Use of Plasma Pulse Thrusters for Deorbit on Small Satellites

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Introduction

Space debris is a growing concern for many[1] and with the new trend of small satellites for educational and experimental purposes this problem may only get worse. If it can be found that adding a propulsion system can assist in reliably deorbiting a satellite, some regulations that have stated propulsion systems are not allowed[2] may change or be waived. Once propulsions systems are allowed on CubeSats on NASA missions, CubeSats could begin experimenting and learning more about higher orbits (600 km altitude or higher), orbit maintenance and orbital maneuvers, as well as collect data and serve as proof of concepts for experimental propulsion systems. The main propulsion systems surveyed were plasma pulse thrusters (PPTs) for their growing popularity as an application on the small satellites. These thrusters were surveyed for their available ΔV and then compared to some interesting de orbit techniques.

PPT Survey Process

The first thing to be researched were the plasma pulse thrusters themselves[3, 4, 5]. It was found that many have already been fabricated, tested, and sold for CubeSat class satellites. It was decided to collect information on four PPTs and compare them to illustrate the general qualities and get an idea of how much ΔV would be available for working within a mission's budget. The formula used to calculate the ΔV of the thrusters was:

$$\Delta V = V_e * \ln\left(\frac{M_0}{M_1}\right)$$

Where:

$$V_e = I_{sp} * g_0$$

I_{sp} is the specific impulse, which is usually provided by the manufacturer in the thruster data sheet. g_0 is standard gravity or the general value of gravity used at the Earth's surface; 9.8 m/s was used for standard gravity. M_0 is the total initial mass, or the mass of the thruster with propellant. M_1 is the total final mass after complete burn, which would be the mass of the thruster only.

Once a minimum figure of 151 m/s of available ΔV was found, experiments began with the STK modeling software, trying to maximize the use of 151 m/s of ΔV. Many tutorials and practice mission sequences needed to be run to find which inputs were needed to find the proper output data.

PPT Survey Results

Clyde Space CubeSat Pulse Plasma Thruster:
608s I_{sp} ; 151 m/s ΔV
Clyde Space CubeSat μPulse Plasma Thruster:
590s I_{sp} ; 296 m/s ΔV
Busek Micro-Pulsed Plasma Thruster (BmP-220):
536s I_{sp} ; 438 m/s ΔV
Mars Space Ltd. Micro-PPT for NanoSats:
640s I_{sp} ; 562 m/s ΔV

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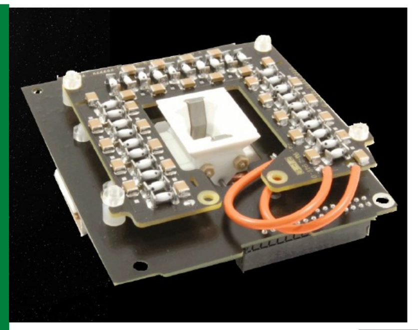
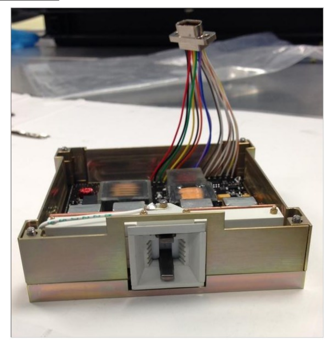
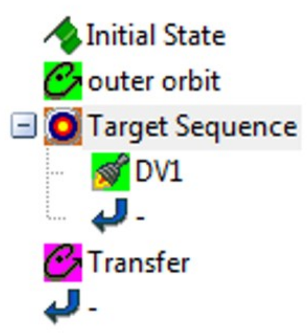


Above: Clyde Space's CubeSat μPPT[3] that produces 296 m/s of ΔV. **Right:** Clyde Space's CubeSat PPT[3] that produces 151 m/s of ΔV.

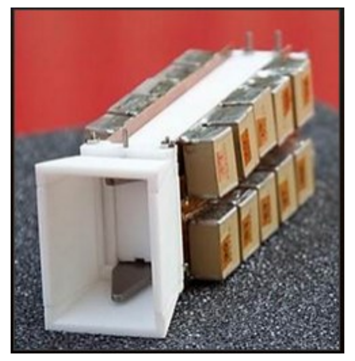


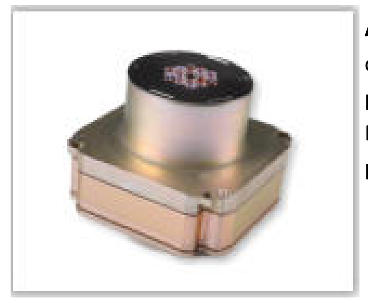
Scenario 1 MCS Tree



Scenario 2 MCS Tree

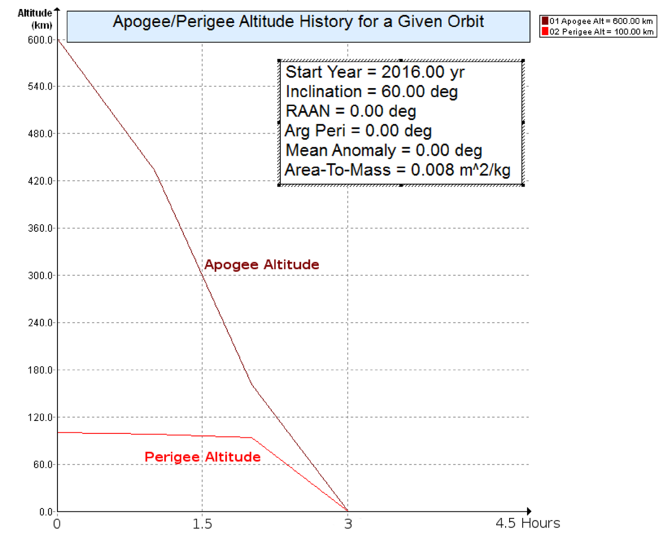
Scenario 3 MCS Tree



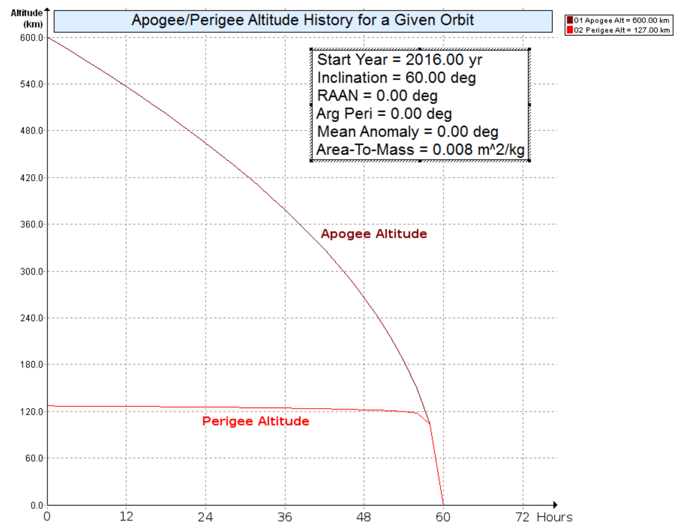


Above: Mars Space Ltd.'s Micro-PPT for NanoSats[4] that produces 562 m/s of ΔV. **Right:** Busek's BmP-220 PPT[5] that produces 438 m/s of ΔV.

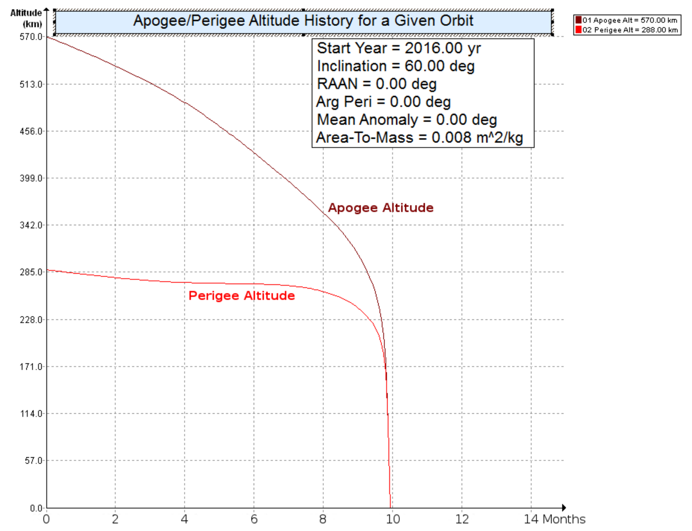
Scenario 1 final decay



Scenario 2 final decay



Scenario 3 final decay



STK—Building Deorbit Algorithms and Creating a Simulation

- Defining the satellite to be used:

  Specific drag figures were needed to accurately model natural decay. One of the mission sequences would involve aerobraking (allowing the atmosphere to decay the orbit). For CubeSats as small as 1U a figure of 2.2 could be considered accurate for a drag coefficient[6].

- Create the Mission Control Sequence (MCS) using the Astrogator propagator:

  Astrogator was used as a type of graphical programming language[7] to produce ephemeris, or data positions of the satellite with time. MCS segments pass their output data as the input data to the next segment until a desired outcome is achieved.

  * The initial state was defined using Earth High-Precision Orbit Propagator (HPOP) Default v10.
  * The initial outer orbit chosen had a circular 600 km altitude with a 60° inclination. Any altitude less (for a 1U CubeSat) has a natural life short enough to consider it a non-threat to the space debris issue[8].
  * Debris Assessment Software (DAS) was used in conjunction with STK to asses a CubeSat's natural life. DAS has NASA's flight requirements programmed into it to help verify missions. It was found that DAS and STK were providing slightly different figures, generally DAS was reporting the natural life approximately 10% longer than STK.
  * Maneuvers:

  The MCS programmed experimental maneuvers can be seen in the MCS Trees segment of the poster. The Kármán Line is the generally accepted line between space and the atmosphere of Earth. The atmosphere at 100 km is dense enough to "grab" the satellite and burn it as it approaches the Earth.

Satellite Parameters Used

Dry mass of 1 kg; Coefficient of Drag 2.2; Cross sectional area 0.01 m^2; Fuel Density 2.2 g/cm^3; Max fuel mass 10 g; Keplerian coordinates were used.

Summary

The first scenario type was a Hohmann type transfer using only one burn to create a transfer ellipse, substituting the usual second burn for aerobraking. It resulted in a fast overall 3.76 hour deorbit but it used the most ΔV at -0.142 km/s.

The second scenario type was a multiple burn type transfer that utilized four increasing ΔV burns with a 5 minute coast in between burns. This transfer was a middle road transfer that took 60.92 hours to deorbit the satellite with only slightly less ΔV at –0.140 km/s.

The third and final scenario type was an "eco-mode" type deorbit that takes roughly a year to deorbit but with significantly less ΔV. The transfer starts with a –0.050 km/s ΔV burn followed by aerobraking for 10 months. The satellite is then positioned at apogee to prepare for a second ΔV burn of –0.050 km/s. The satellite then aerobrakes again until it reaches a targeted 100 km altitude (resulting in another few months). Total ΔV required is –0.100 km/s. Total time of deorbit (according to STK data) is 11 months.

A second version of scenario 3 was run to experiment with values and it was found that with –0.080 km/s ΔV, the deorbit time increased to 13.3 months (according to STK data). More experiments could be run like scenario 3 to see if this effect could be maximized.

Future Work

When going through the research presented and further studying PPTs it was found that describing a PPT burn using a ΔV value is quite inadequate. Using ΔV values makes the assumption that the velocity change happens instantaneously. PPTs are very slow burning and low thrust engines and can take a significant amount of seconds to make a burn. Advanced mathematics and a new simulation program may be needed to model this effect appropriately.

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