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Stuff, W. (2022). Orbital Debris Analysis and Orbital Decay Analysis of ARKSAT-2. *Mechanical Engineering Undergraduate Honors Theses* Retrieved from https://scholarworks.uark.edu/meeguht/114

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ORBITAL DEBRIS ANALYSIS AND ORBITAL DECAY ANALYSIS OF ARKSAT-2

Undergraduate Honors Thesis

William Stuff

April 29, 2022

ABSTRACT

ARKSAT-2 is a cube satellite developed by the University of Arkansas for its second CubeSat mission. There are two objectives of the ARKSAT-2 mission. The first objective of this mission is to test a novel cold gas thruster propulsion system using water-propylene propellant. This propulsion system will be used for attitude control of the satellite. The second objective for the ARKSAT-2 mission is to test a Solid-State Inflation Balloon (SSIB) that has been designed and developed for this mission. The SSIB is designed to be a simple and cost-effective method for deorbiting the vehicle. In cube satellites, a software known as NASA Debris Assessment Software (DAS) is used. DAS is limited in the fact that it is designed for satellites that do not have propulsive capability. Due to the nature of the vehicle containing a propulsions system, a new way of using DAS was required. This new process of using DAS was developed and implemented for ARKSAT-2. In addition, orbital decays were analyzed to look at when the orbits of ARKSAT-2 and the ISS would match, and when ARKSAT-2 would re-enter Earth's atmosphere.

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ACKNOWLEDGEMENTS

The author thanks the University of Arkansas and the University of Arkansas Department of Mechanical Engineering for its help. I would also like to thank Dr. Adam Huang for his continued support and for allowing me to take part in this project. I would also like to thank the rest of the ARKSAT team, namely Cassie Sands, Roman Dowling, Samuel Cano, and Charles Smith. It has been wonderful working with you all. I would also like to thank Dr. David Jensen for taking the time to review my thesis.

ABBREVIATIONS

DAS	Debris Assessment Software
FCC	Federal Communications Commission
Isp	Specific Impulse
ISS	International Space Station
ODA	Orbital Debris Assessment
NASA	National Aeronautics and Space Administration
SSIB	Solid-State Inflatable Balloon

INTRODUCTION

Background

The ARKSAT-2 mission is a 2U sized cube satellite. A 2U cube satellite is a standardized size meaning its dimensions are 10 cm x 10 cm x 22.7 cm. This cube satellite was made possible through NASA's CubeSat Launch Initiative. This NASA program provides the necessary support that makes it possible for smaller teams to launch their own satellites into space. ARKSAT-2 has two primary mission objectives. The first of these objectives is to test a novel cold gas thrust propulsion system for attitude control of the vehicle. This cold gas thrust system uses water-propylene propellant. The system is also designed to provide some orbital maneuvering capability albeit in a very limited capacity. The primary advantages of such a system are that it is cost effective, and the water-propylene propellant is non-toxic. Part of the assessment of this system is to measure the response of the system. The next primary objective of this mission is to test a Solid-State Inflatable Balloon de-orbiting system. The SSIB works by inflating 37 cm Mylar™ balloon at a low altitude at the end of its mission thus increasing the surface area of the satellite. This increased surface area will cause there to be more aerodynamic drag on the satellite and thus it will de-orbit faster. This system is composed of a solid-state gas generator that will produce N2 gas to inflate the balloon. The overall goal of this system is to decrease the orbital lifetime of the satellite. The exact date of launch is unknown, but for the purposes of this study, a date of February 2023 was used for a launch date and May of 2023 was used as the satellite's deployment date. These are the projected dates for the mission that ARKSAT-2 was most recently slated to be launched on, NG-18.

Objective

To develop and implement a new process for using NASA DAS that will enable the limited software to be used for satellites with propulsive capability. In addition, to conduct orbital decay analysis of ARKSAT-2 to determine how far into its mission it will match the altitude of the ISS, and when it will re-enter Earth's atmosphere.

ORBITAL ANALYSIS

Current Orbital Debris Assessment on Non-Propulsive Satellites

In order to limit the amount of orbital debris and to ensure that satellites will not collide with one another, the FCC requires that orbital analysis be conducted on the cube satellite using Debris Assessment Software (DAS) developed by the NASA Orbital Debris Program Office. This software is designed to assist in mission planning and to assist NASA in conducting orbital debris assessments (ODA). However, this software is quite limited in capability as it is primarily designed for satellites that do not have attitude control and the ability to change their orbits. The current iteration of this software is designed to be used from 2015 until 2030, after which a new version of the software will be required.

A Novel Method of Using NASA DAS

Due to the propulsive capabilities of ARKSAT 2, a new approach needed to be developed in order for NASA DAS to still be used for FCC approval. The approach essentially mimics that of a flight envelope of an aircraft. In that there are certain orbits that it is known the satellite will deploy and operate at. With these known limitations of the satellites orbit, the ODA can be done multiple times within that flight envelope at different altitudes. This enables a more complete analysis of the satellite’s debris risk. In addition to the satellite being at different altitudes, the attitude of the spacecraft will be variable as well. The reason that this is important is that the drag on the satellite in the atmosphere will depend on the cross-sectional area of the satellite. The cross-sectional area that will be contributing to this drag will depend on the orientation of the satellite. To account for this, the simulations needed to be ran using three different possible cross-sectional areas. These three areas are calculated using the possible cross-sectional areas of a nominal 2U sized cube satellite.

2U Satellite Cross Sectional Areas	
Minimum	0.01000 m^2
Medium	0.00227 m^2
Maximum	0.00248 m^2

From these calculated areas, area to mass ratios could be calculated which is the value required for running the ODA. The approximate mass of the satellite has been calculated to be 1.8678 kg. From the calculated areas of the satellite and the known mass, the area to mass ratio was calculated for each of the three possible cross-sectional areas.

2U Satellite Cross Area to Mass Ratios	
Minimum	0.00535389 $\frac{m^2}{kg}$
Medium	0.01215333 $\frac{m^2}{kg}$
Maximum	0.01328035 $\frac{m^2}{kg}$

In addition to the variance of the possible cross-sectional areas, the possible orbits of the satellite will be variable as well. From the deployment service provider, it was determined that ARKSAT-2 will be deployed anywhere from 50 to 80 km above the orbit of the ISS. The orbit of the ISS changes frequently, but an orbit with an apogee of 419 km and a perigee of 413 km ended up being used. Therefore, the actual deployment orbit of the satellite will be approximately 463 km perigee and 469 km apogee at the low end and 493 km perigee and 499 km apogee at the high end. As a rule, the probability of debris collision increases as the orbit of the satellite increases.

In addition to the deployment orbit being variable and the potential cross-sectional area of the satellite being variable, the propulsive capabilities of the satellite allow for there to be more variation in its orbit. For the purposes of this analysis, a worst-case scenario was assumed to be approximately 50 km above its deployment orbit and 50 km below its deployment orbit. If the satellite had somehow continuously used its water-propylene thrusters in one direction, this is what the worst-case scenario would be based on the ISP of the thrusters. Although it is extremely unlikely that this would occur, a worst-case analysis is still needed. All in all, there were a total of nine different orbits being analyzed. The reason that this number was selected, was that it was determined that it was an adequate amount to analyze for the total possible orbital range. 50 to 80 km above the ISS every 15 km and then $\pm$ 50 km for each of those orbits. In addition to the nine different orbits being analyzed, there were three potential cross-sectional areas that needed to be analyzed as well. So, the total number of orbital scenarios that were simulated using DAS was 27 scenarios.

Running the Simulation

DAS is a software that is primarily designed for satellites that will not be changing their orbits, therefore it is a relatively simple but powerful tool to utilize. The required values for these simulations are the area to mass ratio, and the orbital information of the satellite. In addition to the apogee and perigee that were used as previously discussed, the inclination of the orbit was used as well. This value was matched with that of the ISS. Once these values were inputted into DAS, the simulation itself was simple to run.

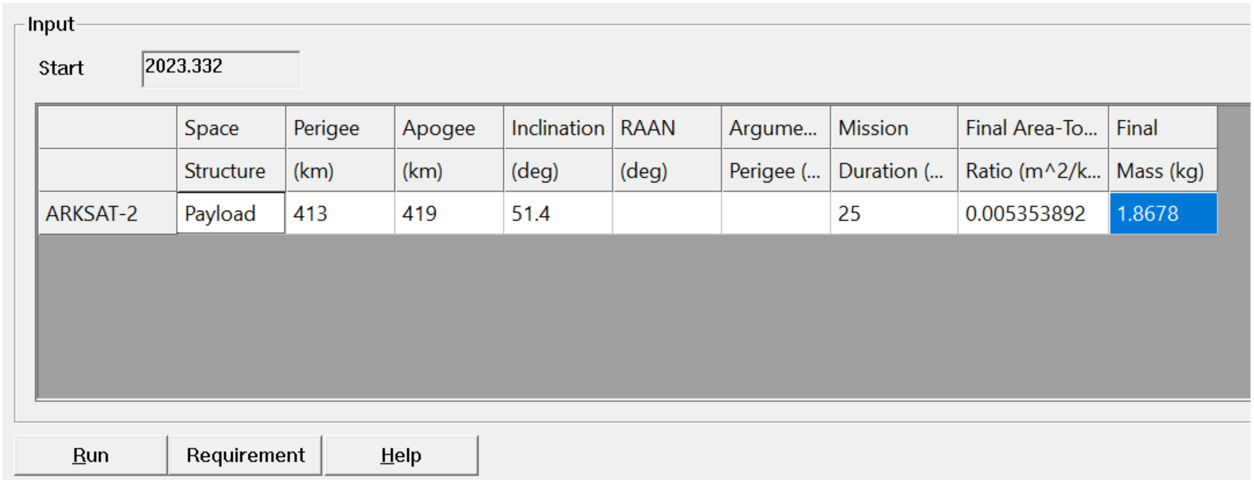

Figure 1: DAS Input for the lowest orbit and smallest cross-sectional area.

The ODA has six separate requirements that the software checks compliance for. Those six requirements are as follows:

1. Mission Related Debris Passing Through LEO
2. Mission Related Debris Passing Near GEO
3. Probability of Collision with Large Objects
4. Probability of Damage from Small Objects
5. Postmission Disposal
6. Casualty Risk from Reentry Debris

Once these six requirements have each been conducted, the satellite is determined to be compliant with current FCC orbital debris requirements. For this particular satellite, all 27 scenarios were run through the compliance checker.

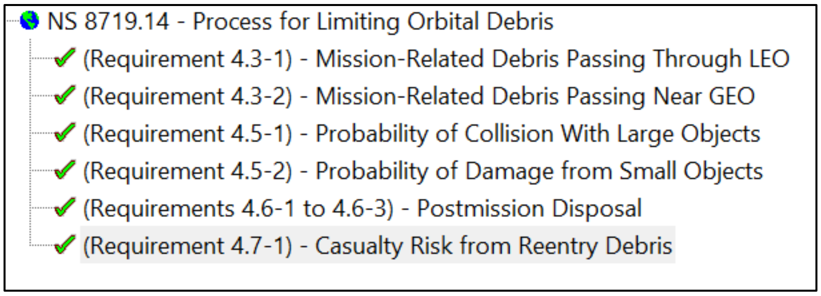

Figure 2: DAS Output after ODA has taken place.

Orbital Decay Analysis

In addition to the ODA capability of NASA DAS, the software also has the ability to conduct orbital decay analysis of satellites. This orbital decay analysis was done for two reasons. One of the reasons that this was conducted is to look at the trajectory possibilities that the spacecraft could take. This could show the effects that of how the trajectory of the spacecraft changes based on how things are varied. The next reasoning for this analysis is to give a rough comparison of the actual orbit decay vs the orbital decay of the satellite that will deploy its mylar balloon at an extremely low altitude. The purpose of this mylar balloon is to cause a detectable reduction in its orbital lifetime and this rough estimate could serve as a double check that the mylar balloon is working as intended.

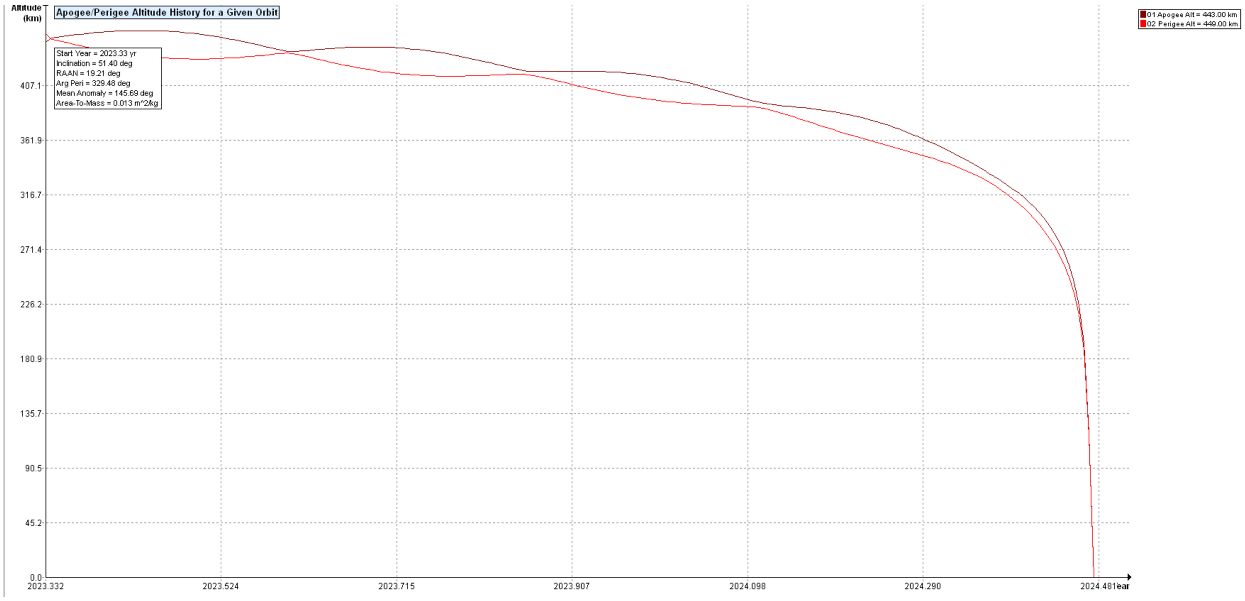

Figure 3: DAS Orbital Lifetime Decay Output

The actual simulation of the satellites orbital decay is similar to that of its orbital debris assessment. A total of 27 simulations were ran with the different satellite areas and the different orbital altitudes. The decay analysis is like the debris assessment in that it requires similar data to be inputted into the software. Once this data is inputted, the simulations of the orbital decay of the satellite are run.

RESULTS AND DISCUSSION

After conducting the ODA for each orbital scenario, ARKSAT-2 was found to be compliant with current FCC debris assessment rules and regulations. The results of this ODA have yet to be approved by the FCC, primarily due to the unsure nature of such a satellite launch far in the future. When launch dates change, that means that these scenarios would need to be rerun with this new date in mind.

In addition to finding that the satellite is compliant with FCC rules, simulations were successfully run showing the orbital decay of the satellite. By running these simulations, specific timelines were able to be determined for both the total time and orbit and the amount of time that it will be in the critical altitude above the International Space Station. Due to the nature of the ISS having people on board, it is imperative that a collision with the station be avoided. For the highest possible area and the lowest possible area to mass ratio, the projected date that the satellite would deorbit is in 2036. Although, it should again be emphasized that this is in the highly unlikely scenario that the thrusters are continually fired in one direction only. The most probable orbital case for a collision with other objects in space would be that of the highest possible orbit. For the worst-case scenario, the satellite will be in orbit above the International Space Station for much of its orbital lifetime. Its current projected time above the International Space Station would be until approximately 2035.

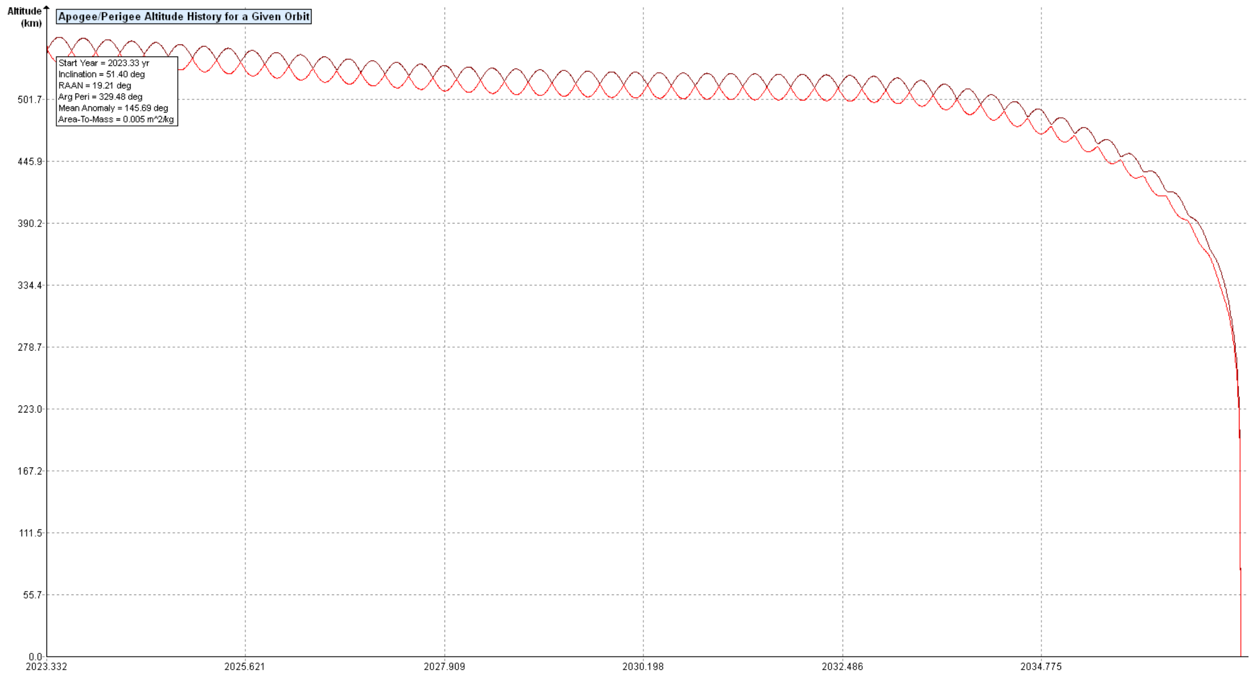

Figure 4: DAS Output for Worst Case Orbital Scenario

For this same orbit with the maximum possible area to mass ratio, the satellite would be projected to be deorbited in approximately 2030. In this scenario, the amount of time that the satellite would spend above the International Space Station would be until about 2028.

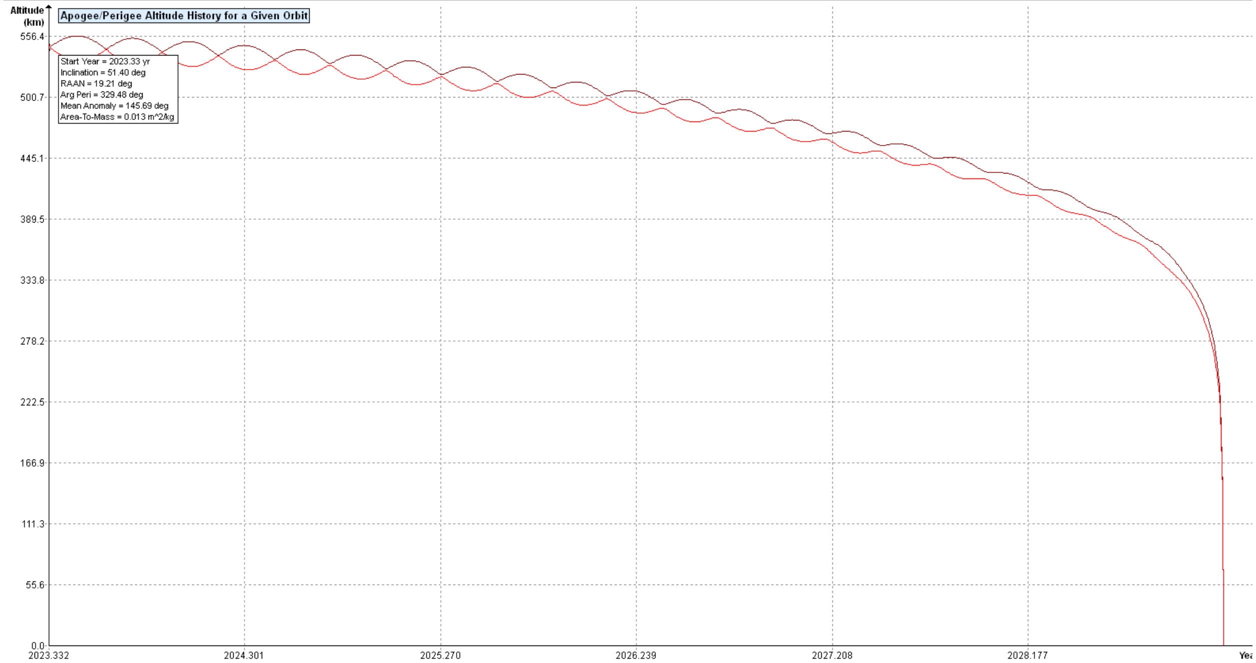

Figure 5: DAS Output for Highest Possible Orbit and Highest Possible Area

For the lowest possible orbits and highest poossible areas the results can be quite different. In the lowest possible orbit with the highest possible area, the projected time to de-orbit decreases to approximately early 2024. With the time spend above the International Space Station being until about midway through 2023.

The amount of time in orbit has been tabulated for each scenario in the tables below.

	APOGEE (km)	PERIGEE (km)	TIME TO ISS (YRS)	ORBITAL DECAY TIME (YRS)
50 KM ABOVE	463	469	≈2.52	3.36
+50	513	519	≈10.19	11.12
-50	413	419	≈0.64	1.53
65 KM ABOVE	478	484	≈3.12	4.42
+50	528	534	≈11.35	12.38
-50	428	434	≈0.972	1.94
80 KM ABOVE	493	499	≈5.04	6.71

+50	543	549	≈12.59	13.73
-50	443	449	≈1.43	2.45

Figure 6: Tabulated Minimum Area Results

	APOGEE (km)	PERIGEE (km)	TIME TO ISS (YRS)	ORBITAL DECAY TIME (YRS)
50 KM ABOVE	463	469	≈1.22	1.62
50	513	519	≈3.18	3.47
-50	413	419	≈0.26	0.77
65 KM ABOVE	478	484	≈1.38	2.06
50	528	534	≈4.17	4.55
-50	428	434	≈0.65	0.98
80 KM ABOVE	493	499	≈2.14	2.56
50	543	549	≈6.11	7.33
-50	443	449	≈0.72	1.24

Figure 7: Tabulated Medium Area Results

	APOGEE (km)	PERIGEE (km)	TIME TO ISS (YRS)	ORBITAL DECAY TIME (YRS)
50 KM ABOVE	463	469	≈1.16	1.55
50	513	519	≈2.79	3.19
-50	413	419	≈0.30	0.71
65 KM ABOVE	478	484	≈1.42	1.92
50	528	534	≈3.58	4.09

-50	428	434	≈0.68	0.91
80 KM ABOVE	493	499	≈1.98	2.38
50	543	549	≈5.10	5.83
-50	443	449	≈1.33	1.33

Figure 8: Tabulated Maximum Area Results

The amount of time that the satellite will spend in orbit is highly variable and deprends on numerous conditions that are outside of the teams control. The actual deployment altitude of the satellite itself is outside of our control and numerous other external effects can cause their to be a change in the orbital characteristics of the spacecraft. DAS offers a great insight into the possible orbital trajectories of the satellite and allows for the propulsive capabilities of the it to be taken into account with this novel approach. Going forward, this “flight envelope” approach will allow for orbital debris assessments to be conducted using NASA DAS, a software initially envisioned for satellites without propulsive capability in mind.

CONCLUSIONS

- This novel approach to simulating the orbit of ARKSAT-2 using NASA is effective in showing the different possible orbital scenarios of the spacecraft.
- Through the simulation of the orbital decays of the different scenarios, the total mission life for each scenario was able to be determined.
- It has also been able to be determined for each scenario for how long it will be above the orbit of the ISS.

FUTURE WORK

The actual timeline for the launch and deployment of the satellite is highly variable and is likely to be subject to change. Due to this, it is possible that these scenarios will need to be rerun. However, now that this novel approach to using NASA DAS has been established, it should be a straightforward process on how to approach simulating these types of satellites going forward. Once a timeline has been finalized and all of the scenarios have been completed, it will need to be submitted for approval to the FCC. In addition to this process working for ARKSAT-2, it could be implemented in future satellites that have propulsive capabilities as well.

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