

ROBUST ACCESS TO URANUS VIA SOLAR ELECTRIC PROPULSION

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The 2022 Planetary Science Decadal Survey, Oceans, Worlds, and Life (OWL), recommended a Uranus Orbiter and Probe (UOP) as the next Planetary flagship-class mission. However, OWL called for a 2031 launch and a Jupiter gravity assist, which are not compatible with realistic expectations of when UOP might be funded. In this work, we present a means of reaching Uranus in any launch year by use of a solar electric propulsion transfer stage followed by chemical capture. The design presented here can be implemented with today's technology and includes a detailed sensitivity analysis.

The 2022 Planetary Science Decadal Survey, Oceans, Worlds, and Life (OWL), recommended a Uranus Orbiter and Probe (UOP) as the next Planetary flagship-class mission [1]. However, OWL called for a 2031 launch and a Jupiter gravity assist to reach Uranus in 13.4 years using chemical propulsion. However, National Aeronautics and Space Administration (NASA)'s budget did not allow for an commencement of mission formulation following publication of the Decadal Survey, and therefore a 2031 launch is not possible. The next Jupiter-assisted trajectory to Uranus is not available until 2044, so alternate means of reaching Uranus must be investigated.

OWL identified several options for reaching Uranus in later launch years by means of chemical propulsion and gravity assists of the Earth and Venus. These designs have been further developed by Karimi *et al.* [2] and Landau *et al.* [3]. In general, an inner solar system tour results in a different trajectory every year if gravity-assist bodies other than the Earth are used. For a given spacecraft mass requirement post-Uranus Orbit Insertion (UOI), the spacecraft in each launch year will need to carry a different propellant mass, reach a different and potentially challenging perihelion distance, spend a different length of time in cruise, or all three. Other researchers have considered super heavy lift vehicles such as NASA's Space Launch System (SLS) or SpaceX's Starship/Superheavy, new technologies such as aerocapture [4, 2], or combinations thereof.

With these challenges in mind, the Johns Hopkins University Applied Physics Laboratory (JHUAPL) and NASA's Goddard Space Flight Center (GSFC) jointly assessed options for reaching Uranus with a launch in the mid to late 2030s. Our objective was to find a way to execute UOP in a cost-constrained environment, without new technology. One finding of this study is that a commercially-derived solar-electric propulsion (SEP) transfer stage can enable access to Uranus with the same flight time, propellant mass, and perihelion distance regardless of launch year. All of the configurations that we studied were required to deliver at least 4000 kg post-UOI, inclusive of the orbiter and probe as shown in Figure 1 as well as the propellant necessary to execute the science phase [5].

We began by surveying a wide variety of thruster configurations, solar array sizes, and flight times, as shown in Figure 2. From this study, we determined that an array of four Safran PPS5000 thrusters [6], combined with a 35 kW solar array, meets UOP's delivered mass requirement with a flight time of <14 years, a benign perihelion of no worse than 0.8 AU, while staying within the envelope of a commercially procurable

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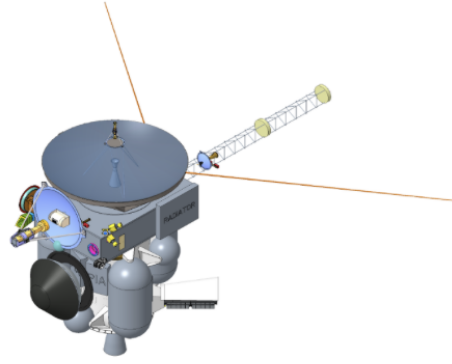


Figure 1. The Uranus Orbiter and Probe flight system, as it would appear in the Uranus system

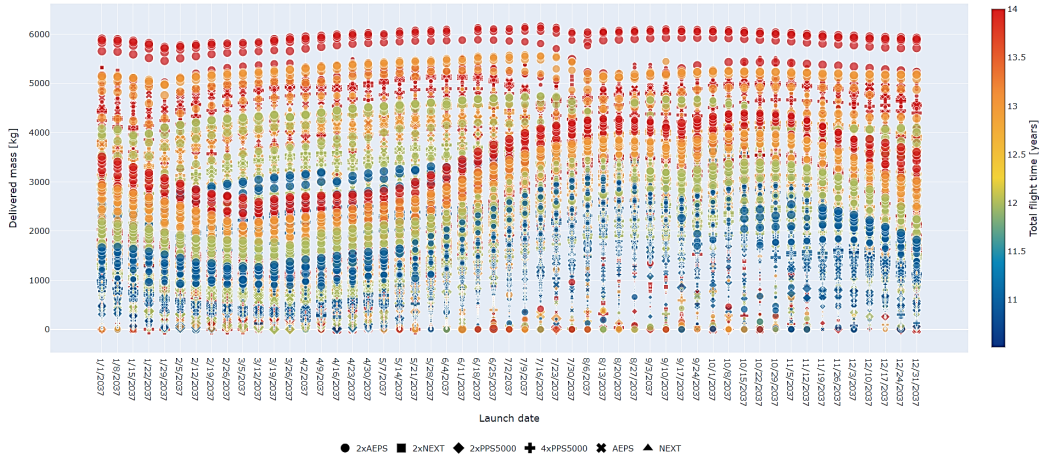


Figure 2. Several thousand permutations of launch date, thruster configuration, solar array size, and flight time. Each point is a complete mission design. Marker size describes solar array output at 1 AU, with the smallest markers representing 30 kW and the largest representing 60 kW. The 2037 launch year is shown as an example.

spacecraft bus. Figure 3 depicts the SEP stage with UOP attached. We developed a family of trajectories with launch years from 2033-2040 using this stage as shown in Figure 4, demonstrating programmatic flexibility to go with this high technical heritage approach.

We then developed a high-fidelity reference trajectory, as shown in Figure 5. This particular UOP launches in October, 2035 to a C_3 of $20.3 \text{ km}^2/\text{s}^2$ on a Falcon Heavy Expendable or equivalent, and then combines SEP thrust arcs with two Earth Gravity Assists (EGAs) in 2036 and 2039 to reach Uranus in July, 2049. We developed a detailed concept of operations (ConOps) for the thrust periods, and assessed the system's robustness to a loss of thrust at any point during the trajectory. We found that this design is particularly robust, offering 19 days of recovery margin in the worst case immediately after EGA1, and in excess of 26 days of recovery margin at all other times in the mission.

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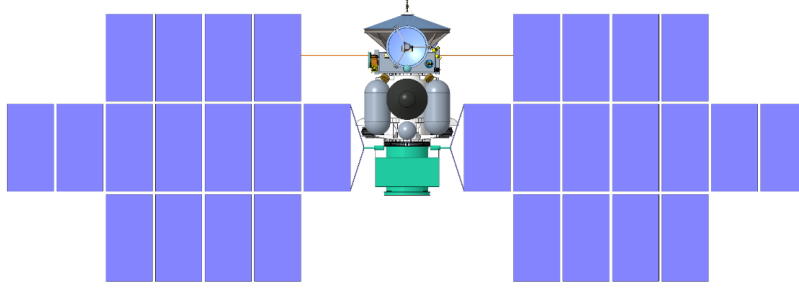


Figure 3. The Uranus Orbiter and Probe flight system mated to an SEP transfer stage

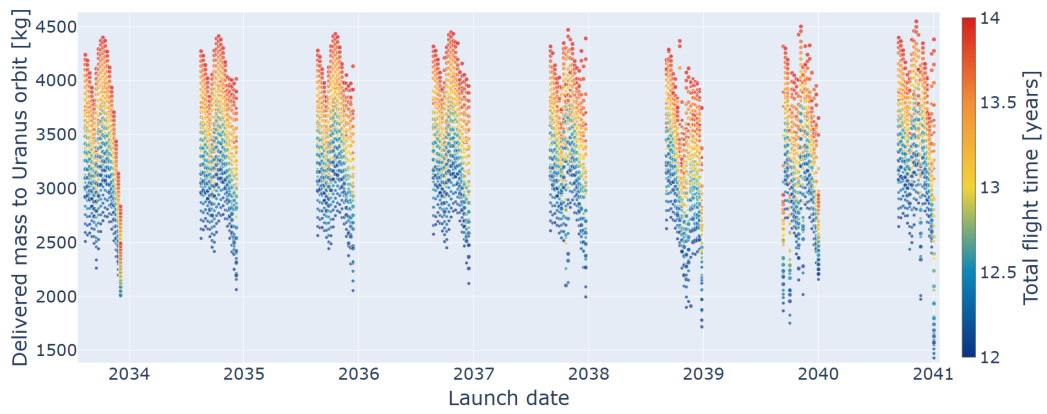


Figure 4. Several years of trajectory opportunities to Uranus using the PPS5000 Hall thruster. A SEP-enabled Uranus Orbiter and Probe can launch in any year.

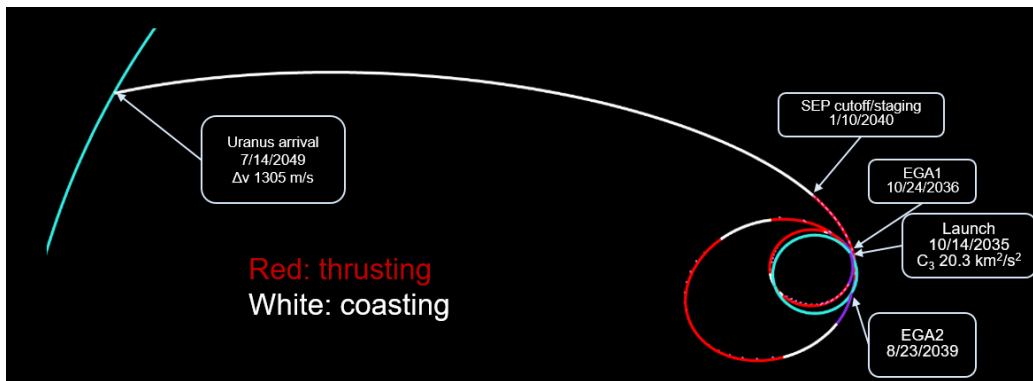


Figure 5. An example 13-year trajectory using the PPS5000 Hall thruster

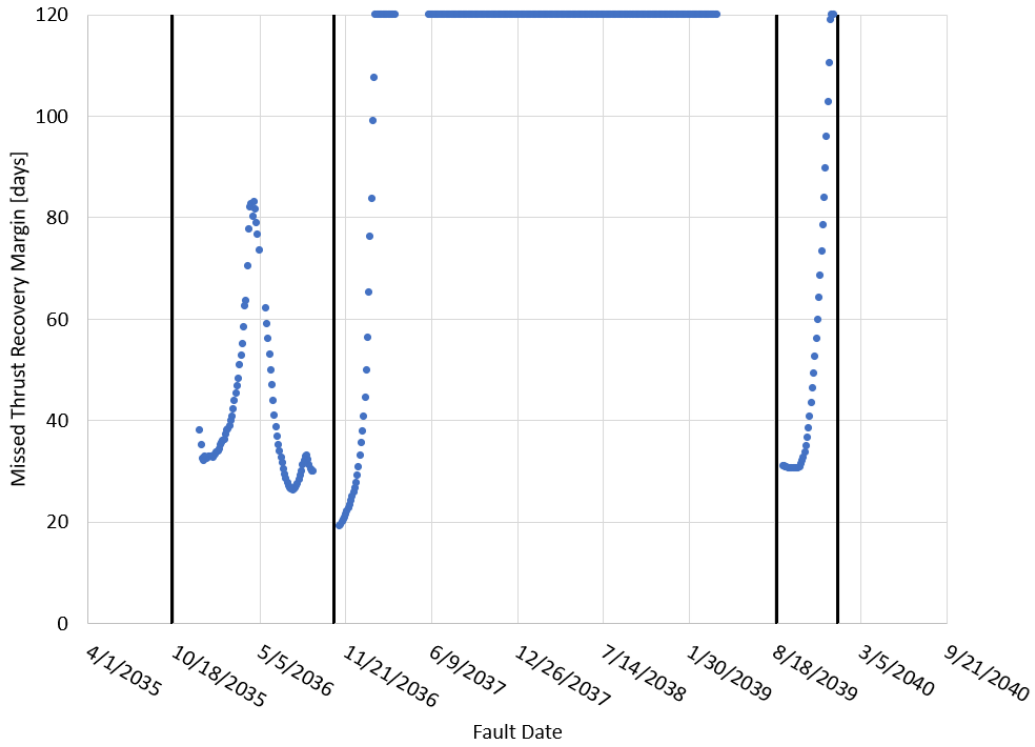


Figure 6. The SEP-enabled Uranus Orbiter and Probe can recover from a loss of thrust of greater than 19 days at any point in the trajectory.

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