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Electrospray Mission Modeling for CubeSats

Angie Hatch, Jonathan Black
Air Force Institute of Technology
2950 Hobson Way, WPAFB OH; 703-692-4322
angela.hatch@usmc.mil

ABSTRACT

Several electrospray thrusters are in development for CubeSats, including variants that require high power but in return yield significantly higher ΔV. In order to analyze the capabilities provided by such thrusters, a Mission Modeling Tool (MMT) is developed that combines reports from Satellite Toolkit (STK) with MATLAB programming and a GUI interface in order to analyze the state of health of satellite subsystems over a period of time. After developing MMT, several scenarios are analyzed for a CubeSat outfitted with a 56-W solar array, carrying a payload of eight electrospray thrusters, and established in a Sun Synchronous (SSO) orbit. First, satellite orientations and the effects of Local Time of Ascending Node (LTAN) on the power provided in a 600 km SSO are studied. Next, generic power scenarios are analyzed for pointing and ΔV experiments in order to determine the optimal number of thrusters and modes that should be utilized. It is shown that pointing experiments should use two thrusters in active mode with two in standby, while the ΔV experiment should use a combination of three and four thrusters in active mode. In this manner, 1 km/s of ΔV can be reached in 177.7 days.

INTRODUCTION

The CubeSat standard was first developed by Stanford University and California Polytechnique University (CalPoly) to provide a standardized, low-cost nano-satellite program for universities. Not only does it provide capabilities for small platforms in space, but it also provides valuable satellite engineering experience for students and academic programs. Since the CubeSat standard was first developed, over 40 CubeSats have been launched into space[1]. CubeSats are typically launched in a standardized CubeSat launcher known as the Poly Picosatellite Deployer, or P-POD, which allows CubeSats to rideshare and to be launched as a secondary payload, thus more easily obtaining a launch opportunity.

One drawback to being launched as a secondary payload is that the CubeSats are then often released in orbits that are non optimal for their mission. One way to correct the non-optimal orbit is by including propulsion on a CubeSat. On-board propulsion could allow the CubeSat to maneuver into its desired orbit and/or maintain or extend its desired lifetime. Additionally, the use of propulsion could open up broad new mission applications such as formation flying or operating in a swarm.

For a propulsion system to be successful on a CubeSat, it must meet Size, Weight, Power, and Safety (SWAPS) requirements. The propulsion system must have a small size and a low mass. Additionally, it needs to run on little power and meet safety concerns for secondary payloads. The propulsion system should be affordable and at an appropriate Technology Readiness Level (TRL).

One promising propulsion system for CubeSats is the electrospray thruster, which has made significant advances since the 1990s and can provide a much higher Isp and ΔV than the alternatives at a lower amount of power[2]. The electrospray thruster is an electrically powered propulsion system that uses charged droplets that are accelerated at high velocities to obtain thrust[3]. Advances in electrospray technology have led to high power high ΔV thrusters that look especially promising to CubeSats.

It was desired to complete an initial mission analysis of the Air Force Institute of Technology (AFIT) Bus with the high power high ΔV thrusters as a payload. In order to analyze the mission, a Mission Modeling Tool (MMT) was developed in order to analyze the satellite subsystems and study their interactions over a period of time. Once MMT was developed, it was used to find the optimal pointing, orbit, and use of thrusters for a notional electrospray AFIT CubeSat mission.

AFIT BUS

Part of AFIT's graduate studies program in Astronautical Engineering includes a three-course satellite design sequence that results in an engineering development unit (EDU) CubeSat. The EDU undergoes space qualification testing, and can then later become the baseline for the design and construction of a flight model CubeSat. During iterations of the satellite design sequence, AFIT has developed its own CubeSat bus that includes a custom made Command and Data Handling (C&DH) board, Electrical Power System (EPS), and an Attitude Determination and Control System (ADCS) unit. The bus is either based on the Colony I or Colony II bus, and is built in-house at the AFIT machine shop.

The iteration of the AFIT Bus used for this analysis is Version 2, which was a 3U version completed in May 2012 and is shown in Figure 1. The AFIT 3U Bus is composed of a C&DH Board, an EPS and Battery Board, a Sun Sensor Board, and an ADCS. The bus fits standard PCB 104size boards. A 104-pin header, based on the Pumpkin, Inc., header is used to pass information from subsystem to subsystem. All boards are built in house, as well as the 3U structure.

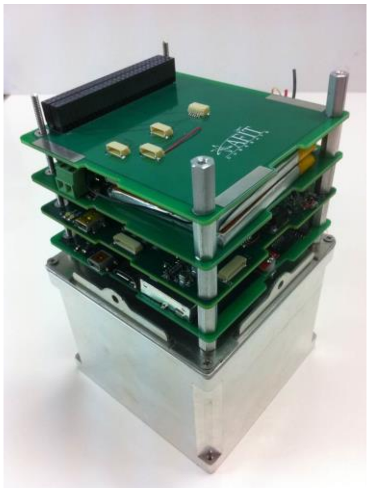

Figure 1: AFIT 3U Bus

The C&DH board includes an STM32 Microcontroller, a MicroSD card with up to 8 GB of storage, an 802.11 Wi-Fi Radio, and a 9-DOF board. The GPS chip used provides time and date information as well as a Pulse Per Second (PPS) synchronization signal.

The EPS and Battery Board includes batteries, thermocouples, solar panel connectors, and battery terminals. The batteries are two 3.7V, 2 Ah Lithium Polymer batteries with a 14.8 Wh capacity. Three thermocouples are used to monitor temperature, and a heater patch is included for the battery.

The ADCS unit is a 1U self-contained sealed enclosure that includes three Maxon motors, three Amplifier DEC Module controllers, three reaction wheels, three torque coils, a mounting structure, and the ADCS board. Attitude is determined through the combined inputs of the GPS, 9-DOF, sun sensors, and magnetometers. The 9-DOF includes gyros, accelerometers, and an additional magnetometer.

AFIT Bus Updates

In order to make the AFIT 3U Bus a viable candidate for the high power high ΔV thrusters, it must meet the requirements of providing enough power for the thrusters and providing enough pointing accuracy that the pointing maneuvers can be quantified. This requires several changes to the AFIT 3U Bus, including improved batteries, solar panels, and attitude determination.

Two additional batteries added in parallel to the AFIT 3U Bus would result in the bus being able to provide 7.4 V and 5.2 Amp-hrs, doubling the amount of Watt-hours provided. Additionally, updating the batteries from Lithium Polymer to Lithium Ion provides a more stable and reliable power source.

The previous solar panel configuration for the AFIT 3U Bus was in a space dart configuration, with body mounted panels on all four sides of the CubeSat and four deployable solar panels. However, a marked increase in power can be realized by upgrading the types of solar cells, the solar panel configuration, and the attitude of the CubeSat. By updating the solar panels to the Pumpkin, Inc. 56W array, as shown in Figure 2, seven solar panels with a total of 56 total cells would generate 56W of solar array power[4].

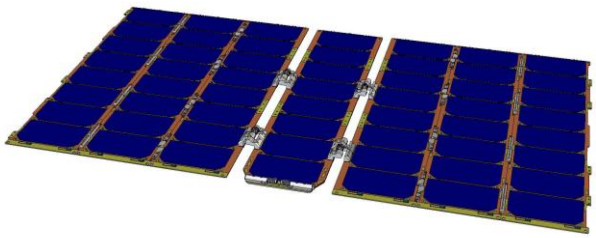

Figure 2: Pumpkin, Inc. 56 W Solar Array[4]

In order to test the thrusters in orbit, precision and ΔV maneuvers are planned. To adequately characterize the maneuvers, it is valuable to have the best possible attitude determination. Thus, it was decided that a star tracker should be added to the ADCS unit.

With the upgraded batteries, solar panels, and attitude determination, the AFIT 3U Bus will satisfactorily meet the requirements for flying with the high thrust high ΔV electrospray thrusters.

MISSION MODELING TOOL

In order to analyze the mission of the upgraded AFIT 3U Bus with the electrospray thrusters, it was decided to upgrade a previously developed AFIT modeling tool called Colony II Bus Mission Modeling Tool, or C2BMMT.

C2BMMT was created as a way to quickly analyze several satellite subsystems of the C2B at the same time in order to validate the mission concept of operations. C2BMMT was creating by a previous AFIT student, Capt Blythe Andrews, in 2012 and was based on the framework of Satellite Simulator, or SatSim, which was a satellite mission analysis program created in 2010 by another previous AFIT student, Capt Judson McCarty[5,6].

Using MMT

MMT uses MATLAB to input reports from STK into a Simulink model that represents the satellite. After the Simulink model is run, the results are output via either scopes or exported to an Excel spreadsheet. The scopes provide a quick graphical view of the subsystem parameters over time, while the Excel spreadsheet allows the user to compare values of all subsystems at a certain time step.

All orbit propagation is completed in STK. By using STK, the processing time is significantly faster than programming the obit propagation in Simulink. In order to create the STK reports, a default satellite is created with the orbit and attitude required for the mission. Next, reports are generated that include information on the latitude, longitude, and altitude; sun vector; lunar vector; maneuver; attitude; and ephemeris.

A MATLAB file is then used to pull the reports into the Simulink model. A GUI window automatically opens and allows the user to input the required task lists. The ability also exists to enter different task lists for sun safe and sun survival modes. After the reports and task lists have been loaded into the program, the Simulink model opens and is ready to be used.

The Simulink satellite model holds default mask values for the subsystems of the AFIT 3U Bus. If changes need to be made, then the user is required to double click on the colored boxes and enter the new values. Once those changes have been made, the Simulink model is run and telemetry can be viewed via either scopes or Excel.

Creation of MMT

MMT is based on the same framework as C2BMMT. The framework is composed of external models, the satellite model, and telemetry storage. The external model imports data into the model, the satellite model is used to represent the satellite subsystems, and the telemetry storage model outputs the results of the analysis[5].

The satellite model of MMT was updated to represent the AFIT 3U Bus instead of the Colony II Bus. This required changes to the ADCS, EPS, and Payload Subsystems in order to reflect the 3U AFIT Bus.

The ADCS subsystem model was changed by removing the IMU and adding a star tracker. The EPS model was adjusted to reflect four Lithium-Ion batteries, and the solar panels were changed to the Pumpkin, Inc. 56W array. The payload subsystem was also modified in order to allow the payload to be turned on only when in sunlit conditions. Since the electrospray thrusters modeled require a high amount of power, it was necessary to include this option.

MMT was modeled to calculate Sun Safe and Sun Survival modes. Similar to the C2B, it was decided that the AFIT 3U Bus would turn off its payload and star tracker and orient itself to point its solar panels at the sun in Sun Safe mode. In Sun Survival mode, the 3U AFIT Bus will turn off the payload, star tracker, and reaction wheels and the spacecraft's attitude is not actively controlled. If the bus voltage drops below 5 V or 4 V then the satellite will enter into Sun Safe or Sun Survival mode, respectively.

Adding Propulsion to MMT

Propulsion also needed to be added to MMT in order to study the ΔV and fuel used during the mission. In order to simulate the propulsion maneuvers, it was decided to use the Astrogator orbit propagator in STK. This way, the ephemeris and attitude reports that are generated in STK for use in MMT reflect the thruster's maneuvers.

In order to pull the maneuver information into MMT, an additional report was created in STK that listed the ΔV, fuel used, and semimajor axis. MMT code was then modified to pull in the additional maneuver report along with the other STK reports. An additional maneuver subsystem was added to the Simulink satellite model in order to pull in the maneuver text file and output the data into the telemetry output.

With the addition of propulsion, MMT can be used to study a variety of different thrusters for use of CubeSats. Since it is created in STK, it is easy for the user to modify the engine parameters to represent the type of thruster that should be analyzed. Additionally, Astrogator can be used to reflect a variety of different thruster maneuvers.

GUI update for MMT

The MATLAB m-files for MMT are an improved and updated version of the m-files used for C2BMMT. The m-files are automated so that the user just has to run the main m-file. When that m-file runs, a single GUI screen appears where the user can input all the task list data. The single GUI screen is user friendly because it allows the user to see all the inputs that are required at once.

Another improvement to the m-files is the addition of an option to use default values. Calculating the task lists in MMT is often the part that takes the most amount of time, and C2BMMT requires the user to calculate the task lists for each scenario run, regardless if the task lists had not changed from the last scenario run. In order to improve this, an option in the MMT GUI screen allows the user to use the previous calculated task list values.

MISSION ANALYSIS

After MMT was created, it was used to analyze several mission scenarios for the AFIT 3U Bus with high power, high ΔV electrospray thrusters as a payload.

The mission concept called for an array of eight miniaturized electrospray thrusters. Previous analysis had determined that the primary configuration should be five thrusters on one end of the spacecraft, with three on the other end of the spacecraft. For the analysis, the background configuration of four thrusters on either end of the spacecraft was also studied.

The thrusters being studied for the mission were assumed to use 7 W apiece in primary mode. Each thruster is also required to operate in standby mode before it enters primary mode in order to heat the fuel for use, with standby mode requiring 5 W apiece. Because the thrusters require a significant amount of power, it was desired to study a sun-synchronous orbit (SSO) in order to allow the most amount of power to be generated at the solar arrays as possible. It is recognized that the significant amount of power could create thermal issues; however, the thermal analysis is left for follow on study and will be managed by shutting down the thruster payloads as required to avoid overheating.

Launch opportunities were studied for the AFIT 3U Bus and the electrospray thrusters. Possible launches in 2014 included into a 600 km and 675 km orbit, while possible launches in 2015 also included 600 km SSO. It was decided that the 600 km SSO launch in 2014 would be the primary launch for planning purposes. Thus, power profiles needed to be developed for a 600-km SSO.

Characterization of 600 km SSO

Three different spacecraft attitudes were studied with MMT. The first attitude studied, Sun Aligned, was set up to have the solar panels aligned with the sun vector, with the satellite rotating in all directions in order to maintain sun alignment. This was deemed the highest power attitude; however, this attitude is not optimal for thrusting since the thrusters are not aligned with the velocity vector as the satellite rotates to maintain sun alignment. However, since the Sun Aligned attitude is the attitude that the satellite will default to in Sun Safe mode, it was desired to study how much power is possible in this best-case orientation.

The next attitude studied was Sun Constrained, which aligns the +X vector of the satellite with the velocity vector so that the spacecraft is always thrusting along the velocity vector, but the spacecraft is allowed to roll about the velocity vector axis to achieve the maximum sun angle.

The final attitude studied was the default Nadir Aligned attitude, which sets the solar panels to face zenith and does not align to the sun vector or rotate. Although this attitude provides the worst power of the scenarios chosen, it is adequate for thrusting maneuvers as the thrusters are aligned with the satellite's velocity vector. This orientation also characterizes the low end of how much power will be available.

SSO orbits have a precession rate that matches the orbit of the Earth. By matching the Earth's precession, the SSO orbit passes over the same spot on Earth at the same mean local solar time. A special type of SSO orbit is the dawn-dusk orbit, which is defined as an orbit that has a Local Time of Ascending Node (LTAN) at 0600. With this orientation, the orbit plane faces the sun constantly and the satellite has maximized its amount of time in the sunlight. In fact, satellites in an SSO dawn-dusk orbit only go into eclipse approximately three months out of the year[7].

A dawn-dusk SSO orbit would provide the most amount of power possible for the AFIT mission. However, CubeSats are launched as secondary payloads and have to accept the orbit into which they are launched. Thus, it is necessary to characterize the 600-km SSO for different LTANs. Using MMT, solar array generation numbers were calculated as a function of LTAN for the three described attitude orientations. The LTAN was stepped through one hour at a time during the analysis, with each profile run over one year using the AFIT 3U Bus characteristics. The mean OAP and maximum OAP was recorded for each profile and then compared to all the data.

Figure 3 shows the mean OAP for each profile, while Table 1 shows the maximum, minimum, and average mean OAP's for the profiles.

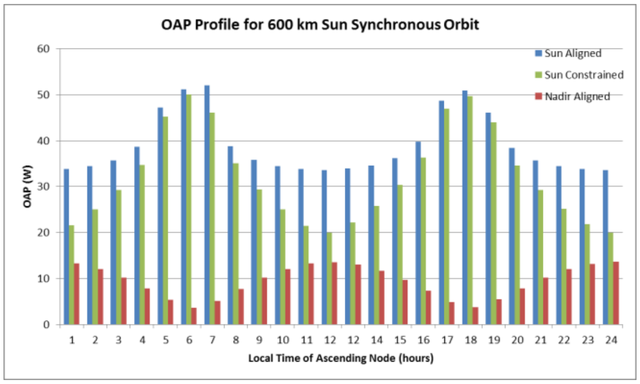

Figure 3: Mean OAP for 600 km SSO

Table 1: OAP results for 600 km SSO

Profile	Max mean OAP	Min mean OAP	Average mean OAP
Sun Aligned	50.9 W	33.6 W	39.0 W
Sun Constrained	49.7 W	19.9 W	32.0 W
Nadir Aligned	13.6 W	3.6 W	9.4 W

Based on the data, the Sun Constrained orbit is the deemed the best orientation for the mission. Although it does not achieve as much power as the Sun Aligned case, the thrust vector points along the spacecraft's velocity vector which is desired for thruster maneuvers. The Nadir Aligned case provides significantly less power than the Sun Aligned and Sun Constrained cases and therefore is not recommended.

Inclination Trades for 600 km Orbit

Next, inclination trades were conducted for the Sun Aligned, Sun Constrained, and Nadir Aligned profiles. The inclination was varied from 98 degrees to 0 degrees over a year-long scenario in MMT and the results were compared for each case. The right ascension of the ascending node was set to 0 degrees for all scenarios. Figure 4 shows the graphical results for the three profiles, and Table 2 displays the maximum, minimum, and average mean OAP for each profile.

With the inclination changes, the mean OAP changed less significantly than it did for the LTAN changes in the previous analysis. As expected, Sun Aligned had the highest mean OAP while Nadir Aligned had the least. Sun Constrained once again was shown to be the preferred choice for attitudes, as its values were significantly higher than Nadir Aligned but with a better attitude for thrusting.

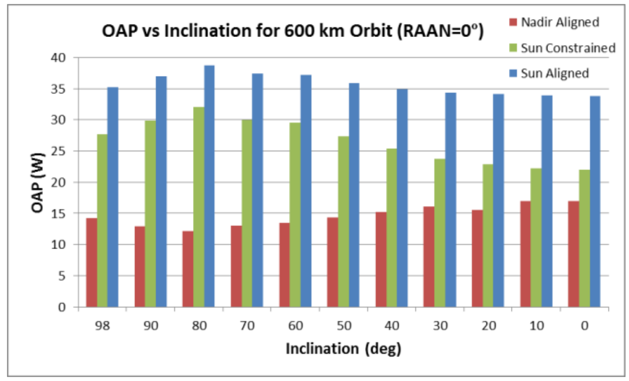

Figure 4: OAP vs Inclination for 600 km Orbit

Table 2: OAP results for 600 km Orbit, RAAN=0

Profile	Max mean OAP	Min mean OAP	Average mean OAP
Sun Aligned	38.7 W	33.8 W	35.7 W
Sun Constrained	30.0 W	22.0 W	26.6 W
Nadir Aligned	17.0 W	12.2 W	14.6 W

Generic Power Scenarios

The concept of operations for flight testing the miniaturized electrospray thrusters includes both pointing experiments and a ΔV experiment. The pointing experiments are used to characterize the performance and control authority of the thruster system. Single axis and multiple axis rotations will be performed in order to prove that the thrusters can be used for stationkeeping. The pointing experiment will most likely require several thrusters acting on both ends of the spacecraft to induce and then stop the rotations. This will require some thrusters to be in active mode while other thrusters are in standby mode. The pointing experiments will be short term and will most likely be finished in approximately a month.

Meanwhile, the ΔV experiment will be a long term experiment that will take several months, with the thrusters firing continuously in order to prove the capability of reaching 1 km/s of ΔV. The ΔV experiment will use some combination of thrusters onboard in a bounded manner such that the altitude of the spacecraft is not prohibitively raised, yet changes in altitude are significant enough to be detected and show overall ΔV achieved.

Because the experiments will use different combinations of thrusters in active and standby mode, it was desired to study which combinations of thrusters could be used without prohibitively draining the spacecraft batteries. Using multiple thrusters requires a significant amount of power, with each individual thruster unit assumed to require 7 W to operate in active mode and 5 W to operate in standby mode. Based on the amount of power available as described in the earlier section, it must be determined what is realistic for the number of thrusters that can be turned on in active mode or in standby mode to complete the maneuver experiments. Thus, the objective of the generic power scenarios is to determine how much time each combination of thrusters in active and standby modes can be used before the bus enters Sun Safe mode.

The generic power scenarios were based on solar power generation numbers found in the previous analysis. The Sun Constrained attitude was used based on its relatively high power numbers and acceptable orientation for the thrusters. A maximum, mean, and minimum cases were chosen for the Sun Constrained attitude as base scenarios. The maximum case used a LTAN set to 0600 for a dawn-dusk orbit, based on results from Figure 3. The mean case used a LTAN set to 1500, which most closely matched the average OAP calculated for the Sun Constrained scenario. Finally, the minimum case used a LTAN Set to 1200. The same Task List setup was used for all three scenarios, as shown in Table 3.

Table 3: Generic Power Scenarios Task List

Component	Status	Power Used
Transmitter	On- In view of ground station	10 W
Receiver	On- 50% duty cycle	0.5 W
C&DH	On	0.25 W
Payload 1	Varied	Varied
Payload 2	Varied	Varied
Reaction Wheels	On	2.28 W
Star Tracker	On	2 W
Sun Sensors	On	0.6 W
Torque Coils	Off	0 W
Magnetometer	On	0.0033 W
Bus Power		5.633 W

To analyze the pointing experiments, the scenarios were run for one month, which is the amount of time that is expected to be allotted during the mission. For the month chosen, the average OAP was 55.2 W for the maximum case (dawn-dusk), 28.8 W for the mean case, and 19.5 W for the minimum case. The power consumed by the thrusters was modeled in the Payload Subsection of MMT, with standby mode modeled as a secondary payload. Fifteen different scenarios were studied, with different combinations of numbers of thrusters turned on and in standby, as shown in Table 4.

The maximum case generated enough power that every scenario had sufficient power. All scenarios showed healthy battery voltage with the batteries reaching full charge early in the scenario, except for Scenario 10 with modeled five thrusters being turned on all the time with two thrusters in standby for a total thruster power draw of 45 W. Scenario 10 had a slow increase in DoD and decrease in battery voltage over the lifetime of the scenario, but the bus maintained a high enough voltage over the month modeled that it never entered Sun Safe mode.

Table 4: Generic Power Scenarios

Scenario	Thrusters in Active Mode	Thrusters in Standby
Scenario 1	5 continuous	0
Scenario 2	4 continuous	0
Scenario 3	3 continuous	0
Scenario 4	2 continuous	0
Scenario 5	1 continuous	0
Scenario 6	5, only when sunlit	0
Scenario 7	4, only when sunlit	0
Scenario 8	3, only when sunlit	0
Scenario 9	2, only when sunlit	0
Scenario 10	5, only when sunlit	2, only when sunlit
Scenario 11	4, only when sunlit	2, only when sunlit
Scenario 12	3, only when sunlit	2, only when sunlit
Scenario 13	2, only when sunlit	2, only when sunlit
Scenario 14	2, only when sunlit	2 continuous
Scenario 15	2 continuous	2 continuous

The mean power case could not provide enough power for six of the 15 scenarios over the month period. However, operating the thrusters only when in sunlit conditions allowed the spacecraft to be able to operate more thrusters at the same time without entering Sun Safe mode. When the thrusters were on all the time, only the scenarios with two or less thrusters on did not enter Sun Safe mode. However, when the thrusters operated when sunlit only, up to four thrusters could be operated and not cause the spacecraft the enter Sun Safe mode.

The minimum power case did not provide enough power for 12 out of the 15 scenarios tested. The only scenarios that did not enter Sun Safe mode were when only one thruster was on all the time and when two thrusters were on only when sunlit. However, only operating one or two thrusters at a time severely limits the types of pointing experiments possible.

Table 5 summarizes the final battery DoD voltage for all three scenarios. Although the maximum power case provides sufficient power for all of the scenarios tested, it is not realistic to assume that a CubeSat will be launched into a dawn-dusk orbit due to CubeSats being secondary payloads. It is also unlikely that the CubeSat will be launched into the minimum power orbit, although it is wise to be prepared for the possibility. For the rest of the analysis, it will be assumed that the CubeSat is operating in the mean power scenario.

Table 5: Final Battery DoD Summary

Scenario	Final DoD (maximum)	Final DoD (mean)	Final DoD (minimum)
Scenario 1	0%	82.92%	82.93%
Scenario 2	0%	82.90%	82.93%
Scenario 3	0%	82.88%	82.92%
Scenario 4	0%	40.80%	82.91%
Scenario 5	0%	0%	27.72%
Scenario 6	0%	82.91%	82.92%
Scenario 7	0%	20.00%	82.92%
Scenario 8	0%	0%	82.92%
Scenario 9	0%	0%	44.22%
Scenario 10	9.19%	82.92%	82.92%
Scenario 11	0%	82.92%	82.93%
Scenario 12	0%	63.31%	82.92%
Scenario 13	0%	0%	82.92%
Scenario 14	0%	82.88%	82.92%
Scenario 15	0%	82.89%	82.92%

Assuming that the pointing experiments will need to be conducted for at least 21 days, then a combination of scenarios 4-5, 7-9, and 12-14 could be used. This means that up to two thrusters can be always on, two through four thrusters can be on in sunlit conditions only, and up to three thrusters can be turned on when sunlit only with two thrusters in standby mode. If one pair of thrusters needs to be in standby while the other pair is on, then the best scenarios are Scenarios 13 and 14, with Scenario 13 being the optimal scenario for the experiment due to Scenario 14 having a positive DoD trend and entering Sun Safe mode after 30.77 days.

Another option would be to use any of the possible scenarios listed until the spacecraft transitions to Sun Safe mode, and then stop the pointing experiment and allow the batteries to charge before continuing. It was tested how long it would take the batteries to fully change from a 82.9% DoD with the payloads turned off in the mean power case. 82.9% DoD correlates to the depth of discharge when the satellite is in Sun Safe mode. Results showed that it would take 11.86 days to recharge completely. Since only thirty days are allotted to the pointing experiment, 11.86 days would be prohibitively long time to recharge the batteries. Thus, Scenario 13 is deemed the best option for the pointing experiments.

ΔV Experiment

The ΔV experiment was simulated by using MMT with the thruster addition. The spacecraft was modeled in a Sun Constrained attitude with a LTAN of 1500 for the mean power case. Based on results from the previous section, thrusters were only fired when in sunlit conditions. Three different cases were studied. The first case assumed five thrusters operated in active mode in sunlit conditions, the second case assumed four thrusters operated in active mode in sunlit conditions, and the third case assumed three thrusters were fired only when sunlit.

For the first case, the batteries drained over the course of the maneuver and Sun Safe mode was entered at 21.78 days. One Sun Safe mode is entered, the payload is turned off and the satellite maneuvers to a sun aligned orientation. This means that entering sun safe mode effectively stops the ΔV experiment from continuing. The total ΔV that occurred before the spacecraft entered Sun Safe mode was calculated to be 0.161 km/s, over 315 total maneuver segments.

However, previous calculations showed that it would take 11.86 days to recharge the batteries with the thrusters turned off. Although this was prohibitive for the shorter time length of the pointing experiments, it is acceptable for the longer length ΔV experiment. Assuming that the spacecraft immediately turns the thrusters off when it reaches Sun Safe mode and enters recharging mode until the batteries are fully charged, all the fuel could be used with 4.6 repetitions of maneuvers followed by recharging the batteries. In this manner, it would take 147.16 days to use all available propellant in the five thrusters, and a total ΔV of 0.743 km/s would be achieved. After the propellant is used, the remaining three thrusters on the other side of the spacecraft can fire. The altitude change from firing the thrusters would be detectable but maintained within some bounds during the thruster operation in order to not raise the orbit altitude significantly.

Next, the second case of four thrusters firing continuously in active mode in sunlit conditions was studied. Before Sun Safe mode was entered, the thrusters accomplished 895 maneuver segments, with a total ΔV of 0.416 km/s. Similar to the first case, the spacecraft can now enter a recharging segment and then begin firing the thrusters again. However, the second case only requires one recharging segment in order to use all available propellant. With this process, 0.605 km/s of ΔV can be achieved in 106.84 days. The timeframe is less than the first case due to less time needing to be spent recharging the batteries.

The third case of three thrusters firing continuously in active mode in sunlit conditions was then analyzed. This case never entered Sun Safe mode so a battery recharge segment was not required. It took 96.46 days to use all the propellant with a total ΔV achieved of 0.455 km/s. A summary of Cases 1, 2, and 3 are shown below in Table 6.

Table 6: Summary of Cases 1, 2, and 3

Case	Total Time	Total ΔV
Case 1: 5 thrusters	147.16 days	0.743 km/s
Case 2: 4 thrusters	106.84 days	0.605 km/s
Case 3: 3 thrusters	94.46 days	0.455 km/s

In order to achieve 1 km/s of ΔV, some combination of Cases 1, 2, and 3 must be used. In the primary configuration of five thrusters on end of the spacecraft and three thrusters on the other end, combinations of five and then three, three and then five, three and then four, or four and three thrusters can be used. For the backup configuration of four thrusters on either side of the spacecraft, combinations of four and four, four and three, and three and four can be used.

If five thrusters are initially fired, then the next half of the scenario will use three thrusters. The first half of the scenario would realize 0.743 km/s, so the three thruster maneuver would only need to achieve 0.257 km/s of ΔV in order to reach the target of 1 km/s. This would take an additional 53.35 days. The total time for the 1 km/s ΔV maneuver would be 200.51 days.

If four thrusters are used for the first half of the maneuver, then either four thrusters or three thrusters can be used for the second half of the maneuver. Using four thrusters again for the second half of the maneuver would require 62.0 additional days, totaling 168.84 days for the complete 1 km/s maneuver. If instead three thrusters are used for the second half of the maneuver, then it would take an additional 82 days, resulting in 188.84 days.

If three thrusters are fired for the first half of the maneuver, then either four thrusters or five thrusters can be fired for the second half, depending on the thruster configuration. If four thrusters are fired for the second half, then 1 km/s could be achieved in 177.74 days. If five thrusters are fired for the second half, then the maneuver would take instead 202.97 days.

The results are summarized below in Table 7. The quickest way to achieve 1 km/s ΔV in the primary thruster configuration of five thrusters on one end of the spacecraft with three thrusters on the other end is by firing three thrusters for the first half of the scenario until they use all their fuel, and then firing the remaining four thrusters for the second half of the scenario. This allows 1 km/s of ΔV to be achieved in 177.74 days.

If the spacecraft is in the backup configuration of four thrusters placed on either side of the spacecraft, then the best option is firing four thrusters for the first half of the maneuver until the fuel is expended, and then firing the remaining four thrusters for the second half of the scenario. 1 km/s of ΔV can then be reached in 168.84 days.

Table 7: Summary of 1 km/s ΔV Maneuvers

Combinations of Thrusters	Total Time
5 / 3	200.51 days
4 / 4	168.84 days
4 / 3	188.84 days
3 / 4	177.74 days
3 / 5	202.97 days

SUMMARY

An important first step of power analyses for various design reference missions has been completed for the AFIT 3U Bus with the miniaturized electrospray thrusters as a payload. With the analyses completed, it will be possible to choose a concept of operations for how to operate the thrusters within the power budget provided by the AFIT 3U Bus. A Sun Constrained orientation with a mean OAP of 28.8 W provides a good baseline for the Concept of Operations in a 600 km SSO. It is recommended that the pointing experiments be conducted with two thrusters on and two in standby mode while the satellite is in sunlit conditions. The optimal ΔV experiment configuration for the primary thruster configuration is a combination of three thrusters fired for the first half of the maneuver followed by four thrusters fired for the second half of the maneuver. In this manner, 1 km/s of ΔV can be achieved in 177.7 days.

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