JOURNAL OF THE BRITISH INTERPLANETARY SOCIETY • VOLUME 76 2023 PAGES 424-432

The Design of CubeSats for Outer Solar System Scientific Missions

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DOI https://doi.org/10.59332/jbis-076-12-0424

In the past decade, CubeSats have emerged as a cost-effective solution for scientific missions beyond Earth's orbit, though they have not yet gone further than orbiting Mars, as with NASA's MarCO CubeSats. This paper discusses the technical challenges and solutions for designing CubeSats for Outer Solar System missions, specifically in the context of the proposed Astraeus Mission to Titan. These CubeSats, called the Mites, aim to measure heavy anions in Titan's upper atmosphere and have undergone analysis to determine their optimal size and drag coefficient. A significant challenge addressed is the CubeSats' power system, with solar panels being less effective at greater distances from the Sun. The paper proposes investigating Radioisotope Power Systems (RPS) as an alternative. However, there is the additional challenge of packaging the RPS in a sufficiently small form factor so that the upper atmospheric experiment can be completed. This must cover the greatest range of longitudes, latitudes, and ranges hence the orbital decay rate must be controlled to achieve this. The paper also explores the Mites' long-duration exposure to space during transit and strategies to minimise cosmic radiation exposure. Whilst this is completed in the context of the Astraeus Mission, the data obtained can guide similar missions and aid others in overcoming the limitations of CubeSats so that they can be used more frequently for Outer Solar System science missions.

Keywords: Titan, CubeSat, Radioisotope Thermoelectric Generator, Orbital Decay, Outer Solar System

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1 INTRODUCTION

1.1 Background

CubeSats, a class of mini-spacecraft originally pioneered by California Polytechnic State University in 1999, have significantly advanced space research by offering a cost-effective and accessible platform for various scientific and exploratory missions. Notably, the Mars Cube One (MarCO) mission marked a milestone as the first interplanetary mission using CubeSats, demonstrating their capability as communication relays during the InSight Mars lander's descent in 2018 [1]. CubeSats have slashed the cost of satellite development, allowing for the deployment of swarms of satellites for simultaneous, multipoint measurements, which can significantly enhance our understanding of space environments.

Despite these advancements, CubeSats face considerable challenges in missions to the Outer Solar System. The limitations of CubeSats in these missions stem from their small size, which restricts payload capacity and communication capabilities, posing hurdles in the vast expanse of the Outer Solar System. One of the critical adjustments for CubeSats undertaking missions to the Outer Solar System is the transition from solar to radioisotope power systems. The Radioisotope Power Systems (RPS) Program, managed by NASA, focused on developing advanced systems for producing electrical power using heat from the natural decay of Plutonium-238. These systems are ideally suited for long-duration operations in extreme environments and are crucial for missions where sunlight is infrequent or obscured, such as in the Outer Solar System [2]. A recent development in RPS technology from the University of Leicester details the feasibility of using Americium-241 as a fuel source for small spacecraft [3].

Radiation exposure in long-duration space missions is another significant concern for CubeSats. NASA Langley Research Center has developed an innovative radiation shield using the Z-shielding method, layering metal materials to protect CubeSat electronic circuits from ionizing radiation [4]. This approach can dramatically extend the life of CubeSat electronics, effectively reducing the total ionising dose and internal charging effects. However, cheaper alternatives could be explored to provide the same protection from ionising radiation to enable long-term operations of the spacecraft. The concept of hosted mission architectures, as exemplified by the MarCO mission, presents a viable solution to some of these challenges. MarCO, developed by NASA's Jet Propulsion Laboratory,

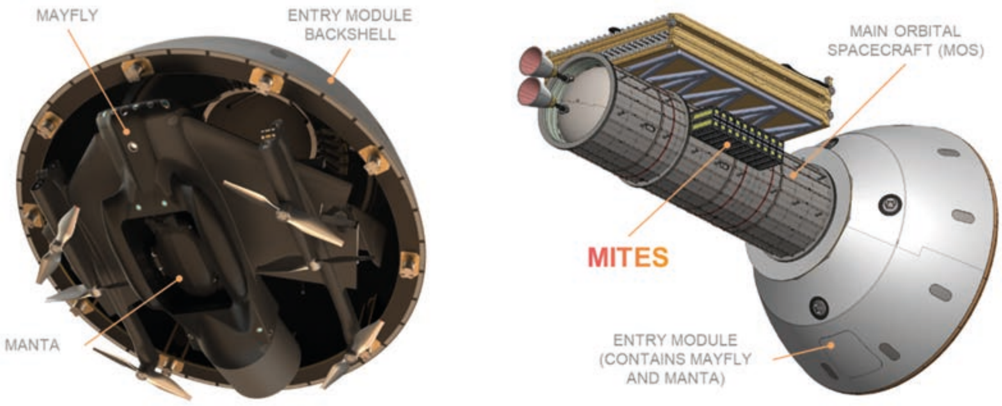

Fig.1 **Visualisations of the Astraeus Mission Architecture including the MOS, Mites, Mayfly and Manta.**

accompanied the InSight Mars mission lander, and served as a communications relay. This mission showcased how CubeSats could be integrated with larger missions to leverage shared resources, such as radiation protection and communication systems, thereby addressing some of the constraints typical of CubeSat missions [5].

Addressing the problems of power requirements and minimising radiation exposure does not account for local operations. The MarCO spacecraft provided communication relay services to the InSight Lander for less than 8 months. Replenishing this spacecraft with new units, should the mission have called for it, would be a relatively simpler task compared to an Outer Solar System mission due to the transfer duration. Therefore, increasing the lifespan of each spacecraft and sending multiple of the same type of spacecraft hosted on a main vehicle would be a desirable architecture for Deep Space science missions.

1.2 Astraeus Mission

The Astraeus mission is a comprehensive space exploration initiative focused on Titan, Saturn's largest moon. Its primary objective is to delve into the mysteries of Titan, examining its atmospheric composition, surface characteristics, and the potential for harbouring life. This mission stands out for its ambition to understand Titan's complex methane cycles, diverse landscapes, and atmospheric phenomena, providing insights into planetary processes and astrobiology.

The mission's architecture integrates a variety of spacecraft as displayed in Fig. 1. The Main Orbital Spacecraft (MOS) serves as the mission's hub, orbiting Titan and conducting detailed observations of its terrain and magnetosphere. Additionally, a fleet of 3U CubeSats called Mites is designated for atmospheric analysis, deployed annually to study the atmospheric conditions. The mission also includes the Mayfly, an unmanned aerial vehicle for atmospheric and surface exploration, and the Manta, an underwater vehicle tasked with investigating Titan's hydrocarbon lakes. These elements work in synergy, with MOS acting as a communication relay between Earth and the mission's components.

The operation of the Astraeus mission is multifaceted: The MOS orbits Titan, mapping its surface and studying its magnetosphere, while simultaneously facilitating communication. The Mites probe the atmosphere, analysing its composition and dynamics. On Titan's surface and beneath its lakes, the Mayfly and Manta explore respectively, with the Mayfly examining the atmosphere and surface, and the Manta delving into the hydrocarbon lakes to analyse their composition. This holistic approach aims to provide a comprehensive understanding of Titan, combining orbital, atmospheric, and surface exploration to unravel the secrets of this enigmatic moon.

1.3 Concept of Operations for the Mites

The Mites are a fleet of twenty 3U CubeSats designed to decay through the upper atmosphere of Titan over one Earth year. The larger batch of identical spacecraft enables a lower cost for this portion of Astraeus at the benefit of more data gathered over a greater volume of the atmosphere. Two Mites are released from the MOS each Earth year to measure the change in atmospheric composition, temperature, pressure and charge. An Ion and Neutral Mass Spectrometer (INMS), as developed by Mullard Space Science Laboratory for the QB50 mission [6], will be used to measure heavy anions within Titan's atmosphere. Each orbit around Titan reduces the altitude of the vehicle due to drag and gravity. The vehicle begins its life in a 1500 km x 900 km orbit at a 45^0 inclination and deorbits to an altitude of 500 km over one Earth year. This allows for an annual experiment that covers the greatest range of longitudes, latitudes and altitudes. An example of the orbital decay path followed by the Mite during its mission lifespan is detailed in Fig. 2.

1.4 Requirements

The Mites, with their decaying orbits, aim to take in-situ measurements at high altitudes: from the base of Titan's exosphere,

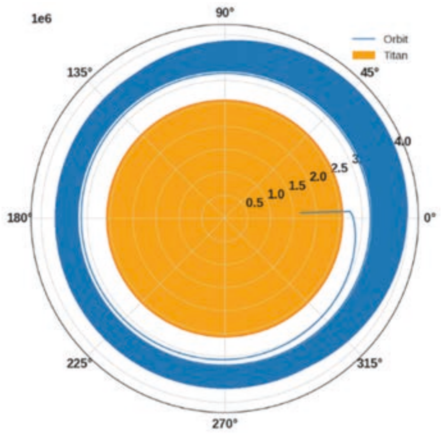

Fig.2 **A polar plot of the orbital decay of the Mite from a starting altitude of 1500 km.**

down to the upper atmosphere. Several of the science goals, outlined in the Astraeus Science Traceability Matrix (STM) [7], would benefit from such measurements. A summary of the relevant goals is outlined in Table 1.

TABLE 1: The primary science goals requiring in-situ, high-altitude measurements

ID	Questions
02	Is there evidence of cryovolcanism on Titan?
04	What is the nature of Titan's impact craters?
07	What role do electrons, ions and anions play within plasma in Titan's magnetosphere and Titan's ionosphere and what processes control their loss?
011	What is the chemical and physical structure of Titan's atmosphere?
012	What dynamic processes govern Titan's atmosphere?
013	How does Titan's atmosphere interact with its surface and outer environment?
014	What is the potential for prebiotic chemistry in Titan's atmosphere?
015	What is the nature of the heavy anions in Titan's atmosphere?

The full engineering requirements of the Mites are shown in Table 2. While most requirements were inferred directly from Astraeus STM, some additional requirements were imposed on the vehicles. Requirement 0-4 requires all recorded measurements to be transmitted off the vehicle before the end of the flight. This is because a decaying orbit will likely lead to the termination of the vehicles.

Requirement 0-5 comes from the need to measure seasonal variations in the measured values: seven years is the length of one Titan season and will therefore allow seasonal variations to be measured. The system architecture allows for up to seven Mite vehicles to be carried. Requirement 1-5.1 therefore sets the minimum required operational lifetime of each Mite vehicle to allow for measurements over the full seven years. The science goals of Astraeus STM highlighted a requirement for measurements at altitudes of 1,500 km down to the surface. The Mite vehicles, benefiting from their degrading orbit, will be required to take measurements at altitudes from 1,500 km down to 500 km, at which point aerodynamic forces cause a rapid de-orbit. These are reflected in requirements 0-7, and 0-8.

2 SYSTEM ARCHITECTURE

The Mites system architecture consists of a majority of commercial off-the-shelf (COTS) components as shown in Figure 3. This reflects the subsystems that feature on most spacecraft. The main payloads are the Ion and Neutron Mass Spectrometer (INMS) and Atmospheric Parameters Measurement Suite (APMS). The INMS is modelled after the same unit used in the QB-50 mission. The APMS consists of pressure, temperature, and humidity sensors to measure the atmosphere on the face of the Mites that is perpendicular to the velocity vector. Additional data is gathered from the accelerometers located on the onboard computer to calculate the turbidity of the atmosphere.

It is expected that all avionics would require additional radiation hardening due to the increased duration of cosmic radiation exposure during the mission. However, two significant areas require analysis for a CubeSat optimised for the Outer Solar System: the power system and form factor. The choice of power system contributes to the choice of form factor however this is also dependent on mission operations. Each Mite will experience orbital decay during its mission life and therefore parasitic forces, such as atmospheric drag and gravity, will also determine the final form factor. The following sections detail the analysis conducted to select an Am-241 RTG and 3U CubeSat structure for the power system and form factor respectively.

2.1 Power System

The choice of power system to power a satellite is often deter-

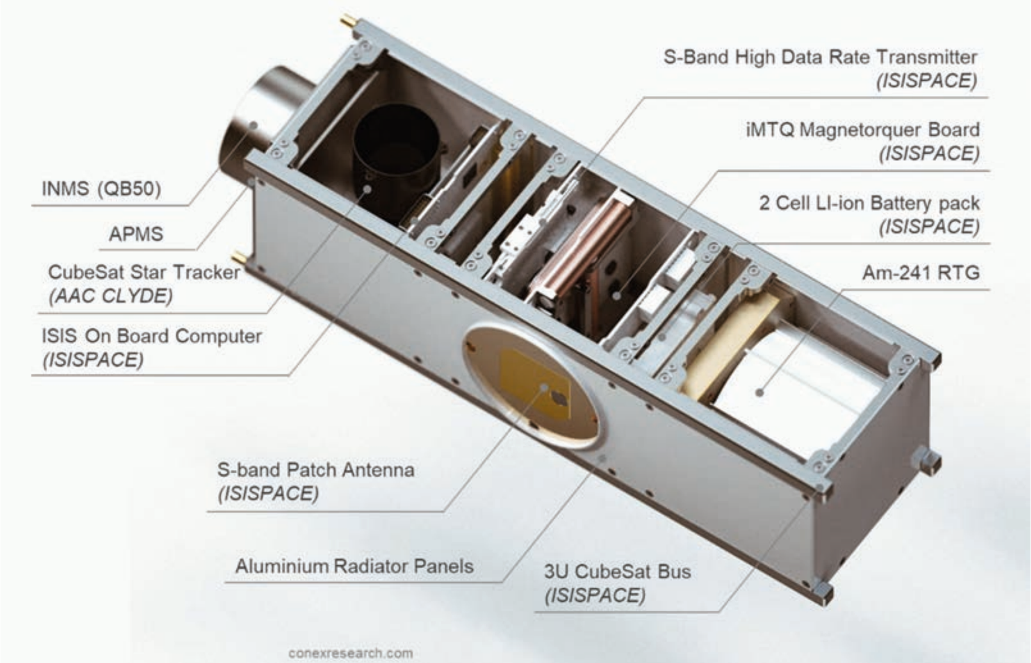

Fig.3 A labelled diagram of the Mites systems architecture.

TABLE 2: The engineering requirements for the Mite vehicle

ID	Description	Verification	Requirement
0-1	The Mites shall be capable of performing the specified in-situ ion-mass spectrometry experiments	Are the associated level 1 requirements (1-1.X) met?	Yes
1-1.1	Ion-mass spectrometry experiments shall be carried out at the resolution specified	Calculate the largest increment in altitude between ion-mass data measurements within the given altitude range	5 km
1-1.2	Ion-mass spectrometry experiments must be carried out across the day and night cycle	Calculate the largest increment in local time between ion-mass data measurements	Hourly (Minutes when in Ionosphere)
1-1.3	Ion-mass spectrometer shall be held in the direction of travel while data is recorded	Calculate the maximum directional error	<1°
1-1.4	Ion-mass measurements must be taken across various local times to include day and night	Calculate the range of local times sampled	Complete day/night coverage
0-2	The Mites shall be capable of completing the energetic particle detection experiments	Are the associated level 1 requirements (1-2.X) met?	Yes
1-2.1	Energetic particle detection experiments shall be carried out at the resolution specified	Calculate the largest increment in altitude between data measurements within the given altitude range	50 km (5 km in ionosphere)
1-2.2	Spectroscopy measurements shall be taken with sufficient temporal resolution	Calculate the largest increment between data measurements	Minutes
0-3	The Mites shall be capable of completing the EM Spectroscopy experiments	Are the associated level 1 requirements (1-3.X) met?	Yes
1-3.1	Spectroscopy experiments shall be carried out at the resolution specified	Calculate the largest increment in altitude between data measurements within the given altitude range	10 km
1-3.2	Spectroscopy measurements shall be taken with sufficient temporal resolution	Calculate the largest increment between data measurements	Hourly
0-4	All recorded data shall be transmitted before the termination of each Mite	Ratio between the size of data collected and the size of data transmitted by communication systems during the operational life of the Mites	Yes
0-5	Mite measurements shall be carried out across at least seven years	Calculate the gap between the planned first and last measurements during the entire mission	Seven years
1-5.1	Each Mite's operational lifetime shall be at least one year	Calculate the gap between the planned first and last measurements during one mite's operation	One year
0-7	Measurements from the Mites shall begin at the specified altitude	Set as the starting altitude of the MOS when releasing a Mite when simulating orbital decay	1,500 km
0-8	Measurements from the Mites shall extend down to the specified altitude	The minimum altitude achieved by simulations of orbital decay	500 km
0-9	Measurements from the Mites shall provide a resolution (horizontally) of at least the specified value	Calculate the distance between measurements along a Mite's orbit	50 km

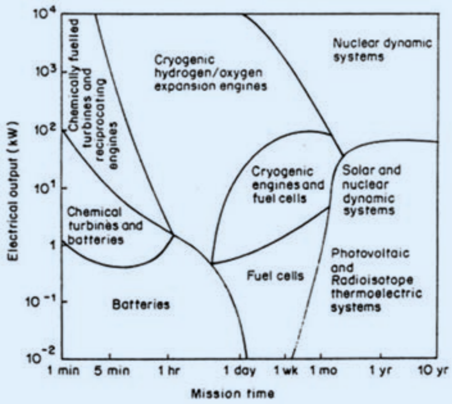

Fig.4 Power outputs - mission duration relationship between energy source and appropriate operation scenario [8].

mined by both the power requirement as well as the expected mission duration shown in Fig. 4. CubeSats typically generate power using solar arrays. A new parameter however has to be considered for the Mite design, the distance from the Sun. For solar arrays, power generation is proportional to the intensity of incident light. The intensity of light from the Sun is inversely proportional to the square of radial distance from the sun. As Titan is approximately nine times further away from the sun than the Earth, the solar arrays required in Titan's orbit would need to be eighty-one times greater in surface area than if they were to generate the same power in Earth's orbit.

Because of this, the choice of power system became a much more significant consideration than conventional CubeSat missions. The possibility of a small Radioisotope Power System (RPS), specifically a Radioisotope Thermoelectric Generator (RTG) was considered. Existing research of previous RTGs was considered to derive a parametric model for the power system to determine its size, mass, and potential power output. The RTG was then modelled within the particle modelling software Geant4 to determine how to protect the internal components of the CubeSat from radiation exposure.

As derived from Fig. 4 RTG systems are normally used for relatively high power, long duration missions. Most RTGs deployed in satellites or even rovers on Mars generate approximately 100W of power at a time, with the Perseverance rover powered by a 110W RTG [9]. The Mite is expected to require 3W of power at a time, though the system shall be capable of delivering 5W. Recently, new fuels that are holistically competitive with the conventional Plutonium isotope used (though this remains the fuel of choice due to its high specific power output) have been identified. Americium 241 has been researched heavily in many studies as a potential fuel due to its availability as a product from nuclear power plant operation.

2.2 Radioisotope Selection

RTGs most commonly use Pu-238 as a power source. However, this isotope is not highly available, and its availability is expected to deplete further. Its application in industries, such as defence, means space missions would most likely not be prioritised. Am-241 has been identified as a potential alternative, though its power output is approximately one-fifth that of Pu-238. Another isotope which has been researched is Strontium-90, proposed for the PocketRTG concept [10].

Fuel pellets within an RTG are encased within a small tube and then housed within an aeroshell structure. These components come together to create the Radioisotope Heat Unit (RHU). The aeroshell aims to maximise the thermal conductivity between the fuel pellets and the power conversion system whilst also offering some radiation protection. Graphite and carbon fibre are the most common materials that are utilised for this purpose due to their high thermal conductivity whilst also having radiation-stopping properties making it suitable for this application.

The volume constraint posed on the design meant that the power conversion system to be deployed would need to be minimised and simplified. To introduce redundancy, power systems often use multiples of the same power conversion system, especially in the case of dynamic systems, such as Brayton cycles and Stirling engines. However, due to the size constraint, the ability to have redundancy systems is significantly limited. Therefore the reliability of the power conversion system has to be increased by using static power conversion systems. Thermocouples are currently the most often used system, being used within NASA's Multi-Mission RTG (MMRTG), which is deployed within the Perseverance Rover. The MMRTG utilises 8 panels of thermocouples which in total hold 268 thermocouples. The current proposal for the CubeSat RTG is to utilise sixteen thermocouples connected to the heat source.

2.3 Shielding

The RTG system itself must be sufficiently shielded to ensure sensitive components within the CubeSat are not damaged by radiation induced by the fuel pellets. To develop a better model of the radiation environment, Geant4 is used to model the emission of radiation from the fuel pellets and how it interacts with the volume of the remainder of the satellite. This then allows the shielding between the RTG and the payload to be better defined in terms of its thickness and material.

2.4 Mass Estimate

To predict the mass of the system, two methods were deployed. The first is a prediction through parametric analysis, by considering previous RTGs that have been deployed and considering the specific power output of Americium in comparison to Plutonium. When considering the power outputs and sizes of RTGs throughout their deployment, the relationship observed is visibly linear. The smallest reactor considered in this study was SNAP-3B which was 2.1 kg and had an electrical power output of 2.7 W which was achieved with 96 grams of Pu-238 [11]. The largest RTG considered in the study was the GPHS-RTG deployed for several in-space missions, creating a total power output of 300 W.

A plot of seven RTGs with their power output and mass was created. One anomalous RTG was identified (the MMRTG used on Curiosity and Perseverance) as having a much smaller specific power compared to the other reactors, therefore it was removed from consideration when the mass-power relationship was being created. The plot for the graph is shown in Fig. 5. A line of best fit was established as well to allow an estimate

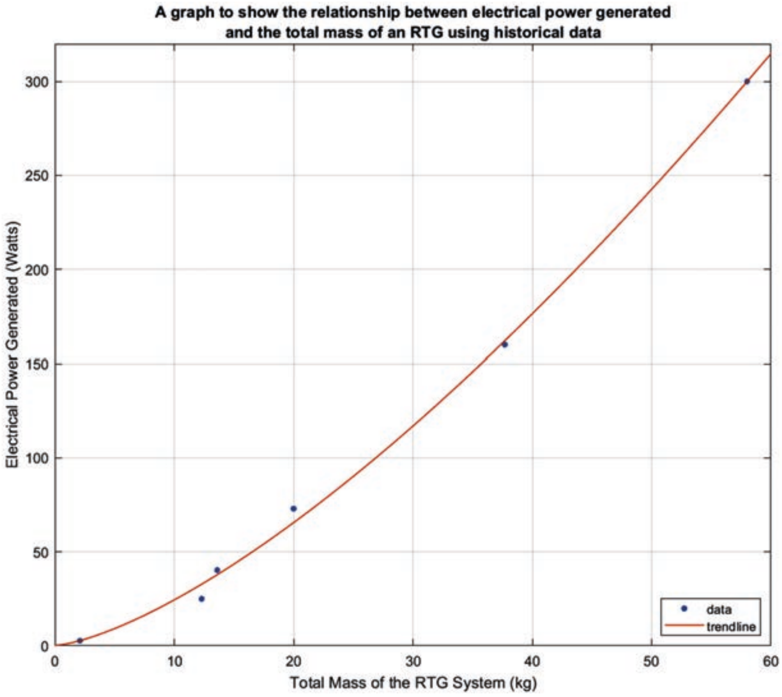

Fig.5 A graph to show the relationship between electrical power generated and mass of RTGs.

TABLE 3: The mass of the major subsystems of the RTG used on the Mites

System Level	System/Subsystem Name	Quantity (Total)	Material	Mass (Per Unit)	Mass Total (g)
1	RTG	1	-	140	2,121.825
2	**– Radioisotope Heat Unit**	**1**	-	-	**1,001.825**
3	– Aeroshell	1	Graphite	341.825	341.825
3	– Am-241 Pellet	3	Americium-241	220	660.000
2	**– Power Conversion**	**8**	Lead Telluride	**140**	**1,120.000**

to be calculated for the RTG mass. At first, mass was seen to increase linearly with power output. However, larger systems appeared to produce a greater amount of power than would be expected, hence the graph is modelled to steepen.

The estimated mass value found for the RTG to generate 5 W of electrical power if Plutonium was to be considered is 3.34 kg. Previous RTG that use Americium have had efficiencies of up to 6% [3] however for a more conservative estimate, it was assumed that the thermoelectric system shall operate at 5% efficiency. For a Plutonium RTG operating at 5% efficiency, this equates to 180 g of Plutonium-238 [12]. Americium-241's power output however is 0.1146 W/g [13], approximately one-fifth of Plutonium's however, meaning the amount of Americium that would be required is 870 g. However, the radioactivity of Americium is not more significant than that of Plutonium, meaning the vast majority of the mass of the rest of the system would remain unchanged. Therefore, the total mass for the system by parametric calculation is found to be 4.03 kg.

The second value of the estimated mass for the RTG was calculated by considering the mass of Americium-241 needed for the system and encapsulating it within a thermal casing. Several pellet shapes were theorised for the system until one was found to be easiest to encapsulate and capture heat from. Lead Telluride thermocouples were then modelled to surround the thermal casing. The mass estimate before further shielding was added became 2.12 kg as shown in Table 3. As no significant shielding at this point had yet been considered, the value being much lower than the parametric value makes sense. This would also mean that over 2.5 kg could be dedicated to shielding to protect the critical components from radiation emission. However, this must be determined using a simulation of the radiation output of the RTG design using Geant4. Upon modelling the radiation environment and characterising the shielding more, a further step would be to establish the power conversion system and consider other materials as well.

2.5 Orbital Decay Simulations

The lifecycle of one Mite spacecraft is determined by the rate of orbital decay as it conducts the INMS experiment through Titan's exobase. The rate of orbital decay of the vehicle is primarily driven by its weight as a result of Titan's gravity and the drag due to Titan's atmosphere. The impact of these parameters affects the form factor and operation of the Mites. Therefore, the orbital decay of the Mites due to Titan's gravity and atmosphere was modelled to determine the design parameters of the Mites. Solar radiation pressure also contributes to orbital decay but was neglected in initial estimates. This is due to the effect of this parameter being approximately 1,000 times less at Titan compared to Earth.

2.6 Performance Requirements

The rate of orbital decay must be compliant with the requirements 1-1.3, 1-1.4, 1-2.1, 1-3.1, 1-3.2 and 1-5.1 in Table 2. This performance must be achieved with the boundary conditions defined in requirements 0 - 7, 0 - 8 and 0 - 9 of Table 2. Fig. 6 summarises this performance by indicating the spatial resolution between the orbital path taken by the spacecraft. It should be noted that Fig. 6 does not display all the orbital paths that

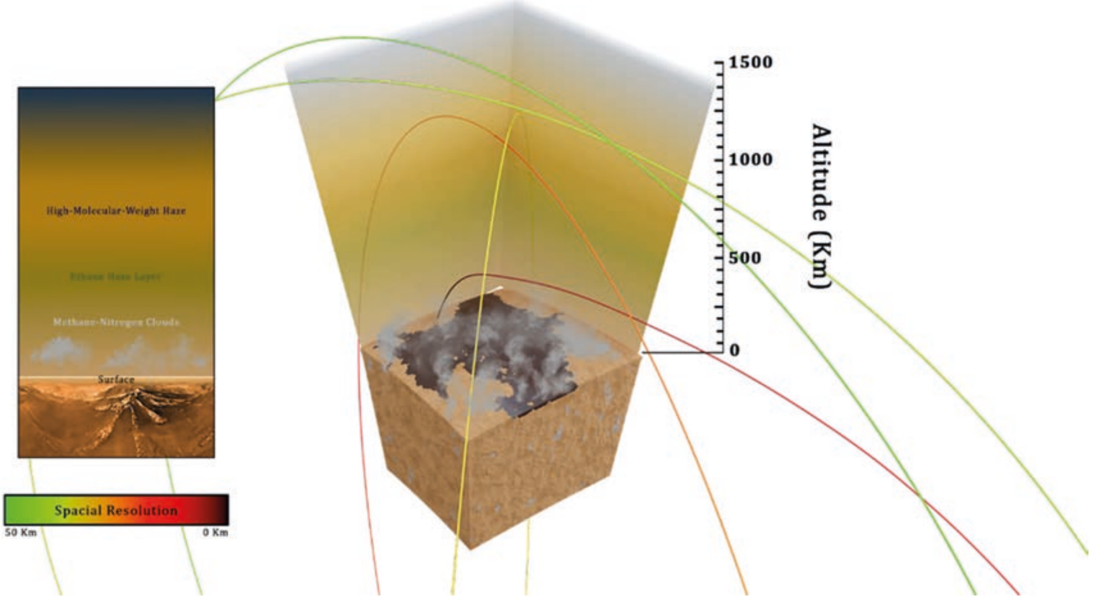

Fig.6 A 3D visualisation of the orbital trace drawn by the path of the satellite at different altitudes.

would be taken by a Mite throughout its life. However, orbital paths shown in the figure communicate that the spatial resolution shall decrease from 50 km to 5 km when travelling the ionosphere compared to the stratosphere, respectively.

2.7 Simulation Model

The orbital decay simulation is an ordinary differential equation solver which calculates the position, velocity and acceleration of a spacecraft as a function of time using Kepler's equations of orbital motion. The atmospheric drag was calculated using Titan's atmospheric density data as compiled by Yelle. This parasitic force contributed to the orbital decay as well as the force due to gravity; however, this is captured by Kepler's equation. The data generated by the Fortran solver [14] is then transferred to a Python environment for visualisation. This integration of Python and Fortran enables rapid iteration to optimise the orbital decay rate of the Mites.

The solver requires the six inputs about the spacecraft's dimensions, orientation and orbital position shown in Table 4. The values for the initial altitude and velocity of the Mite are defined from the concept of operations (ConOps) of the vehicle. Each Mite shall be released at the perigee of the orbit displayed in Fig. 7. This allows for the spacecraft to be initialised and de-tumbled at the minimum velocity compared to the same operation being completed at the apogee.

A 3U CubeSat form factor was selected due to the abundance of COTS structures for this spacecraft size. Furthermore, the orbital decay experiment that the Mites shall perform is modelled off the QB-50 mission which used a 2U form factor. The additional volume required for the Am-241 RTG increased the overall spacecraft length. The value of M is selected from the CubeSat Design Specification [15] however, it should be noted that there have been notable deviations from the standard within the commercial Space industry. Notably, CubeSat dispensers such as Exolaunch's EXOPod Nova and RocketLab's Canisterized Satellite Dispenser, have achieved a maximum capacity of 8 kg for 3U CubeSat [16, 17]. This additional mass was rejected from the analysis due to the vehicle design being sufficiently below this maximum value.

2.8 Results and Discussion

The orbital decay performance could only be calculated once the values of C_D and α were defined. These two parameters are intrinsically linked to one another as $C_D \propto \alpha$ therefore a design space must be created to identify the valid combinations of C_D and α that would provide the required performance. The first performance parameter that was evaluated was total mission duration as all design candidates must be operational for greater than one Earth year (Requirement 1-5.1). The two parameters were varied between the limits detailed in Table 4 in equal increments to produce 50 input values for each parameter. This resulted in 2,500 calculated values for the total time of the mission as shown in the carpet plot in Fig. 8. This indicates that the mission duration decreases as C_D and α increase.

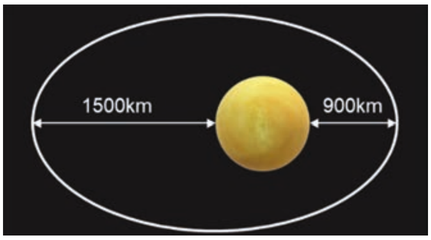

Fig.7 A simple diagram of the initial orbit of the Mites upon release from the Main Orbital Spacecraft (MOS).

A horizontal plane parallel to the XY plane at a time equal to one Earth year was applied to the carpet plot. Similarly, a vertical plane parallel to the YZ plane at a $C_D = 2.2$ was added as this aligns with common values for the C_D of a 3U CubeSat [18]. This could be refined further with computational fluid dynamics of the Mites; however the historical data was sufficient for the preliminary performance estimate. The defined design space contains all valid design points which would fulfil the requirements detailed in Table 2. The red dot in Fig.8 is an example of these design points which can be analysed further by re-running the simulation with the resulting values of C_D and α.

The results of this analysis in Fig. 9 suggests that the current design point has a total mission life of 18 months, performs approximately 3,400 revolutions of Titan and travels over 50,000,000 km downrange of the initialisation point. These values indicate that the design method allows for near-compliance with design requirements using an inexpensive simulation technique. However, the spacecraft is unable to deliver the required spatial resolution below an altitude of 800 km. Furthermore, the current design point would likely be inoperable below 700 km due to a combination of the following factors:

1. **Communications attenuation due to velocity:** The gradient of the altitude vs. time graph is near vertical indicating a large velocity. The rapid change in position would reduce the efficacy of the communication system. There would be a reduced transmission rate between the Mites and MOS leading to minimal data collected below 700 km being received by terrestrial ground stations.
2. **Communications attenuation due to the atmosphere:** The thicker atmosphere will attenuate the signal

TABLE 4: The starting parameters for the orbital decay simulation

Parameter	Symbol	Description	Value
Initial Altitude	h	The initial altitude of the spacecraft at the point when the simulation begins.	1,500 km
Initial Orbital Velocity	U	The initial velocity of the spacecraft at the initial altitude.	1,424.15 ms^{-1}
Mass	M	The mass of the spacecraft.	6.00 kg
Area	A	The cross-sectional area of the spacecraft.	0.01 m^2
Drag coefficient	C_D	The 3D drag coefficient of the spacecraft.	2-4
Angle of attack	α	The angle between the velocity vector and the longitudinal axis of the spacecraft.	0°-5°

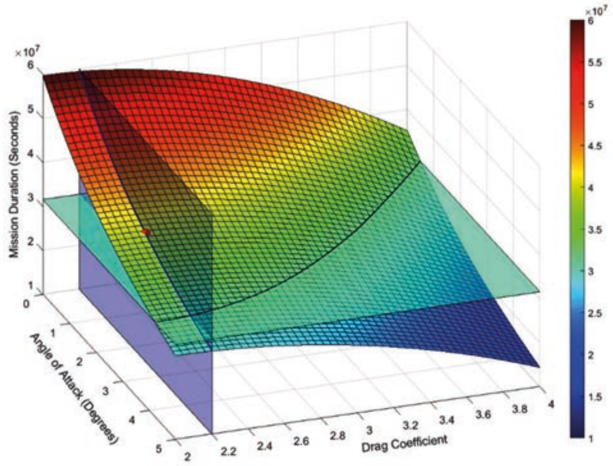

Fig.8 **A carpet plot showing the relationship between CD, α and mission parameters.**

transmitted by the Mites. The relatively low-power S-band antenna will struggle to transmit at lower altitudes.

3. **System failure due to atmospheric heating:** The high velocity and denser atmosphere discussed in the previous two points will result in atmospheric heating. As a result, the Mites subsystems would experience failure leading to loss of contact.

Addressing any of these factors requires additional models that are coupled to the orbital decay simulation. The greater issue raised by Fig. 9 is that it is unknown how the spacecraft would fail in the lower atmosphere. The Mites are equipped with an Am-241 RTG which, if damaged, could result in ecological damage to Titan. This shall be investigated further by analysing the required systems to ensure a Mite survives its entire orbital life and does not damage on entry and landing on Titan. However, this is beyond the scope of this paper.

3 CONCLUSIONS

This paper has comprehensively explored the innovative design and operational considerations essential for deploying CubeSats in outer solar system missions, with a particular focus on the proposed Astraeus Mission to Titan. The Mites are envisioned to better understanding of the complex atmospheric phenomena on Titan. The challenges of designing CubeSats capable of enduring the extreme conditions of outer space, especially the drastic reduction in solar power availability and increased cosmic radiation exposure, have been addressed in detail. The potential adaptation of Radioisotope Power Systems (RPS) and innovative radiation shielding techniques offer promising solutions to these challenges. However, further simulation in Geant4 would allow for a greater fidelity of the radiation protection mass required for internal and external protection.

Moreover, this study has delved into the complexities of orbital decay, ensuring that the Mites can effectively navigate and operate within Titan's upper atmosphere. The integration of robust computational models and simulations has been instrumental in optimising the Mites' design for their critical mission. The insights gleaned from this research not only pave the way for the successful implementation of the Astraeus Mission but also set a precedent for future CubeSat missions in the outer solar system. The methodologies and findings of this study serve as a framework for developing cheaper Outer Solar System science missions through established and abundant components. Furthermore, the economies of scale using large batches of identical spacecraft and arranging the mission architecture to host the CubeSats to minimise their mass aid to minimise system and operational costs.

Regarding future work that goes beyond the scope of this paper, further research needs to occur on the shielding material for the RPS. Currently, Lead Telluride has been selected due to its heritage, however, a future study must be completed to determine which materials would yield a greater energy transfer efficiency. This may allow for a smaller mass of fuel to be used leading to a reduction in the total mass and volume of the RTG. Another aspect yet to be explored is the thermal regulation of the RTG. An assumption of complete radiation of waste energy (approximately 95 W) has been applied. This requires a surface area of at least 0.65 m^2 which is almost five times greater than the surface area of the Mites spacecraft. As a result, waste power will need to be reduced in future work or a method of increasing radiation will need to be implemented like a deployable radiator. However, the increased surface area will reduce the total duration of orbital decay and thus the spacecraft may no longer be compliant with requirements 1-5.1. Finally, the effect of 660 g of Am-241 per Mite spacecraft breaking up upon entry into the Titan atmosphere has yet to be explored. A trade study will be conducted to investigate the impact of this and to investigate the possible methods to avoid total loss of the Mites during the de-orbit.

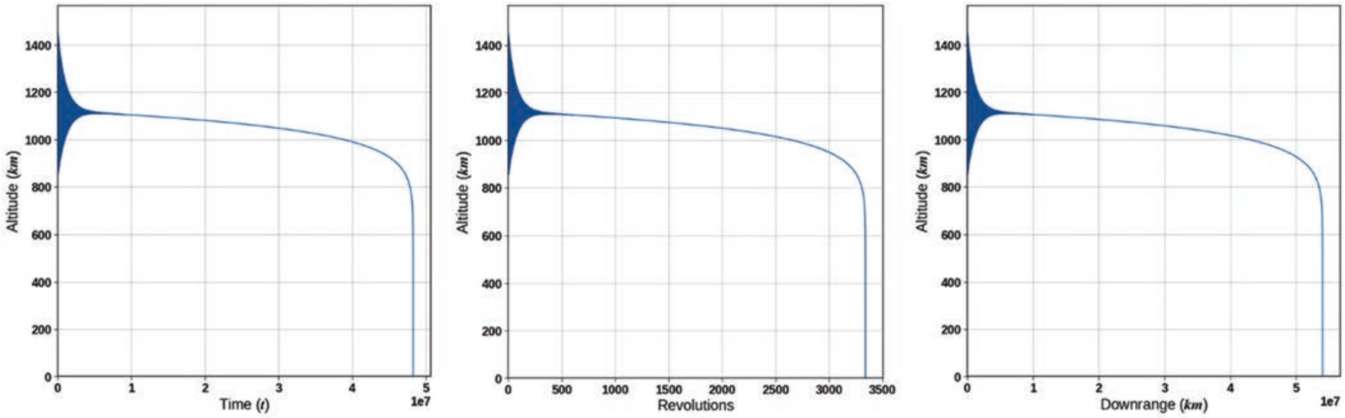

Fig.9 **Graphs showing the orbital decay performance for the design point (CD = 2.2, α = 2.5⁰) for altitude vs time (left), altitude vs revolutions around Titan (middle) and altitude vs downrange distance (right).**

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APPENDIX

Interplanetary Trajectory

The constraints imposed by the NASA's ephemeris data, which are limited to projections only up to the year 2050 from the available SPICE Kernels, have profound ramifications on the computational capabilities of simulation software such as NASA's General Mission Analysis Tool (GMAT), particularly in the context of mission planning beyond the launch year of 2040. In our efforts to simulate the trajectory of Astraeus from Earth to Saturn using GMAT, we encountered obstacles stemming primarily from the absence of precise positional data for the planets and their moons, for our anticipated arrival dates to the Saturnian system in the 2060s.

Concurrently, an examination of the NASA trajectory browser presented an intriguing pattern. It revealed that missions scheduled for launch from Earth to Saturn, including a gravity assist manoeuvre at Jupiter, appear to be feasible only when the launch date falls within or before the year 2036. Beyond this threshold, the trajectory browser ceases to provide any viable trajectory options that incorporate a Jupiter gravity assist.

From these observations, a discerning inference can be drawn that spacecraft launched from Earth after the year 2036, necessitating a transit duration exceeding 5 years, would encounter Jupiter in a position that is suboptimal for executing a gravity assist manoeuvre conducive to an efficient trajectory for reaching Saturn. Consequently, this circumstance raises critical considerations for the gravity assist manoeuvre planning that could potentially include the inner solar system planets as gravity assist targets.

Received 15 November 2023 **Approved** 14 January 2024