Mission Analysis for Piezo Dust Detector (PDD) Satellite ARMADILLO

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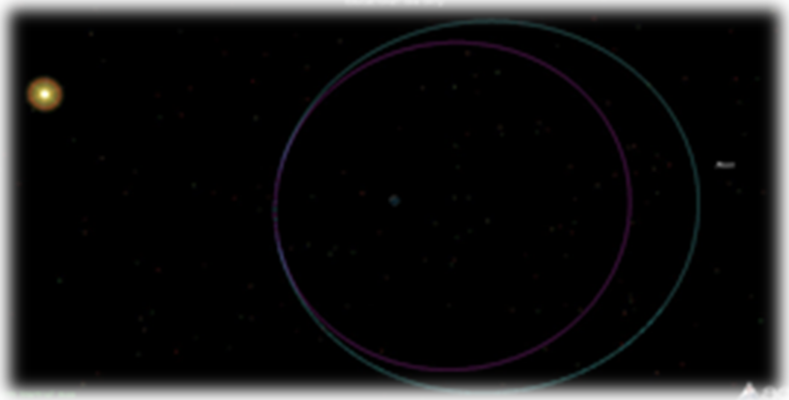

Abstract

The ARMADILLO satellite is a picosatellite that the University of Texas at Austin Satellite Design Lab is developing and testing and in collaboration with Baylor University have added a piezo orbital debris sensor for detecting low earth dust debris. We are trying to identify the maximum flight time (lifetime) of the ARMADILLO satellite to efficiently collect data that will be transferred to our ground stations in Austin, TX and Stuttgart, Germany for further research. With the use of Satellite Tool Kit (STK), we are able to observe how inclination, altitude, RAAN, eccentricity and delta V are affected by varying flight conditions. We found that the lifetime of the satellite increased exponentially with respect to the semi-major axis. The primary transfer rate (115.2 kbit/sec) and the backup transfer rate (1.2 kbit/sec) onboard the satellite are sufficient for data transfer, yet re-entry must be timed accordingly to provide late-life access to the ground stations. To prolong lifetime it is best to perform a single Hohmann transfer in early orbits, whereas to quickly descend it is best to induce an elliptical orbit with a single burn. Maneuvers at 200km and 150km are feasible only if 15m/s of fuel remains—that fuel could be most efficiently used at 200km in a polar inclination.

Introduction

The ARMADILLO (Attitude Related Maneuvers And Debris Instrument in Low Orbit) satellite is a 3UCubeSatwith the dimensions of a picosatellte(30 cm by 10 cm by 10 cm). The satellite will have an added payload of a piezo orbital debris sensor that will be used to take measurements of atmospheric debris. The sensor detects and records impacts along the orbit at varying altitudes. The satellite maintains a low earth orbit (LEO) with altitudes ranging from approximately250 km- 550 km.

Methods

Satellite Properties/Initial Constraints

Before running any simulations, the University of Texas at Austin Satellite Design Lab provided specific constraints to be place on the satellite. These constraints were applied in Satellite Took Kit (STK), a program designed to model, engineer and analyze operations of space and cyberspace[i], under the parameters for force model and lifetime, as seen in Table 1.

Force Model		Lifetime	
Atmospheric drag coefficient (Cd)	2.0	Dry mass of satellite	3.3 kg
Area/mass ratio (front) used in drag calculations	0.009 m^2/kg	Drag Area	0.03 m^2
Solar radiation pressure (SRP) coefficient (Cr)	1.0	Area Exposed to Sun	0.01 m^2
Area/mass ratio (side) used in SRP calculations	0.003 m^2/kg	Atmospheric Density Model	Jacchia-Roberts
Daily F10.7	150.0		

Table 1: STK Constraints for Force Model and Lifetime

Satellite Tool Kit/Propagator

We used two STK propagators depending on the simulation case. In cases with no maneuvers, the HPOP propagator was solely used because of the accuracy of its orbital erosion, classical conditions and lifetime. In cases with maneuvers, however, both the HPOP and Astrogator propagators were employed. The initial conditions were first entered into HPOP in order to obtain the orbital conditions after a period of time (e.g., 20 days) or at a certain altitude (e.g., 150 km). Next, the new conditions were entered into Astogator, the maneuver was performed (for instance, a Hohmann transfer), and the changed conditions were recorded. Within the Astrogator propagator, Earth Point Mass was used as the specific propagator between orbital maneuvers in order to retain orbital consistency. Finally, the conditions obtained through Astrogator were re-entered into the HPOP propagator and the lifetime was found. This method, while roundabout, was deemed as the most accurate and consistent with the Austin data. Moreover, within HPOP we were unable to perform maneuvers, while within Astrogator we were unable to derive lifetime—therefore, a combination of the two propagators was utilized.

Simulation Focus/Properties Tested

While the ARMADILLO satellite could initially orbit at any altitude between 250 km and 1000 km, we primarily investigated orbits between 250 km and 550km. We focused on these orbits because they present the worst case scenarios for the satellite—at altitudes over 550km the lifetime is significantly greater than required (at 550km and a Kennedy Orbit, the lifetime was found to be 11.3 years). The semi-major axis was tested at increments of 50km, starting at 6620km and ending at 6920km. We performed initial tests on Equatorial, Sun-synchronous, Polar and Kennedy orbits. Based on the data we obtained and the likelihood of the various orbits, we focused on Polar and Kennedy orbits. Additionally, the orbits we simulated were primarily circular. Satellite lifetime was the initial obstacle to overcome so that the satellite has optimal flight time to collect the necessary data. We also performed a variety of simulations on access to the ground stations; in one test we compared access time to RAAN. In order to carry out this test we performed multiple simulations in which we changed the RAAN by 10° while leaving other conditions constant. In another test we examined the feasibility of data transfer—in order to perform this check we found the total amount of time the satellite had access to Austin and Stuttgart. We divided these times by the total lifetime to get access percent—and then multiplied the access percent by the amount of time in a day. In this fashion we obtained the average amount of access time per day. In our final extensive investigation, we tested how best to prolong lifetime and perform maneuvers at 150km and 200km. This test was performed using both propagators; within Astrogator, we utilized target sequences—the first deltaV was user defined and the second deltaV was calculated by STK (Hohmann transfer).

Results

Orbit Types

a, km	**e**	**I**	**RAAN**	**Orbit Count**	**Lifetime, days**	**Umbra, Mean**	**Austin, Mean**	**Stuttgart, Mean**
6620	0	28.5	14.1705	126	7	2223.231	400.73	n/a
6670	0	28.5	14.1705	463	28	2192.52	453.609	n/a
6720	0	28.5	14.1705	1319	82	2174.018	482.134	n/a
6770	0	28.5	14.1705	3165	200	2159.43	542.076	n/a
6820	0	28.5	14.1705	7645	1.3 years	2147.195	542.076	123.363
6870	0	28.5	14.1705	17702	3.1 years	2136.705	646.389	195.893
6920	0	28.5	14.1705	63297	11.3 years	2127.616	661.483	295.528

Table 2: Lifetime, Umbra and Access on a circular Kennedy Orbit

Equatorial Orbit: According to our simulations, a satellite in equatorial orbit will be more likely to collide with particles. Increased particle collisions on the one hand will provide more data for the PDD, but on the other hand these collisions will reduce lifetime. STK simulations also revealed that there is no satellite access to either ground station until the semi-major axis is 7374 km—therefore we deem this orbit least advisable because direct data transfer will be impossible in descent.

Sun Synchronous Orbit: Sun-synchronous orbits proved to produce a slightly longer lifetime than polar orbits when the satellite orbits at about the same altitude. In order for the semi-major axis to be less than 6930km the inclination is restricted between 96.5° and 97.5°. Throughout these experiments RAAN and eccentricity were kept constant at values of 291.232° and 0, respectively.

Polar Orbit: We ran simulations ranging the inclination from 80° to 100° and found that inclination has a negligible effect on satellite lifetime if altitude remains constant. However, inclination does have large impact on umbra and access to ground stations. Once the semi-major axis is equal to or greater than 6670km, there is no umbra if the inclination is 100°. Once the semi-major axis is equal to or greater than 6720 km, the satellite has no umbra at an inclination of 96° or 100°. Finally, if the semi-major axis is 6920km or greater, there is no umbra at an inclination of 92°, 96° or 100°. Overall, as the semi-major axis increases the amount of umbra decreases and as the inclination increases the umbra decreases. Polar orbits experience the least amount of collisions and thus the longest lifetimes.

Kennedy Orbit: This likely launch inclination has more access to Austin than the other simulated orbits but its access to Stuttgart is limited. As is shown on the table below (Table 2), a satellite on a Kennedy Orbit would not have access to Stuttgart at a semi-major axis of less than

6820km—a significant concern in descent. However, our simulations have found that the access to Austin alone is enough for 5.1MB of data transfer (see *Data Transfer*). It should also be noted that as the semi-major axis increases the mean umbra decreases and the mean transfer time per pass increases. Finally, Kennedy Orbits experience more particle collisions than Polar orbits and thus degenerate more rapidly.

Overall we found that the lifetime of the satellite increased exponentially with respect to the semi-major axis (see Table 2). Increasing the semi-major axis of the Kennedy Orbit shown above from 6620km to 6670km increased the lifetime by 21 days—yet increasing the semi-major axis from 6870km to 6920km increased the lifetime by over eight years. This trend was common to all four orbits we analyzed.

RAAN and Access

We experimented to find a correlation between the right ascension of the ascending node (RAAN) and access as the semi-major axis increases. We found that as the semi-major axis increases, the percent access time (time the satellite has access divided by lifetime) increases. This isn't because the number of passes per day is increasing (in fact the opposite occurs) but because the average access time per pass increases. Figure 1 shows this to be true. When the semi-major axis is 6670km, the average access time per Austin pass is about 376seconds—when the semi-major axis is increased to 6920km; however, the average access per Austin pass increases to 471seconds. Based on the data we obtained, there appears to be a roughly linear correlation between altitude and access for both Austin and Stuttgart. Moreover, the average access time per pass for both Austin and Stuttgart is relatively equal; when the semi-major axis is 6820km, the average access time per Austin pass is 433.4secondsand the average access time per Stuttgart pass is 433.5seconds. Our results indicate that in a polar orbit, average access time per pass is largely independent of the position of the access point.

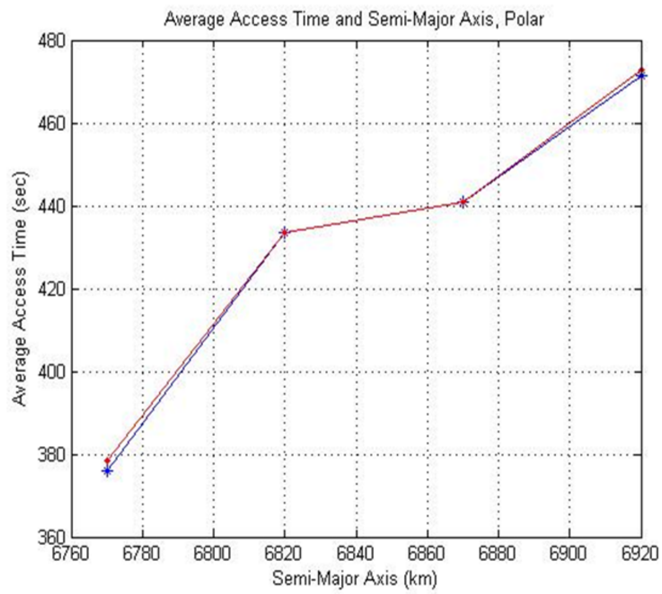

Figure 1: Access Time with Austin and Stuttgart at Polar Orbit

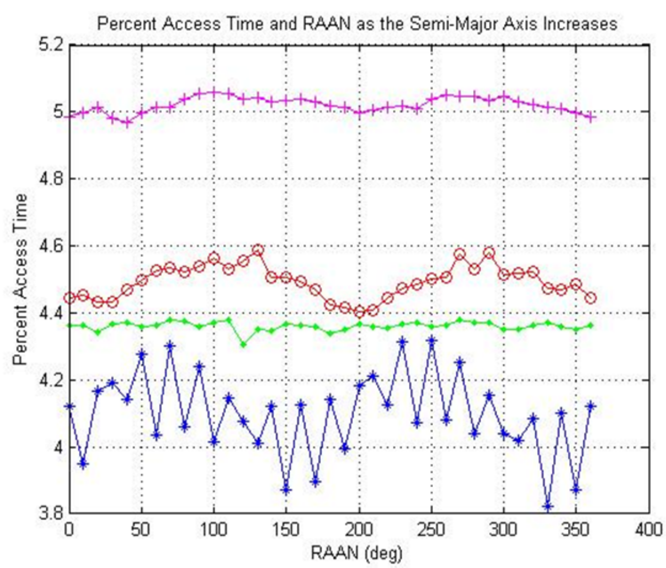

Figure 2: Percent Access Time and RAAN

Our simulations showed that there was a relationship between RAAN and access. As you can see from the

Figure 2, there is wave pattern in which the Percent Access Time peaks at around 100° and 250° and dips at around 25°, 200° and 325°. Moreover, as the semi-major axis increases the Percent Access Time increases—a polar orbit with a semi-major axis of 6670 km (blue) has around four-percent access time while a polar orbit with a semi-major axis of 6820 km (purple) has around five-percent access time. Finally, orbits at lower altitudes are more affected by changes in RAAN whereas orbits at higher altitudes exhibit fewer perturbations—notice the jagged blue line in contrast to the smooth purple line. At a sufficiently high altitude we expect the line relating Percent Access Time and RAAN to be completely smooth (changes in RAAN will eventually have no effect on Percent Access Time). This study was created more out of academic curiosity than necessity, yet the results may prove helpful closer to launch date when we have more information about ARMADILLO's likely range of RAAN.

Data Transfer

We checked the feasibility of data transfer at both the primary transfer rate (115.2 kbit/sec) and the backup transfer rate (1.2 kbit/sec). We found that as the Semi-Major axis increases, the maximum amount of MBs Transferred per Day increases (shown in Table 3 below). Moreover, polar orbits are capable of transferring more data than Kennedy inclinations; both of these trends are a result of the greater access time provided by increasing altitudes and increasing inclinations. Our simulations show that as long as the semi-major axis is equal to or greater than 6570km, there is more than sufficient access time to transfer the data at 115.2 kbit/sec. For instance,at a semi-major axis of 6570km and an inclination of 28.5° on average 21.3MB could be downloaded from the satellite per day—more than 316% greater than the requisite amount. This is advantageous because not every passwould be needed for data transfer—satellite operators could pick and choose passes based on convenience.

Inclination	Semi-Major Axis, km	MBs Transferred Per Day 115.2 kbit/sec	MBs Transferred Per Day 1.2 kbit/sec
90	6520	4.364493750	0.045463477
28.5	6520	4.987982812	0.051958154
90	6570	23.55521002	0.245366771
28.5	6570	21.26250000	0.221484375
90	6670	37.65548703	0.392244657
28.5	6670	24.54340874	0.255664062
90	6720	44.75585938	0.466210937
28.5	6720	35.69702148	0.371838379
90	6770	57.26343888	0.596494155
28.5	6770	43.86150000	0.456890625
90	6820	66.23609628	0.689959336
28.5	6820	49.28903718	0.513427471

Table 3: Max MBs Transferred Per Day at Different Semi-Major Axis and Inclinations

While the 115.2 kbit/sec transfer rate would be feasible, the 1.2 kbit/sec transfer rate would not be able to transfer 5.1MBs in LEO. The 1.2 kbit/sec, however, is sufficient to obtain data from the PDD should the semi-major axis be greater than 6520km. According to STK, at a semi-major axis of 6570km and an inclination of 28.5° 0.22 MB of data could be downloaded with the backup transfer rate—more than the 0.148MB required for the PDD. One concern revealed by our simulations occurs during re-entry; it is likely that the satellite will only get a single access point. While one good pass is more than sufficient for the PDD, it is important that de-orbit maneuvers be timed so this last pass occurs right before the satellite disintegrates.

Prolonging Lifetime

Based on the data obtained from STK, using propulsion at the beginning of the satellites lifetime is more effective than using it later in the satellites lifetime. In one situation (semi-major axis 6720km, 0 eccentricity, 90° inclination, 180 argument of perigee, 0° RAAN) using 45m/s of propellant at the start of the orbit increased the lifetime to 351days; whereas, using 45m/s of propellant after twenty days increased the lifetime to 286days, and using 45m/s of propellant after sixty days increased the lifetime to only 188days.

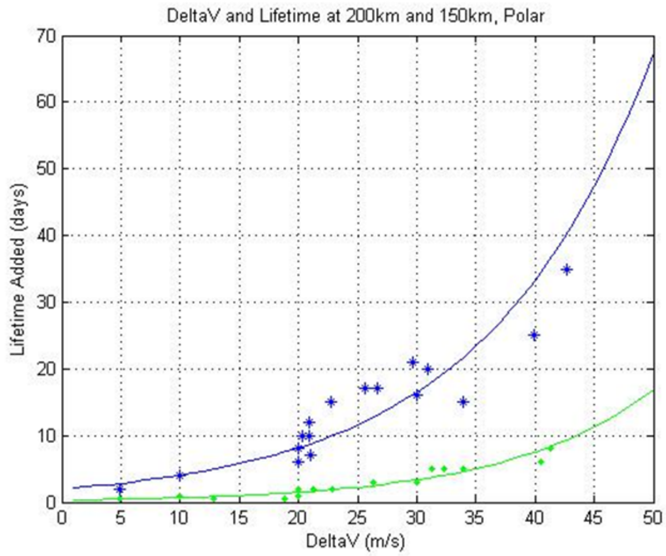

Figure 3: Polar Orbit Lifetime and DeltaV

Additionally, circular orbits have a longer lifetime than elliptical orbits. A Hohmann transfer using 45 m/s of total fuel (initial semi-major axis 6720 km, 0 eccentricity, 90° inclination, 180 arg. of perigee, 0° RAAN) increased the lifetime by 351 days—yet a single burn using 45m/s only increased the lifetime by 264days. Thus, it would be effective to use Hohmann transfers to increase lifetime—at both orbit start and at 200km and 150km—and single burns for de-orbit.

Finally, using less than 15m/s of propellant for 200km and 150km transfers does not increase the satellite lifetime. When 10m/s of total propellant were used for a Hohmann transfer (initial semi-major axis 6580km, 0 eccentricity, 89.9° inclination, 350 arg. of perigee, 0.12° RAAN) the satellite lifetime remained 294days—and when 10m/s were used at an altitude of 150km, the lifetime again persisted at 294days. While using less than 15m/s of fuel does increase the orbit count and the altitude, it thus fails to prolong lifetime.

We tested Hohmann transfers at 200km and 150km in order to increase PDD data during descent. We used scatter plots to map our results and then calculated best fit lines for the points. Using a set amount of fuel increased the altitude of the satellite by nearly identical amounts regardless of the original altitude or inclination. However using propellant at 200km increased the lifetime of the satellite more than using equal propellant at 150km for both Polar and Kennedy orbits, as is shown on the given

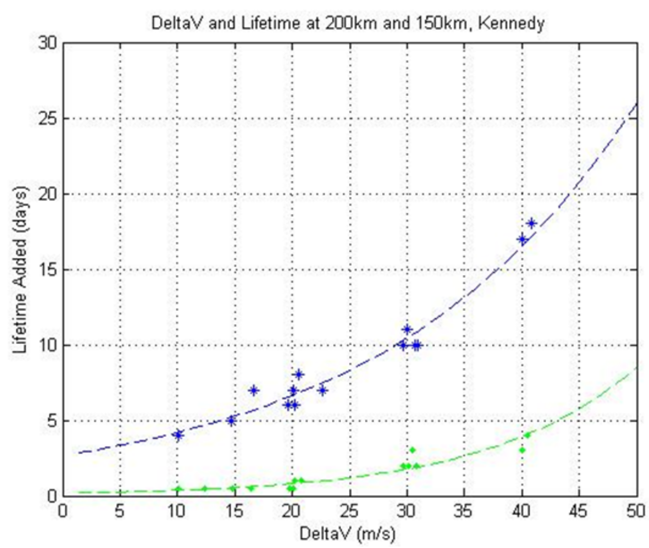

Figure 4: Kennedy Orbit Lifetime and DeltaV

graphs. The best fit lines for DeltaV and Lifetime at 200km and 150km, Polar are as follows: 200km (solid blue): $2.0036e^{0.0703x}$and 150km (solid green): $0.2993e^{0.0807x}$. The best fit lines for DeltaV and Lifetime at 200km and 150km, Kennedy are as such: 200km (dashed blue): $2.6621e^{0.0456x}$ and 150km (dashed green): $0.1693e^{0.0784x}$. It should be noted that all four of the best fit lines are exponential—as the deltaV increases (increasing altitude), the lifetime increases at a growing rate due to altitude degeneration differences.

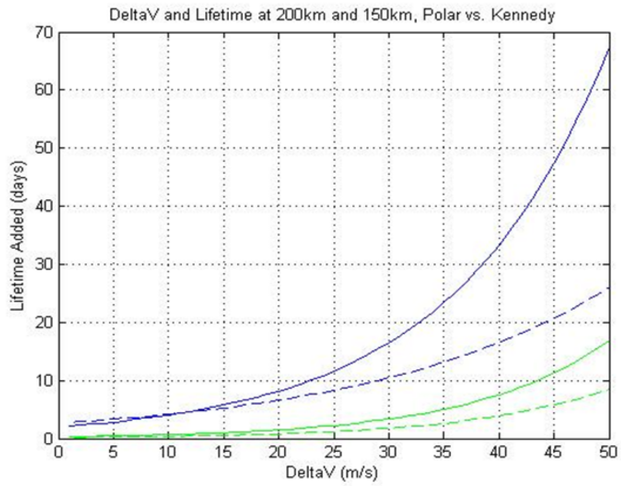

Figure 5: Comparison of Polar Orbits and Kennedy Orbits

Moreover, increasing the DeltaV along a polar orbit increases lifetime more than equal increases at Kennedy inclinations (see Figure 5). This is due to the increased number of particle collisions at 28.5°—causing the orbit to degenerate more rapidly. Performing at maneuver at 200km and a polar inclination would thus be the most efficient.

Conclusion

Based on the STK simulations we performed a polar or sun-synchronous orbit would provide increased lifetime, better access and more total PDD data than a Kennedy orbit. An equatorial orbit would not be feasible for the ARMADILLO satellite. Obtaining a RAAN of 100° or 250° would be profitable during re-entry but not essential. The resources onboard the satellite are sufficient for data transfer, yet re-entry must be timed to provide late-life access. To prolong lifetime it is best to perform a single Hohmann transfer in early orbits, whereas to quickly descend it is best to induce an elliptical orbit with a single burn. Finally, maneuvers at 200km and 150km are feasible only if 15m/s of fuel remains—that fuel could be most efficiently used at 200km in a polar inclination.

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