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COMMUTE: Cubesat swarm Orbital Maneuvers for a Mission to study Uranus’ aTmospheric Environment

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ABSTRACT

Following recommendations from the 2023-2032 Planetary Science and Astrobiology Decadal Survey, new mission concepts are being developed with the focus of launching Uranus’ exploration missions in the early 2030s. To minimize both fuel consumption and cruise time on our way to Uranus, we propose a Jupiter-Uranus gravity assist trajectory using a Falcon Heavy Expendable Launcher to deliver a 3000 kg spacecraft to Uranus orbit in under seven years. The spacecraft will be composed of a mothership of 2000 kg wet mass and a swarm of CubeSats with a combined wet mass of 1000 kg. Using the ephemerides data of Earth, Jupiter and Uranus, and numerical solutions to the Lambert’s problem for a Jupiter flyby, we found that, with an initial launch window around April 15th, 2032, we reach Jupiter’s sphere of influence and perform a gravitational slingshot maneuver on December 31st, 2034, allowing the spacecraft to reach Uranus on December 31st, 2038. This proposed mission trajectory reaches Uranus with a relatively short cruise period of seven years, compared to the 13-year transfer period of the mission plan detailed in the decadal survey. This shorter transfer time could allow for significant extensions of the scientific mission nominal operations period and, potentially, reduce the cost of the overall mission. The swarm of 16 CubeSats of approximately 62 kg each will be divided into 4 groups of 4 identical spacecraft. Each group will be equipped with specialized instrumentation, exploring Uranus more extensively and performing planned plunges into its atmosphere while using the mothership as a communications relay with the Earth. This research demonstrates that a CubeSat swarm mission to Uranus can be not only viable, but also a fuel and cruise time optimization opportunity, delivering 16 exploration spacecraft to Uranus in under seven years.

INTRODUCTION

The 2023-2032 Planetary Science and Astrobiology Decadal Survey (PSADS) [1] has recommended a Uranus Orbiter and Probe (UOP) [2] as the highest priority concept for a new Flagship mission. First discussed in the previous decadal survey [3], the current PSADS suggests that the Uranus Orbiter should launch in the early 2030s. One of the questions that the PSADS suggests scientists address is: “What processes influence the structure, evolution, and dynamics of giant planet interiors, atmospheres, and magnetospheres?”, with special attention being given to the atmospheric and interior compositions of Uranus.

The interior structure of Uranus has been modeled based on the planet’s mass, volume, and moment of inertia [4], but measurements are still necessary to decrease the uncertainty of the composition and thicknesses of the internal layers of that planet. The magnetic field around Uranus is also of interest as it is dramatically different from that of Earth, presenting multiple poles misaligned with the rotational axis of the planet. The fields emanate from the planetary mantle, instead of the core, indicating that the mantle might be made of superionic ice that continuously moves throughout Uranus [5]. The reason for the extreme tilt of Uranus’s rotational axis – 98° from the ecliptic plane – is also unknown and might also be linked to the internal composition of that planet [6].

The axial tilt of Uranus creates an interesting seasonal pattern: from approximately 2020 until approximately 2040, the northern hemisphere will be facing sunlight while the southern hemisphere will be in darkness [7]. Although the UOP mission mentioned in the PSADS proposes an arrival at Uranus in 2044 to study the planet when both poles are receiving sunlight, we believe that also studying Uranus during the solstice-to-equinox transition could significantly help understand the interior and atmospheric composition of that planet.

As such, it is essential to study possible mission trajectories and mission architectures that could minimize both fuel consumption and cruise time on our way to Uranus while maximizing scientific return.

ORBITAL CRUISE TRAJECTORY

We propose a Jupiter-Uranus gravity assist trajectory using a Falcon Heavy Expendable Launcher [8] to deliver a 3000 kg (wet mass) spacecraft to Uranus orbit in under seven years. The orbital trajectories were generated through MATLAB and Python codes using the ephemeris data and planetary characteristics available from the JPL Horizons database [9]. The trajectories were initially generated using impulsive maneuvers and the approximate location of the Earth, Jupiter, and Uranus on a heliocentric inertial frame of reference. The trajectories were then optimized for actual ephemerides and realistic maneuvers using numerical solutions to Lambert's problem, which is a standard solution for an orbital maneuver between two pre-selected position vectors and a desired time of flight [10].

We found that, with an initial launch window around April 15th, 2032, we were able to reach Jupiter's sphere of influence and perform a gravitational slingshot maneuver on December 31st, 2034. Earth and Jupiter are placed so that a normal Hohmann transfer starting around the Earth in 2032 is aligned with a Jupiter arrival in 2034, minimizing the required launch ΔV and making this transfer very fuel efficient. This gravitational slingshot maneuver happens at an altitude of approximately 5 million kilometers from Jupiter's atmosphere and increases the spacecraft's heliocentric velocity by a factor of 3.83, going from 7.04 km/s to 27.01 km/s. The flyby changes the velocity vector of the spacecraft in both magnitude and direction, giving it the required extra energy to reach Uranus on December 31st, 2038. A schematic representation of the Earth-Jupiter-Uranus trajectory is shown in Figure 1, along with the year of each planetary encounter. To be at the right altitude for that flyby, though, trajectory correction maneuvers might be necessary. We estimate a ΔV of 0.29 km/s for that task.

The arrival at Uranus assumes a capture into a highly eccentric, highly inclined elliptical orbit of eccentricity 0.8 and semi-major axis of 147,794.5 km. This orbit is not the most fuel efficient capture option, but it presents a good balance between low fuel consumption and good spacecraft placement, delivering a periapsis altitude of 4,000 km and an apoapsis altitude of 240,471 km. The relatively low periapsis allows for good data collection, while the high apoapsis allows for time focused on data transfer and battery replenish. The ΔV required for orbital insertion is 3.56 km/s, which represents approximately 1434.9 kg of fuel (for flyby and insertion) assuming an specific impulse (I_{sp}) of 341 s^{-1}. This proposed mission trajectory reaches Uranus with a relatively short cruise period of seven years, compared to the 13-year transfer period of the mission plan detailed in the PSADS.

This shorter transfer time could allow for extensions of the scientific mission nominal operations period, data collection during the final stages of Uranus's solstice and, potentially, mission cost reduction. This trajectory also involves fewer maneuvers than the one discussed in the PSADS, thus reducing mission complexity and risk.

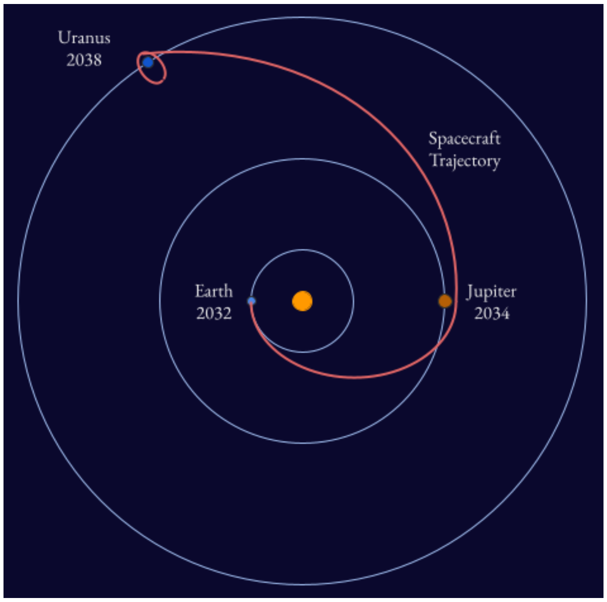


Figure 1: Schematic representation of the proposed cruise trajectory, showing Earth departure in 2032, Jupiter flyby in 2034, and Uranus orbital insertion in 2038, totalling 7 years of cruise period. Not to scale.

SCIENCE OBJECTIVES

The primary goal of the proposed mission is to study the atmospheric environment of Uranus. We aim to contribute to the understanding of the atmospheric composition and vertical temperature profiles while also characterizing the intrinsic magnetic fields of Uranus. The questions our mission helps address are all part of Question 7 in the PASDS [1]: *What processes influence the structure, evolution, and dynamics of giant planet interiors, atmospheres, and magnetospheres?* Within question 7, we believe a swarm of CubeSats could feasibly address parts of the subquestions 7.1, 7.2, 7.3, 7.4, and 7.5, as outlined below. Those questions were selected based on the similarity of the measurements that could address them. Given the dispersion of assets, the higher planetary coverage, and the high revisit rate, we believe a swarm of small spacecraft is capable of helping answer a significant array of scientific questions. When combined to a another, equinox focused, mission, we could have start answering the following:

- *7.1* What are giant planets made of and how can this be inferred from their observable properties?
  - *7.1.a* Are the helium and noble gas abundances across the giant planets consistent with interior and solar evolution models?
  - *7.1.b* How do bulk abundances of major species and ice-to-rock rations compare with nebular models?
  - *7.1.c* How are condensable species and disequilibrium species distributed and transported in the planetary atmospheres and interiors?
- *7.2* What determines the structure and dynamics deep inside giant planets and how does it affect their evolution?
  - *7.2.a* How does composition change with depth in giant planet interiors?
  - *7.2.b* How are elements and heat transported from the deep interior to the atmosphere?
  - *7.2.c* What is the deep rotational and dynamical state of giant planets?
  - *7.2.d* How are complex magnetic fields of the giant planets generated?
  - *7.2.e* How are the interiors of the giant planets evolving today?
- *7.3* What governs the diversity of giant planet climates, circulation, and meteorology?
  - *7.3.a* What processes maintain banded patterns and unique polar regions on each giant planet, how do they connect with the deep interior, and what controls their variability?
  - *7.3.b* How do stratospheric properties trace interactions with internal and external phenomena?
  - *7.3.c* How and why do discrete meteorological features (storms, vortices, etc) evolve?
  - *7.3.d* What chemical and physical processes influence the gas and aerosol absorbers that produce the diverse colors and spectral properties of the giant planets?
  - *7.3.e* How does moist convection shape atmospheric structure in hydrogen-dominated atmospheres?
- *7.4* What processes lead to the dramatically different outcomes in the structure, content and dynamics of the outer planets' magnetospheres and ionospheres?
  - *7.4.a* What processes govern the content and dynamics of the giant planets magnetospheres?
  - *7.4.b* What is responsible for the differences between the magnetosphere of the gas giants and ice giants?
  - *7.4.c* How is energy redistributed with latitude and altitude within giant planet ionospheres and thermospheres, and what is responsible for their high (and variable) temperatures?
  - *7.4.d* How do external inputs and local ion chemistry produce the complex variability observed in ionospheres?
- *7.5* How are giant planets influenced by, and how do they interact with, their environment?
  - *7.5.a* How is angular momentum lost, and tides dissipated, from the giant planets?
  - *7.5.b* How is atmospheric composition influenced by ring rain, large impacts, and micrometeoroids?
  - *7.5.c* How does seasonally variable solar insolation influence middle atmospheric chemistry and haze production?

SPACECRAFT DESIGN

Instrument Selection

Given the large number of unknown characteristics of Uranus, various types of instruments could be useful in uncovering answers to the PSADS questions. To be able to host as many instruments as possible, we are proposing to separate the spacecraft into a mothership of 2373 kg wet mass and a swarm of CubeSats with a combined wet mass of 640 kg. The mothership would contain the required fuel for the Jupiter flyby and the Uranus orbital insertion, in addition to having two duplex radios: one to communicate with the CubeSats and a different, more powerful system, to relay data to and receive commands from the ground station on Earth. The CubeSats would weigh 40 kg each, being dispersed into a swarm of 16 spacecraft. The swarm would be divided into four groups of four identical spacecraft each, with each group specialized for a specific instrument.

We selected a short list of possible instruments based on instruments from the Cassini spacecraft and other planetary science missions, as this proposed mission aims to answer similar questions as the Cassini mission about the atmosphere, magnetosphere, and natural satellites [11], as well as questions similar to other planetary science missions, such as GRACE [12]. The list of instruments and association acronyms are shown in Table 1.

Table 1: Instrument Selection Shortlist

Acronym	Name	Source
INMS	Ion and Neutral Mass Spectrometer	Cassini
UVIS	Ultraviolet Imaging Spectrograph	Cassini
GRS	Gamma Ray Spectrometer	Odyssey
CIRS	Composite Infrared Spectrometer	Cassini
MAG	Magnetometer	Cassini
OTD	Optical Transient Detector	MicroLab-1
RPWS	Radio and Plasma Wave Science	Cassini
CAPS	Cassini Plasma Spectrometer	Cassini
VIMS	Visible and Infrared Mapping Spectrometer	Cassini
MKI	Microwave K-band Instrument	GRACE
MIMI	Magnetospheric Imaging Instrument	Cassini
ISS	Imaging Science Subsystem	Cassini

Given the breadth of the Scientific objectives for this mission, instruments were selected from the short list based on their ability to answer a broad spectrum of scientific questions. This study can be seen in Table 2.

Instruments are rated 1 if they are the primary instrument for the associated question, answering many components of said question. Instruments are rated 0.5 if they are considered supplemental to the primary, providing extra data to answer the question more fully than the primary sensor on its own. An instrument is rated 0 if it may prove helpful in answering the question, but is not considered necessary to fully answer it. Finally, an instrument is not rated for a question if it provides no information to answer said question. Ratings are color coded for ease of understanding.

Table 2: Instrument Selection Study

	INMS	UVIS	GRS	CIRS	MAG	OTD	RPWS	CAPS	VIMS	MKI	MIMI	ISS
Q7.1.a	1	1						1				
Q7.1.b	0		0.5					0.5		1		
Q7.1.c		0		0.5				1				
Q7.2.a					1					1		
Q7.2.b		0		1								
Q7.2.c					1					1		
Q7.2.d					1							
Q7.2.e				0.5	1			0.5				
Q7.3.a		0		1		0.5	0.5	1				
Q7.3.b		0.5		1	0.5			0.5			1	
Q7.3.c						1	1					
Q7.3.d				0.5		1			1			
Q7.3.e	0.5	0.5		0.5					0.5			1
Q7.4.a					1			0.5		0.5		
Q7.4.b					1							
Q7.4.c		0.5		0.5			0.5					1
Q7.4.d								1		0.5		
Q7.5.a												
Q7.5.b						0.5						1
Q7.5.c						0.5		1				
Total	1.5	2.5	0.5	5.5	6.5	3.5	2	7	1.5	4	1	3

Based on the instrument selection study, the first group of identical spacecraft, Group A, would focus on magnetic field mapping, having as payload a Cassini-inspired magnetometer. Group B would contain multispectral imaging sensors, collecting data on the surface temperature and composition of Uranus's atmosphere. Group C would perform gravity mapping by measuring differences in orbital perturbations and accelerations of each spacecraft. Group D would have a short mission, having the goal of plunging into Uranus' atmosphere while performing temperature and atmospheric composition measurements at various altitudes as it descends through the atmosphere. Together, the four groups of spacecraft will have a larger coverage and revisit rate than what would be possible with a single spacecraft, exploring Uranus more extensively.

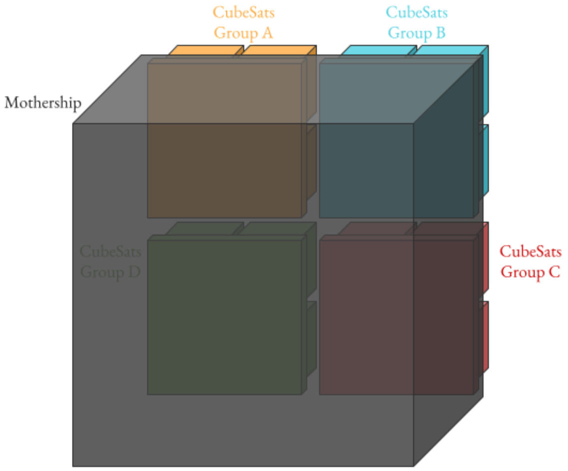
It is important to note that, while the instruments from these missions provide a good understanding of sensor types and answerable questions, they have power and size requirements that are designed to be met by one large spacecraft, rather than the smaller CubeSat design. Thus, we have sourced commercial-off-the-shelf (COTS) sensors and used average values as analogues to the instruments on this shortlist to provide more realistic requirements for preliminary design. It is likely that the final instruments will have requirements somewhere between these two extremes. The substitute for Group A is a group of three magnetometers on a boom, the substitute Group B is a multispectral imager, the substitute Group C is a K-band transmitter and antenna, and the substitute Group D is a plasma sensor for composition and a hot wire thermometer for temperature. A comparison of Cassini instruments and CubeSat COTS can be seen in Table 3, where the Cassini instruments are written in blue, bolded font and CubeSat instruments are highlighted in light orange.

Table 3: Instrumentation Comparison

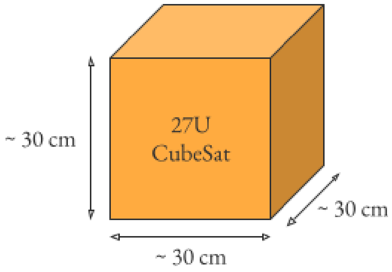
Instrument	Power Requirements (W)	Mass (kg)
MAG [13]	**3.1**	**3.0**
Magnetometer (3)	1.3 - 3.0	0.3
CAPS [13]	**14.5**	**12.5**
Plasma Sensor	5	0.1
Huygens SSP [14]	**10**	**4.2**
Thermometer	0.5	< 1*
CIRS [13]	**26.4**	**39.2**
Multispectral Imager	2.6-4.6	0.5
MKI [13]	**> 3***	**3.0**
K-band Transmitter	2	1

**When precise information was not found, bounding values were estimated by the authors.*

Figure 2 shows a schematic of how the mothership and the four groups of CubeSats would be integrated during cruise. Figure 2(a) shows the mothership in translucent gray and the four groups of CubeSat mounted behind the mothership. Each group is in a different color to easen identification. Each group is composed of four identical CubeSats, getting to a total of 16 CubeSats. Figure 2(b) illustrates the size and shape of each of the CubeSats, which will have equally sized walls of 3U x 3U each and will weigh approximately 40 kg.



(a)



(b)

Figure 2: (a) Schematic representation of the Mothership/CubeSat architecture. (b) Schematic representation of the 27U CubeSats.

CubeSat Design Overview

Because of the number of unknown characteristics of Uranus, instruments were selected based on their ability to answer a broad spectrum of scientific questions.

When approaching the design of the CubeSats, there were three main design challenges – the power, communications, and thermal subsystems. This is due to the need for higher energy densities to counteract the effects of the diseconomies of scale that occur for power generation and heat retention in spacecraft as they get smaller. A greater portion of heat is radiated away as the surface area grows in relation to the volume, and it is harder to fit modern nuclear power options, such as the MMRTG, in small spacecraft. The challenge of communications emerges from this issue of power and size, as long distance communications are often the most power intensive components of a mission [15], and receiver antenna size is directly related to the signal strength [16]. However, it is possible to overcome these design challenges through the use of carefully selected hardware and engineering budget calculations. A few assumptions were also necessary, and they are stated where appropriate.

Power Subsystem

In our design of the CubeSats' power subsystems, we propose using two individual General Purpose Heat Sources (GPHSs) combined with an emerging technology, the Thermoradiative Cell (TRC) [17]. Each GPHS generates 250W of thermal energy, which can then be used by a TRC [18]. A TRC is a device that, given a heat source, "allow[s] an order of magnitude increase in mass specific power (~30 vs ~3 W/kg) and a three orders of magnitude decrease in volume (~0.2 vs ~212 L) as compared to a conventional multi-mission radioisotope thermal generator (MMRTG)" [19].

In addition to our nuclear power source, we propose a battery to act as a buffer for high power situations, such as data transfer. As an initial design, we use a lithium ion battery with approximately two hours of regular power consumption. A summary of the power budget can be seen in Table 4. These values represent peak draw, not the average power consumption. For example, when using the amplifier to transmit, the CubeSat would minimize the use of the reaction wheels to save power, and when not actuating the cold gas thrusters draw no power. See the entries titled "Average" to exclude power spikes. Sensing would not occur during a power spike.

Table 4: Power Budget

Universal Components			
Component	**Power Use (W)**	**Excess Power (W)**	**Group**
Generator (GPHS & TRC)	+33.861		Universal
GNC Sensors [20]	-3.7		Universal
Reaction Wheels (4) [20]	-9.2		Universal
Radio	-2.6		Universal
Computer [21]	-10		Universal
Memory (2) [21]	-.6		Universal
Clock [20]	-1.5		Universal
Cold Gas (6) [22]	-<63		
Total		-56.34	Universal
Amplifier	-13	-62.68	Universal
Average total		14.861	
Group-Specific Components			
Component	**Power Use (W)**	**Average Excess Power (W)**	
Multispectral Imager	4.6	10.261	B
Plasma Sensor	5	9.861	D
Thermometer	0.5	14.361	D
Magnetometer (3)	3	11.861	A
K-Band Transmitter	2	12.861	C

Radiation Prevention

Radiation is a significant design challenge for any deep space spacecraft, let alone CubeSats which are normally designed to function for far less time than a flagship mission. This is mitigated through several factors.

Environmental radiation can be mitigated through shielding. While the CubeSats are in transit to Uranus, they can be shielded by the mothership, requiring no additional mass on the CubeSats themselves and lowering the lifetime radiation dose significantly. After reaching Uranus, it has been projected for similar missions that 100 mils (2.54 mm) of aluminum shielding is enough to mitigate radiation for standard, radiation hardened electronics for the lifetime of this mission [23].

Internal radiation through the GPHSs' decay can also be mitigated through shielding. From Figure 3, we can determine the worst case lifetime radiation dose. We can then determine the necessary shielding thickness using the equation:

$$I = I_0 \, e^{-\mu r} \tag{1}$$

Where I_0 is the incident radiation intensity, I is the residual radiation intensity, r is the thickness of the shielding material, and μ is the linear attenuation coefficient of the material you are using as shielding.

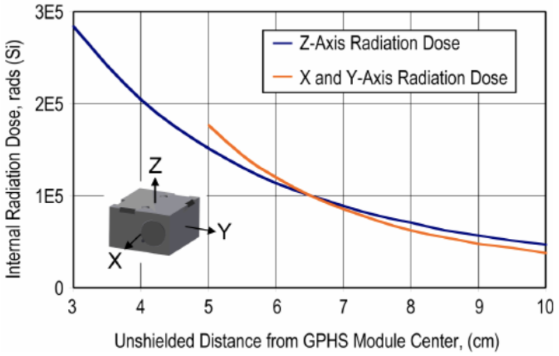


Figure 3: GPHS Lifetime Radiation Dose [24]

In the case of two GPHSs, assuming no shielding from each other (worst case), we can reduce the worst case lifetime radiation dose to 1 krad using an aluminum shield with a thickness of 0.445 cm.

Thermal Subsystem

As the only method of heat transfer in space is radiation, we can approximate the worst case scenario by treating the spacecraft as a black body that is absorbing no radiation. This allows us to determine the maximum possible heat lost for any given temperature. Taking the optimum temperature range of a lithium ion battery as the working range (10 °C - 30 °C), we can use the Stefan-Boltzmann Law to determine that we lose approximately 197 W of thermal energy at 10 °C. We can make up that energy deficit using Light weight radioisotope heater units (RHUs). These units weigh 0.04 kg and generate 1.1 W of thermal energy [25]. From these numbers, we can calculate that if we had to rely solely on RHUs, we would need 7.164 kg.

However, we understand that in reality we will not need close to this amount. The two GPHSs that are used to generate electrical power will radiate significant waste heat, and there will also be planetshine once the spacecraft arrives at Uranus, which is a small, but notable component.

Communications Subsystem

As previously stated, communications are often some of the most power intensive and size dependent tasks for a spacecraft, both of which are at a disadvantage for CubeSats in comparison to traditional spacecraft. This disadvantage led to the biggest design challenge of this proposed mission – the communication between the CubeSats and the mothership. This was a challenge because the CubeSats sized radios generally have a maximum output of around 2 W [26], and for the boundary case of the transfer distance being the major axis of the Uranus capture orbit (almost 300,000 km), 2 W is a very small transfer power, even with a high-gain antenna.

This issue was mitigated by a variety of factors. First, it is necessary to add an amplifier to the transmission signal, which would boost the transmission power from 2 W to 10 W. It is also necessary to use a frequency with a lower bit rate, which lowers noise. For that reason, we decided to use the UHF band for satellite to mothership communications. Finally, it is important to recognize that the worst-case scenario, that the transfer distance is the major axis, is impossible. This is because the spacecraft would need to send a signal directly through the planet. Thus, we can reduce the distance by about the diameter of Uranus, which is around 50,000 km. The last step would be to add a low noise amplifier to the receiver on the mothership. A breakdown of the link budget can be seen in Table 5.

Table 5: Link Budget [27]

General Information		
Characteristic	**Value**	**Unit**
Distance	244000	km
Transmitter Information		
Characteristic	**Value**	**Unit**
Frequency	0.45	GHz
Bit rate	0.010	Mbps
Transmit Power	10.0	W
Transmit Power	40	dBm
Transmit antenna gain	7.5	dBi
Transmit system losses	-4	dB
EIRP	43.5	dBm
Path loss	-193.26	dB
Receiver Information		
Characteristic	**Value**	**Unit**
Receive antenna diameter	1.7	m
Antenna Efficiency	80	%
Receive antenna gain	17.1	dBi
Receive amplifier	10.0	dBi
Noise Temperature	150.0	K
Receive system noise figure	-176.84	dBm/Hz
Total Received Power	-118.7	dBm
Receiver system losses	-4	dB
Cross polarization loss	0	dB
Link Margin Computation		
Characteristic	**Value**	**Unit**
Received Eb/No	14.4	dB
Required Eb/No	8.0	dB
Link margin	**6.4**	dB
Required link margin	6	dB

Mass and Volume Budget

We found that the mass and volume of the CubeSats were not limiting factors after elements that were completely out of the feasible size and mass ranges were disregarded. The full mass and volume breakdown can be seen in Table 6.

Table 6: Mass and Size Budget

Universal Components			
Component	**Mass (kg)**	**Size (L)**	**Group**
Generator (GPHS, Shielding, & TRC)	5.744	1.491	Universal
GNC Sensors	0.365	< 1*	Universal
Reaction Wheels (4)	0.6	0.267	Universal
Radio	0.094	0.2	Universal
Computer	1	< 3.125*	Universal
Memory	0.08	< 1*	Universal
Clock [RefNumber]	0.016	0.004	Universal
Amplifier	1*	0.0121	Universal
Worst Case Heat RHU	7.164	0.537	Universal
60 Ah Battery	7.23	5.469	Universal
Antenna	0.3	8.553, deployable	Universal
Cold gas thrusters (6) [22]	0.420	0.0705	Universal
Fuel & tank	0.6	9.819	Universal
Structure	3.6217	27	Universal
Total	28.2347	22.995	Universal
Margin	11.7653	4.005	
Margin, %	29.4%	14.8%	
Group-Specific Components			
Component	**Mass (kg)**	**Size (L)**	**Group**
Multispectral Imager	0.3	1	B
Plasma Sensor	0.1	0.5*	D
Thermometer	< 1*	0.125*	D
Magnetometer (3)	0.5	0.3	A
K-Band Transmitter	1	0.8	C

**When precise information was not found, bounding values were estimated by the authors.*

Mothership Design

The mothership, in comparison to the CubeSats, presents a more classical design for a deep space science mission, in that it has the size and mass allowances for heavy components, such as MMRTGs, and the associated benefits that come with them. In the case of this proposed mission, the purpose of the mothership is to be transportation and a communication relay. This can be seen as part of the link budget found previously in Table 5 by examining the receiver antenna diameter. According to the presented analysis, the mothership would need an antenna that is 1.7 meters in diameter to have a safe link margin. This need for solid communications links is the main design driver leading into the current high level design.

To aid in the purpose of being a communications relay, the mothership would likely include multiple MMRTGs, mostly to provide power for communications. Our preliminary design for the mothership indicates the need of having three radio links using a 1.7 m diameter antenna each to communicate with the CubeSats, while reserving the final, largest antenna and most powerful radio to downlink to Earth via NASA's Deep Space Network (DSN). This larger radio and antenna have been based on the system used in the New Horizons mission and is therefore of a similar size and characteristics, having a 2.1 m diameter high-gain antenna and operating in the X-band.

When not communicating with the CubeSats, the mothership could also accomplish science objectives by using the different frequency receivers to study Uranus in the radio frequencies. However, any additional mass for the mothership would likely go toward power generation or fuel, rather than adding instruments to said spacecraft and diluting its purpose.

CONCLUSIONS

This work demonstrates that a CubeSat swarm mission to Uranus might be a viable solution for answering many aspects of the seventh question stated in the 2023-2032 Planetary Science and Astrobiology Decadal Survey. A swarm of small spacecraft fits well with this scientific endeavor because of the broad scope of the question, which is looking for contributions to the understanding of the structure, evolution, and dynamics of the interior, atmosphere, and magnetosphere of Uranus. The swarm proposed here is divided into four sets of CubeSats, with each set containing instruments that specialize in answering some components of the broad question in the decadal survey. Our preliminary analyses have shown that typical technical budgets of a spacecraft (electrical power, thermal control, mass, volume, communications link and fuel) do close with adequate margin, confirming the feasibility of the mission architecture.

The proposed mission also presents improvements over the coverage and revisit rates of the planetary surface, as each group of specialized spacecraft is composed of multiple copies of the same system that can be maneuvered into orbits with different inclinations and altitudes. These improvements could result in more thorough scientific discoveries in a shorter mission lifetime.

Finally, the cruise trajectory proposed here allows for an Uranus arrival in 2038, when the planet is still transitioning from solstice to equinox, bringing a unique perspective into the planetary internal movement and structure. The cruise is also 5 years shorter than the Earth-Earth-Jupiter-Uranus trajectory discussed in the PSADS. This results in a mission with lower complexity and more potential of high-return scientific mission extensions.

FUTURE WORK

Going forward, we will continue to work on refining the design of the CubeSats and the mothership. The first step will be to create a concept of operations (ConOps), separating the operation into different modes of power consumption and task execution. Next, a data budget will be created to confirm that the proposed data rate is enough to downlink all the collected data. The next step will be to iterate on all the technical budgets, refining the approximations and retiring many assumptions. With an improved system concept, we will analyze the currently available commercial parts and evaluate the need of creating custom parts for the CubeSats. Supplemental data and orbital visualizations will also be generated using NASA's GMAT and Poliastro. If further funding becomes available, the design of the scientific instruments could be tackled, closing the gap between large instruments previously flown in interplanetary missions, and small CubeSat-rated instruments with lower capabilities.

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