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Design of a Smallsat for Uranus

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I. Introduction

This work presents a design for a smallsat designed as a ride-along payload with the Uranus Orbiter and Probe (UOP) mission, with the mission of demonstrating the feasibility of operating a smallsat in environment of Uranus, demonstrating a new energy conversion system, and investigating the magnetosphere, magnetopause, and radiation belts of Uranus. The design was developed by the NASA Glenn Compass systems engineering team in coordination with Phase II of NASA's Innovative Advanced Concepts (NIAC) program.

II. TITUS Smallsat

A. Baseline Mission

Exploration of Uranus was named by NASA's planetary science decadal survey as NASA's highest priority for a flagship-class planetary science mission to fly during the coming decade [1]. To this end, the Uranus Orbiter and Probe ("UOP") has been proposed as a mission to be launched to the Uranus system in the 2030s [2]. This study looks at enhancing the value of the mission by attaching a small ride-along "daughter" satellite to the mission, allowing science observations to be made at multiple locations and distances from Uranus.

The magnetosphere and radiation belts of the outer planet Uranus are not well explored. Uranus is unique in that its rotational axis is tilted nearly perpendicular to the plane of its orbit, and the pole of the magnetic field is tilted 47 degrees from the rotational axis, resulting in a magnetic field that presents widely varying angles to the solar wind, ranging from polar to equatorial. In addition, the magnetic field of Uranus shows extreme magnetic field asymmetry, unlike the magnetic fields of the inner planets or the gas giants [3]. The details of the interaction of the solar wind

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with the planet is not well understood [4-6]. Likewise, the radiation belts of Uranus are not well understood, with the current evidence showing that the electron belts are anomalously high energy, while the proton belts are anomalously low [3,7,8].

Voyager 2, the only spacecraft to visit Uranus, spent only hours passing through the magnetosphere. Subsequent modeling also suggests that the lone flyby may have observed Uranus during an unusual period of solar activity [8,9]. Hence, it is of high scientific interest for a mission to Uranus to conduct measurements of the magnetic fields and the radiation belts, over an extended period of time [4-6,10]. Preferably, simultaneous measurements would be taken at two (or more) points in the magnetosphere, allowing the time variation of the magnetic field and radiation belts to be distinguished from the positional variations, and the measurements taken at multiple distances from the planet, ranging from near the cloud tops (to map the higher-order multipole components of the field) to the extended magnetotail, with the time series of measurements extended over many years to characterize the reaction of the magnetopause to changes in the solar wind activity.

The Technology Innovation Thermoradiative Uranus Smallsat (TITUS) satellite is a conceptual design to do exactly this. The TITUS science package [11] would complement UOP magnetospheric science during multiple orbits. By separating from the UOP and making simultaneous measurements with UOP at a different portion of the magnetosphere, TITUS would achieve distinct spatial and temporal samplings of the complex magnetic field, radiation environment, and magnetopause of Uranus. The TITUS observations would thus fill in the three-dimensional profiles of the interaction of the magnetic field with the solar wind. Likewise, the TITUS spacecraft will fill in details on the radiation belts, with multiple passes through both Uranus' electron and proton belts.

A single TITUS smallsat would provide exceptional science value, by mapping out the three-dimensional nature of the magnetic field and plasma environment in collaboration with the UOP spacecraft, but flying more than one, to allow simultaneous measurements at three or more locations, would provide even more detailed science.

Figure 1 shows an artist's conception of the TITUS spacecraft in orbit around Uranus.

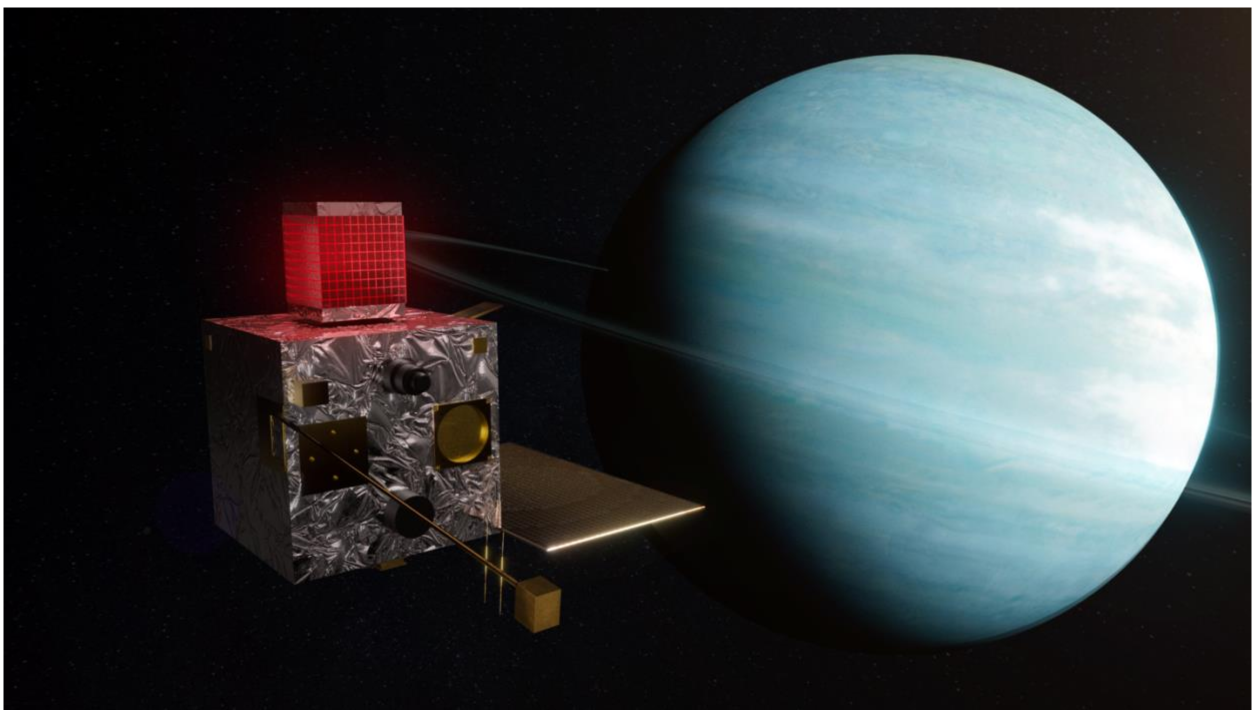

Fig. 1: Artist's conception of TITUS around Uranus.

B. Technology Choice

The Technology Innovation Thermoradiative Uranus Smallsat (TITUS) is a proposed smallsat technology demonstration concept mission to showcase an innovative power source utilizing thermal power conversion from a thermoradiative cell (TRC). Thermoradiative energy conversion is a new concept for electrical power generation from a thermal source, in which a solid-state conversion element radiates waste heat directly to deep space, without the requirement for a separate radiator [12-14]. In principle, this new energy conversion technology could allow small, compact system to produce power from a radioisotope thermal source [15-17]. It is an objective of this study to do a design to fill out the details of how such a conversion system could be utilized in a spacecraft.

The proposed TRC has higher thermal to electrical power conversion efficiency than the heritage Multi-mission Radioisotope Thermoelectric Generator (MMRTG) power systems used in current NASA outer-planet missions [18], with a lower volume and higher mass specific power density. This makes a TRC particularly attractive for small-scale missions to the outer planets or other locations where low-light environments render solar power impractical [17]. The mission would primarily serve as a proof-of-concept for TRC technology through a low-risk smallsat companion to NASA's proposed Uranus Orbiter & Probe Mission. TITUS is to demonstrate TRC powering of a functional smallsat in communication with the UOP while conducting supporting science measurements for a duration of 5 years or more.

To reduce the risk involved in qualifying a new radioisotope source, the spacecraft design was baselined to use a single General Purpose Heat Source (GPHS) unit as the thermal input to the power supply. These are space-qualified plutonium-238 isotope thermal sources that produce 250 watts of heat at beginning of life, with a long history of use as the thermal source for Radioisotope Thermoelectric Generator (RTG) power supplies for planetary missions [19]. Individual fuel assemblies ("clads") contain a single 151-gram Plutonium-oxide pellet clad in Iridium, producing 62.5 watts of thermal power, with four such clad fuel assemblies put together into a GPHS unit, or "brick" (figure 1). The 250-Watt (thermal) brick has a size of roughly 9.3 cm x 9.3 cm x 5.3 cm. With a Pu-238 half-life of 87.7 years, the source will be more than suitable for producing power for the duration of the mission.

The power system requires the thermoradiative panel to have a view to deep space, and the power supply was implemented as a "power cube" with thermoradiative cells on four of the outward facing sides of the cube, leaving the top surface free to allow access to the interior to insert the GPHS source prior to launch, and the bottom surface to mount to the spacecraft. The power cube is 13.6 cm square by 18.6 cm high, with a mass of 2.21 kg, producing a nominal 37.5 Watts of electrical power (about 17 W/kg) at an operating temperature of 650K. This is shown in figure 3. The pressure vessel enclosing the GPHS allows pressurization of up to 203 MPa; a requirement driven by the need to maintain the high-temperature fuel pellets in an inert gas environment before launch.

Although the design here baselined Plutonium 238 as the thermal source, availability of the plutonium isotope may be limited in the near future. If Plutonium is not available, NASA and European Space Agency have been studying use of an alternate isotope heat source, Americium 241 [20]. This has a lower thermal output, but longer half-life of 432.6 years. The volume-specific power is 1.17 W/cm^3 for AmO_2, compared to 5.66 for PuO_2. We did a design trade to see the effect of substituting Americium, using the identical design as the GPHS brick, but substituting AmO_2 pellets for PuO_2. With this substitution, the number of clads needs to be increased, with the resulting power cube slightly larger (16.5 cm cube instead of 14 cm), increasing the 33 kg mass of TITUS to 41 kg.

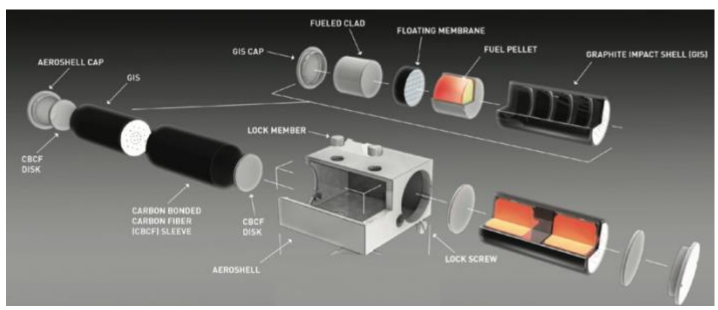

Fig. 2: Exploded view of General Purpose Heat Source (GPHS) unit, showing how four individual fuel clads are assembled into the 250-W$_{th}$ brick.

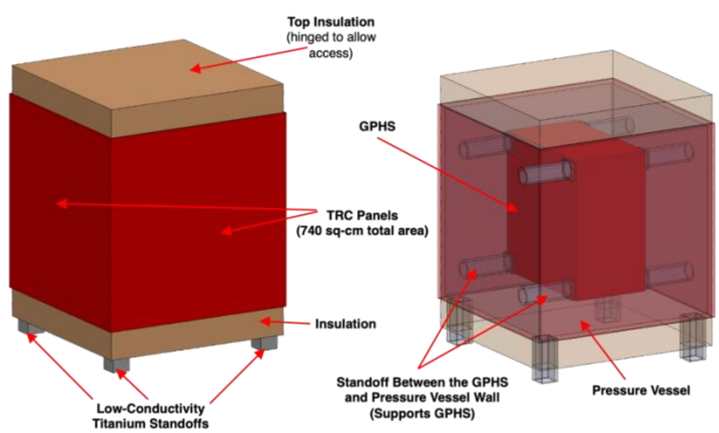

Fig. 3: 37.5-We "power cube" power source, external view (left) and internal (right) showing the mounting of the GPHS radioisotope source.

C. Spacecraft Orbit and Communications Link

To put the TITUS smallsat into an orbit that sweeps a path distant from the main UOP probe, after the UOP is captured into Uranus orbit we release the TITUS from the UOP at the first (or any subsequent) apoapsis following the deployment of the atmospheric probe, but before the beginning of the moon flybys. TITUS will remain in the high eccentricity, high-inclination orbit around Uranus, passing repeatedly through the magnetopause and dipping through the magnetic field and radiation belts, while the primary UOP spacecraft uses multiple moon fly-bys to progressively nudge the spacecraft into shorter period orbits at near-equatorial latitude. This allows the simultaneous measurements of the magnetic field and particle environment at widely separated points.

We examined the possibility of deploying TITUS at a later stage in the UOP mission, giving it an orbit with a larger fraction of its time in the inner magnetosphere, but trajectory analysis showed that without orbital correction maneuvers, the later deployment would result in a lack of orbital knowledge due to chaotic perturbations caused by close passages by Titania.

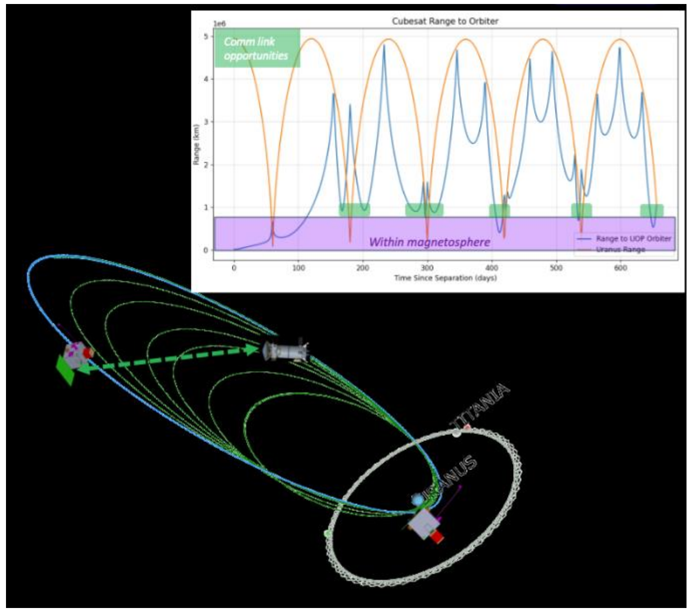

Fig. 4: The orbit of the TITUS smallsat (blue) compared to the orbits of UOP probe around Uranus (green). Inset graph shows the range from TITUS to the UOP (blue) and the distance between TITUS and Uranus (orange) for the first 2 years after separation. The violet shading at the bottom indicates when the spacecraft is within the average expected distance of the magnetopause of the Uranus magnetosphere [9] at 22.2 R_U (although the actual extent of the magnetosphere will fluctuate with solar activity), while the green shading indicates communications opportunities with the relay spacecraft within one-million km range.

Figure 4 shows the orbit around Uranus, and the range from TITUS to the UOP (serving as the communications relay) and to Uranus over the first two years of the mission, during which time the UOP gradually decreases the inclination and semimajor axis of its orbit. TITUS will make six passes into the magnetosphere during this period. Orbital analysis shows that this orbit will be stable against perturbations over the five-year course of the primary mission.

TITUS is designed to use the UOP as a data relay for high-data rate X-band downlink capable of 47 kbsp data rate at a distance from the UOP of one million kilometers. While TITUS will be able to relay data at longer ranges, the lower bit-rate at longer distances means the link will be done only for the relatively small data volume of housekeeping and engineering data. The primary communications antenna is based on the “reflectarray” technology demonstrated on the Mars Cube One (MARCO) communications satellites [21] successfully demonstrated in the Insight Mars Lander mission. In event of a spacecraft emergency, the spacecraft can communicate using the same antenna directly to Earth, although the DTE data rate is limited to 40 bps downlink and 25 kbps uplink. A second UHF link is used with four omnidirectional patch antennas, for the case where omnidirectional communications (without pointing) is required, typically for health-monitoring “pings.”

The smallsat is designed to operate with no orbital propulsion. It incorporates five 10-mN cold-gas thrusters, at a specific impulse of about 40 seconds, which are used to cancel out any deployment tip-off if needed, and to de-saturate the reaction-control wheels that provide attitude control.

D. Science Instrumentation

Instrumentation on the TITUS smallsat consists primarily of science instrumentation to measure the magnetosphere and radiation belts, along with engineering measurements such as sun- and star- trackers and a small camera, primarily for public outreach images. The science instruments cover similar functionality as the plasma and magnetic sensors on the UOP spacecraft, but smaller and lighter weight instruments have been chosen as more suitable to the smallsat mission. Although the smaller instruments have a correspondingly lower state of technology readiness, all the instruments chosen have a pedigree from earlier missions. For example, the Langmuir probe and magnetometers were based on the design of the fluxgate magnetometer flown on the Experimental Albertan Satellite #1 (“Ex-Alta 1”) spacecraft, a student-build cubesat developed at the University of Alberta [22]; the Suprathermal ion spectrometer is based on an instrument baselined for the CuSP cubesat [23], and the Low-Energy Module (LEM) is based on a design for the NUSES spacecraft [24].

The instrument choice shown in Table 1, along with the science traceability matrix, showing how the chosen instrument set addresses NASA science questions for the Uranus system.

Science Question	Measurement	Requirements	Selected Instrument
1. What dynamo process produces Uranus's complex magnetic field? [2]	Internal magnetic field structure	Close Passes	Digital Fluxgate Magnetometer (DFGM)
2. What are the plasma sources & dynamics of Uranus's magnetosphere and how does it interact with the solar wind? [2]	Particles & fields over range of space (distance, longitude, latitude, local time) and time (spin, solar wind variability)	Multiple Passes	Suprathermal Ion Spectograph (SIS), Multi-needle Langmuir probe (m-NLP), Low energy module (LEM)
3. How does the magnetosphere interact with Uranus's upper atmosphere and satellite surfaces? [2]	Energetic particle fluxes at satellite orbital ranges	Magnetic fields and particle flux densities	
4. How do internal and external sources and drivers shape particle populations and enable particle transport within Uranus's magnetosphere? [9]	3D vector magnetic field	Range: ±20,000 nT; Resolution ≤ 0.1 nT; Temporal Res: 10 s	Digital Fluxgate Magnetometer (DFGM)
	Plasma energy, angular, and distributions	Range: ~10 eV – 30 keV; Species: e^-; temporal Res: 10 s	Multi-needle Langmuir probe (m-NLP)
	Suprathermal ion energy, angular, and compositional distributions	Range: ~1-200 keV/Q; Species: H, He; temporal Res: 10 s	Suprathermal Ion Spectrograph (SIS)
	Energetic particle energy, angular, and compositional distributions	Range: 30 keV - 10 MeV; Species: e^-, H, He, C, O; Temporal Res: 10 s	Low energy module (LEM)
5. Contribute to: What does Uranus's global current system look like and how does this couple to upper atmospheric dynamics? [9]	3D vector magnetic field	Same as Science Question 4	Digital Fluxgate Magnetometer (DFGM)
6. Contribute to: Which processes source and shape Uranus's radiation belts? [9]	Same as SQ 4	Same as Science Question 4	Same as Science Question 4

Table 1: Science questions, instrument choice, and science traceability matrix.

E. Thermal Control

Because of the wide variety of thermal environments encountered, controlling the temperature required a detailed analysis to avoid either excessive high or low temperatures. In addition to making sure that the system does not overheat when on the launch pad, the mission originates at Earth (1 AU from the sun), may have a Venus flyby during the outbound trajectory to Uranus (0.72 AU), and then operates in the low-temperature environment at Uranus (~19.19 AU from the sun). Calculations were made of the operating temperature within the spacecraft bus and thermoradiative conversion system throughout the mission. The spacecraft and payload would operate using mainly an uncontrolled passive thermal system, since the spacecraft size and surface area as well as the waste heat generated are sufficient to maintain the spacecraft components within their operating temperature range throughout the mission.

Solar intensity and view angle as well as the view to warm bodies (Earth, Venus) were used to determine the worst case hot and cold conditions. The worst-case warm spacecraft operation would take place during a possible outbound Venus flyby, when the thermal input can include solar radiation, reflected light and IR radiation emitted from Venus, and the heat from the GPHS heat source.

The spacecraft itself, other than the power supply, is configured with an exterior surface coated to have an emissivity of 0.85 and a solar absorptivity of 0.14 to regulate the internal temperature to within the maximum operating temperature limits of the electronic components. To avoid overheating the thermoradiative cells during this worst-case Venus flyby, the top insulation preventing the heat loss from the isotope source is hinged to allow it to be opened to let the isotope heat source radiate directly to space, keeping the thermoradiative cells from overheating.

The worst-case cold temperatures occur when no equipment is in operation at Uranus, where the solar intensity of about 3.7 W/m^2 is only 0.27% that of Earth orbit. The system was designed to tap a small amount of the heat produced by the isotope source to keep the spacecraft internal temperature warm. The spacecraft walls are thermally connected with heat pipes so that they will spread the heat load and equalize the internal thermal temperature. Heaters are used to make up any loss or reduction in the waste heat during operation to maintain the internal temperature.

Thermal systems modeled:

- Thermal paint to provide the desired emissivity and solar absorptivity of the spacecraft outer panels.
- Heat Pipes to spread the heat between the spacecraft walls
- Heaters for controlling the payload components temperature
- Temperature Sensors, Controllers, Switches, Data Acquisition

F. Spacecraft Design

The spacecraft design is shown in Figure 5, with interior component layout seen in Figure 6. The entire TITUS smallsat is smaller than a single one of the MMRTG Radioisotope power system units used to power the UOP.

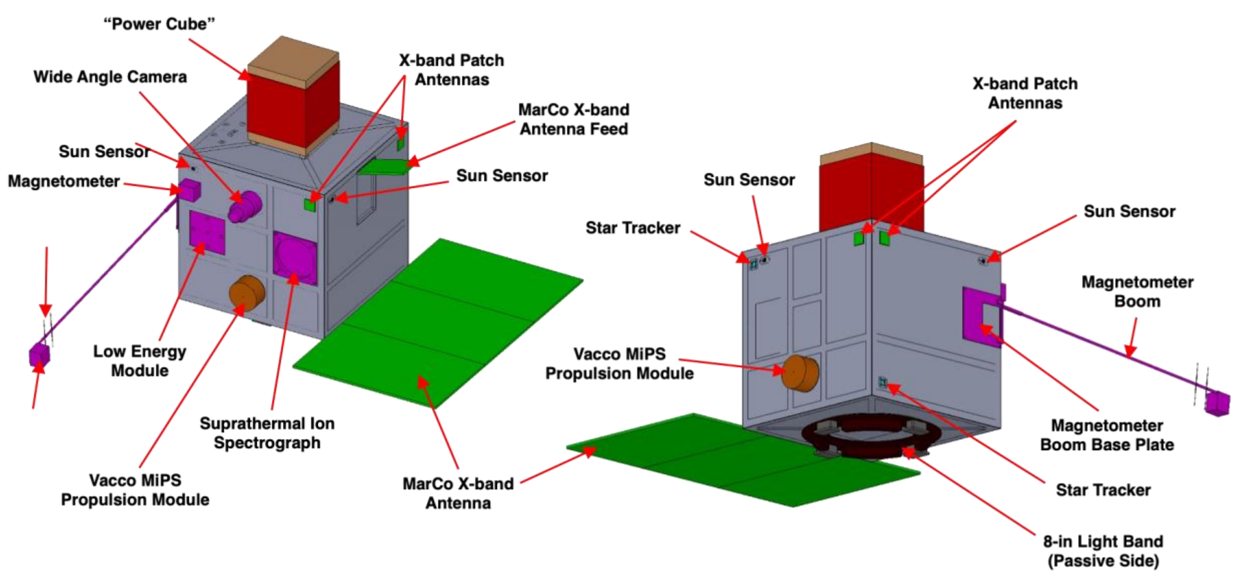

Fig. 5: Schematic diagram of the TITUS smallsat with major components labeled. Label code: Magenta shows science instruments; green the deployed communications reflectarray, and red the power system.

Table 2 gives a breakdown of the mass by subsystem, including mass growth allowance per AIAA recommended standards [25]. The entire smallsat mass is about 34 kg. This is about one percent of the 2500 kg dry mass of the UOP spacecraft, showing that the resources to fly one, or several, of the TITUS smallsats as a rideshare payload would not be a large burden on the UOP mission.

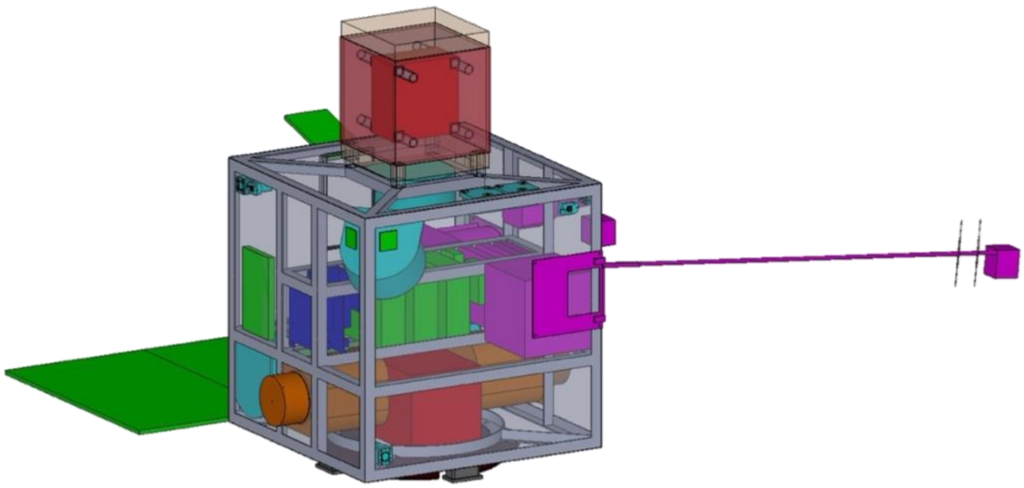

Fig. 6: Interior view of TITUS showing internal components. Label code: Magenta shows science instruments; light blue attitude determination and control, dark blue shows the command and data handling, green communications, and red the power system.

Description	Basic Mass	Growth	Growth	Total Mass
Case 1_TITUS CD-2025-225				
	(kg)	(%)	(kg)	(kg)
TITUS	27.79	22%	6.16	33.95
Bus	21.88	23%	4.92	26.80
Science	4.32	30%	1.30	5.61
Attitude Determination and Control	4.19	10%	0.43	4.62
Command & Data Handling	0.41	30%	0.12	0.53
Communications and Tracking	2.65	18%	0.47	3.12
Electrical Power Subsystem	2.02	23%	0.47	2.49
Thermal Control (Non-Propellant)	1.11	18%	0.20	1.31
Propulsion (Chemical Hardware)	1.20	5%	0.06	1.26
Propellant (Chemical)	1.52	0%	0.00	1.52
Structures and Mechanisms	4.45	42%	1.88	6.33
TRC	5.91	21%	1.23	7.15
Electrical Power Subsystem	2.01	10%	0.19	2.21
Thermal Control (Non-Propellant)	0.10	18%	0.02	0.12
Fluids	0.00	0%	0.00	0.00
Structures and Mechanisms	3.80	27%	1.02	4.82

Table 2. Spacecraft mass breakdown by top-level subsystem.

III. Conclusions

The Uranus smallsat design study had the objective of demonstrating that a smallsat could be capable of significant science operations in the outer solar system, with adequate performance margin in all systems parameters including science measurements, attitude control, and communications of science data to Earth. The TITUS design showed that there were no showstoppers in these objectives. An additional goal of the study was to show the benefits of the small radioisotope power system enabled by the thermoradiative cell technology now under development, and this technology was seen to show promise as a significant improvement in power systems for small satellites,

Although the design exercise focused on the mission of a smallsat for Uranus, the basic design could be adapted to nearly any mission required to operate in regions of space for which solar power is unavailable, including the outer planets and shadowed regions of the moon.

IV. Acknowledgement

We would like to acknowledge the work of the NASA Glenn Compass systems engineering team in putting together the details of the spacecraft design. This work was funded by Phase II grant 80NSSC24K1102 from the NASA Innovative Advanced Concepts (NIAC) program.

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