by projecting the 3 dimensional shape of the rotated CubeSat onto the plane perpendicular to the orbital velocity.

Maneuver Detection and GPS Error

There are several different methods that can be implemented to verify that a translational maneuver has been completed. One way is to utilize the accelerometers within the onboard inertial measurement unit (IMU) to detect any acceleration caused by the propulsion unit. However, the MPU-6000 IMU onboard BeaverCube can only detect accelerations of magnitude 5.98×10^{-4} m/s^2 and greater. Translational maneuvers produced by the TILE 2 system have a maximum magnitude of 12.5×10^{-6} m/s^2, rendering this type of maneuver undetectable to this IMU. Two-line element (TLE) propagation will be used on BeaverCube for payload and other satellite operations. However, it is unlikely that TLE results will be accurate or precise enough to determine the altitude change made by a maneuver. According to previous research, errors in TLE generated altitudes are approximately 1 km for most satellites in LEO, with errors for satellites in ISS orbit reaching 20 km in the worst case.[8,9] Due to the limitations of the onboard IMU and TLE propagation, translational maneuvers will be detected using the GPS receiver onboard BeaverCube.

A GPS receiver collects information by receiving signals from constellations of navigation satellites in medium Earth orbit (MEO), such as the GPS, GLONASS, BeiDou, and Galileo constellations. The receiver determines its altitude and velocity by performing its own calculations based on the broadcast orbit and navigation message information from the navigation satellites.

The accuracy of altitude determination by a GPS constellation varies, and is dependent on several key factors. One of these factors is the geometric/position dilution of precision (G/PDOP) of the GPS constellation.[10] GDOP is utilized to quantify how errors in measurement will affect the final estimation of the position of the GPS receiver, and is defined as the ratio of the variance in the output location to the variance in the input data.[10] A low GDOP is desirable, as it means that small errors in the input data will not result in larger errors in the output location of the receiver. GDOP is most strongly influenced by the relative positioning of GPS satellites with respect to the receiver; if visible satellites are close together, it is more difficult to get an accurate position of the receiver, which results in a higher GDOP value.[11] Effects such as receiver clock drift and internal receiver noise also contribute to errors in the accuracy of a GPS receiver on-orbit.[12]

METHODOLOGY

There are three major mission constraints that are relevant to the success of the propulsion system demonstration: the maneuver starting altitude, pointing error, and GPS error. Maneuver starting altitude and pointing error affect the altitude change made by a maneuver of a given duration. GPS error affects the accuracy with which altitude change can be measured on orbit. Table 3 lists each mission constraint, along with details of their respective effects on the propulsion demonstration. Additionally listed are environmental factors and other mission parameters that determine this mission constraint.

Table 3: Summary of Key Factors

Mission Constraint	Effect of Mission Constraint on Propulsion Demonstration	What Determines this Mission Constraint
Starting Altitude	Starting altitude determines the magnitude of the effect of drag due to the variation of atmospheric density as well as the distribution of orbital velocities.	Starting altitude is determined through mission planning. The ISS program and CSpOC must approve the timing and parameters of each maneuver.
Pointing Error	Pointing error determines the proportion of thrust that is on-axis as well as the drag area of the satellite.	Pointing error is determined by the ADCS and attitude control software implementation.
GPS Error	GPS Error determines what altitude change must be made for a maneuver to be detected.	GPS Error is determined by the properties of the GPS receiver and the position of the satellite relative to the constellations of GPS satellites.

Expected values and uncertainties for each of these mission constraints were determined through theoretical and numerical analysis along with consideration of programmatic constraints. Altitude change was determined for maneuvers of varying duration. Uncertainty in altitude change for a given maneuver duration was found by simulating both the best- and worst-case mission constraint values given in Table 4.

Table 4: Best-, Expected-, and Worst-Case Mission Constraints

Parameter	Best-Case	Expected	Worst-Case
Starting Altitude	428.65 km	392.32 km	361.9 km
Pointing error	0°	5°	15°
GPS Error	2.8 m	2.9 m	3.0 m

Thrust determination error is the error in calculating the system thrust from the results of a maneuver. It was determined by propagating uncertainties in mission constraints that are not controlled during maneuvers through Eq. (1). Optimal maneuver duration was chosen based on the uncertainty in maneuver detection error, the uncertainty in altitude change, and the expected thrust determination error for a given maneuver duration.

Several assumptions, as listed below, were made to simplify the following analysis. Thrust produced during a maneuver was assumed to remain constant, and hardware was assumed to retain beginning of life performance throughout the mission. Hardware was also assumed to remain at operational temperatures during maneuvers with no performance degradation. Additionally, power draw was assumed to remain at nominal levels for all hardware. Effects of orbital parameters other than eccentricity were not investigated.

Table 5: Standard Mission Parameters

Mission Parameter	**Value**
Earth Radius	6378 km
Semimajor axis	6798 km
Eccentricity (eccentric orbit)	0.0014898
Eccentricity (circular orbit)	0
RAAN	30.184°
Inclination	51.702°
Argument of Perigee	102.927°
Maneuver Duration	4 hrs
Drag Area (for maneuvering)	0.01 m^2
Drag Area (for propagating)	0.024 m^2
Drag Coefficient	2.2
Ejection Velocity from ISS	1 m/s
Satellite Mass	4 kg
Pointing Error	0° in Az/El
GPS Velocity Error	0.03 m/s

All data was gathered from either theoretical approximations which use Eq. (1) and (2) or from numerical simulations in STK. Altitude change in STK was found by simulating the chosen orbit with and without a maneuver and finding the difference in the semimajor axis (SMA) between these two simulations at the end of the maneuver. Changes in the altitude of apogee and perigee were determined with the same method. STK simulations used the Earth HPOP Default v10 (HPOP) force model, which accounts for drag effects in addition to variations in the shape of the Earth. The Jacchia-Roberts model was used for the density of the atmosphere, which is considered accurate between altitudes of 90 and 2500 km.[13] The effects of drag were investigated by simulating maneuvers both with and without drag. All mission parameters were equal to the values given in Table 5 unless the parameters were explicitly stated to vary. The orbital parameters were identical to the ISS orbit parameter prediction in STK for November 1st, 2020. Eccentric orbits were modeled with the eccentricity of the ISS orbit while circular orbits had an eccentricity of 0.

Maneuver Starting Altitude

Demonstration of the propulsion system will commence after the imaging system of BeaverCube has been commissioned. This is expected to occur after approximately one month on orbit, but this time period may be as long as three months. All maneuvers performed must be approved by the ISS and CSpOC. Expected-, best-, and worst-case starting altitudes for maneuvers were found by modelling satellite deployment from the ISS and propagating the orbit for 1 to 3 months.

To account for variations in the location of the ISS, orbital position and altitude at deployment were varied. ISS starting altitude range was determined by looking at the hourly altitude of the ISS between January 2015 and April 2020 as reported by the National Aeronautics and Space Administration Jet Propulsion Lab HORIZONS Web-Interface. Assuming the total altitude of all course corrections remains under 5 km, the altitude of the ISS at the time of BeaverCube release will be between 405 km and 435 km. The separation velocity as a result of deployment was modeled as a 1 m/s ΔV impulsive maneuver. The drag area for propagation was 0.024 m^2, which was found by estimating the average drag area during imaging payload operations. It should be noted that the orbit parameters for this modeling are listed in Table 5, with the exception of semimajor axis and true anomaly. ISS orbital position during deployment was modeled both at perigee and apogee. Therefore the starting true anomaly was either 0 or 180 degrees while the semimajor axis was varied so that the modeled altitude at release would coincide with the investigated altitude of release.

The effects of starting altitude were investigated by comparing maneuvers starting between 350 and 430 km, inclusive. Atmospheric density values for theoretical calculations were found using a MATLAB implementation of the Jacchia reference atmospheric model.

Pointing Error

The effects of pointing error were investigated by simultaneously varying the azimuth and elevation angle of the propulsion thrust vector from -20° to +20°. The effects of pointing error on eccentricity and inclination were investigated by varying azimuth and elevation angle independently. Altitude change for varying pointing error was determined by simulating a maneuver with the chosen pointing error and comparing it to a simulation of propagation with no pointing error. Drag area for a given pointing error was found using MATLAB to rotate the satellite by the azimuth and elevation error and project it onto the plane normal to the velocity vector. The effects of drag area were found using Eq. (3):

$$dH = \frac{dH}{dA}\frac{dA}{d\alpha}d\alpha \quad (3)$$

where dH = altitude change for a given change in pointing error; $\frac{dH}{dA}$ = slope of drag area vs. altitude change; $\frac{dA}{d\alpha}$ = slope of pointing error angle vs. drag area; and $d\alpha$ = change in pointing error.

$\frac{dH}{dA}$ was found by simulating the altitude change for drag areas varying from 0.01 to 0.04 m^2, finding a linear fit, and taking the derivative of the linear fit. $\frac{dA}{d\alpha}$ was found by calculating the drag area for pointing errors between -20° and +20°, finding a piecewise linear fit, and taking the derivative of the piecewise fit. The effects of off-axis thrust were determined by rotating the thrust vector by the pointing error in azimuth and elevation and projecting the resultant vector on the satellite velocity vector. This thrust was then used with Eq. (1) to determine altitude change.

GPS Error

Variations in the accuracy of the GPS receiver onboard BeaverCube were investigated by calculating the estimated (1-σ) position error in STK. This was done using a dilution of precision (DOP) simulation for a GPS receiver in LEO; the simulation utilized J2 propagation for a period of 30 days for estimating the GPS error in both circular and eccentric orbits.[14] The effects of starting altitude on GPS error were determined by varying the initial altitude of the DOP simulation from 300 to 430 km. The effects of the initial date of firing were also determined through the same DOP simulation. In this case, the start date was varied between Nov. 1st, 2020 and Oct. 1st, 2021 in one month increments. The initial conditions for BeaverCube each month were held constant, ensuring that any variations in GPS error were the result of the positioning of the GPS constellation and not due to irregularities in the orbit of BeaverCube.

Maneuver Duration

Orbit average power and maneuver power draw were used to determine the time that the satellite can perform propulsive maneuvers before propulsion must be shut off for low-power-mode charging. The relationship between maneuver duration and altitude change was determined by comparing altitude changes while varying maneuver durations between 15 min and the maximum maneuver duration of approximately 9 hrs. The effect of starting the maneuver at different locations on orbit was determined by comparing altitude changes for varying maneuver durations starting at perigee or apogee. Expected altitude changes for varying maneuver durations were calculated using expected starting altitude and pointing error values. Uncertainty in altitude change was found by simulating varying maneuver durations with both the best- and worst-case mission constraints given in Table 4.

Thrust Determination Error

Thrust determination error is dependent on factors that are unknown when completing a maneuver, namely the detection and pointing error. These accuracies cannot be determined on orbit due to the lack of truth values for comparison. Errors from Eq. (1) must also be included. Thrust error for calculations based on altitude change was found by taking the derivative of the right side of Eq. (1) with respect to the altitude change for a maneuver, multiplying by the uncertainty in altitude change to get the velocity change uncertainty, and dividing by the duration of the maneuver to get thrust uncertainty. The result is shown in Eq. (4).

$$\delta T_{altitude} = \left(\frac{1}{2\mu t}\left(\frac{R_0 + \Delta H}{\mu}\right)^{\frac{-3}{2}}\right)\delta H \quad (4)$$

where δT = thrust determination error using altitude change; ΔH = altitude change; t = maneuver duration in seconds; R_0 = maneuver starting altitude; and δH = altitude change uncertainty resulting from pointing error, GPS error, and error from Eq. (1).

Thrust error for calculations based on velocity was found by taking the derivative of the left side of Eq. (1) with respect to velocity change, multiplying by the uncertainty in velocity change, and dividing by the duration of the maneuver to get thrust uncertainty. The result is shown in Eq. (5).

$$\delta T_{velocity} = \frac{\delta H}{t} \quad (5)$$

where $\delta T_{velocity}$ = thrust determination error using velocity change.

Maneuvers were assumed to start at 392.32 km and maneuver duration was assumed to have no errors. GPS velocity detection was assumed to have an error of 0.03 m/s.[14]

RESULTS

Starting Altitude

Table 6 summarizes the results of modeling CubeSat deployment from the ISS at varying ISS starting altitudes and deployment orbit locations. The best deployment and maneuvering conditions from an altitude perspective would be to deploy at apogee and then start maneuvering at apogee one month after deployment. The worst condition from an altitude perspective would be to deploy at perigee and then start maneuvering at perigee three months after deployment.

Table 6: Starting Altitude Results

Case	Release Position	Maneuver Position
Best	Apogee	Apogee
Expected	Apogee	Perigee
Worst	Perigee	Perigee
Release Altitude (km)	**Time After Release (months)**	**Maneuver Altitude (km)**
435	1	428.65
420	2	392.32
405	3	361.9

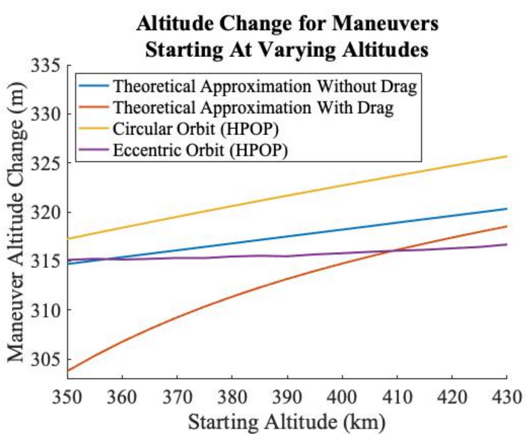

Figure 3: Altitude changes for maneuvers starting at varying altitudes.

Figures 3 and 4 show the effects of varying starting altitude on altitude change due to drag and velocity variation. Altitude change for a given ΔV increases for higher altitudes due to the inverse square root relationship between orbital velocity and altitude as well as the decrease in drag due to particle density. The decrease in altitude change at lower altitudes is smaller for the eccentric orbit as seen in Figure 3. It is possible that this is due to the alternation between higher and lower altitudes in the eccentric orbit, which mitigates the effects of changing the average altitude. Due to the effects of drag on altitude change, the optimal procedure for propulsive maneuvers is to initiate them as soon after deployment as possible, maximizing starting altitude.

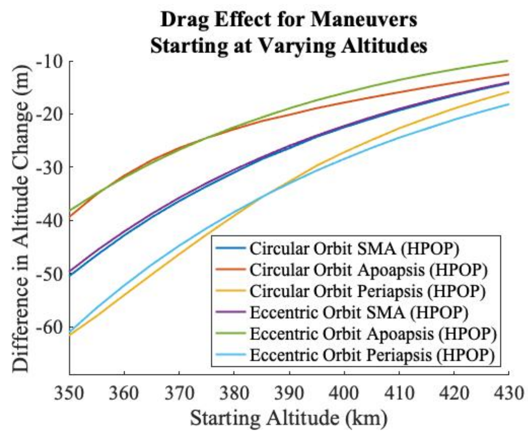

Figure 4: Difference between maneuvers simulated with and without drag.

Pointing Error

Figure 5 shows the effect of varying azimuth and elevation simultaneously. The effect of varying azimuth alone was identical to the effect of varying elevation alone. A greater azimuth-elevation error combination results in a lower altitude change because a greater proportion of the thrust vector is off-axis. As seen in Figure 6, an increase in off-axis thrust due to increasing pointing error decreases the altitude change. The effects of drag also increase with pointing error due to the increased drag area. The effect of drag on altitude change is greater than the effect of off-axis thrust until pointing error exceeds +/- 15°. Exceeding +/- 15°, the off-nominal thrust angle is the largest source of altitude change. As the detrimental effects of drag area and off-axis thrust increase with pointing error, it is clear that the optimal pointing error for making propulsive maneuvers to increase altitude is 0° in azimuth and elevation.

The magnitude of inclination changes resulting from off-axis thrust in the azimuth and elevation directions were lower than $5° \times 10^{-5}$ with larger changes for simulations with variations in azimuth. Eccentricity variations were smaller than 7×10^{-6}

for all simulations with little variation between the effect of azimuth and elevation.

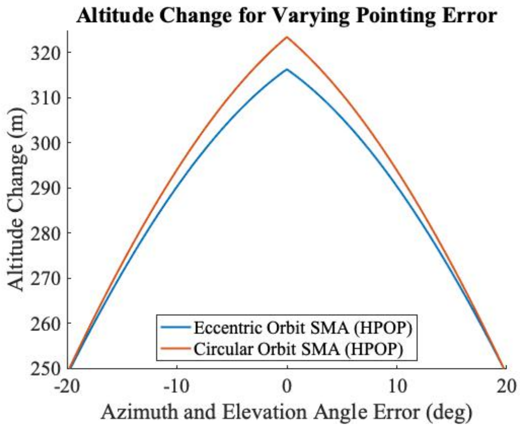

Figure 5: Altitude changes for maneuvers with varying pointing error.

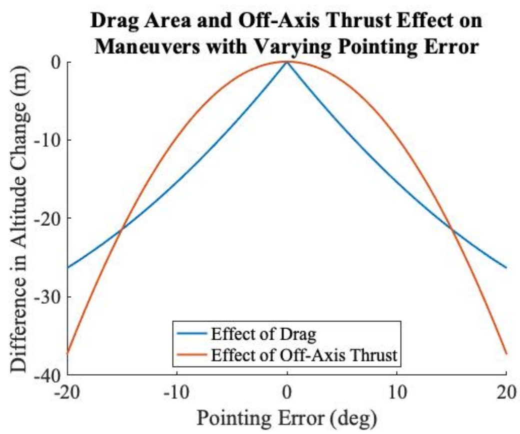

Figure 6: Effect of drag area and off-axis thrust due to pointing error.

GPS Error

As seen in Figure 7, the dependence of GPS (1-σ) position error on the initial maneuver altitude of BeaverCube is approximately linear. There is a clear decrease in the error calculated from the DOP simulation as the initial altitude increases. This is most likely the result of GPS signal propagation delay as the signal passes through different levels of the atmosphere. This results in greater errors at lower altitudes with larger tangent paths through higher atmospheric density. Based on this relationship, the best course of action to take in terms of maneuver detectability would be to commence maneuvering while BeaverCube is at its highest altitude.

GPS position error is also dependent upon the date when firing commences, as is illustrated by Figure 8. While GPS error follows an overall linear trend in relation to firing date, there are somewhat cyclic changes in the calculated error as time progresses. These cycles see the error increasing as time progresses, but have a roughly three month period between peaks. It is possible that the least favorable configuration of GPS satellites has a period of about three months; further confirmation and analysis of this effect is planned in future work.

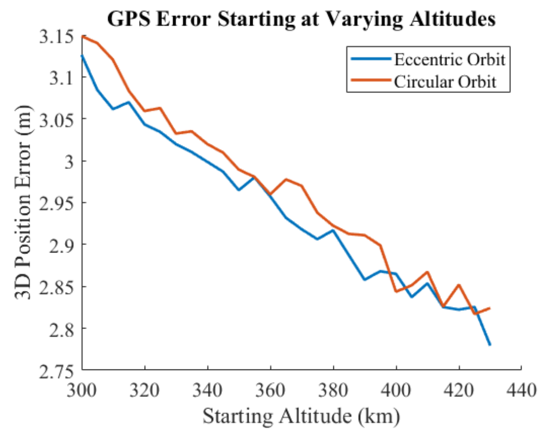

Figure 7: Expected GPS (1-σ) 3D position error with varying starting altitudes.

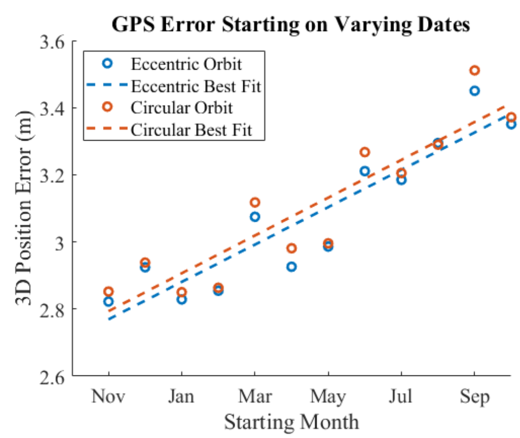

Figure 8: Expected GPS (1-σ) 3D position error with varying start dates.

Maneuver Duration

Maximum maneuver duration limited by power availability was calculated using the parameters in Table 7. Net power production over a 24 hour period is found by subtracting the hourly power consumption from the hourly power production and multiplying by 24. Adding the net power production during the 24 hour period to the available battery capacity multiplied by the allowed discharge percentage and dividing by the satellite power draw during maneuvers yields the maximum maneuver time. As seen in Table 7, the BeaverCube power system is capable of supporting a 9 hour maneuver. However, this requires 100% discharge, which could damage the battery thereby causing an end to the mission. To avoid this risk, battery discharge is limited to 75%, which results in a maximum possible maneuver duration of 7.7 hours.

Table 7: Power Budget Parameters

Mission Parameter	Value
Orbit Average Power Consumption	5.09 W
Orbit Average Power Production	6.43 W
Battery Capacity	40 Wh
Power Draw During Maneuvers	8 W
Max. Maneuver Time - Full Discharge	9.0 hr
Max. Maneuver Time - 75 % Discharge	7.7 hr

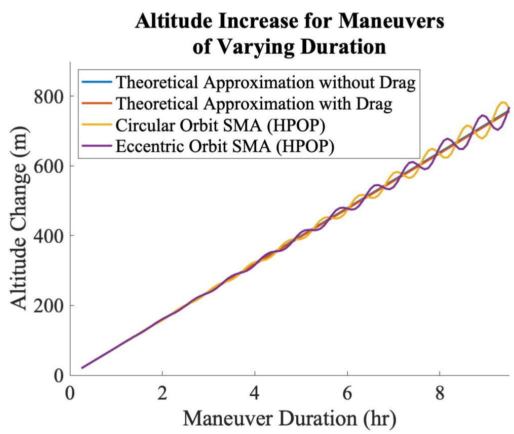

Figure 9: Altitude increase for maneuvers of varying duration.

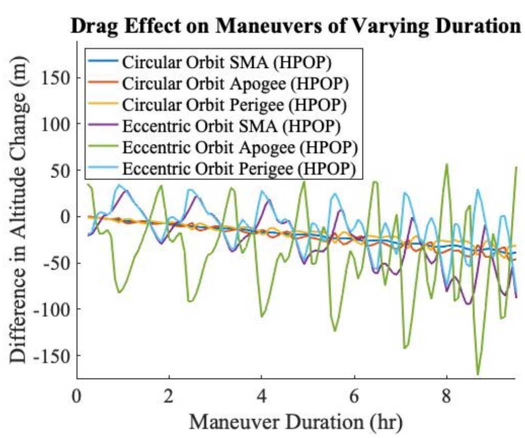

Figure 10: Effect of drag for maneuvers of varying duration.

Figures 9 and 10 show the effects of drag and maneuver duration on altitude change. The dependence of altitude change on maneuver duration is linear for theoretical approximations and sinusoidal for numerical simulations. This sinusoidal behavior is due to the spiral nature of low-thrust maneuvers not accounted for in the derivation of Eq. (1).[6] Longer maneuvers have a larger total drag effect as the drag force is acting over a longer period of time. However, the ratio of total drag effect to total altitude change remains approximately constant at 0.05. The relationship between drag and maneuver duration is a complex periodic function for eccentric orbits due to the variation in density between apogee and perigee.

Uncertainty and Thrust Determination Error

Figure 11 shows the expected maneuver altitude change with an uncertainty band. This band shows the uncertainties in starting altitude and pointing error. Table 4 shows the parameters used for the expected, best, and worst cases used to determine uncertainty. Uncertainties vary between 4 and 9% of the expected altitude change.

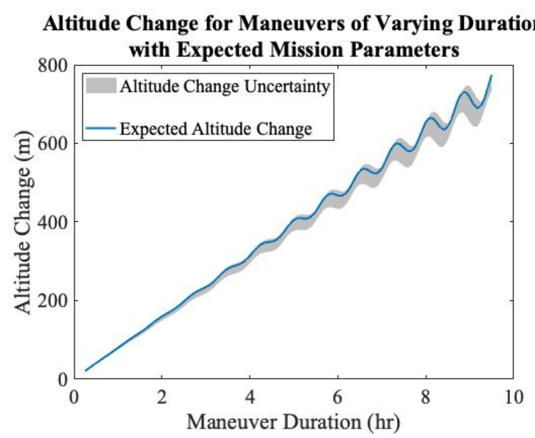

Figure 11: Uncertainty in altitude change for maneuver of varying duration.

Figure 12 shows the error in thrust determined using the change in both altitude and velocity. Errors using altitude change are larger than errors using velocity change because Eq. (1) assumes a constant eccentricity of 0. As a result, altitude change varies between numerical simulations and theoretical calculations. The differences between numerical and theoretical results vary between 0 and 10%, with larger errors for longer maneuvers. Errors using velocity change decrease with increasing maneuver duration because velocity error is divided by the maneuver duration as shown in Eq. (5).

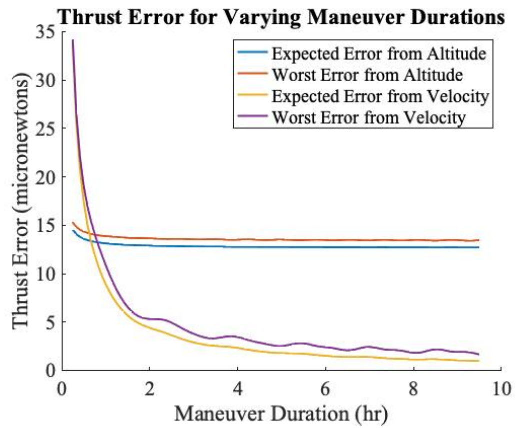

Figure 12: Thrust determination error for varying maneuver duration.

DISCUSSION

Maneuver Duration

Once the imaging system on BeaverCube has been commissioned, the propulsion unit may only be granted permission to fire a limited number of times. As a result, the duration of each potential maneuver must be chosen to maximize the likelihood and accuracy of maneuver detection, even in a worst-case scenario.

Worst-case scenario parameters are given in Table 4. The altitude change required for a maneuver to be detectable in this worst-case is 9 m, 3 times the standard deviation of the GPS error. For the TILE 2 propulsion system, the worst configuration in which thrust could be produced would occur if only 2 of the 4 thrusters were operational, resulting in half of the expected thrust and altitude increase. In this case, the altitude change would need to be twice the value previously calculated, or 18 m. A maneuver with a duration greater than 15 minutes would result in an altitude change greater than 19 m, satisfying this requirement.

As thrust determination error decreases with increasing maneuver duration, the optimal duration to minimize thrust error is the longest maneuver that the system is capable of producing. Battery discharge must be limited to 75% to avoid damage to the battery, which requires maneuvers to remain under 7.7 hours. Additionally, longer maneuvers have the potential to increase the corrective force required from the ADCS to point the satellite, resulting in larger pointing errors and possible loss of satellite control.

A maneuver duration of 3.5 hours avoids the risk of damaging the battery while minimizing thrust error. This maneuver duration results in an altitude change of 280.6 m. The best- and worst-case altitude changes are 261.7 m and 285.3 m, respectively. The lower bound of this uncertainty range is 252.7 m above the 9 m, 3-σ uncertainty in the GPS error. For this maneuver duration, the expected thrust determination error is approximately 5.1% when using altitude change and 25.6% when using velocity change.

Operational Implications

The results of this maneuver planning maximize the likelihood of detecting maneuvers subject to uncertainties in starting altitude, GPS error, and pointing error. However, it is possible to plan the timing and execution of the maneuver to improve the probability of detection and further reduce thrust determination error.

One factor that will have a large impact upon the propulsion demonstration detectability and the thrust determination error is the date on which firing approval is granted. As the altitude of BeaverCube decays, any maneuver performed will result in a smaller change in altitude compared to one made at a higher orbit. Additionally, GPS error increases as time after deployment increases. To maximize the likelihood of detection, maneuvers should be performed as early as possible. Time-dependent variations in GPS error stem from GPS constellation orbital dynamics, which result in less-than-optimal constellation configurations for the onboard receiver. Firing several months to a year after deployment, the expected (1-σ) position error could increase from as low as 2.8 m to more than 3 m. This indicates that firing should take place as soon as possible to minimize the GPS error, and thus, the thrust determination error. However, it should be noted that, due to the cyclic behavior of GPS error over time, it may be beneficial to wait to fire until a local minimum error value is reached.

While both GPS error and maneuver starting altitude results indicate that maneuvers should be performed as soon as possible, the time at which firing approval is granted has significant implications upon the safety of the mission. Any CubeSat with a propulsion system could be considered a recontact hazard for the ISS. As such, there must be a delay between initial deployment from the ISS and the initial firing of the TILE 2 system. During this period, the primary focus of BeaverCube will be to successfully commission the imaging system without the additional risk incurred by firing the propulsion unit. Following the imaging payload demonstration, maneuvers will be initiated as soon as approval is granted.

If the GPS receiver onboard BeaverCube were to malfunction, translational maneuvers would difficult to confirm with the IMU or TLEs. In this case, there remains the potential for the system to perform a rotational maneuver. However, this should only be utilized as a last resort, due to the risk of spinning up the satellite.

Due to programmatic constraints, maneuvers will be individually commanded. Splitting up maneuvers may allow for a greater altitude change than initially estimated, as the system could fire for the maximum duration deemed safe, recharge the battery, and fire again. Provided charging cycles are close together, the altitude decay between subsequent maneuvers could be small enough that the changes in altitude would nearly sum. This approach would be beneficial from a detectability point of view, but requires more communication cycles with BeaverCube, increasing the potential for delays and transmission errors.

Limitations

All analysis assumed that hardware would retain beginning of life performance throughout the mission. Degradation of hardware over time due to exposure to the space environment could cause a significant decrease in function. In particular, battery capacity and solar panel efficiency could decrease, shortening the maximum possible maneuver time. Additionally, there may be variations in hardware performance that could affect the power budget given in Table 7. These variations have not yet been characterized for BeaverCube and as such were not included in this analysis. As the maneuver duration chosen to meet the mission requirements is far from the maximum possible maneuver duration of 9 hours, the authors do not believe that including these variations would significantly change the conclusions. As discussed previously, there is no data available for thrust variation for electrospray thrusters over the lifetime of the system and as such this data was not included in this work.

The magnitude of inclination and eccentricity variations were less than $5^\circ \times 10^{-5}$ and 7×10^{-6}, respectively. As seen in the starting altitude and maneuver duration results sections, the eccentricity of the ISS orbit has a small effect on the altitude change for a given maneuver. Thus, coupling between the effects of pointing error on eccentricity and inclination and the effects of these orbit parameters on altitude change was assumed to be negligible.

Future Work

Looking forward, there are several topics which could be investigated further in order to fully characterize low-thrust maneuver planning. As the estimated pointing error is one of the largest factors influencing maneuver analysis, an exploration into other potential ADCSs could be beneficial. Along the same lines, a military-grade GPS receiver may be able to achieve a higher level of accuracy than the receiver currently on BeaverCube, and should be investigated. One scenario which must be considered is where the GPS receiver fails completely. Without a functioning, onboard receiver, TLE propagation would be necessary for translational maneuver detection. Continuing work in maneuver planning should include a closer investigation of TLE propagation to mitigate the potential loss of maneuver detectability. Despite the lower magnitude of accuracy of TLE propagation compared to GPS, redundancies in maneuver detection can only improve the odds of mission success. In addition, the effects of the precession of the ISS orbital plane relative to GPS must be examined to see if it coincides with the peaks in expected GPS error seen in Figure 8. Finally, to fully characterize how the TILE 2 thruster will perform over the course of its operation, the thrust variation of the system will need to be investigated.

CONCLUSIONS

This paper has demonstrated some of the techniques used for low-thrust, translational maneuver planning required to maximize the likelihood of success of a propulsion demonstration. Parameters that affect propulsive maneuvers such as starting altitude, pointing error, and GPS error were investigated to determine the optimal maneuver duration for the BeaverCube mission. The proposed maneuver duration for the TILE 2 system is 3.5 hours. A maneuver of this duration satisfies the requirement of exceeding the expected detection error of 3 m by three standard deviations. This eliminates overlap between the uncertainty in detection error and altitude change and produces the smallest error in thrust calculation.

Most low-thrust maneuver planning prior to this has largely focused on station keeping for geosynchronous orbits along with Earth escape trajectories for deep space exploration. However, the introduction of high-efficiency propulsion systems, such as the Accion TILE 2, could see a shift from past methods. As ion electric propulsion systems become more prolific, methods for maneuver planning in LEO, such as the methods discussed in this work, will become more relevant. While the mission parameters used in this work are specific to BeaverCube and the TILE 2 system, the techniques used to investigate parameters relevant to the propulsion demonstration can be generalized to other low-thrust systems. In particular the dependence of maneuvers on starting altitude, pointing error, altitude change, and GPS error can be utilized to guide future maneuver planning for low-thrust maneuvers in LEO. As low-thrust, high-efficiency systems become more widespread for use in CubeSats, the need for maneuver planning for LEO missions will become a critical part of satellite mission planning.

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