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Trojan Tour Decadal Study

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Planetary Science Decadal Survey

Mission Concept Study Final Report

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Executive Summary

The purpose of this study was to define a preferred concept approach along with the risk/cost trade space for a Trojan Tour Mission launched in the 2019–2023 time frame and targeted to be within the New Frontiers mission class envelope of less than $900M in FY15 dollars. The study was conducted by a team led by Mike Brown with members of the Primitive Bodies Panel working with the JHU/APL Space Department as the design center. NASA Glenn Research Center's COMPASS team made significant contributions as part of the design team in the areas of mission design, radioisotope electric propulsion (REP) concept development, and Advanced Stirling Radioisotope Generator (ASRG) performance.

Three mission concepts were developed to assess the feasibility of a mission with one or more flybys of Trojan asteroids before an extended rendezvous with a different Trojan asteroid. The three concepts included two with chemical propulsion, one solar powered and one with two ASRGs for power, and a REP design with six ASRGs for power. The ballistic trajectory options allowed the full payload to be carried on an Atlas V 411 for the chemical ASRG concept, while the chemical solar power concept required the larger lift mass of the Atlas V 541, both with a cruise time of 10 years. The REP trajectory option allowed the full payload to be carried on an Atlas V 431 with a cruise time of 8 years. Launch windows for a Trojan rendezvous mission occur approximately every 13 months, corresponding to the synodic period of Jupiter, but the same specific Trojan rendezvous target is not usually repeatable.

All three concepts achieved the science objectives at a primary target asteroid with one or more flybys prior to the rendezvous. While specific flyby targets were not defined, both the ballistic and electric propulsion trajectory designs allowed for sufficient time in the "Trojan cloud" prior to the primary rendezvous to be statistically confident that one or more flybys are achievable. The chemical ASRG concept closed with the required mass and power margins and also enables potential secondary science objectives such as landing. The chemical solar array concept closed with required margins, but with some notable technical challenges related to solar array performance at low solar intensity levels and low temperatures at solar distances greater than 5 AU. This concept does not appear to enable any secondary science objectives. The REP concept closed for the primary target and also enables secondary science objectives such as landing and probably a second rendezvous. While the REP concept did not close for a second rendezvous target in this study, the study team believes that a solution is certainly achievable within the next decade.

The chemical ASRG concept was selected by the panel as the preferred point design to develop in detail and cost since it meets all of the study objectives while minimizing risk and technical complexity. There are no new technologies needed for this concept; however, two of the components are currently at Technology Readiness Level (TRL) 6, specifically, the ASRGs and Advanced Materials Bi-propellant Rocket (AMBR) engine. However, they are expected to be flight ready several years before this mission would need them. All other components are at TRL 7 through 9.

Cost for the chemical ASRG mission was estimated at $938M, assuming FY15$ and reserves. Descope options would include the lower priority instruments, including the UV spectrometer, LIDAR, and thermal imager. Savings from these descopes would be the cost of the instrument plus some reductions in integration and test, mission operations, and science team support. Another possible descope would be to carry only a single Ka-band traveling wave tube amplifier (TWTA). The cost reductions associated with this descope include the price of the TWTA, some JHU/APL oversight, reduced cost of the antenna by having a single feed, and reduced RF switches, diplexers, waveguides, etc. The total cost savings of these descopes is approximately $40M, although detailed savings associated with each has not been performed.

Overall, this study has developed a feasible mission concept for a Trojan asteroid tour that can achieve all of the science objectives for one or more flybys and rendezvous with minimal technology development. With the required study reserves, the total mission cost is $38M over the targeted New Frontiers cost range of $900M in FY15$ and is within the targeted cost range with descope options.

1. Scientific Objectives

Science Questions and Objectives

Motivation and Background

Jupiter shares its orbit with a host of small bodies. An estimated 600,000+ objects larger than 1 km in diameter librate about the L4 and L5 points in the Jupiter–Sun system (Jewitt et al. 2000; Yoshida and Nakamura 2005), the same rough order of magnitude as the number of similar-sized main-belt asteroids. No mission has gone through the regions in space where Jupiter Trojan asteroids are found (also called the "Trojan clouds"); every outer solar system mission has either remained at Jupiter or used a Jupiter gravity assist en route to points beyond. What we know about the Trojan asteroids is based on observations of these objects as point sources and analogy with spacecraft visits to objects believed to be similar (Rivkin et al. 2009).

Compositional data from Trojan asteroids are scarce. The albedos that have been measured are quite low for the largest objects (diameter > 57 km), with a mean optical geometric albedo of 0.04 found for a sample of 32 objects by Fernandez et al. (2003). These low albedos (among the lowest in the solar system), in conjunction with the Trojans' distance from the Earth, have made ground-based observations difficult. Visible and near-IR spectroscopy of the brighter (and larger) Trojans reveals featureless spectra with shallowly to steeply red spectral slopes, comparable to C-, P-, and D-type asteroids as well as cometary nuclei (Jewitt and Luu 1990; Lazzarin et al. 1995; Dotto et al. 2008, and references therein). Despite the lack of detected absorption features, the Trojans' low albedos and red colors are consistent with, but not unique indicators of, macromolecular hydrocarbons, as on cometary nuclei. Similar lack of spectroscopic evidence for ices, organics, and other volatiles also occurs for comet nuclei, whose bulk compositions are icy but masked by a thin, dark, refractory mantling layer. As smaller objects in the Trojan clouds have been observed, a wider spread in spectral slopes has been seen and evidence for two distinct spectral groups has emerged (Szabó et al. 2007; Roig et al. 2008; Emery et al. 2009), although it is not clear whether the differences indicate a diversity of compositions or a diversity of regolith ages on Trojan surfaces (Bendjoya et al. 2004; Fornasier et al. 2007). Somewhat higher albedos (a median value of 0.12 for 44 objects of 5–24 km in diameter, Fernandez et al. 2009) can be found for some of these smaller Trojan asteroids, although the increased albedo does not compensate for the smaller sizes and high-quality spectroscopy remains difficult for these smaller objects.

Densities are available for only two Trojans, both binary systems. They give disparate results: the primary in the Patroclus system has a mean density of 1.08 g/cm^3 (Marchis et al. 2006), while the orbit of Hektor's satellite implies a density of 2.4 g/cm^3 for that object. As seen in Figure 1-1 (from Marchis et al. 2006), these values require significant porosity for Patroclus for any reasonable composition, while Hektor's composition conversely implies either a lack of ice and volatiles (perhaps lost during satellite formation) or a significantly lower porosity than Patroclus, or both.

The compositions inferred for Trojan asteroids from these studies are roughly similar to cometary compositions: ice-rich, organics-rich, largely pristine bodies. However, the exact composition expected depends upon the formation location of these objects.

More recent work has cast some doubt on the conventional wisdom concerning the Trojan asteroids. Observations of Trojan asteroid surfaces near 3 μm (Jones et al. 1990) find no evidence of organics, OH-bearing minerals, or ice, all of which have strong absorptions at those wavelengths. Detailed observations and modeling of the largest Trojan (624 Hektor) by Cruikshank et al. (2001) showed that a few weight percent of water (or its equivalent in OH bound in minerals) could exist on its surface within observational uncertainties but that organics were not required to duplicate its spectral slope. Emery and Brown (2004) further noted from 2–4 μm spectra of 8 Trojans that organics could not be responsible for the red spectral slopes due to the absence of corresponding absorptions near 3 μm (Figure 1-2). Recent Spitzer observations in the mid-IR (5–38 μm) by Emery et al. (2006) show evidence for silicates on Trojan surfaces and a surprising similarity to cometary comae interpreted as caused by either extremely underdense surfaces or silicates embedded in relatively transparent materials. Again, no organics were necessary for those fits. This has been surprising, since our understanding of small bodies and nebular composition leads to a strong expectation that Trojans should be volatile- and organic-rich objects.

Relations and Origin of Trojan Asteroids

Until recently, most dynamicists favored the idea that the origin of the Trojans was linked to the growth and evolution of Jupiter. In these scenarios, a gaseous envelope accreted onto Jupiter's core and quickly increased its mass. This allowed the libration regions near the L4 and L5 Lagrange points to expand, such that planetesimals wandering near these zones would be captured. As Jupiter increased its mass, the libration amplitudes of the captured planetesimals would shrink, forcing some objects into orbits consistent with known Trojans. An alternative capture mechanism was proposed by Morbidelli et al. (2005), which is part of a trio of papers making up the so-called "Nice model" (Figure 1-3) (Tsiganis et al. 2005; Gomes et al. 2005). In the Nice model, slow planetary migration was induced in the Jovian planets by gravitational interactions with small bodies. Eventually, after a delay of ~600 My (~3.9 Gy ago), Jupiter and Saturn crossed a mutual mean motion resonance. This triggered a global instability that led to a reorganization of the outer solar system. Uranus and Neptune were driven into and migrated across the comet disk, which in turn caused comets to be scattered throughout the solar system. Many ended up ejected or eliminated, but resonant interactions via a migrating Jupiter/Saturn injected a small fraction onto stable orbits within the Trojan, Hilda, and outer main belt regions (see also Levison et al. 2009). In this case, the Trojan asteroids would represent the most readily accessible depository of Kuiper belt material*.* This scenario provides a natural connection between the Trojan asteroids, trans-Neptunian objects (TNOs), Centaurs, and irregular satellites, implying a common origin in the outer solar system. It also leads to the interpretation that the spectral variability among the Trojans could be caused by compositional differences resulting from slightly different formation locations. The Trojans offer a critical test of the planetary migration model of Morbidelli et al. (2005), which has implications not only for the Trojans but also for the dynamical evolution of the Kuiper belt and the solar system as a whole.

Diversity

The opportunity to visit multiple Trojan asteroids was deemed particularly important by the panel. The mission architecture described here (chemical propulsion, Advanced Stirling Radioisotope Generator [ASRG] power) can support flybys prior to reaching the rendezvous target, though a radioisotope electric propulsion (REP)-propelled mission could rendezvous with multiple objects, as discussed in Section 2. Only a small fraction of the expected Trojan population has been discovered at this writing, so flybys were investigated in a statistical fashion rather than by identifying particular targets. Using model values for the L4 population larger than 1 km (Yoshida and Nakamura 2005), rough bounds on the physical extent of the Trojan cloud, and a homogeneous distribution of objects within the cloud, we estimate a ~50% probability of passing within 250,000 km of a 1-km diameter object for every AU of travel within the Trojan cloud *without making any trajectory alterations.* The delta-V cost of altering trajectories is quite small moving within the Trojan cloud, and while more in-depth calculations are out of the scope of the study we are confident that the diversity goal can be met through at least one if not more flybys.

Prioritized Science Goals and Objectives

- *Characterize the bulk chemical composition of a Trojan asteroid surface.*

This was considered the most important objective by the panel. Four different instruments in the payload contribute to achieving this goal through the following three objectives:

1. *Determine the relative and absolute abundances of key elements* is addressed by the gamma-ray spectrometer (GRS), which will provide at least hemispheric-level spatial resolution on the rendezvous target for 6–12 key elements (Fe, Mg, Si, etc.). Depending on the size and rotational properties of the specific target, higher resolution can be achieved.

2. *Infer or constrain the presence of subsurface ice*. A neutron spectrometer is included in the payload and will determine the hydrogen abundance in the near surface, with spatial resolution comparable to the rendezvous/orbit distance. Some data on any flyby targets are also possible as bonus science.

3. *Determine the mineral composition of the surface*. Reflectance spectroscopy using a mapping IR spectrometer will provide detail unobtainable from Earth. The target will be mapped to 100 m/pixel over the 1- to 5-μm region, a wavelength region sensitive to silicates, water/OH, aqueous alteration products, and other volatiles. In addition, the study included a UV spectrometer, providing data in the 115- to 600-nm region, where iron oxides are found. Although less directly applicable to this objective, the multispectral map generated for the following goal is also relevant to this goal. This last objective is also applicable to the flyby target(s), within the constraints of the flyby geometry.

- *Observe the current geologic state of the surface and infer past evolution and the relative importance of surface processes.*

Knowledge of the geologic state and evolution of the target requires understanding the cratering history, the presence and distribution of any "ponds," any regolith processing (or "space weathering"), and the distribution of tectonic features like grooves or ridges. Three instruments contribute to this goal, which is addressed through the following three objectives:

1. *Study the morphology, albedo, and color of the target object(s).* The wide-angle camera (WAC) provides a multispectral map of the entire target surface (less any region that is dark for seasonal reasons) to a resolution of ≤10 m/pixel. This will provide data concerning space weathering, and albedo differences across the target. The study included a narrow-angle camera (NAC) that is monochrome but has roughly 10× higher spatial resolution, allowing ponds, craters, and boulders to be mapped to much smaller sizes than the WAC alone would allow. Inclusion of a thermal imager will enable a temperature map to be generated with an error equivalent of ~2–3 K at 100 K (much lower error at higher temperatures), providing an additional means of measuring albedo. Both WAC and NAC data will also be obtained at any flyby target, allowing this objective to at least be partially met for such objects.

2. *Study the texture of the regolith*. The mission studied achieves this goal through two means: data from the thermal imager will allow a thermal inertia map to be generated, providing constraints on regolith particle size and skin depth. Using the WAC, multispectral observations at different phase angles will provide a photometric means of constraining texture and particle size. It is unlikely that this objective will be fully met for flyby targets, but it may be partially fulfilled.

3. *Measure the topography of the target object at high spatial resolution*. Again, two different data sets will be able to address this objective: laser altimetry with range precision of ~1 m and spatial resolution <5 m, and stereo imagery with the WAC/NAC (precision depending upon orbital/rendezvous specifics).

- *Characterize the bulk physical properties and interior structure of a Trojan asteroid.*

A full picture of the origin and evolution of the target, and of Trojan asteroids in general, will require knowledge of how the targets are put together: whether they are rubble piles, how they compare to other small bodies, how close or far from hydrostatic equilibrium they are. The basic physical properties of the target asteroid(s) are addressed through the following three objectives:

1. *Determine the mass and internal mass of the target*. Radio science data and telemetry can be used to show the acceleration experienced by the spacecraft, providing the overall gravity field and higher degree gravity, from which mass distribution can be calculated. As is typical, these data come "for free" over the

course of normal operations. NEAR Shoemaker measured Eros's mass to 0.1%, with a 25% uncertainty in its initial Eros flyby, likely to be roughly the same error obtained for these flybys.

2. *Determine the size, shape, and volume of the target asteroid*. Imaging using the WAC/NAC will provide size/shape/volume for the lit portion of the target asteroid. If the rendezvous period is close to a solstice of a high-obliquity object, an appreciable fraction of the target may be unavailable to the WAC/NAC. However, the LIDAR and thermal imager will both be able to obtain data for the nighttime fraction of the object, allowing a complete shape/volume to be measured. Again using the NEAR example, the mass and volume were determined well enough for Eros to allow the density to be calculated with an accuracy of ~1%. The flyby target will of necessity be less well constrained unless it has a favorable season and/or obliquity.

3. *Determine and monitor rotation state of the target*. The rotation period of asteroids can be well constrained from Earth-bound telescopes, and no doubt the mission target would be intensively studied before rendezvous. However, additional observations in situ would be accomplished by repeated observations of landmarks on the surface, allowing higher precision observations and an unambiguous determination of the rotation pole.

- *Search for or constrain outgassing from subsurface volatiles.*

It seems likely that ice exists somewhere in the interior of Trojan asteroids. It is possible that this material is still slowly subliming and escaping into space. Detecting or constraining this outgassing is the final goal for this mission, with a single objective:

1. *Monitor the near-surface environment for possible outgassing (of H_2O, OH, CO_2, CO, etc.).* These species and their daughter products are typically observed in comets in the UV, and the UV spectrometer is carried in the study payload primarily to address this objective. An additional possibility is via very-high-phase imaging, which might be able to detect relatively large amounts of outgassing if present, though compositional information may be difficult to extract from such data.

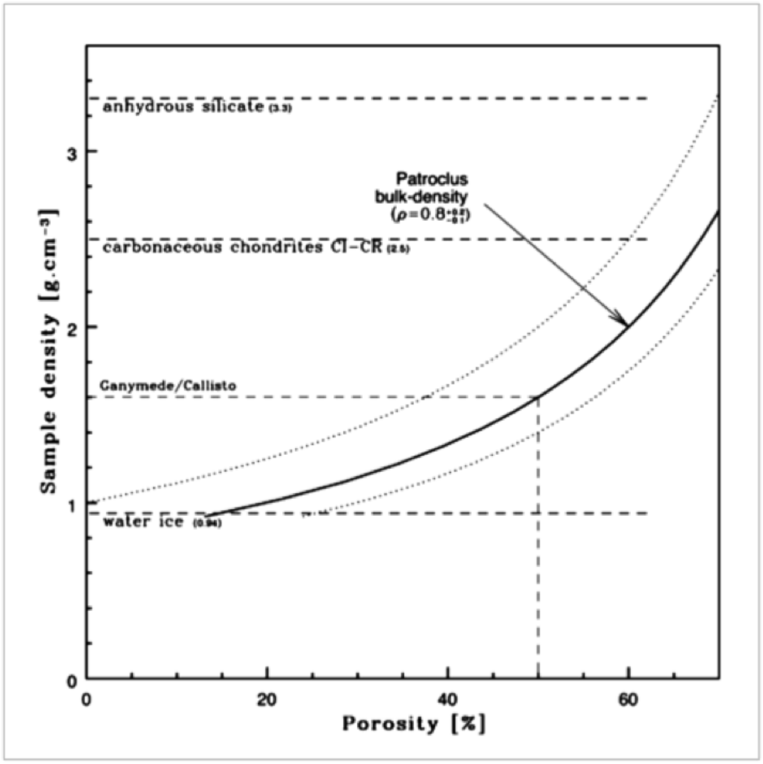

Figure 1-1. Patroclus's density is below that of water ice, and is represented on the figure by the solid curve, with dotted curves representing the uncertainties on that figure. Dashed lines represent the densities of representative solar system compositions: water ice, carbonaceous chondrites, anhydrous silicates, and the icy Galilean satellites. Each composition, read across to Patroclus's density curve, implies a porosity, read down from the curve to the *x* axis. For instance, if Patroclus has the same composition as Ganymede/Callisto, its implied porosity is 50%. Regardless of composition, Patroclus has an appreciable bulk porosity, with an icy, porous nature most likely. (from Marchis et al. 2006)

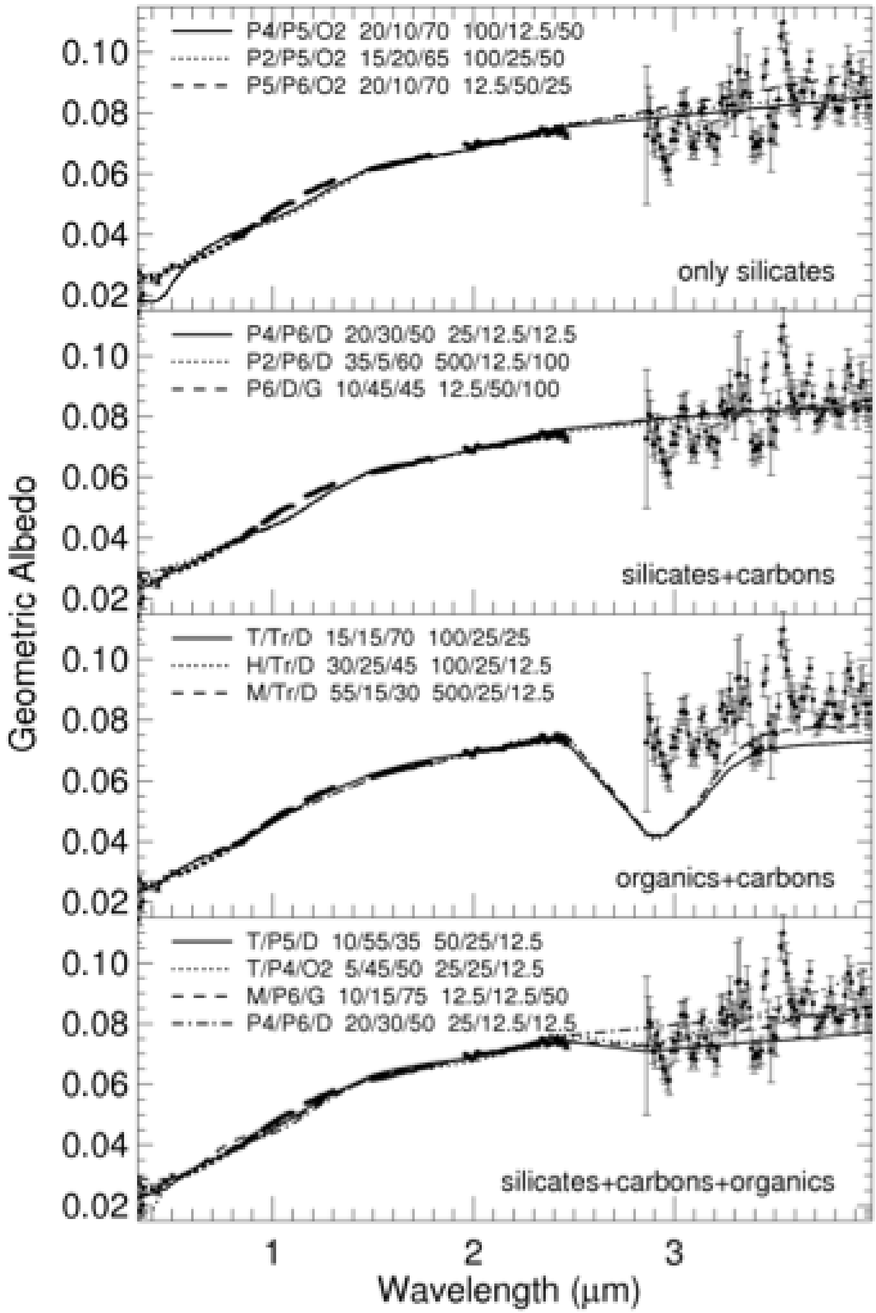

Figure 1-2. These fits to the spectrum of 624 Hektor show that while a small fraction of organic material may be present on Trojan surfaces, it is not required to explain the spectral data. In fact, the absence of any detectable absorption in the 2.8- to 4.0-μm region severely limits the type and abundance of organic material that is possible. (from Emery and Brown 2004)

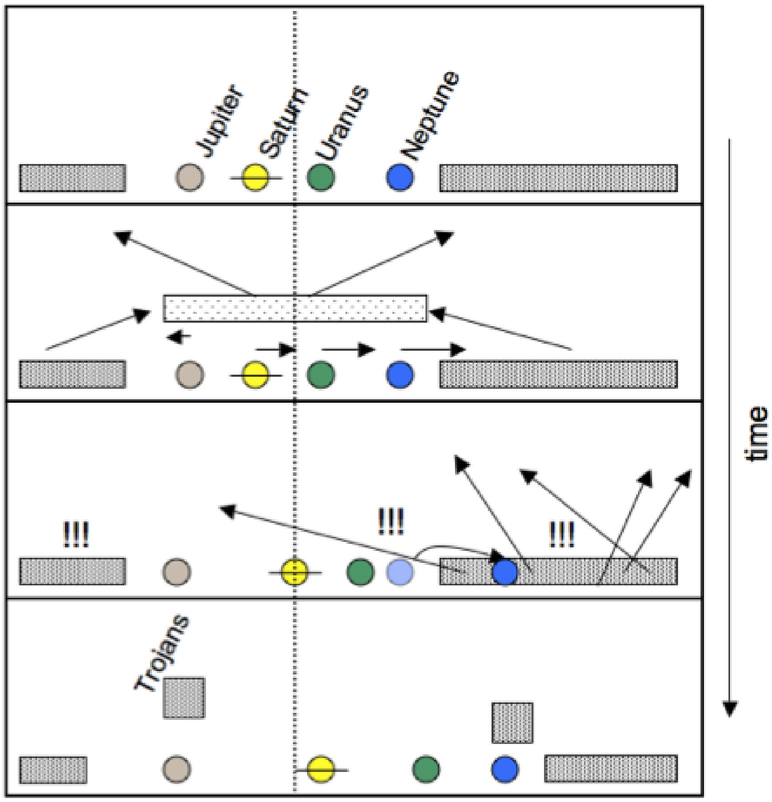

Figure 1-3. This cartoon illustrates the Nice model view of dynamics early in solar system history: the giant planet region was originally more compact, with the asteroid belt (left box) and Kuiper belt (right box) extended farther than currently (top panel). As a result of interactions between the small bodies and the gas giants, the former populations were put into unstable orbits and removed from the system, while the gas giants evolved either inward (Jupiter) or outward (the others) until Jupiter and Saturn reached a mutual resonance (vertical dotted line). At that point (third panel), Uranus and Neptune were rapidly transported outward, scattering the small bodies and capturing a population into the Trojan regions of Jupiter, resulting in what we see today (bottom panel).

Science Traceability

The instrument and mission measurements derived from each of the science objectives are given in the traceability matrix (Table 1-1), along with the existing analog instrument used in the study.

Table 1-1. Science traceability matrix.

Goal	Objectives	Measurements/Data sets	Payload	Existing Analog Instrument
1. Chemical composition of surface	1A. Relative and absolute abundances of 6 to 12 key elements (Fe, Mg, Si, etc.)	Elemental composition of surface.	GRS.	MESSENGER GRS
	1B. Search for evidence of subsurface ice	Hydrogen abundance in near surface.	Neutron spectrometer (NS)	MESSENGER NS
	1C. Mineral composition of surface	1- to 5-µm map of surface to 100 m/pixel (and band depth maps).	Mapping IR spectrometer	New Horizons Ralph/LEISA
		115–600 nm spectroscopy	UV spectrometer.	MESSENGER MASCS UVVS
2. Geologic state, processes, and evolution of surface	2A. Morphology, albedo, and color of surface	Multispectral map to 10 m/pixel. Monochrome map of selected areas to 1 m/pixel.	Wide angle camera/narrow angle camera (WAC/NAC).	MESSENGER MDIS
		Temperature/thermal map of surface. (Surface coverage dependent upon season.)	Thermal instrument.	LRO Diviner
	2B. Surface regolith texture	Monochrome map to 1 m/pixel.	NAC.	MESSENGER MDIS
		Thermal inertia map of visible surface.	Thermal instrument	LRO Diviner
	2C. Detailed topography of surface	Stereo imagery of surface, photogrammetry.	WAC/NAC	MESSENGER MDIS
		Altimetry with ≤5 m precision.	LIDAR	NEAR laser altimeter
3. Bulk physical properties and interior structure	3A. Global mass and internal mass distribution	Mass measurement to ±3%.	Radio science	—
	3B. Size, shape, and volume	Shape model, volume to ±3%.	WAC/NAC. LIDAR.	MESSENGER MDIS, NEAR laser altimeter
	3C. Rotation state	Repeated imagery of landmarks.	WAC/NAC	MESSENGER MDIS
4. Outgassing	4A. Monitor near-surface environment for possible outgassing (H_2O, OH, CO_2, CO?)	115–600 nm spectroscopy.	UV spectrometer	MESSENGER MASCS UVVS
		Very-high-phase imaging.	WAC/NAC	MESSENGER MDIS

2. High-Level Mission Concept

Study Request and Concept Maturity Level

The objective of this study was to conduct mission studies to assess the feasibility of a mission having one or more flybys of Trojan asteroids before an extended rendezvous with another Trojan asteroid. The science team provided four main scientific goals with prioritized objectives associated with each goal (described in Section 1) along with a recommended primary and secondary payload. This study was conducted at a concept maturity level (CML) of 4 (Table 2-1). The result of this study was to evaluate the trade space and develop a preferred point design that achieved at least the primary mission close to the cost range of less than $900M in FY15$.

Table 2-1. Concept maturity level definitions.

Concept Maturity Level	Definition	Attributes
CML 6	Final Implementation Concept	Requirements trace and schedule to subsystem level, grassroots cost, verification and validation (V&V) approach for key areas
CML 5	Initial Implementation Concept	Detailed science traceability, defined relationships and dependencies: partnering, heritage, technology, key risks and mitigations, system make/buy
CML 4	Preferred Design Point	Point design to subsystem level mass, power, performance, cost, risk
CML 3	Trade Space	Architectures and objectives trade space evaluated for cost, risk, performance
CML 2	Initial Feasibility	Physics works, ballpark mass and cost
CML 1	Cocktail Napkin	Defined objectives and approaches, basic architecture concept

Overview

The following constraints were defined as part of the study per direction of the Study Science Champions:

- Launch window 2019–2023
- Rendezvous and orbit a target asteroid with one or more flybys as the spacecraft travels through the Trojan cloud along the way to the primary target
- Mission targeted to a New Frontiers class; single spacecraft without stages
- Landing not to be considered

The study was conducted in two phases. The study team began by focusing on chemical propulsion concepts. A survey of potential target asteroids for the launch years of interest with cruise durations of 10 to 12 years was performed. Primary and secondary targets were selected to allow definition of design parameters to proceed with a point design. Asteroid 911 Agamemnon was selected as the primary target, with asteroid 4060 Deipylos as the backup target. Asteroid characteristics such as magnitude and albedo were taken under consideration, but the main selection criterion was the amount of energy required to reach the asteroid, which directly relates to the lift mass capability of the launch vehicle and the onboard propulsion of the spacecraft. The following parameters were selected as the required minimum mission capabilities:

- Characteristic energy C3: ≥75 km^2/s^2
- Total delta-V: ≥1633 m/s (deterministic)
- Cruise time: 10 years or less
- Orbital operations: 9 months at the target

Several other targets were found in the asteroid survey for each launch year that would also meet these requirements. Other scientific data could influence a mission Implementing team to select a different target. The launch opportunities for the Trojan asteroids repeat approximately every 13 months.

Since a landing was not required in the science objectives, two different power systems were considered, a solar array–powered concept and an ASRG-powered concept. This is a mission trade that is described in detail in the Key Trades section to follow. Both concepts were designed for the same mission requirements and to include the primary and secondary payload. Both designs closed, meeting the study margins. The trajectory allowed the full payload to be carried on an Atlas V 411 for the ASRG concept, while the solar-powered concept required the larger lift mass of the Atlas V 541 for the required C3.

After launch and a nominal 6-week checkout period, the spacecraft enters a spin-stabilized cruise period with two contacts per week. Approximately 9 months after launch the first deep-space maneuver is executed. The spacecraft enters hibernation mode with a weekly status beacon and a monthly 8-hour contact. Approximately 2 years after launch a Jupiter gravity assist is executed unpowered. The spacecraft then hibernates for approximately 3 years until the second deep-space maneuver occurs. This is followed by 3 or 4 years of cruise in hibernation mode. The spacecraft will wake up from hibernation mode once it enters the Trojan cloud for instrument checkouts and flyby science of one or two asteroids.

Upon arrival at the primary target, an orbit insertion maneuver will be executed approximately 10 years after launch. An initial orbit altitude of 400 km is selected for the beginning of science collection at the asteroid. Science data and the asteroid gravity field will be studied for 2 to 3 months, and the orbit will be gradually reduced to the lowest altitude deemed safe, likely in the range of 50–100 km altitude, for the primary science collection phase. Primary science measurements will be gathered for 6 months. The rendezvous science profile is based upon the successful series of rendezvous events performed by the NEAR spacecraft at the asteroid 433 Eros. The ASRG concept enables a potential landed mission, but this was not addressed in detail in this study.

Next the study team focused on an electric propulsion concept. As a result of past study experience, a solar electric propulsion (SEP) concept was immediately eliminated for a mission going to the Trojan asteroids at solar distances of 5 AU to 6 AU because of low solar intensity levels. Instead, the study team developed a REP concept. This concept has the benefit of enabling a landing and possibly a second rendezvous because of the large propulsive capability. This concept is highly mass constrained because as mass increases and the power-to-mass ratio decreases, the efficiency of the REP system dramatically drops. The following design constraints were applied for the REP mission concept:

- Characteristic energy C3: 78–81 km^2/s^2
- Cruise time: 6 to 8 years
- Limit to six ASRGs total to minimize mass
- Minimize mass to fit on Atlas V 431 launch vehicle

Given these design constraints, the primary target asteroid 1143 Odysseus was selected to proceed with the point design. Asteroid 2002 ER25 was selected as a second rendezvous target. As with the chemical propulsion concepts, both primary and secondary payloads were included in the design. The REP thrusters are enabled approximately 140 days after launch, allowing early operations checkout and instrument commissioning. The REP thrusters are duty cycled at 90% to allow two contacts per week with the spacecraft during the 8-year cruise. The REP trajectory is direct, without any gravity assists. With this trajectory, the spacecraft spends the last 5 years of cruise within the Trojan cloud, giving an abundance of flyby opportunities. Upon arrival at the primary target asteroid, there will be 2–3 months of orbit reduction followed by 6 months of primary science collection. The spacecraft departs the primary target, cruises for two additional years to the secondary target, and concludes with an orbital science phase at the second target.

For the targets selected within the time constraints of this study, the REP concept closed with full margins for the primary science objectives, but not including the secondary target. Further efforts could be made to decrease mass or optimize the targets.

Following the completion of the three concept developments, the study team met with the science champion to discuss the preferred concept to carry forward. Table 2-2 compares the science for each of the three mission concepts. The technical merits of each mission concept are summarized in the Key Trades section below. The concept with chemical propulsion and ASRG power was selected as the point design to present in detail and cost since it meets all of the study objectives while minimizing risk.

Table 2-2. Mission concepts science comparison.

Concept	Diversity	Operations	Mission Length	Other
Chemical solar	Prime rendezvous + pre-rendezvous flyby(s)	Battery → Limited eclipses, no noon orbit	~10 years to primary target	Jupiter flyby with possible flyby science
Chemical 2 ASRG	Prime rendezvous + pre-rendezvous flyby(s)	No orbit restrictions. Potential for landing.	~10 years to primary target	Jupiter flyby with possible flyby science
REP 6 ASRG	Prime rendezvous + pre-rendezvous flyby(s) + possible 2nd rendezvous + post-rendezvous flyby(s)	No orbit restrictions. Potential for landing.	~8 years to primary target	Large propulsion capability enables 2nd rendezvous

Technology Maturity

The technology readiness levels (TRLs) of all of the components of the ASRG-powered, chemical propulsion mission to Trojan asteroids are shown in the master equipment list (MEL). There are no new technologies needed for this mission; however, two of the components are currently at TRL level 6. All other components are at TRL 7 through 9.

The two key components that are currently at TRL 6 are the ASRG power unit and the Advanced Materials Bi-propellant Rocket (AMBR) engine (Table 2-3). They are both under development as part of ongoing NASA programs at the Glenn Research Center (GRC). The current schedules call for both items to be flight qualified well before they are required for a Trojan Tour mission. In addition, the AMBR engine is not a critical development item, since existing TRL 9 engines could be substituted for the AMBR engine. The penalty of switching to a different engine would be a slightly lower specific impulse (I_{sp}), which would require a little more fuel. This fallback position has not been studied in detail; however, the overall mission concept would still be expected to close although it might require moving to the Atlas V 421 launch vehicle.

Table 2-3. TRL 6 items.

Component	Technology Progress	Flight Readiness
ASRG	Under development at NASA GRC	2014
AMBR engine	Under development at NASA GRC	2014

Key Trades

A number of trades were performed both at the mission level as well as within each flight element to arrive at preferred concept. Table 2-4 summarizes the major mission trades performed as part of this study.

Table 2-4. Significant mission trade studies.

Area	Trade Options	Results
Destination	•Asteroid 911 Agamemnon (selected) •Asteroid 4060 Deipylos •Asteroid 1143 Odysseus Total energy to reach target destination was also a major consideration.	•At this time, all Trojans were considered of equal science value. •Our approach was to look for low-numbered, named asteroids, assuming that these would be larger and better defined. •We constrained the search to targets that could be reached within 10–12 years flight time, or less. We picked targets with a diameter >50 km. •It was assumed that once a Trojan mission was named, the number of potential targets would significantly increase as was the case for Kuiper belt objects (KBOs) with New Horizons.
Cruise Propulsion Approach	•Chemical (selected) •Solar electric propulsion (SEP) •Radioisotope electric propulsion (REP) Significant factors were power, time of flight, and cost.	•SEP was eliminated because of the inability to generate the required power levels beyond ~3.5 AU without having excessively large solar arrays (>300 m^2). •REP technology produced a viable concept that met all of the margins. However, REP required 6 total ASRGs (4 ASRGs for the REP system, 2 ASRGs for the rest of the spacecraft), which led to significant cost increases, more technically complex accommodations, and concerns about plutonium availability. •The REP concept did not produce guaranteed science enhancements (to justify increased costs) within the stated study margins, although a potential solution was very close to providing a second Trojan rendezvous. •Chemical propulsion enabled cost-saving techniques such as cruise hibernation and a true spin-stabilized attitude control mode. •Chemical propulsion was the most cost-effective, low-risk solution that achieved all of the science objectives.

Area	Trade Options	Results
Power source (for use with chemical propulsion)	•Solar arrays •ASRGs (selected)	•The ASRG concept used existing technologies, was lower mass, and cost less while achieving all of the science objectives and enabling potential science enhancements. •ASRGs and solar power at ~5 AU will have tight power margins and necessitate a low-power spacecraft design, particularly throughout the avionics subsystem. •The spacecraft concept with ASRGs resulted in a small flight system that enabled use of an Atlas V 411 launch vehicle and use of a “thermos bottle” thermal design and that provides additional maneuverability and unconstrained science observations during rendezvous. •Large, ~86-m^2, Ultraflex solar arrays required for primary power. This concept needed to continuously keep the panels pointed at the Sun and used reaction wheels for attitude control. This significantly grew the spacecraft in mass and total support structure, and forced the mission onto an Atlas V 541 launch vehicle. The larger spacecraft also needed a more active thermal control system with higher-powered heaters and larger radiators. •Potential science is limited by the size and flexible body effects of solar arrays. Science may also by limited by the capacity of the battery and the inability to endure long eclipses from the Sun. For example, the mission would be unable to perform noon–midnight orbits around the target asteroid. •Factored in lessons learned from the Juno Project regarding solar arrays designed for comparable solar distances. They reported significant challenges with low-intensity low-temperature (LILT) solar cells, as cells must be individually tested to determine if they are acceptable for the mission; ~40% of the Juno solar cells have been rejected.

The study developed three different spacecraft concepts using a concurrent engineering process to explore the trades described above. A summary of these concepts and their merits is shown below.

The chemical propulsion, ASRG-powered design closed with the required margins, achieves all of the primary science objectives, and enables potential secondary science objectives (e.g., landing). The primary science target was a rendezvous with 911 Agamemnon, with a backup target of 4060 Deipylos. See Figure 2-1.

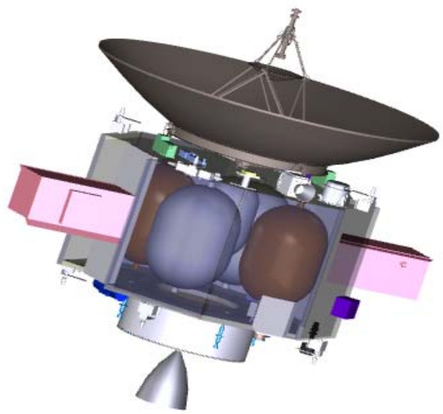

Figure 2-1. Chemical propulsion, ASRG concept.

The chemical propulsion, solar array–powered design closed with the required margins and achieves all of the primary science objectives with some notable technical challenges. This concept does not appear to enable any secondary science objectives. The primary science target was a rendezvous with 911 Agamemnon, with a backup target of 4060 Deipylos. See Figure 2-2.

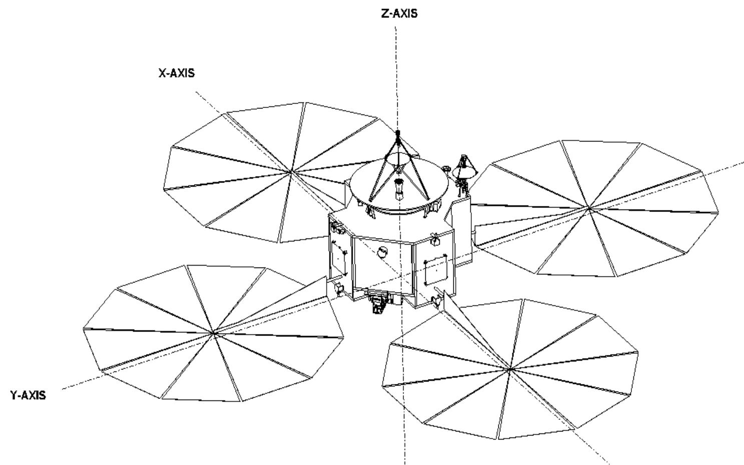

Figure 2-2. Chemical propulsion, solar array concept.

The REP concept closed for the primary Trojan rendezvous target of 1143 Odysseus but not for the second rendezvous target of asteroid 2002 ER25. We believe that a solution is certainly achievable within the next decade. The REP design achieves all of the primary science objectives and enables secondary science objectives such as landing and probably a second rendezvous with some greater concept maturity. See Figure 2-3.

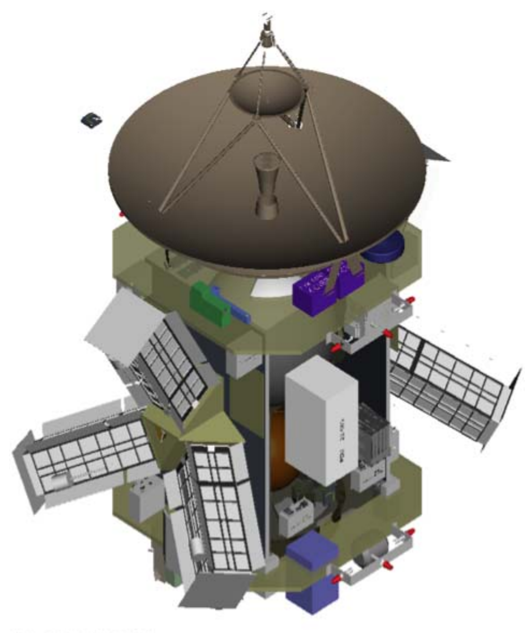

Figure 2-3. Radioisotope electric propulsion concept.

Some trade-offs were performed in almost all technical areas as a part of this study. The significant flight element level trades that were performed are summarized in Table 2-5.

Table 2-5. Significant element level trade studies.

Area	Trade Options	Results
Data return and telecommunications design	Dish size, power, arrayed ground stations, others	• Average date rate of 12.5 kbps is required; will return approximately 360 Mbits/day; 9.7×10^{10} bits over the entire mission. • Full science return, with a factor of ≥2 margin, can be achieved with a 2.5-m high-gain antenna (HGA), 17-W RF traveling wave tube amplifier (TWTA), single 34-m Deep Space Network (DSN) ground station, and 8-hour/day contacts. • ASRG architecture does not support higher power TWTA. •HGA size of 2.5 m balances pointing requirements, cost, and RF performance. •Adequate science can be returned without arraying DSN ground antennas.
Attitude control	3-axis, spin stabilized, thruster-based control, reaction wheels	•Hybrid control mode of both 3-axis and spin stabilization allows for hibernation during cruise and fine control and knowledge during Trojan encounter; demonstrated in flight on New Horizons. •Reaction wheels consume more power and increase total mass •Thruster only actuators provide sufficient control •IMU and star trackers for attitude knowledge •Sun sensor for sun direction knowledge in contingencies
Size and design of power subsystem elements	Number of ASRGs, potential optimized ASRG, use of a battery	•More than two ASRGs considered excessively risky and politically challenging for New Frontiers (or smaller) class mission. •Optimized ASRG concept lacks confidence and maturity. •Two-ASRG design achieved all power needs and study margins with the use of a small battery for peak loads during large propulsive maneuvers (limited number of discrete events). •Battery provides additional capabilities during contingencies.
Thermal design	Traditional thermal design vs. “thermos bottle” design	•Traditional thermal system with component specific heaters and radiators requires higher power inputs. •“Thermos bottle” design balances power and thermal energy, resulting in lower overall power consumption; facilitates ASRG power system. •“Thermos bottle” design requires small, compact spacecraft body. •Radioisotope heater units (RHUs) incorporated into “thermos bottle” design to maintain low power demands and ensure adequate thermal input at spacecraft extremities.
Main engine selection	100 lbf HiPAT vs. 150 lbf AMBR engine	•Comparable best demonstrated performance (328 I_{sp} for HiPAT and 333.5 I_{sp} for AMBR) •Use of AMBR results in total propulsion mass savings of ~13.4 kg. •HiPAT has flight heritage •AMBR currently requires flight qualification which increases engine cost; can assume AMBR will establish flight heritage prior to a mission next decade given NASA incentives for demonstrating this technology.
Processor	RAD750 vs. LEON3FT	•RAD750 has flight heritage on planetary missions. •RAD750 requires higher power inputs and has significantly higher costs. •LEON facilitates low-power avionics required to support ASRG power design. •Flight processor requirements satisfied by LEON; no driving need for additional capability of RAD750 identified.

3. Technical Overview

Instrument Payload Description

The instrument complement is described in Tables 3-1 through 3-8 and text. The Trojan Tour mission has the seven instruments. Three of them (WAC and NAC imagers, mapping IR spectrometer, and thermal imager) are imaging instruments and can generate large volumes of two-dimensional or three-dimensional data. The remaining instruments (UV spectrometer, gamma-ray spectrometer, neutron spectrometer, and LIDAR) generate only moderate data volumes.

While the implementing team will select the actual instruments in a future Trojan Tour mission, we have taken a set of existing instruments as the candidates for this mission. The imager is the MESSENGER MDIS, which is a dual imaging system with both wide-angle and narrow-angle cameras. The mapping IR spectrometer is the LEISA portion of the Ralph instrument on the New Horizons mission. The thermal imager is a greatly simplified version of the Diviner instrument on the Lunar Reconnaissance Orbiter (LRO) with only the 25-μm and longer channels in the B focal plane. The DIVINER two-axis gimbal is removed and the simplified instrument is body mounted to the spacecraft.

The gamma-ray spectrometer and the neutron spectrometer are the GRS and NS instruments from the MESSENGER mission. The UV spectrometer is the ultraviolet visible spectrometer (UVVS) portion of the Mercury Atmospheric and Surface Composition Spectrometer (MASCS) instrument on the MESSENGER mission.

Table 3-1. Wide-angle camera.

Item	Value	Units
Type of instrument	*Wide angle camera (WAC)*	
Number of channels	*12 filters*	
Size/dimensions	*7.1 × 7.1 × 26.6*	*cm × cm × cm*
Image size	*1024 x 1024*	*pixels*
Instrument, pixel fields of view	*10.5 ,140*	*degrees, μrad*
Instrument average science data rate	*1.4* *120*	*kbps* *Mbits/day*
Instrument fields of view	*10.5*	*degrees*
Pointing requirements (knowledge)	*350*	*μrad*
Pointing requirements (control)	*0.1*	*degrees*
Pointing requirements (stability)	*140*	*μrad/s*

The science objectives of the WAC are to determine the large-scale structure of the Trojan asteroid. For the purpose of this study, the WAC design is based on the MESSENGER WAC, without gimbal. The camera has a 10.5-degree field of view (FOV) and consists of a refractive telescope using a dogmar-like design having a collecting area of 48 mm^2. A 12-position multispectral filter wheel provides color imaging over the spectral response of the detector (395–1040 nm). The detector is a CCD array with 1024 × 1024 pixels, producing an image per filter of 1.05 Mbit with 8× compression. Assuming a division of the remote sensing data downlink, 120 Mbits/day are allocated to the combination of the WAC and NAC. A pixel scale of 7 m is achieved when the spacecraft is at 50 km altitude. The instrument FOV is co-aligned with other remote-sensing instruments.

Table 3-2. Narrow-angle camera.

Item	Value	Units
Type of instrument	*Narrow angle camera (WAC)*	
Number of channels	*monochrome*	
Size/dimensions	*7.1 × 7.1 × 26.6*	*cm × cm × cm*
Image size	*1024 x 1024*	*pixels*
Instrument, pixel fields of view	*1.5 ,17*	*degrees, μrad*
Instrument average science data rate	*1.4* *120*	*kbps* *Mbits/day*
Instrument fields of view	*1.5*	*degrees*
Pointing requirements (knowledge)	*350*	*μrad*
Pointing requirements (control)	*0.1*	*degrees*
Pointing requirements (stability)	*34*	*μrad/s*

The science objectives of the NAC are to determine the smaller-scale structures of the Trojan asteroid than can be determined with the WAC. For the purpose of this study, the NAC design is based on the MESSENGER NAC, without gimbal. The camera has a 1.5-degree FOV and consists of a reflective telescope. It is a monochrome imager, and it is assumed that there will be a band-limiting filter to set the spectral response. The detector is a CCD array with 1024 × 1024 pixels, producing an image per filter of 1.05 Mbit with 8× compression. Assuming a division of the remote sensing data downlink, 120 Mbits/day are allocated to the combination of the WAC and NAC. A pixel scale of 1.25 m is achieved when the spacecraft is at 50 km altitude. The instrument FOV is co-aligned with other remote-sensing instruments.

Table 3-3. Mapping IR spectrometer.

Item	Value	Units
Type of instrument	NIR mapping spectrometer	
Number of channels	2 on LEISA	
Size/dimensions (for each instrument)	40.6 × 49.5 × 29.5	cm × cm × cm
Instrument average science data rate	1.4 120	kbps Mbits/day
Instrument fields of view	0.9 × 0.9	degrees
Pointing requirements (knowledge)	350	μrad
Pointing requirements (control)	0.1	degrees
Pointing requirements (stability)	25	μrad/s

The science objective of the near-infrared (NIR) mapping spectrometer is to determine the mineralogy of the asteroid surface, For the purpose of this study, its heritage was based on the linear etalon spectral array (LEISA) portion of the Ralph instrument on New Horizons. The instrument consists of a 75-mm telescope that feeds the LEISA (128 × 128 pixel HgCdTe detector). LEISA is a spectral mapper with two channels (1.25–2.5 μm, and 2.1–2.25 μm); however, the wavelength coverage would be altered to provide a 1- to 5-μm passband. The total amount of data per image per filter for the mapping spectrometer, assuming 8× compression, is 3.36×10^7 bits. For this study, data allocated to the spectrometer were 120 Mbits/day. The pixel scale is 123 μrad, giving a 6.1-m pixel resolution at 50 km altitude. The instrument FOV is co-aligned with other imaging instruments.

Table 3-4. Thermal imager.

Item	Value	Units
Type of instrument	IR thermal imager	
Number of channels	3	
Size/dimensions (for each instrument)	15.4 d × 30.5 l	cm × cm
Instrument average science data rate	0.35	kbps
Instrument fields of view	15 × 0.10	degrees
Pointing requirements (knowledge)	350	µrad
Pointing requirements (control)	0.1	degrees
Pointing requirements (stability)	0.05	degrees/s

The science objective of the IR thermal imager is to determine the distribution of thermal emission by measuring the temperatures as a function of latitude and longitude, as well as changes with time and location at low resolution. The IR thermal imager achieves this objective by measuring emitted IR radiation in three spectral channels with wavelengths ranging from 25 to 200 µm. For the purpose of this study, its heritage was based on the LRO Diviner instrument. A three-mirror off-axis telescope is mounted within an optical bench assembly. At the telescope focal planes are three 21-element pixel thermopile arrays, each with a separate spectral filter. The instrument FOV is co-aligned with other imaging instruments, operating as a multi-spectral pushbroom mapper. For one thermal image, per one filter, and assuming an 8× compression, the data is 1.3×10^5 bits. 30 Mbits/day are allocated to thermal images. A 625-m/pixel scale is achieved when the spacecraft is at 50 km altitude.

Table 3-5. UV spectrometer.

Item	Value	Units
Type of instrument	UV spectrometer	
Number of channels	3	
Size/dimensions (for each instrument)	46.3 × 15.8 × 14	cm × cm × cm
Instrument average science data rate	150	bps
Instrument fields of view (if appropriate)	0.25 x 0.25	degrees
Pointing requirements (knowledge)	350	µrad
Pointing requirements (control)	0.1	degrees
Pointing requirements (stability)	0.1	degrees/s

The science objective of the UV spectrograph is to examine the surface composition of the asteroid and search for outgassing products. The instrument is an off-axis telescope feeding a moving grating spectrometer. The spectral passband extends from 115 to 600 nm. The focal plane detectors are three photon-counting photomultiplier tubes, but only one is active at a time. The UV spectrometer is allocated 13 Mbits/day.

Table 3-6. Gamma-ray spectrometer.

Item	Value	Units
Type of instrument	Gamma-ray spectrometer	
Number of channels	2048	
Size/dimensions (for each instrument)	28 d × 40 l	cm × cm
Instrument average science data rate	150	bps
Instrument fields of view (if appropriate)	Omnidirectional	
Pointing requirements (knowledge)	1	degrees
Pointing requirements (control)	1	degrees
Pointing requirements (stability)	1	degrees/s

The science objective of the gamma-ray spectrometer is to determine the atomic composition of the asteroid surface. Gamma-ray instruments provide information on selected elements, including iron, as well as measurements of any radioactive elements. The gamma-ray spectrometer has a cryo-cooled high-purity germanium detector surrounded by an active anticoincidence shield of borated plastic scintillator. The gamma-ray spectrometer is allocated 13 Mbits/day.

Table 3-7. Neutron spectrometer.

Item	Value	Units
Type of instrument	Neutron spectrometer	
Number of channels	3	
Size/dimensions (for each instrument)	15 x 15 x 22	cm × cm x cm
Instrument average science data rate	150	bps
Instrument fields of view (if appropriate)	Omnidirectional	
Pointing requirements (knowledge)	1	degrees
Pointing requirements (control)	1	degrees
Pointing requirements (stability)	1	degrees/s

The neutron spectrometer will determine the average atomic mass of the asteroid and it is very effective in detecting ice (hydrogen) near the surface of the asteroid. The neutron spectrometer is based on the NS instrument on MESSENGER. The gamma-ray spectrometer is allocated 13 Mbits/day.

Table 3-8. LIDAR.

Item	Value	Units
Type of instrument	Laser altimeter	
Number of channels	1	
Size/dimensions (for each instrument)	18 d × 49.5 l	cm × cm
Instrument average science data rate	116	bps
Instrument fields of view	400	μrad
Pointing requirements (knowledge)	350	μrad
Pointing requirements (control)	0.1	degrees
Pointing requirements (stability)	25	μrad/s

The LIDAR is used to determine the overall shape model of the asteroid and also to provide some high-precision transects of the surface elevation. The LIDAR is based on the NEAR Laser Rangefinder. The LIDAR is allocated 10 Mbits/day.

The data generation rates for the imaging instruments when they are taking pictures are less than 3 Mbit/s. These rates are easily handled by the 32-Gbit spacecraft data recorder. The non-imaging instruments generate data at much lower rates. It is assumed that all science data will be compressed before downlink. The image data may use a variety of compression techniques, both lossless and lossy. This study assumes an 8× wavelet compression for the image data and a lossless compression for all non-imaging data.

With the 12.5-kbps average data rate from the orbit around the target Trojan asteroid and one 8-hour pass per day to a 34-m dish with 8 hours of actual data downlink for 360 Mbits per day, over a 270-day orbital phase, this mission can return approximately 9.7×10^{10} bits for the entire mission. We have estimated the coverage of Agamemnon, allowing 75% of the downlink for the imaging instruments, 15% for the non-imaging instruments, and 10% for housekeeping data. With these allocations, this mission can map the surface of the asteroid to an overall resolution of about 10 m per pixel. In addition there is adequate downlink for local high-resolution images of selected areas to 1.25 m per pixel from an altitude of 50 km. These numbers will, of course, be modified by the actual altitude profile of the orbital phase of the mission. The mapping IR spectrometer can provide full surface coverage to 60 m per pixel resolution. The thermal imager can provide full coverage to better than 625 m per pixel resolution. Payload data rates are given in Table 3-9.

Table 3-9. Payload data rates.

Instrument	Instantaneous Data Rate	Data Per Day
Imager WAC/NAC (MDIS)	3 Mbps	120 Mbits/d
Mapping IR Spectrometer (Ralph-LEISA)	50 kbps	120 Mbits/d
Gamma-ray spectrometer	4 kbps	13 Mbits/d
Neutron spectrometer	4 kbps	13 Mbits/d
Thermal imager	50 kbps	30 Mbits/d
UV spectrometer	4 kbps	13 Mbits/d
LIDAR	4 kbps	10 Mbits/d

The mass and power of the instruments are given, respectively, in Table 3-10 and Table 3-11.

Table 3-10. Instrument mass table.

Subsystem/Component	FLIGHT HARDWARE MASSES Total CBE Mass (kg)	Contingency	Total MEV Mass (kg)
Instruments	**44.5**	**15%**	**51.2**
Imager (WAC/NAC)	4.00	15%	4.60
Mapping IR Spectrometer	10.50	15%	12.08
Gamma Ray Spectrometer	10.00	15%	11.50
Neutron Spectrometer	3.00	15%	3.45
Thermal Imager	8.00	15%	9.20
UV Spectrometer	4.00	15%	4.60
LIDAR	5.00	15%	5.75

CBE, current best estimate; MEV, maximum expected value.

Table 3-11. Instrument power table.

Trojan Asteroid ASRG Power Budget Subsystem/Component	Total Steady-State Power CBE (W)	Contingency	Total Steady-State Power MEV (W)
Instruments	68.50	30%	89.05
Imager (WAC/NAC)	7.00	30.0%	9.10
Mapping IR Spectrometer	7.00	30.0%	9.10
Gamma Ray Spectrometer (GRS)	10.00	30.0%	13.00
Neutron Spectrometer (NS)	6.00	30.0%	7.80
Thermal Imager	7.00	30.0%	9.10
UV Spectrometer	4.50	30.0%	5.85
LIDAR	12.00	30.0%	15.60
Survival Heater Power	15.00	30.0%	19.50

Flight System

The flight system for this mission consists of one flight element, the spacecraft, as no staging or other elements are required to meet the study science objectives. All functions are incorporated on the spacecraft to meet the science objectives, including communication functions with Earth, maneuvers, a stable platform for the science measurements, and powering of all systems. All electronics subsystems are redundant to accommodate the 11-year mission design life. The closest approach altitude at the Jupiter flyby (>15 Jupiter radii) is high enough that the spacecraft requires no additional radiation shielding, although some electron dose may be picked up. A more refined mission design should look to optimize the flyby at an altitude >20 Jupiter radii. An environment with a total ionizing dose (TID) of 30 krad is assumed for all parts. The block diagram for the spacecraft is provided in Figure 3-1.

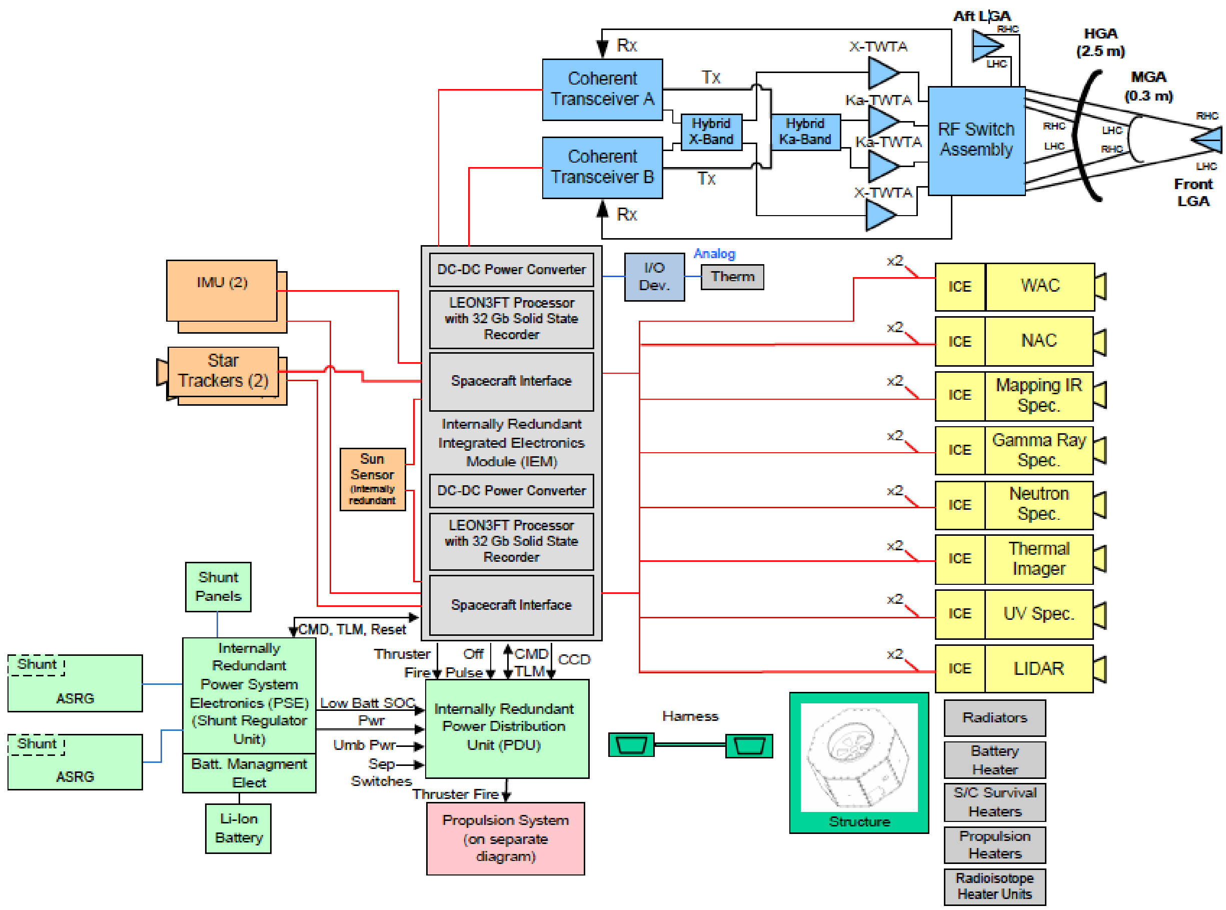

Figure 3-1. Spacecraft block diagram.

Structure

The flight structure (Figure 3-2) is composed of a central aluminum cylinder surrounded by aluminum honeycomb/composite face-sheet panels in an octagonal layout. This specific layout was reached in order to package five propulsion tanks (two fuel, two oxidizer, and one pressurant) while minimizing the surface area of the structure to meet thermal design requirements.

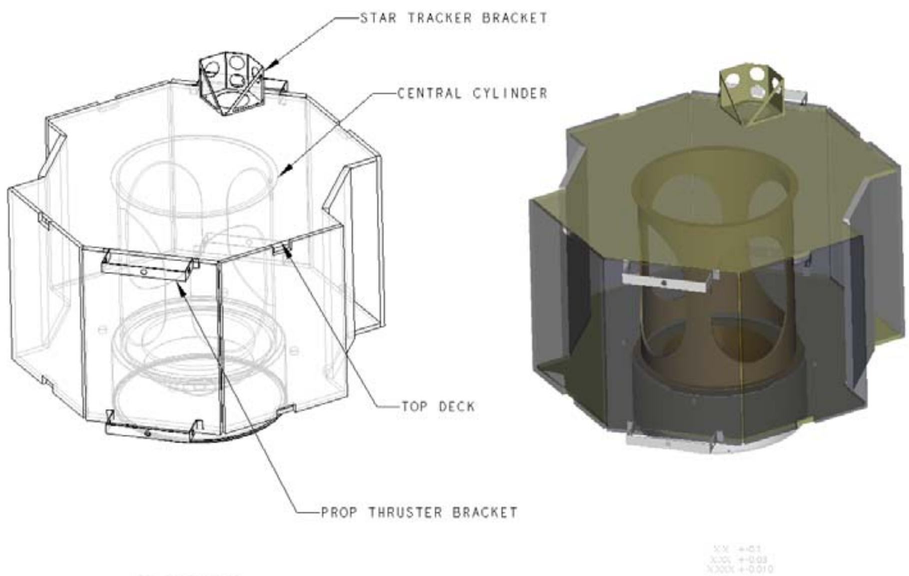

Figure 3-2. Flight structure.

The central aluminum cylinder supplies the primary structural integrity of the spacecraft while also acting as the primary structure for the propulsion system. The two fuel and two oxidizer tanks mount to the cylinder, with the pressurant tank mounted in the center of the cylinder. The cylinder provides a direct load path from the upper and lower honeycomb decks, through the adapter to the launch vehicle. This design platform was based on previous JHU/APL designs.

The design uses all 10 panels (upper, lower, and eight side panels) for component mounting. The upper honeycomb deck is the mounting surface for several components: high-gain antenna, star cameras, communication transceivers, and the inertial measurement units. The majority of the mass of these components is mounted along the perimeter of the central aluminum cylinder and in line with the load path to minimize panel bending.

The eight honeycomb side panels are used to mount the remainder of the spacecraft electronics as well as the ASRGs (Figure 3-3). All of the panels will be designed to minimize weight, while optimizing electronics layout and overall spacecraft center of gravity. Some panels may require the use of support struts.

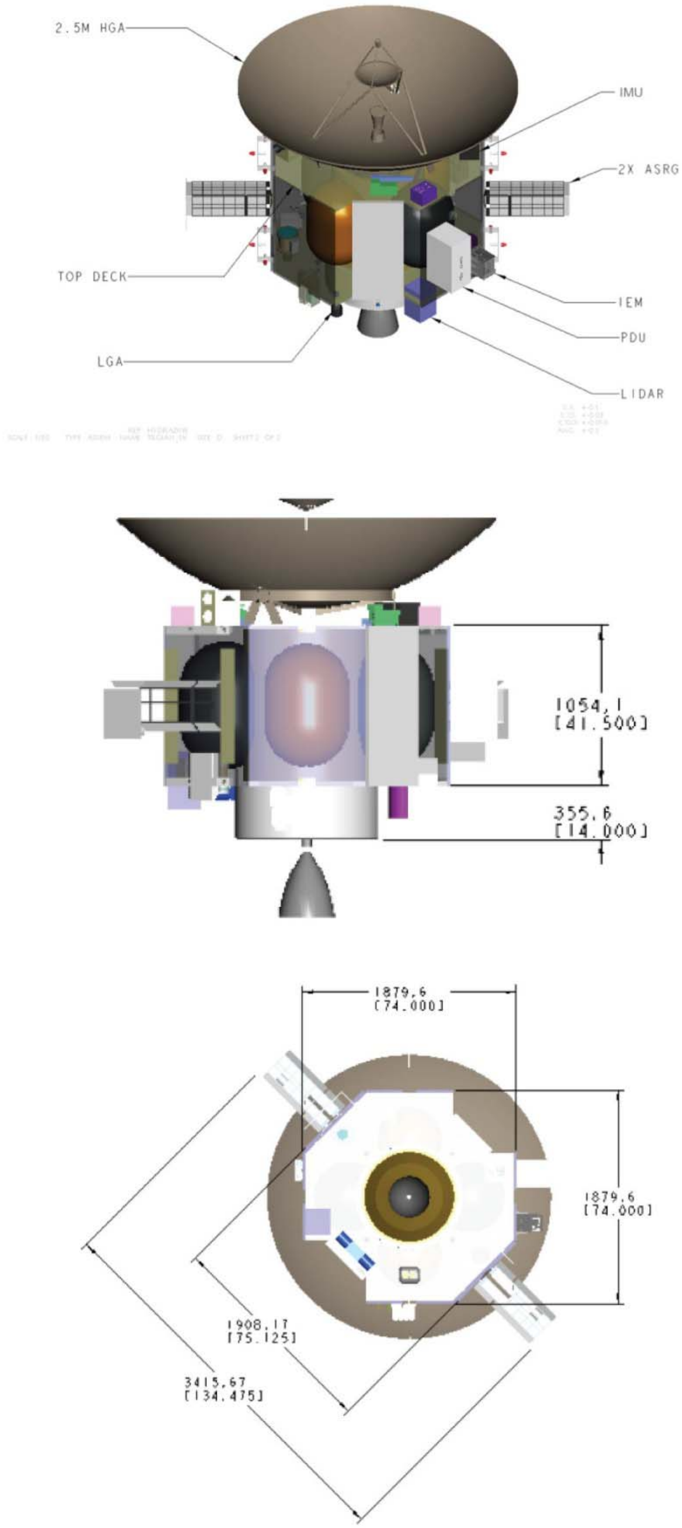

Figure 3-3. Spacecraft chemical ASRG concept (dimensions shown in mm [inches]).

The lower honeycomb deck is primarily responsible for housing the payload instruments (Figure 3-4). Each of the eight instruments has been placed so that their FOVs are unobstructed.

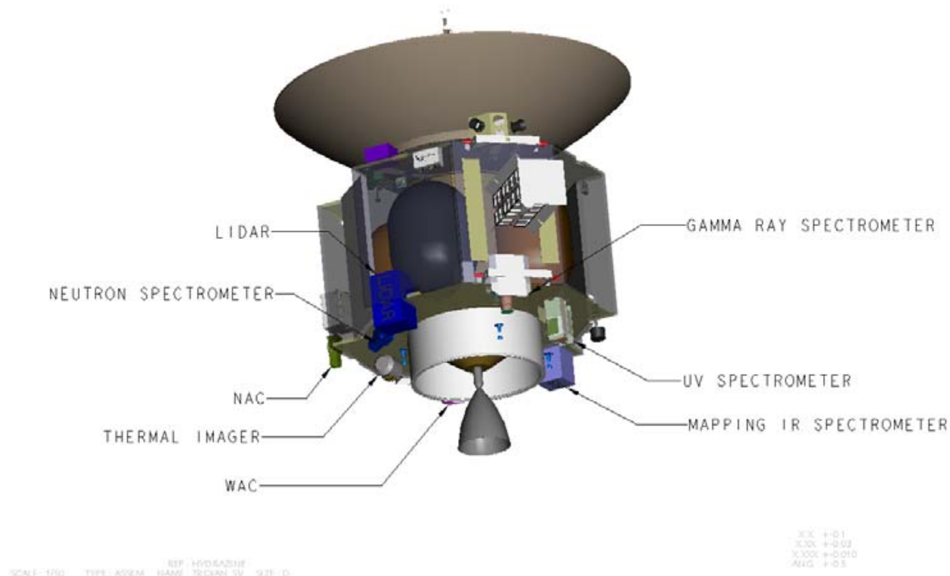

Figure 3-4. Spacecraft chemical ASRG concept with instrument layout.

Below the lower deck, a tapered mounting bracket houses the main propulsion thruster. Surrounding this thruster is a launch vehicle interface ring that doubles as a thermal shield for the science instruments. The current design has each of these components machined from 6061 aluminum.

For this specific mission, there are no external mechanisms required. All of the antennas and science instruments are fixed to their respective decks. The only mechanisms used are incorporated within the individual science instruments.

Propulsion

The propulsion subsystem is a pressure-regulated dual mode system that provides delta-V and attitude control capability. Pressure-regulated systems of this size and type have significant flight history. The system is built around the Aerojet 667N (150 lbf) AMBR engine: a bipropellant apogee engine with a wide operating range. The AMBR engine is currently at TRL 6, yet has demonstrated a maximum I_{sp} of 333.5 s, a substantial improvement over state of the art. It is expected that the AMBR engine will be fully qualified well before it is needed for this mission. If the AMBR engine qualification is delayed, there are other fully qualified engines that could be substituted.

All other components, including commercial off-the-shelf (COTS) propellant and pressurant tanks, have extensive flight heritage. The propulsion system incorporates 16 monopropellant thrusters: four 20-N (5-lbf) Aerojet MR-106E (MESSENGER, NEAR heritage) steering thrusters and 12 Aerojet 0.9-N (0.2-lbf) MR-103H (New Horizons heritage) ACS thrusters. The dual-mode system, shown in Figure 3-5, will be procured as a complete system from a subcontractor.

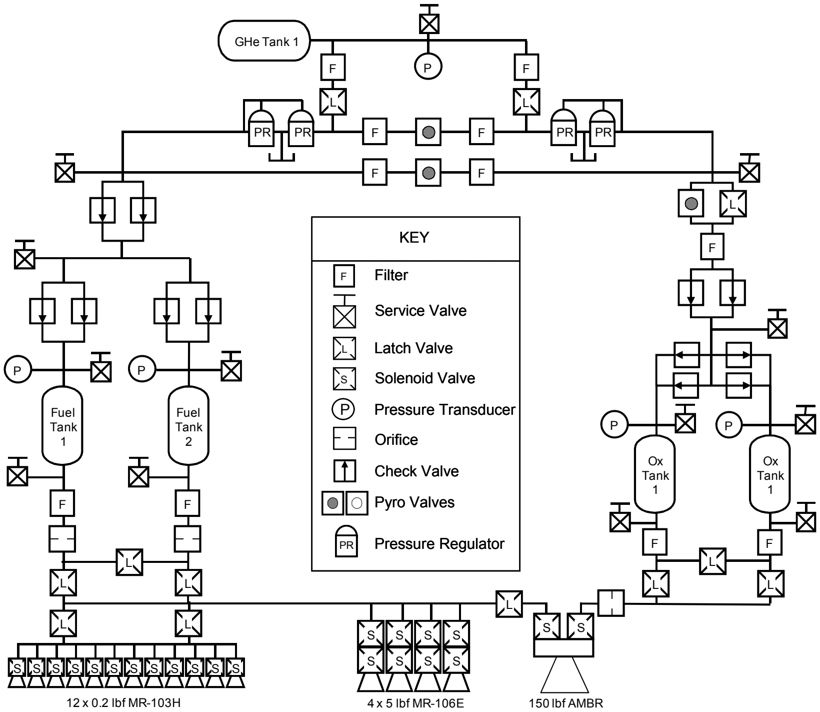

Figure 3-5. Propulsion system schematic.

Several flight-proven options exist for each component of the propulsion system; therefore the tanks, as well as all other heritage items, will not require qualification testing. There will be two INMARSAT-heritage hydrazine tanks, two INMARSAT 3-heritage oxidizer tanks, and one Lockheed Martin A2100-heritage pressurant tank. Different propellant management devices (PMDs) will be developed for inside the propellant tanks. The baseline propellant load is 314.9 kg of hydrazine and 242.0 kg of oxidizer. For a 614.5-kg launch dry mass, this provides 1933 m/s of delta-V.

The remaining components used to monitor and control the flow of propellant (latch valves, filters, orifices, check valves, pyro valves, pressure regulators, and pressure and temperature transducers) will be selected from a large catalog of components with substantial flight heritage on JHU/APL's and others' spacecraft.

Electrical Power System

The power system consists of two ASRGs, shunts, internally redundant power system electronics (PSE) including a shunt regulator unit (SRU), internally redundant power distribution unit (PDU), and a 20 amp-hour Lithium Ion (Li-Ion) Battery with management electronics. The PDU switches loads and controls thrusters via commands from either integrated electronics module (IEM). Field-effect-transistor (FET) switches incorporate resettable circuit breakers and hardware-based load management to protect the ASRG bus from fault. ASRG controllers will be mounted separately from the ASRG itself to improve thermal distribution across the spacecraft.

The power output from an ASRG is 140 W at (beginning of life [BOL]) and decays gradually with time, as shown in Figure 3-6.

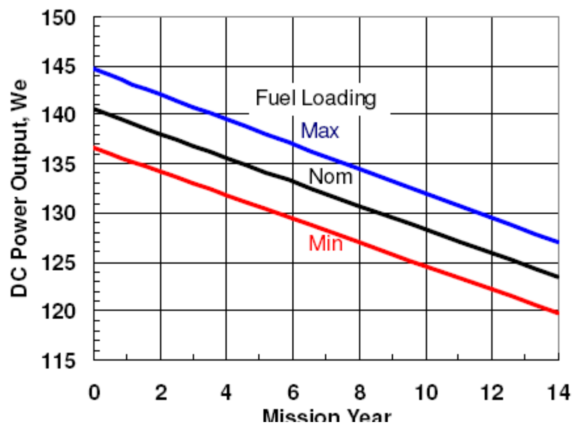

Figure 3-6. ASRG power output vs. mission year.

Command and Data Handling (C&DH)

The main processor, interface electronics, data recorder, and DC-DC power converter are housed in redundant IEMs. A 32-Gbit non-volatile solid-state recorder (SSR) will be integrated onto each IEM main processor. The low-power, SPARC-based LEON3 fault-tolerant processor supports commanding, data handling, data storage (using the SSR), and guidance and control (G&C) functions.

Guidance and Control (G&C)

The G&C system consists of two star trackers (ASTs), two inertial measurement units (IMUs), and one internally redundant Sun sensor assembly (SSA) with multiple sensor heads for attitude determination, of which only one AST and one IMU are needed for nominal operations. Attitude control is maintained solely by hydrazine thrusters. The G&C system is designed to provide three-axis control for science calibration and encounter operations (including high-speed data playback) and spin-stabilized control for cruise operations, hibernation, and large trajectory correction maneuvers using the bipropellant engine.

The G&C system design is based upon New Horizons heritage, and attitude sensors have flight heritage from New Horizons, STEREO, and MESSENGER. Placement and sizing of the attitude control hydrazine thrusters allow very small changes in rotational body rates per thruster pulse, which allows precise pointing stability and reduces the number of open/close thruster cycles, which are a life-limiting item. The thrusters are placed in coupled pairs so that attitude maneuvers do not impart a deterministic ΔV on the spacecraft.

The tables in Section 3 state the pointing requirements for the individual payload instruments. Attitude knowledge of 350 μrad, attitude control of 0.1 degree, and pointing stability of 25 μrad/s encompass the requirements of all of the instruments. The G&C system capabilities meet or exceed these requirements as demonstrated on the New Horizons mission. In addition, the pointing error for the medium-gain antenna (MGA) is a cone with a half angle of 3°; for the HGA the corresponding pointing error cone has a half angle of 0.1°. These pointing requirements are also satisfied with this G&C system.

Flight Software

Flight software (FSW) will implement standard C&DH and G&C functionality. C&DH software will

- Support command uplink rates of 7.8 bps to 2000 bps
- Support downlink rates of 10 bps to 180 kbps

- Implement a file system and support the CCSDS File Delivery Protocol (CFDP) for both uplink and downlink
- Support a flash memory–based SSR with a data volume of 32 Gbits
- Collect instrument data and store it to the SSR
- Play back data from the SSR using CFDP
- Support interfaces to the power system, the RF system and the other IEM
- Implement time-based commanding
- Implement an autonomy engine and fault protection

G&C software will implement the guidance, navigation, and control algorithms and support the interfaces to the attitude sensors (IMUs, star trackers, and Sun sensor) and thrusters.

There will also be a simple boot application to load one of two code images from non-volatile memory to RAM and jump to it whenever the flight processor is rebooted. Both C&DH and G&C software will run on a single LEON3 processor within a redundant IEM. The flight software design approach is to use the JHU/APL reusable flight software architecture as the core of its design and then add new or modified applications to meet mission-unique requirements. Modified applications will be mainly in the area of instrument interfaces, G&C sensor interfaces, and G&C control. All flight software described above will receive independent acceptance testing.

The flight software does not contain significant risk nor require any risk reduction activities. If Auto-NAV is implemented to reduce mission operations costs, the effect of this on the software architecture, processor loading, and memory requirements will need to be evaluated. An increase in loading could require a trade between a LEON3 processor and a more powerful processor, such as a RAD750.

Thermal Control System

The thermal control system uses a “thermos bottle” approach by maintaining a constant bus power level, balancing electrical power dissipation and thermal energy to keep the core components warm. This technique has been successfully demonstrated on New Horizons and several other missions. Heat pipes are used to distribute heat throughout the bus. Thermostatically controlled heaters provide thermal control to spacecraft components as needed, and several RHUs are included in the design to provide heat to critical outside elements such as the thruster towers.

RF Communications

The RF communications subsystem for a mission to Agamemnon uses much of the same architecture and technology of past JHU/APL missions, including New Horizons and MESSENGER and also the developments from the Radiation Belt Storm Probes (RBSP), S/Ka Coherent Transceiver for NASA CoNNecT, and Mini-RF IRIS radio developments.

The RF subsystem is shown in the spacecraft block diagram (Figure 3-1) and is driven by the need to reduce power consumption. It is mostly a dual string subsystem to provide redundancy because of the long length of the mission. The overall architecture is similar to the communication system of the New Horizons spacecraft. Notable exception is replacement of X-band by Ka-band at the HGA. Thus, RF communication is bi-directional at X-band through the low-gain antenna (LGA) and MGA, but unidirectional and at Ka-band through the HGA. To conserve power, the unused TWTAs will be shut off.

The JHU/APL-designed Frontier radio, which is based on the New Horizons, RBSP, CoNNeCT, and IRIS designs, is baselined as the transceiver. This radio provides a low-mass, low-power-consumption solution for deep-space missions. Each radio contains one uplink card and one downlink card both at X-band. An additional downlink card enables Ka-band transmission through the HGA. The radios include ranging and coherent Doppler turnaround to support navigation throughout the mission.

The hybrid coupler enables the use of either radio to provide the signal to both TWTAs. The diplexers are used to allow uplink and downlink transmission through the same antenna. The switches enable the selection of the LGA or MGA. The HGA is fed with waveguide from the Ka-band 17-W RF TWTA to decrease the loss from it to the HGA feed. The pointing error for the MGA is a cone with a half angle of 3°; for the HGA the corresponding pointing error cone has a half angle of 0.1°.

The front and aft LGAs are intended for post-launch and initial operations. After initial launch operations are completed, the spacecraft must be oriented with the MGA pointed at Earth for higher rate checkout operations. During the cruise and hibernation periods, the Earth will drift through the MGA FOV of the spinning spacecraft before the spacecraft spin axis must be realigned by ground command. During this time commanding, telemetry, reception, and navigation will be performed with the NASA DSN. During cruise and hibernation, if high rate transmission is needed with the DSN, the HGA will be used. This precessing operation was used on the New Horizons mission. Data rates are discussed in the Concept of Operations section.

If an emergency occurs during cruise, the spacecraft will switch to the MGA and will orient the spin axis toward Earth using the Sun sensor to determine the location of the Earth. This is similar to the emergency mode operation for the New Horizons mission.

Mass and Power Resources

A roll up of the mass is provided in Table 3-12. A more detailed master equipment list is provided in the appendix.

Table 3-12. Spacecraft mass table for chemical ASRG concept.

	FLIGHT HARDWARE MASSES		
Subsystem/Component	Total CBE Mass (kg)	Contingency	Total MEV Mass (kg)
Instruments	44.5	15%	51.2
Structures	86.0	15%	98.9
Propulsion	78.0	6%	82.7
Command & Data Handling (C&DH)	7.4	14%	8.5
Electrical Power (EPS)	88.1	13%	99.9
Guidance, Navigation, and Control	16.7	5%	17.5
Thermal Control (TCS)	37.3	14%	42.4
RF Communications	47.4	14%	53.9
Harness	24.3	15%	28.0
TOTAL DRY MASS	429.7 kg	12%	482.9 kg
Dry Mass Margin	30% (Note 1)		184.8 kg
MAXIMUM DRY MASS			614.5 kg

Note 1: Margin is calculated based on Decadal Mission Study Ground Rules.

Dry Mass Margin% = (Maximum Dry Mass – CBE)/(Maximum Dry Mass)

A roll up of power along with the power phasing by mode is provided in Table 3-13. Note that the power numbers in the first column represent the summation of all the power items for a subsystem with the average power for each mission phase being shown in the subsequent columns. Where denoted, power dissipation inside and outside the spacecraft thermal perimeter are used to determine the thermal energy required to maintain the “thermos bottle” approach.

Spacecraft characteristics for the chemical ASRG concept are shown in Table 3-14.

Table 3-13. Spacecraft power table for chemical ASRG concept.

Trojan Asteroid ASRG Power Budget Subsystem/Component	Total Steady-State Power CBE (W)	Launch (W)	Separation (W)	Checkout (W)	Delta-V Prep (W)	Delta-V DSM (W)	Delta-V TCM (W)	Cruise (W)	Orbit Science (W)	Orbit Science (W)	Orbit Science (W)	Orbit TX (W)	Orbit TX (W)	Orbit TX (W)
									(Inside)	(Outside)	Total	(Inside)	(Outside)	Total
Instruments	68.50	0.00	15.00	30.00	15.00	15.00	15.00	15.00	36.50	17.00	53.50	10.00	3.02	13.02
Spacecraft														
Command & Data Handling	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50	0.00	10.50	10.50	0.00	10.50
Electrical Power System	38.47	12.97	12.97	12.97	12.97	12.97	12.97	12.97	12.97	0.00	12.97	12.97	0.00	12.97
RF Communications	244.00	12.00	47.00	47.00	47.00	47.00	47.00	12.00	29.00	0.00	29.00	47.00	17.00	64.00
Guidance, Navigation, and Control	42.58	0.00	30.89	42.58	30.89	22.00	22.00	30.89	22.00	8.89	30.89	22.00	8.89	30.89
Propulsion	281.26	4.50	23.57	23.57	36.65	119.57	124.77	23.57	4.50	19.07	23.57	4.50	19.07	23.57
Thermal Required Loads	10.57	3.57	3.57	3.57	3.57	10.57	10.57	3.57	0.00	3.57	3.57	0.00	3.57	3.57
Subtotal	695.89	43.55	143.51	170.20	156.59	237.62	242.82	108.51	115.47	48.54	164.01	106.97	51.55	158.53
Harness														
SC Harness (2.5% of Load)	17.40	1.09	3.59	4.25	3.91	5.94	6.07	2.71	2.89		2.89	2.67		2.67
Total Power Dissipation	713.28	44.64	147.10	174.45	160.50	243.56	248.89	111.22	118.36	48.54	168.54	109.65	51.55	171.55
Total Thermos Bottle losses (120 W)									120.00			120.00		
Internal Shunt Heaters (W)									1.64			10.35		
Total Load Power at PDU Output	713.28	44.64	147.10	174.45	160.50	243.56	248.89	111.22			168.54			171.55
ASRG Power Capability		140.00	280.00	280.00	256.00	256.00	256.00	256.00			256.00			256.00
Total Power Capability (at PDU Output)		133.08	266.17	266.17	243.35	348.29	355.91	243.35			243.35			243.35
Actual Margin for Study (MAX-CBE)/MAX		66%	45%	34%	34%	30% *	30% *	54%			31%			30%

- Battery used for delta-V deep-space maneuver (DSM) and delta-V trajectory correction maneuver (TCM) phases.

Table 3-14. Spacecraft characteristics for chemical ASRG concept.

Flight System Element Parameters	Value/Summary, units
General	
Design life, months	11 years
Structure	
Structures material (aluminum, exotic, composite, etc.)	Central aluminum cylinder surrounded by aluminum honeycomb/composite face-sheet panels
Number of deployed structures	None
Thermal Control	
Type of thermal control used	“Thermos bottle” approach with heat pipes, and thermostatically controlled heaters
Propulsion	
Estimated delta-V budget, m/s	1933 m/s
Propulsion type(s) and associated propellant(s)/oxidizer(s)	Dual-mode Hydrazine and nitrogen tetroxide
Number of thrusters and tanks	1 667-N thruster 4 22-N thrusters 12 0.9-N thrusters 2 Hydrazine tanks 2 Oxidizer tanks 1 Pressurant tank
Specific impulse of each propulsion mode, s	333.5 s (bi-prop) 235 s (22-N thrusters) 224 s (0.9-N thruster)
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.).	Dual 3-axis/spinner Spin – Hibernation Spin – Large TCMs 3-axis – Science phases
Control reference	Inertial – Nominal Solar – Safing and Earth comm
Attitude determination	Star tracker IMU Sun sensors
Attitude knowledge capability	Spinning – 0.5 mrad (spin axis) 3-axis – <250 μrad
Attitude Control	Thrusters
Attitude control capability	Spinning – 0.1 deg 3-axis – 0.0586 deg
Pointing stability	<15 μrad/s
Agility requirements (maneuvers, scanning, etc.)	~180 deg in 60 minutes
Command & Data Handling	
Flight element housekeeping data rate	0.5 kbps
Data storage capacity	32 Gbit
Maximum storage record rate	3000 kbps
Maximum storage playback rate	180 kbps
Power	
Primary power source	2 ASRG

Expected power generation at beginning of life (BOL) and end of life (EOL), W	280 W BOL 256 W EOL (1 year fueled storage)
On-orbit average power consumption, W	169 W Orbit Science 172 W Orbit Transmit
Battery type (NiCd, NiH, Li-ion)	Li-ion
Battery storage capacity, amp-hours	20 amp-hours

Integrated Flight System

Figure 3-7 shows the spacecraft flight system integrated with the STAR 48 engine in the Atlas V 4m fairing.

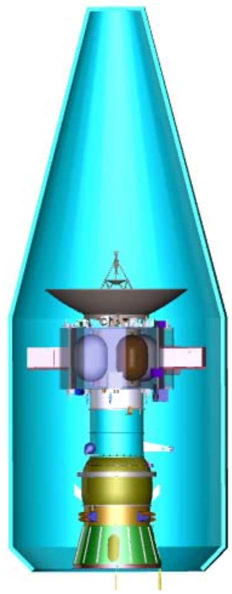

Figure 3-7. Spacecraft stacked with STAR 48 in 4m fairing.

Concept of Operations and Mission Design

Mission Design

The search for viable trajectory candidates included optimization of ballistic solutions to 4105 Trojan asteroid targets. The broad search was performed using the Jet Propulsion Laboratory's (JPL's) Mission Design and Analysis Software (MIDAS). The purpose of the initial broad search is to confirm the availability of numerous targets that can be captured in a given launch opportunity. For the purpose of the broad search, the JPL DASTCOM database is used. Because of perturbations, it is preferred to use JPL's HORIZONS system to generate target specific ephemeris data for the mission duration. Mission arrival dates in the late 2020s lower the reliability of the DASTCOM database; however, the availability of multiple targets remains valid. Given mission time constraints of 12 years, there were between 36 and 63 feasible targets identified in each launch opportunity from 2019 to 2023. Of the potential targets, point designs were chosen that best fit within the launch capability of the Atlas 400 series launch vehicles. Also, for the point design below, the transfer time was constrained to be lower than the optimal arrival date at 10 years. Launch windows for a Trojan rendezvous mission occur approximately every 399 days, corresponding to the synodic period of Jupiter, but the same target is not usually repeatable. The intent of the point design is to characterize the launch and propulsion capability necessary to capture several targets in each of the launch opportunities available.

The baseline mission, shown in Figure 3-8, is for a 10-year constrained transfer time from Earth to Agamemnon using a Jupiter gravity assist (JGA). The JGA significantly raised the trajectory perihelion and also performs the majority of the plane change required for the mission. The spacecraft is launched at a C3 of 73.15 km^2/s^2 with a declination of launch asymptote (DLA) and right ascension of launch asymptote (RLA) of -20.39^o and 239.41^o, respectively. The spacecraft must perform two deep-space maneuvers of 323 m/s and 204 m/s to target the JGA and the target arrival. The spacecraft must also perform a large third maneuver at arrival of 1.11 km/s.

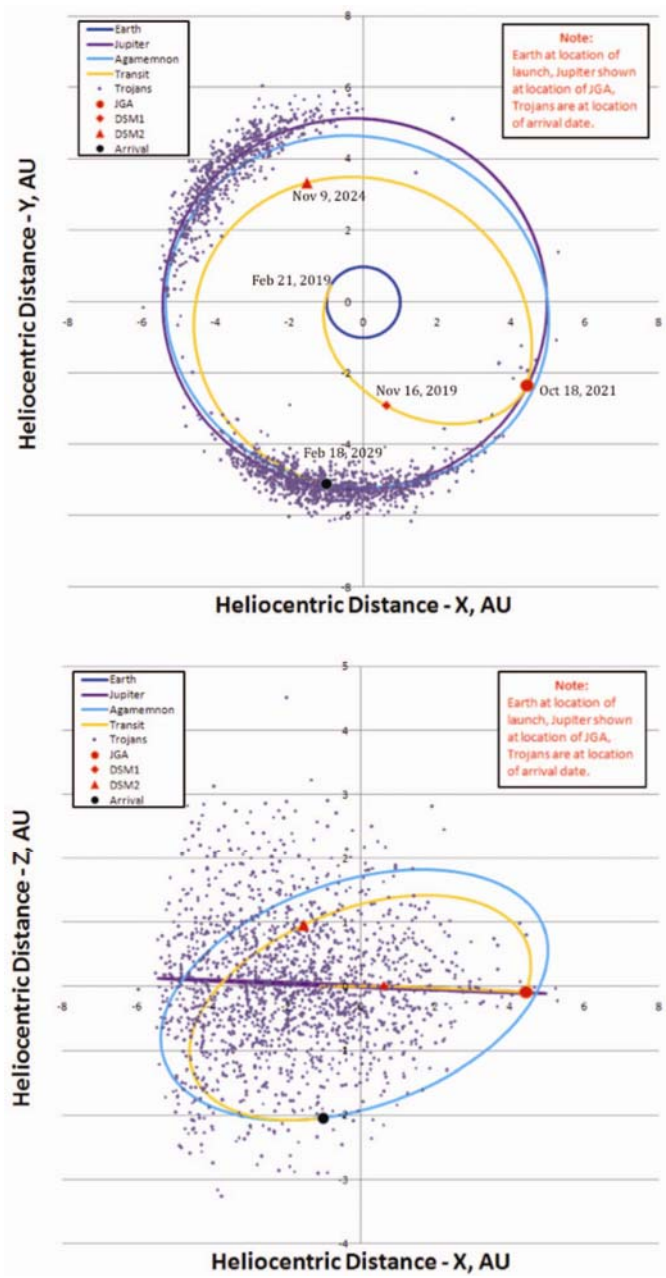

Figure 3-8. Baseline trajectory design in the *X-Y* and *X-Z* heliocentric planes.

To capture a 2-week launch window, the spacecraft must carry a deterministic post-launch ΔV of 1.63 km/s and fit within launch vehicle capability to a launch energy of 75.5 km^2/s^2. A 3-week launch window would increase the launch capability requirement to 78.2 km^2/s^2 without extending the mission beyond a 10-year transfer or increasing the mission ΔV beyond the 1.63 km/s.

Parameters for launch and the trajectory are provided in the Tables 3-15 through 3-17.

Table 3-15. Mission design: Deterministic post-launch delta-V budget.

Parameter	Value	Units
Deep-space maneuver #1	0.3	km/s
Deep-space maneuver #2	0.2	km/s
Orbit insertion burn at target arrival	1.1	km/s
Total deterministic delta-V	1.6	km/s
Total delta-V capability of system	1.9	km/s

Table 3-16. Mission design: Launch parameters.

Parameter	Value	Units
Launch location	CCAFS	
Launch vehicle	Atlas V 411	
Launch window (2/11/19-3/2/19 baseline case)	20	days
Launch C3	78.2	km^2/s^2
Launch mass with required 30% margin	1176	kg
Launch vehicle lift capability	1190	kg
Propellant contingency (available margin above estimated load required for mission)	14	kg

Table 3-17. Mission design: Interplanetary trajectory.

Parameter	Value	Units
JGA altitude	1,072,380	km
Total cruise duration	10	years
Repeatability	Every 13 months*	
* Launch windows to the Trojan asteroids are repeatable, but the same target is not usually repeatable		

The approach to the science orbit definition at the target asteroid is similar to the approach applied to the NEAR mission. The orbit about the asteroid will initially be set to an altitude of 400 km, near the limit of the asteroid’s sphere of influence. The orbit altitude will gradually be reduced, allowing analysis of the asteroid’s gravity field and other science data. The final orbit altitude will not be known until the analysis is complete, but an altitude in the range of 50 to 100 km is likely to be achieved. It is also desirable to reduce the altitude even further to less than 50 km for a limited number of orbits to perform observations.

Concept of Operations

Operations begin with a 6-week spacecraft and instrument checkout after launch. Normal staffing levels will remain through DSM#1, in support of instrument calibrations and building and testing sequences to be used for future critical operations. The mission design allows three sizeable periods of time in hibernation, and the operations team can be reduced significantly during those periods. The lack of cruise science requirements also allows a smaller operations team size even with build-ups for the Jupiter gravity assist and the second DSM. Currently available ground systems and DSN support are more than adequate to support this mission.

Rendezvous with the asteroid 911 Agamemnon and subsequent orbit reduction will put the highest demands on the operations team for the mission. Care will be exercised to reduce the orbit gradually over a 2- to 3-month period. Once at the mapping altitude, optical navigation products will be obtained for orbit determination and mapping to maximize the subsequent science collection value.

Primary science will require one 8-hour contact per day on average for approximately 6 months.

Downlink rate will average 30 kbps over the 6-month primary science phase but will be variable depending on the station and the weather. Ka-band communications is very sensitive to weather and elevation angle so the actual data rate at any pass could vary from 10 to over 60 kbps. At the average rate, data collection capabilities will exceed baseline science requirements by over a factor of 2. This orbital science data rate is, however, impacted by the lack of visibilities with DSN sites in the northern hemisphere. Table 3-18 lists the mission operations and ground data systems. Figure 3-9 shows examples of the best and worst seasons. These charts show all three DSN stations; the two curves are for 10% and 90% cumulative distribution of the weather.

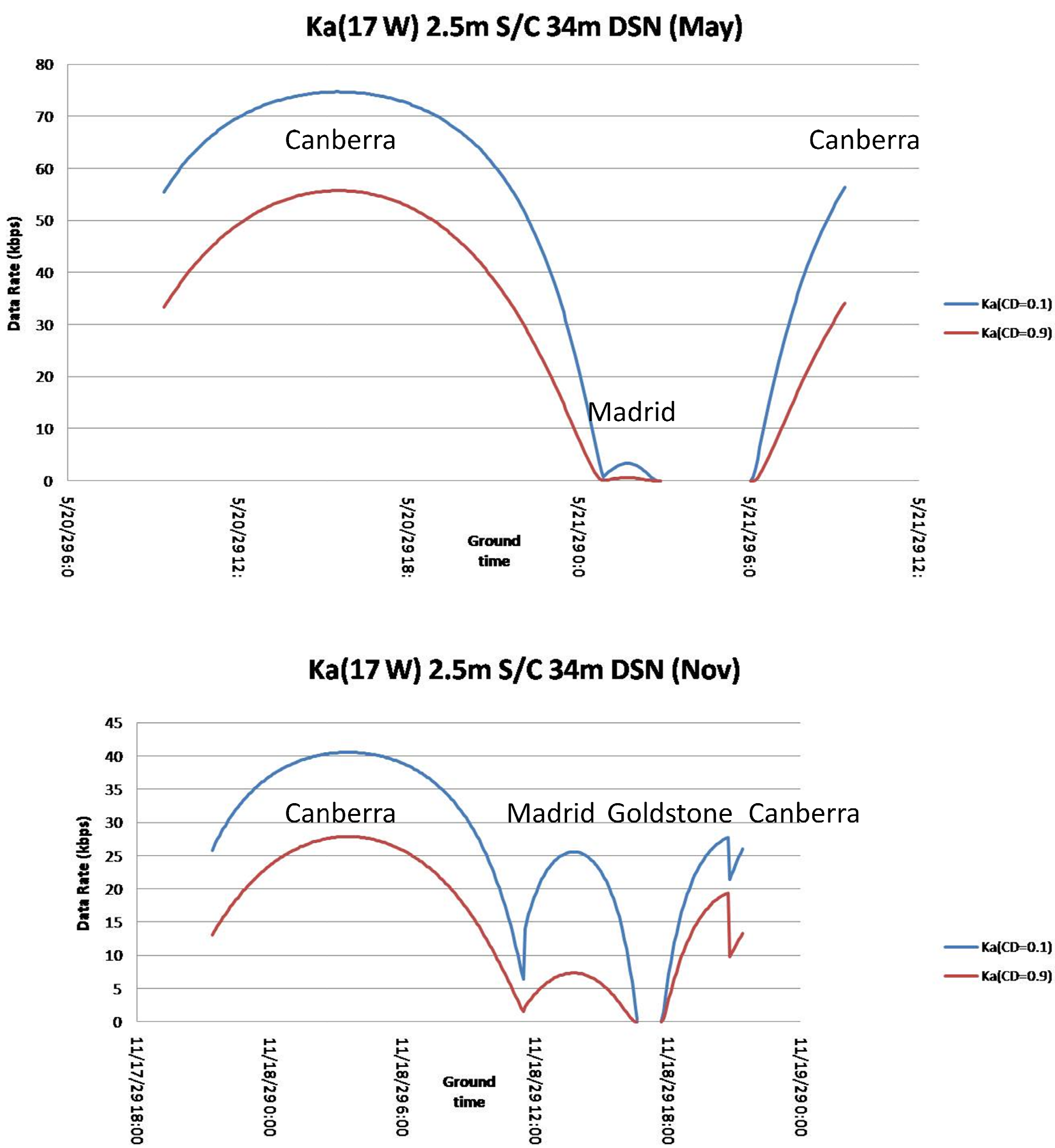

Figure 3-9. Data rate variations for two seasons with DSN.

Table 3-18. Mission operations and ground data systems.

Downlink Information	Early Ops/Instrument Commissioning	Initial Cruise	DSMs and Jupiter GA (each)	Hibernation Cruise	Trojan Cloud Science (each flyby)	Orbit Reduction	Orbit Science
Number of contacts per week‡ (initial no. of contacts→final no. of contacts)	21→3	2	3→21	Beacon/monthly TLM	2→21	3→7	7
Number of weeks for mission phase, weeks	17	12	13	450	3	13	26
Downlink frequency band	X/Ka	X/Ka	Ka	X/Ka	Ka	Ka	Ka
Telemetry data rate(s), kbps	0.01/50./180.	0.01/5.	5–9*	5–9*	5–9*	5–9*	30**
Transmitting antenna type(s) dBi	LGA(X)/MGA(X) /HGA(Ka)	MGA/HGA	HGA	MGA/HGA	HGA	HGA	HGA
Transmitter DC power, W	32(X)/45(Ka)	32(X)/45(Ka)	45	32(X)/45(Ka)	45	45	45
Downlink receiving antenna type	34-m	34-m	34-m	34-m	34-m	34-m	34–m
Transmitter RF output, W	12(X)/17(Ka)	12(X)/17(Ka)	17	12(X)/17(Ka)	17	17	17
Total daily data volume, (MB/contact‡)	0.108(LGA)/180.(MGA)/ 648(HGA)	0.036/18	18–32.4	18–32.4	18–32.4	18–32.4	108
Uplink Information							
Number of uplinks per day	2–3	2 per week	1–2	1 per month	1–2	1–2	1
Uplink frequency band	X	X	X	X	X	X	X
Tele-command rate, kbps	0.031/2.0†	2.0†	0.031†	0.031†	0.031†	0.031†	0.031†
U/L receiving antenna type(s)	LGA/MGA	LGA/MGA	MGA	MGA	MGA	MGA	MGA

* Downlink data rate varies with weather and station. Hourly rate table coordinated between the Missions Operation Center (MOC) and DSN.

** Contact through DSN Canberra only, averaged rate over elevation, weather during worst season. Best season has ~2× data rate.

† Ranging with MGA.

‡ Megabytes per contact. Contact time = 8 hours except for first week post-launch when contact will be continuous.

Given poor visibility to Goldstone and Madrid, multiple contacts per day may not be possible.

Risk List

The top seven risks have been identified with likelihood and consequence levels along with a summarized mitigation strategy (Table 3-19). They are also shown on a 5 × 5 risk matrix (Figure 3-10).

Table 3-19. Top risks.

#	Risk	Type	L	C	Mitigation
1	If complications occur during integration of the ASRGs, then mission schedule will be impacted.	Schedule	2	4	•Implement lessons learned from New Horizons on integration of a nuclear power source. •Implement a rigorous safety plan.
2	If instrument development involves more than minor modifications to existing instruments, then schedule will be impacted.	Schedule	2	3	•Begin instrument development early. •Minimize changes to existing instruments without impacting science.
3	If there are problems in the development of the ASRG, then schedule will be impacted.	Schedule	1	4	•Use a comprehensive test and qualification program.
4	If issues occur with obtaining approvals for nuclear power source, then mission schedule will be impacted.	Schedule	1	4	•Begin approval process as early as possible.
5	If an ASRG fails, then the mission will be degraded.	Technical	1	3	•Qualify ASRG for longer life. •Limit storage time prior to launch with fueled ASRG to 1 year.
6	If system reliability is not shown to be adequate for long mission, then cost will be impacted	Cost	1	3	•Perform reliability analysis early to assess weaknesses in system. •Assess system architecture options to improve reliability.
7	If there are problems in the development of the AMBR engine, then schedule will be impacted.	Schedule	1	2	•Use a comprehensive test and qualification program. •Replace with an existing TRL 9 engine.

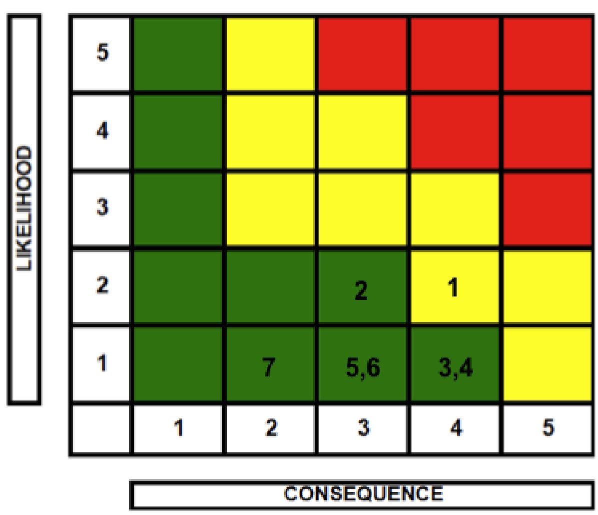

Figure 3-10. Risk matrix.

4. Development Schedule and Schedule Constraints

High-Level Mission Schedule

The following high-level mission schedule (Figure 4-1) is based on a previous schedule for the Ilion mission, which is a relevant mission in the same class and has the same architecture as the chemical+ASRG concept developed in this current study. Table 4-1 shows the key phase durations.

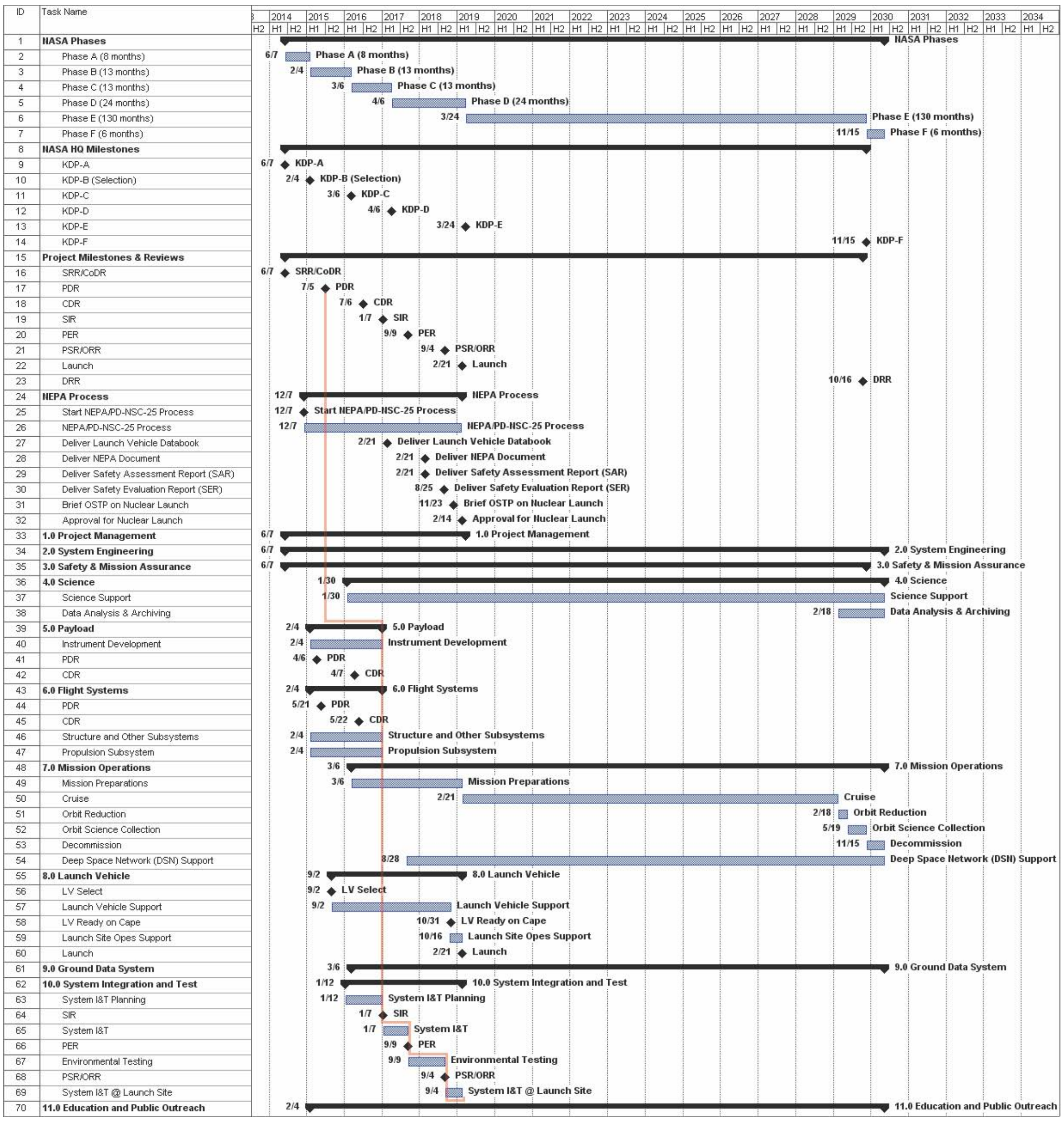

Figure 4-1. High-level mission schedule.

Table 4-1. Key phase duration.

Project Phase	Duration (Months)
Phase A – Conceptual design	8
Phase B – Preliminary design	13
Phase C – Detailed design	13
Phase D – Integration & test (I&T)	24
Phase E – Primary mission operations	130
Phase F – Extended mission operations	6
Start of Phase B to preliminary design review (PDR)	5.03
Start of Phase B to conceptual design review (CDR)	17.27
Start of Phase B to Delivery of instrument payload for system-level I&T	23
Start of Phase B to Delivery of flight systems for system-level I&T	23
System-level I&T	20.15
Project total funded schedule reserve	8
Total development time phases B–D	50

Technology Development Plan

All technology discussions are provided earlier in Section 2.

Development Schedule and Constraints

A detailed schedule for Phases C/D of the mission is shown in Figure 4-1. The development phase critical path includes the spacecraft structure and propulsion design, fabrication, and test as well as the I&T activities. The schedule contains a total of 8 months of funded schedule reserves. The launch opportunity is from 11 February 2019 through 2 March 2019. Additional launch opportunities with 20-day launch windows exist every 13 months (see Mission Design section).

5. Mission Life-Cycle Cost

Cost Estimate(s)

A cost estimate of CML 4 quality was prepared for the Trojan Tour Decadal Survey mission. A CML 4 estimate describes the resources required for a preferred mission design point, taking into account subsystem level mass, power, performance, and risk. The estimate described below expands in fidelity and detail on the mission cost estimate JHU/APL submitted to NASA in February 2009 for Illion, an ASRG-enabled Trojan asteroid mission, and on recently generated, low-fidelity estimates used to select the preferred Trojan asteroid mission concept and design. it takes into account the technical and performance characteristics of individual hardware subsystems and components and, where appropriate, labor requirements by phase and activity. The result is a mission estimate that is comprehensive and representative of expenditures that might be expected if the Trojan Tour mission is executed by JHU/APL with the assistance of the GRC and other NASA organizations as described as above.

Background

The starting point for the current cost estimate is the 2009 Illion cost estimate, with the underlying cost model updated and expanded. Subsystem elements were updated to reflect technology choices and changed mission characteristics. Mission operations and other labor-driven activities were estimated using mission schedules and activity profiles.

Mission Ground Rules and Assumptions

- Estimating ground rules and assumptions are derived from revision 2 draft of “Groundrules for Mission Concept Studies In Support of Planetary Decadal Survey (Groundrules)”.
- Mission costs are reported using the level-2 work breakdown structure (WBS) provided in Revision D of NPR 7120.5. Additional details are available on request.
- Responsibility for the mission is spread throughout the NASA community. JHU/APL will lead the Trojan Tour mission and design, develop, manufacture, integrate, and test the spacecraft. It will lead final integration and environmental testing of the space vehicle and operate the vehicle during Phase E. GRC will be responsible for delivering the ASRGs. A number of organizations, including JHU/APL, will design, develop, and deliver spacecraft instruments.
- Cost estimates are reported in Fiscal Year 2015 (FY15) dollars and Then-Year dollars. Most costs were estimated in FY10 dollars, enabling comparison with current activities and vendor prices and other crosschecks. The FY10 estimates were transformed into FY15 and Then-Year dollars using inflation rates presented in the Decadal Survey Groundrules.
- The 2009 NASA New Start inflation index for 2010 was used to adjust historical cost and price data and parametric results to FY10 dollars.
- The mission does not require Technology Development dollars to mature components to TRL 6. With a few exceptions, all components are rated at TRL 7–9. The AMBR thruster is the lowest-TRL propulsion component at TRL 6. All other propulsion components are assessed at TRL 7–9. The coherent transceivers are assessed at TRL 7. All other RF/telecommunications components are rated at TRL 8–9.

- The estimate assumes that flight qualification of the AMBR thruster will be completed for another mission before the thruster's integration into the Trojan Tour propulsion subsystem starting in 2017. It that is not the case, the cost of the propulsion subsystem will increase by approximately $5 million.
- Pre-Phase-E cost reserves are calculated as 50% of the estimated costs of all components except for the launch vehicle and ASRGs.
- Phase E cost reserves are calculated as 25% of the estimated costs of all Phase E elements.
- No cost reserves are included for DSN charges.

Method

The Trojan Tour mission cost estimate is a combination of parametric, engineering (bottom-up), and analog techniques. The following paragraphs describe each element's basis of estimate.

Phase A. Similar to other New Frontiers missions, $3 million in FY10 dollars is assumed to be available for Phase A. Such a budget provides sufficient funds for JHU/APL managers and engineers to begin mission concept analysis and prepare for the KDP A review. As all components and subsystems will be at or above TRL 6 at the start of the mission, no Technology Development funds are required during Phase A or later.

WBS 01 Management. This element covers business and administrative planning, organizing, directing, coordinating, analyzing, controlling, and approval processes used to accomplish overall project objectives, which are not associated with specific hardware or software elements. It includes project reviews and documentation, non-project owned facilities, and project reserves. It excludes costs associated with technical planning and management and costs associated with delivering specific engineering, hardware, and software products during Phases B–D.

Project management of the Trojan Tour mission is estimated as a factor (12%) of the estimated costs of non-ASRG-specific spacecraft hardware and flight software development (WBS element 06). The cost factor for Trojan Tour project management is 2–4% higher than the JHU/APL factor for MESSENGER, STEREO, and New Horizons program management. The higher percentage covers various top-level NASA management costs not incurred by JHU/APL during prior missions as well as the costs of meeting the newly introduced requirement for Earned Value Management (EVM) on major NASA contracts.

WBS 02 Systems Engineering. The systems engineering element covers technical and management efforts during Phases B–D of directing and controlling an integrated engineering effort for the Trojan Tour mission. It includes the efforts to define the space flight vehicle and ground system, including trade studies, integrated planning, and control of the technical program efforts of design engineering, software engineering, specialty engineering, system architecture development, and integrated test planning, system requirements writing, configuration control, technical oversight, control and monitoring of the technical program, and risk management activities. The systems engineering element also covers mission design and analysis and navigation support (MD&A/NS) through completion of Phase D.

Non-MD&A/NS SE effort is estimated as 14% of non-ASRG spacecraft hardware and software development costs. The factor is based on analysis of JHU/APL MESSENGER, STEREO and New Horizons missions, adjusted to provide for the additional effort needed to comply with milestone documentation requirements established by revision D of NPR 7120.5.

The estimated cost of MD&A/NS is based on an engineering estimate of labor requirements by phase during Phases A–D. Our labor analysis finds that the level of effort for MD&A will average 2.5 analysts throughout Phases A–D, with effort surging prior to major program reviews and during the launch campaign. For navigation services, our analysis assumes that Kinetix will provide support through a subcontract. That means a 3-staff-month task during Phase A ramping up to an average of 1 analyst-month per month during Phase B, then ramping up again at the start of Phase C to average 1.5 staff-months per month during Phases C and D. These levels are significantly less than navigation support provided to some non-JHU/APL missions but consistent with lessons learned from MESSENGER and New Horizons activity.

WBS 03 Safety and Mission Assurance (S&MA). This element covers technical and management efforts of directing and controlling the safety and mission assurance elements of the mission during Phases B–D. It includes design, development, review, and verification of practices and procedures and mission success criteria intended to assure that the delivered spacecraft, ground systems, mission operations, and payloads meet performance requirements and function through completion of Phase D.

S&MA at the mission level is estimated as 12.5% of non-ASRG hardware and software costs. That percentage, which is based on an analysis of recent JHU/APL missions, including RBSP, accounts for oversight during space vehicle integration and test. Oversight of non-JHU/APL instrument providers is included in the Payloads element.

WBS 04 Science/Technology. This element covers the managing, directing, and controlling of the science investigation aspects, as well as leading, managing, and performing the technology demonstration elements through Phase D. It includes the dollars for the Principal Investigator (PI) and Project Scientists (PSs). It also covers the costs of Co-Investigators (Co-Is) and technical personnel responsible for calibration, planning, and operations.

A bottom-up approach was used to estimate science team costs for the Trojan Tour mission. The cost per staff month for each labor category, including an adjustment for travel, is multiplied by the number of scientists in the labor category and the activity duration in months. Labor costs are then summed. During Phases A and B, the PI and PS are assumed to be employed quarter time; Co-Is and technical personnel employed at one and three full-time-equivalent (FTE) levels. During Phases C and D, the effort increases to averaging one full-time PI, one full-time PS, two full-time Co-Is, and three full-time technical personnel.

Approximately $1.5 million is also included in this element to cover the oversight and development of the Science Operations Center (SOC), a requirement that is separate from development of the Ground Data Systems. Reducing the cost of the SOC is the assumption that SOC development will take advantage of existing tools and databases.

WBS 05 Payloads. The payloads element includes the instruments hosted on the space vehicle. Costs were estimated for each instrument by analogy to past instruments built by or for JHU/APL missions. The analogy costs were adjusted for performance differences and technology readiness and to ensure management and engineering resources sufficient to comply with current NASA standards. The analogy-derived estimates were crosschecked for reasonableness using the NICM III system-level instrument cost model.

The instrument costs reported in the Trojan Tour estimate cover development, design, manufacture, integration, and test of one engineering model and one flight unit. It also includes management, engineering, and quality assurance efforts.

Table 5-1 describes the analogy instruments on which our estimates were based.

As Table 5-1 shows, cost data for the analogous instruments are drawn where possible from two data sources—the NICM III instrument data base and JHU/APL cost files. The exception is the New Horizons RALPH IR mapping spectrometer. Data for two non-visible mapping spectrometers in the NICM database were considered. The NICM III data, which have been normalized to FY04 dollars, and the JHU/APL cost data were adjusted to FY10 dollars using NASA New Start Inflation indices. Because of overlaps in the data sets, some crosschecking of cost data for specific instruments is possible.

Table 5-1. Trojan Tour instruments: Cost estimating analogues.

Instrument	Proposed Analog [Source for cost data]	Heritage Instrument (Mission)/Reported Cost (in millions of FY04 dollars)
Imager: narrow angle camera (NAC)	Analogy to NAC portion of MDIS [NICM III, JHU/APL]	MDIS (MESSENGER)/ $17.5M
Wide Angle Camera (WAC)		
IR mapping spectrometer	Analogy to LEISA portion of RALPH [New Horizons]	LEISA portion of RALPH (New Horizons)/(Not available)
Gamma-ray spectrometer	Analogy to GRNS [NICM III, JHU/APL]	GRNS (MESSENGER)/ $13.6M
Neutron spectrometer		
Thermal Imager	Analogy to Mars Climate Sounder (MCS) – nearly identical to LRO DIVINER [NICM III]	MCS (Mars Reconnaissance Orbiter)/$14.0M
UV spectrometer	Analogy to MASCS UV instrument, excluding VIRS components [NICM III]	MASCS (MESSENGER)/$6.2M
LIDAR	Analogy to NEAR [JHU/APL Illion study]	Laser Altimeter (NEAR)/$7M

Adjustments to analogy instrument costs were necessary because management and engineering costs were reported to be significantly lower than typical for current development efforts. The NICM III data set provides the costs of instrument management, systems engineering, quality assurance, and integration and testing. These were used to identify cases where management and engineering costs were significantly below historical averages and to make adjustments where appropriate.

It was also necessary to adjust analogous instrument costs for current technology maturity. Almost all of the analogy instruments were new developments with TRLs reported as TRL 6 or lower. As the Trojan Tour instruments are characterized as TRL 7 or, in the case of the gamma-ray and neutron spectrometers, TRL 8, cost adjustments to account for the savings in non-recurring design and development effort is appropriate. Starting from Book and Hamaker’s 2009 analysis of the effect of TRL on instrument cost,[i] the estimate reduces the total cost by 10% to account for the difference between the typical TRL 6 starting point and TRL 7–8.

For estimating the cost of the UV spectrometer, an adjustment is applied to the cost of the analogous MASCS instrument for the omission of VIRS components.

The payload element also includes the estimated costs of an engineer to provide engineering and management oversight of instrument development and of S&MA personnel to monitor the quality of instrument development.

WBS 06 Spacecraft. This element also includes all design, development, production, assembly, test efforts, and associated test beds and ground support equipment (GSE) to deliver the completed system for integration with the launch vehicle and payload.

JHU/APL will be designing, developing, manufacturing, and integrating and testing the spacecraft. Table 5-2 summarizes how the costs of each subsystem and major component are estimated. Details are provided below.

Table 5-2. Spacecraft: Cost estimating approaches.

Subsystem/Component	Method [Source for cost data]	Heritage (crosschecks)
Structure & mechanical	PRICE-H parametric model [calibrated using New Horizons cost data]	New Horizons
Propulsion subsystem	Engineering estimate including component costs, vendor integration RoMs, JHU/APL engineering labor	MESSENGER
Guidance & control	Engineering estimate based on vendor component costs, JHU/APL engineering labor	Multiple vendors, MESSENGER (labor costs)
Command & data handling (C&DH)	PRICE-H parametric model	IRAD cost reports (Leon 3FT)
Electrical power system including power system electronics (PSE)	PRICE-H parametric model (board level)	RBSP (board costs), mission actuals
Power distribution unit (PDU)	PRICE-H parametric model (board level), 2009 bottom-up estimate for JHU/APL build-to-print PDU	RBSP (board costs), mission actuals
Test beds	Engineering estimate: non-recurring labor, parts counts & prices	STEREO
Thermal control	PRICE-H parametric model, RHU costs (Discovery)	New Horizons, ILN trade studies
RF communications	Analogy to New Horizons, USCM 8 TWTA cost model	New Horizons
Harness assembly	PRICE-H parametric model	
Flight software (FSW) development	Engineering estimate, based on reuse of software routines and GSFC, JPL software libraries	MESSENGER, STEREO, New Horizons

Structure and Mechanical. The structure of the Trojan Tour spacecraft structure is similar to that of JHU/APL's New Horizons spacecraft in several key aspects. Both are aluminum cylinders with aluminum honeycomb panels and decking. Both accommodate nuclear power sources. Neither is required to support mechanisms or solar arrays. The Trojan Tour structure with allocated mass contingency is projected to be about 20% smaller than the New Horizons structure. Because of uncertainty about the final mass and configuration, the PRICE-H model estimates that the Trojan Tour structure will cost about the same as New Horizons.

Propulsion Subsystem. The estimate assumes that the dual-mode propulsion subsystem will be subcontracted to a propulsion specialist such as Aerojet under the supervision of JHU/APL propulsion engineers. The propulsion subcontractor will be responsible for procuring components, integrating them into the spacecraft structure, and testing subsystem performance. The structure-propulsion assembly will be returned to JHU/APL for space vehicle assembly and testing.

The propulsion subsystem cost is estimated using an engineering estimate that draws on component costs, vendor integration RoMs, and JHU/APL engineering labor. The estimate of $32.7 million in FY15 dollars covers the subcontractor costs as well as the effort of JHU/APL propulsion engineers, who will be responsible for design of the subsystem and technical management of the contract. It also covers expenditures for pneumatic GSE required for leak and functional testing

The estimate assumes that another NASA mission will have qualified the AMBR thruster before 2017 when the thruster is required for integration into the Trojan Tour propulsion subsystem. If that is not the case, the cost of the propulsion subsystem would increase by approximately $5 million. It assumes that all other components are at least TRL 6 and that off-the-shelf, non-custom propellant tanks can be used. In other words, no additional qualification testing will be required. No propulsion subsystem-level thermal balance test will be required, and propulsion thermal vacuum testing will be done at spacecraft level. Propellant loading, including any water loading and off-loading required for dynamic testing, will be included in the launch vehicle contract. Finally, the launch vehicle contract will include all propellant and pressurant costs.

The estimated cost is about 25% higher than the MESSENGER bi-propellant propulsion subsystem from Aerojet. The additional cost reflects additional quality assurance and AMBR integration uncertainty.

Guidance and Control Subsystem. The G&C hardware components are purchased items from G&C vendors. Estimated costs are based on analysis of past component costs and recent vendor ROMs. The component also includes approximately 280 staff months of JHU/APL engineering labor to support G&C design, the acquisition of G&C components, and the autogeneration of component interface code.

Command and Data Handling Subsystem. A PRICE-H cost model calibrated with cost data from a JHU/APL IR&D project for development of Leon 3FT IEM boards and from the production of JHU/APL electronics boards was used to estimate the costs of design, development, and production of the C&DH engineering models and production boards in quantities specified in the Mission Equipment List.

Electrical Power Subsystem (EPS). The EPS consists of the ASRGs, PSE, PDU, shunts, and a secondary lithium ion battery.

- *ASRG*s. The ASRGs that power the spacecraft are described in the Decadal Survey Groundrules. Following the Groundrules, the estimate assumes that "the ASRG will be ready for flight no earlier than March 2014 and will have a unit cost of ~$20M." That $20M cost is assumed to be in FY15 dollars. The estimate also assumes that the ASRG cost includes all costs associated with required engineering, mass and thermal models.
- *PSE, PDU*. A PRICE-H component-level cost estimating model calibrated with prototype cost data from RBSP cost actual was used to estimate costs of PSE and PDU electronics slices, fuse modules, and slice hardware. The PDU production estimate was crosschecked using a bottom-up engineering estimate developed in 2009 for a build-to-print PDU based on JHU/APL's RBSP PDU design.
- *Shunts, battery*. A PRICE-H component-level model calibrated with JHU/APL and Marshall Space Flight Center cost data was used to estimate costs of other EPS components.

Development Test Beds. The Trojan Tour mission will require six test beds—four test beds incorporating engineering models (EMs) and two that do not. Costs of design, non-EM hardware, and test bed I&T are based on a 2006 in-house analysis of JHU/APL test bed cost data. EM costs are included in the subsystem estimates. The costs of test bed software development are included in the flight software development estimate.

Thermal Control Subsystem. The estimate is based on a PRICE-H component-level cost model calibrated against vendor ROMs and JHU/APL cost histories, with RHU costs based on Discovery AO guidance.

RF Communications Subsystem. The New Horizons communications subsystem provides an analogy for its Trojan Tour counterpart. Analogy costs are adjusted to account for non-recurring engineering for the Trojan's larger and more complex HGA and Ka-band coherent transceivers. In lieu of vendor ROMs, a USMC-8 (Unmanned Spacecraft Cost Model, 8th edition) cost estimating equation is used to estimate TWTA production costs.

Harness Subsystem. A PRICE-H subsystem cost model calibrated using STEREO harness cost data is the basis of the harness cost estimate.

Flight Software Development. The FSW estimate is based on analysis of the labor histories of MESSENGER, STEREO, New Horizons, and RBSP FSW development and maintenance. Activities covered by the cost estimate include FSW development and maintenance, development of test bed and autonomy software, integration of G&C code, and I&T support. The Trojan Tour estimate is about 20% higher than that of the MESSENGER mission, much of the difference resulting from the inclusion of increased autonomy-related activities and I&T support in the Trojan estimate that were not as extensive in the MESSENGER FSW activity.

WBS 07 Mission Operations. This element covers the management of the development and implementation of personnel, procedures, documentation, and training required to conduct mission operations. Its efforts span all phases of the mission.

The mission operations element covers the following elements:

- Operations personnel
- Launch checkout, early operations support (LCEOS)
- Management, sustaining engineering, and S&MA support (Phase E only)
- Mission design & analysis and navigation support (MD&A/NS) (Phase E only)
- Science team activity (Phase E only)

The first two elements include effort required before the start of Phase E. Missions operations span Phases D and E as personnel must plan and train before the launch. LCEOS is Phase D only: It begins after environmental testing of the space vehicle is complete and ends after launch with the post-launch space vehicle checkout. The other three activities cover strictly Phase E effort.

Operations personnel costs are estimated using a labor profile that starts 2 years prior to launch and ends with completion of the science activity. The profile takes into account the long hibernation cruise activities. During each of the three hibernation cruise periods, slightly more than two full-time-equivalent staff members are projected to be needed to operate the space vehicle. Operational activity peaks at the equivalent of 16 full-time-equivalent staff during initial checkout and during the science phase. Operational activity starts to increase about 6 months prior to each deep-space maneuver and the science phase and decreases within 1 to 2 months after those activities end.

The estimated cost of the LCEOS activity is based on the historical costs of the launch campaign of New Horizons, another nuclear-powered mission.

Like operations personnel, the number of management and engineering, MD&A/NS, and science team members vary whether or not the mission is in hibernation cruise mode.

- Management, Sustaining Engineering, and S&MA Support. Declines to 4 FTE personnel during hibernation cruise phases prior to ramp-up; 4 FTE personnel during the remainder of Phase E.

- MD&A/NS. Declines to averages of 1.25 FTE mission analysts and 1.25 FTE navigation specialists during hibernation cruise phases prior to ramp-up; average 2.5 FTE mission analysts and 2.5 FTE navigation specialists during the remainder of Phase E.
- Science Team. Declines to averages of 0.25 FTE PI, 0.50 FTE PS, 1.5 FTE Co-Is, and 4 FTE technical personnel during hibernation cruise phases prior to ramp-up. Increases during the science phase to 1 FTE PI, 1 FTE PS, 4 FTE Co-Is, and 3 FTE technical personnel.

WBS 08 Launch Vehicle and Services. The mission requires a launch vehicle comparable to the Atlas V 411. Because a vehicle is not listed in the Decadal Survey Groundrules, our launch vehicle starts with Option 1, priced at $178 million in FY15 dollars, and adds $14 million for the cost of a solid-fuel booster. The total estimated cost is therefore $209 million.

The element also includes the costs of a part-time JHU/APL engineer through Phases B–D who will be responsible for interface of the space vehicle to the launch vehicle. Per the Decadal Survey Groundrules, because the mission includes a radioactive component, the element also includes $15 million in FY15 dollars to ensure that the launch complies with NEPA and other safety requirements.

WBS 09 Ground Data Systems (GDSs). This element includes the computers, communications, operating systems, and networking equipment needed to connect and host the mission operations software. It covers the design, development, implementation, integration, test, and the associated support equipment of the ground system, including the hardware and software needed for processing, archiving, and distributing telemetry and radiometric data and for commanding the spacecraft.

A bottom-up estimate for an outer planetary mission GDS was generated using vendor prices for hardware components and licenses and software development labor cost data. For ground software development, we assume that the L-3 Communications InControl satellite operations software will provide the GDS framework and that InControl-compatible routines developed for the RBSP mission can be reused with minor modifications.

WBS 10 System Integration and Test (I&T). This element covers the efforts to assemble the spacecraft and perform space vehicle environmental testing. The estimate cost is analogous to the costs of integrating and environmentally testing the New Horizons space vehicle, another space vehicle with a nuclear power source, no mechanisms, and large and fixed high-gain antenna.

DSN (Deep Space Network) Charges. This element provides for access to the DSN 34-m communications infrastructure that will be needed to transmit and receive mission and scientific data. Mission charges for use of a 34-m dish are estimated with the current DSN rate schedule and a table of DSN connection requirements derived from the Trojan Tour mission timeline. The DSN cost estimate covers pre- and post-contact activity for each linkage.

E/PO (Education and Public Outreach). This element provides for the EPO responsibilities of NASA's missions, projects, and programs in alignment with the Strategic Plan for Education. Available E/PO funds are calculated as 1% of the costs of baseline (non-reserve) mission costs.

Results

The estimated total mission cost in FY15 dollars of the Trojan Tour mission is about $938 billion. The most expensive single cost element is cost reserves, which account for $225 million, or nearly one-quarter of the total mission cost. The next most expensive cost element is the launch vehicle and services at about $209 million, or 22% of the total mission cost. The spacecraft cost is under $200 million, or about 20% of the total mission cost.

Phase E costs, including mission operations and DSN charges and cost reserves, account for less than $90 million, or only 9% of the mission’s total estimated costs. The relatively low Phase E cost projection depends on achieving the low mission operations tempo projected for the three hibernation cruise phases.

Cost estimates are shown in Table 5-3.

Table 5-3. Cost estimates.

	Trojan	Costs by year in Spend-Year dollars																		
NASA WBS	**Description**	**FY14**	**FY15**	**FY16**	**FY17**	**FY18**	**FY19**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**	**FY29**	**FY30**	**Total in SY $M**	**Total in FY15 $M**
	Phase A	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	3
	Technology Development	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
01	**Project Management**	0	2	4	5	5	3	0	0	0	0	0	0	0	0	0	0	0	20	18
02	**Systems Engineering, incl. MD&A & Nav.**	0	3	6	8	9	6	0	0	0	0	0	0	0	0	0	0	0	30	28
03	**Safety & Mission Assurance**	0	0	4	6	6	5	0	0	0	0	0	0	0	0	0	0	0	22	20
04	**Science/Technology (Phases A-D)**	0	0	1	3	3	3	0	0	0	0	0	0	0	0	0	0	0	10	9
05	**Payloads**	0	0	18	47	29	1	0	0	0	0	0	0	0	0	0	0	0	96	89
06	**Spacecraft**	0	11	57	87	59	1	0	0	0	0	0	0	0	0	0	0	0	208	194
07	**Mission Operations**	0	0	2	7	9	14	5	6	4	4	6	5	5	5	18	19	0	107	86
08	**Launch Vehicles & Services, incl. LVA, I/F, NEPA**	0	0	1	3	133	91	0	0	0	0	0	0	0	0	0	0	0	229	209
09	**Ground Data Systems**	0	0	1	2	12	4	0	0	0	0	0	0	0	0	0	0	0	19	17
10	**Systems Integration & Test**	0	0	0	1	14	6	0	0	0	0	0	0	0	0	0	0	0	21	19
DSN	**Space Communications Services (DSN)**	0	0	0	0	0	5	2	0	0	3	0	0	0	1	6	0	0	17	14
E/PO	**E/PO**	0	0	0	0	0	3	0	1	1	1	0	0	0	0	0	0	0	8	7
	Subtotal	2	6	44	121	384	144	7	7	6	7	6	5	5	6	14	19	11	790	713
	Phases A-D	*0*	*4*	*44*	*121*	*384*	*144*	*17*	*74*	*137*	*135*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*1060*	*643*
	Excluding LV	*0*	*0*	*0*	*2*	*32*	*340*	*14*	*29*	*38*	*33*	*8*	*8*	*7*	*5*	*7*	*7*	*6*	*536*	*506*
	Cost Reserves	1	3	21	59	125	26	1	1	1	1	1	1	1	1	4	5	0	254	225
	Phases A-D (excl. LV) : 50%	1	3	21	59	125	26	0	0	0	0	0	0	0	0	0	0	0	236	206
	Phase E: 25%	0	0	0	0	0	0	1	1	1	1	1	1	1	1	4	5	0	18	19
	Total, including Reserves	3	9	65	179	509	171	8	8	7	8	7	7	4	7	28	23	0	1044	938

Confidence and Cost Reserves

Per the Decadal Study Groundrules, the estimate includes cost reserves equal to 50% of the estimated costs of all Phase A–D elements except for the launch vehicle, ASRGs, and DSN charges plus 25% of the estimated costs of Phase E/F elements, excluding Phase E DSN.

A probabilistic cost estimate was not prepared for the total mission, and a numeric confidence level was not assigned.

Mission Descopes and Estimated Cost Savings

Descope options include the elimination of such lower priority instruments as the UV spectrometer, LIDAR, and thermal imager. Cost savings from these descopes would include eliminated instrument costs and reductions in I&T, mission operations, and science team support costs. Cost savings would also result from eliminating one of the two Ka-band TWTAs, including the price of the TWTA, reduced JHU/APL oversight, reduced antenna complexity because of requiring only a single feed, and elimination of some RF switches, diplexers, waveguides, etc. The total cost savings of these descopes is at least $40 million, although detailed savings associated with each has not been performed. The descopes would reduce the estimated total mission cost to under $900 million.

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[i] Book, S., and J. Hamaker. "TRL Impact on Cost as Estimated for the JIMO Effort," JPL Briefing, March 2009.

Appendix A: Trojan Tour Decadal Study Team

Role	Name
Science Champion	Mike Brown
	Faith Vilas
	Marc Buie
Primitive Bodies Chair	Joseph Veverka
NASA HQ POC	Lindley Johnson

Role	Name	Organization
Decadal Program Manager	Kurt Lindstrom	JHU/APL
APL Science POC	Andrew Rivkin	JHU/APL
Project Manager	Helmut Seifert	JHU/APL
Lead Systems Engineer	Kenneth Hibbard	JHU/APL
Systems / Instruments	Robert Gold	JHU/APL
Systems Engineer	Marsha Schwinger	JHU/APL
Systems Engineer / GRC Power	Steven Oleson	NASA GRC

Appendix A: Trojan Tour Decadal Study Team

Role	Name	Organization
Mission Design	James McAdams John Dankanich	JHU/APL NASA GRC
Costing	Lawrence Wolfarth Sally Whitley	JHU/APL JHU/APL
RF	Brian Sequeira	JHU/APL
GN&C	Gabe Rogers Adam Fosbury	JHU/APL JHU/APL
Operations	Mark Holdridge Richard Reinders	JHU/APL JHU/APL
Integration	Melvin White	JHU/APL
Mechanical Design & Engineering	Theodore Hartka Jason Gorczyca	JHU/APL
Thermal Analyst	Bruce Williams	JHU/APL
Software	Stephen Williams	JHU/APL
Avionics / Power	Martin Fraeman	JHU/APL
Power (SA Concept primarily)	Lewis Roufberg	JHU/APL
Propulsion	Stewart Bushman	JHU/APL

Appendix B- Master Equipment List and Power Table

Spacecraft Master Equipment List

Trojan Asteroid Master Equipment List - ASRG Chemical Concept

Subsystem/Component	Unit Mass CBE (kg)	# OF UNITS: Flight Units	Flight Spares	EMs & Proto-types	FLIGHT HARDWARE MASSES: Total CBE Mass (kg)	Contin-gency	Total MEV Mass (kg)	OTHER COMPONENT INFORMATION: Description (Vendor, Part #, Heritage Basis)	TRL	Other Characteristics/ Issues
Instruments					**44.5**	**15%**	**51.2**			
Imager (WAC/NAC)	4.00	1	0	1	4.00	15%	4.60	MESSENGER	7	
Mapping IR Spectrometer	10.50	1	0	1	10.50	15%	12.08	New Horizons RALPH LEISA	7	
Gamma Ray Spectrometer	10.00	1	0	1	10.00	15%	11.50	MESSENGER, with shield	8	
Neutron Spectrometer	3.00	1	0	1	3.00	15%	3.45	MESSENGER	8	
Thermal Imager	8.00	1	0	1	8.00	15%	9.20	LRO DIVINER, simplified	7	without gimbal
UV Spectrometer	4.00	1	0	1	4.00	15%	4.60	MESSENGER MASCS UVVS	7	
LIDAR	5.00	1	0	1	5.00	15%	5.75	NEAR	7	
Structures					**86.0**	**15%**	**98.9**			
Primary Structure	72.44	1	0	0	72.44	15%	83.31	NEW - 8% of total CBE wet mass	7	
Secondary Structure	13.58	1	0	0	13.58	15%	15.62	NEW -1.5% of total CBE wet mass	7	
Propulsion					**78.0**	**6%**	**82.7**			
Oxidizer Tank	5.67	2	0	0	11.34	5%	11.91	ATK-80364	9	
N2H4 Tank	12.91	2	0	0	25.82	5%	27.11	ATK-80334	9	
GHe Tank	9.98	1	0	0	9.98	5%	10.48	ATK-80402	9	
667N (150lbf) Engine AMBR	5.50	1	0	0	5.50	5%	5.78	Aerojet	6	Expected to be flight ready and TRL 9 by 2015
22.24N (5lbf) Thruster (MR-106E)	0.73	4	1	0	2.92	5%	3.07	MR-106E, MESSENGER	9	
0.9N (0.2lbf) Thruster (MR-103H)	0.20	12	1	0	2.34	5%	2.46	MR-103H, New Horizons	9	
Latch Valve	0.34	10	0	0	3.40	5%	3.57	MESSENGER	9	
High Pressure Latch Valve	0.52	2	0	0	1.04	5%	1.09	MESSENGER	9	
Filter	0.02	11	0	0	0.22	5%	0.23	MESSENGER	9	
Fuel/Ox Service Valve	0.15	12	0	0	1.85	5%	1.94	MESSENGER	9	
Helium Service Valve	0.07	1	0	0	0.07	5%	0.07	MESSENGER	9	
Pressure Transducer	0.23	5	0	0	1.15	5%	1.21	MESSENGER	9	
Tubing / Fasteners / Tube Clamps / Etc.	3.00	1	0	0	3.00	15%	3.45	MESSENGER	7	
Electrical Connectors	0.25	1	0	0	0.25	15%	0.29	MESSENGER	9	
Cabling	3.00	1	0	0	3.00	15%	3.45	MESSENGER	7	
Pyrotechnic Valve	0.21	3	0	0	0.62	5%	0.65	MESSENGER	9	
Fuel Check Valve	0.23	3	0	0	0.69	5%	0.72	MESSENGER	9	
Ox Check Valve	0.25	3	0	0	0.75	5%	0.79	MESSENGER	9	
Orifice	0.03	3	0	0	0.09	5%	0.09	MESSENGER	9	
Test Port	0.03	2	0	0	0.06	5%	0.06	MESSENGER	9	
Pressure Regulators	1.20	2	0	0	2.40	5%	2.52	MESSENGER	9	
Propulsion Diode Box	1.50	1	0	0	1.50	15%	1.73	MESSENGER	9	
Command & Data Handling (C&DH)					**7.4**	**14%**	**8.5**			
IEM (internally redundant sets of 3 cards, 6 cards total in one box)	7.00	1	1	5	7.00	15%	8.05	MESSENGER/STEREO	7	
DC-DC Converter Card (x2)									8	
Spacecraft Interface Card (x2)									7	
LEON3 Processor Card (x2)									7	
TRIOS	0.04	10	1	5	0.40	5%	0.42	MESSENGER	9	
Electrical Power (EPS)					**88.1**	**13%**	**99.9**			
Power Distribution Unit (PDU) (redundant)	14.00	1	1	1	14.00	5%	14.70	RBSP	9	
CMD/TLM Slice (x2)									9	
FET Switch Slice (x3)									9	
Propulsion Interface Electronics Slice									9	
Relay/Capacitor Slice (x2)									9	
Fuse Modules (x5)									9	
Battery	15.00	1	1	1	15.00	15%	17.25	RBSP - scaled to 20Ah from 50Ah	7	
Shunts	1.00	4	1	1	4.00	15%	4.60	New Horizons	9	
ASRG	23.28	2	0	0	46.56	15%	53.54	Under development - NASA GRC	6	Expected to be flight ready and TRL 9 by 2015
Power System Electronics (PSE) - SRU	8.56	1	1	1	8.56	15%	9.84		7	

Appendix B- Master Equipment List and Power Table

Guidance, Navigation, and Control					**16.7**	**5%**	**17.5**				
IMU (Honeywell MIMU)	4.70	2	0	1	9.40	5%	9.87	New Horizons		9	
DSS (Adcole FSS with SPS, both internally redundant)	1.25	1	0	1	1.25	5%	1.31	New Horizons		9	
Star Trackers (Galileo Avionica A-STR)	3.00	2	0	1	6.00	5%	6.30	New Horizons		9	
Thermal Control (TCS)					**37.3**	**15%**	**42.9**				
MLI Blankets	26.00	1	0	0	26.00	15%	29.90	New Horizons		9	
RHU	0.04	8	0	0	0.32	15%	0.37	Cassini		9	
Heaters	0.20	5	0	0	1.00	15%	1.15	New Horizons		9	
Tape	2.00	1	0	0	2.00	15%	2.30	New Horizons		9	
Heat Pipes	5.00	1	0	0	5.00	15%	5.75	New Horizons		9	
Radiators	2.00	1	0	0	2.00	15%	2.30	New Horizons		9	
Plume Shield	1.00	1	0	0	1.00	15%	1.15	New -Calc		7	
RF Communications					**47.4**	**14%**	**53.9**				
Coherent Transceiver A - X-Band (1 Rx & 1 Tx), Ka-Band (1 Tx)	2.40	1	0	1	2.40	15%	2.76	New Horizons/ RBSP/ XKa Xcvr		7	
Coherent Transceiver B - X-Band (1 Rx & 1 Tx), Ka-Band (1 Tx)	2.40	1	0	1	2.40	15%	2.76	New Horizons/ RBSP/ XKa Xcvr		7	
X TWTA #2 w/ cotherm	0.81	1	0	0	0.81	5%	0.85	New Horizons, 12W RF X-band TWTA		9	
X TWTA #1 w/ cotherm	0.81	1	0	0	0.81	5%	0.85	New Horizons, 12W RF X-band TWTA		9	
X EPC #2	1.64	1	0	0	1.64	5%	1.72	New Horizons		9	
X EPC #1	1.64	1	0	0	1.64	5%	1.72	New Horizons		9	
Ka TWTA #2 w/ cotherm	0.81	1	0	0	0.81	15%	0.93	17W RF Ka-band TWTA does not exist		8	bracketed by 10W Ka-band TWTA on MRO, 40W Ka-band TWTA on LRO both TRL 9
Ka TWTA #1 w/ cotherm	0.81	1	0	0	0.81	15%	0.93	17W RF Ka-band TWTA does not exist		8	bracketed by 10W Ka-band TWTA on MRO, 40W Ka-band TWTA on LRO both TRL 9
Ka EPC #2	2.19	1	0	0	2.19	15%	2.52			8	
Ka EPC #1	2.19	1	0	0	2.19	15%	2.52			8	
Dish Assy with 2.5m HGA, MGA, LGA	24.80	1	0	1	24.80	15%	28.52	New Horizons		7	
Aft LGA	0.71	1	0	1	0.71	5%	0.75	New Horizons		9	
Ka Hybrid Coupler	0.05	1	0	1	0.05	5%	0.05	LRO		9	
Switch Ass'y, Diplexers	4.61	1	0	1	4.61	15%	5.30	New Horizons		9	
Cables	1.50	1	0	0	1.50	15%	1.73	New Horizons		8	
Harness	24.32	1	0	0	**24.3**	**15%**	**28.0**	6% total CBE dry mass		7	
TOTAL DRY MASS					**429.7 kg**	**13%**	**483.4 kg**				
Dry Mass Margin					30%	(Note 1)	**184.8 kg**				
MAXIMUM DRY MASS							**614.5 kg**				

Consumables	561.89 kg	Assumes 1633 m/s deterministic + 300 m/s nodeterministic
Usable Fuel N2H4	314.20 kg	
Residual Fuel N2H4	2.40 kg	
Usable Oxidizer	241.43 kg	
Residual Oxidizer	1.85 kg	
Pressurant	2.01 kg	
Total Wet Mass (CBE)	991.58 kg	
Total Wet Mass (Maximum)	1176.34 kg	
Launch Capability	1190.00 kg	for Atlas V-411 with Star 48 for C3=78.2 km2/s2
Unused Launch Margin (kg)	13.66 kg	

Appendix B- Master Equipment List and Power Table

Spacecraft Power Modes

Trojan Asteroid ASRG Power Budget Subsystem/Component	Total Steady-State Power CBE (W)	Launch (W)	Separation (W)	Checkout (W)	Delta-V Prep (W)	Delta-V DSM (W)	Delta-V TCM (W)	Cruise (W)	Orbit Science (W) (Inside)	Orbit Science (W) (Outside)	Orbit Science (W) Total	Orbit TX (W) (Inside)	Orbit TX (W) (Outside)	Orbit TX (W) Total
Instruments	68.50	**0.00**	**15.00**	**30.00**	**15.00**	**15.00**	**15.00**	**15.00**	**36.50**	**17.00**	**53.50**	**10.00**	**3.02**	**13.02**
Imager (WAC/NAC)	7.00			7.00					4.00	3.00	7.00			0.00
Mapping IR Spectrometer	7.00			7.00						7.00	7.00			0.00
Gamma Ray Spectrometer (GRS)	10.00			10.00					10.00		10.00	10.00		10.00
Neutron Spectrometer (NS)	6.00			6.00					6.00		6.00			0.00
Thermal Imager	7.00			7.00						7.00	7.00			0.00
UV Spectrometer	4.50			4.50					4.50		4.50			0.00
LIDAR	12.00			12.00					12.00		12.00			0.00
Operational Heater Power	0.00			0.00							0.00			0.00
Survival Heater Power	15.00		15.00	7.50	15.00	15.00	15.00	15.00	0.00	0.00	0.00	0.00	3.02	3.02
Payload Total	68.50	**0.00**	**15.00**	**61.00**	**15.00**	**15.00**	**15.00**	**15.00**	**36.50**	**17.00**	**53.50**	**10.00**	**3.02**	**13.02**
Spacecraft														
Command & Data Handling	**10.50**	**10.50**	**10.50**	**10.50**	**10.50**	**10.50**	**10.50**	**10.50**	**10.50**	**0.00**	**10.50**	**10.50**	**0.00**	**10.50**
IEM Active														
C&DH/SSR/Inst IF/DL Digital	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00		10.00	10.00		10.00
TRIOs	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50		0.50	0.50		0.50
Electrical Power System	**38.47**	**12.97**	**12.97**	**12.97**	**12.97**	**12.97**	**12.97**	**12.97**	**12.97**	**0.00**	**12.97**	**12.97**	**0.00**	**12.97**
SRU Unswitched (= RTG - Shunt - Load)	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50		2.50	2.50		2.50
SRU Telemetry	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17		1.17	1.17		1.17
PDU/PDB (1 cmd + 1 tlm)	9.30	9.30	9.30	9.30	9.30	9.30	9.30	9.30	9.30		9.30	9.30		9.30
PDU/PDB (2 cmd + 2 tlm)	14.00													
PDU/PDB (2 cmd + 1 tlm)	11.50													
RF Communications	**244.00**	**12.00**	**47.00**	**47.00**	**47.00**	**47.00**	**47.00**	**12.00**	**29.00**	**0.00**	**29.00**	**47.00**	**17.00**	**64.00**
Transceiver A														
Receiver Only	6.00	6.00						6.00	6.00		6.00			0.00
TX + RX (X-band)	9.00		9.00	9.00	9.00	9.00	9.00							
TX + RX (Ka-band)	13.00											13.00		13.00
Transceiver B														
Receiver Only	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00		6.00	6.00		6.00
TX + RX (X-band)	9.00													
TX + RX (Ka-band)	13.00													
X TWTA #1														
Standby	8.50								0.00		0.00	0.00		0.00
TX	32.00		32.00	32.00	32.00	32.00	32.00							
X TWTA #2														
Standby	8.50		0.00	0.00	0.00	0.00	0.00		0.00		0.00	0.00		0.00
TX	32.00													
Ka TWTA #1														
Standby	8.50								8.50		8.50			0.00
TX	45.00											28.00	17.00	45.00
Ka TWTA #2														
Standby	8.50								8.50		8.50			0.00
TX	45.00											0.00	0.00	0.00

Appendix B- Master Equipment List and Power Table

Guidance, Navigation, and Control	**42.58**	**0.00**	**30.89**	**42.58**	**30.89**	**22.00**	**22.00**	**30.89**	**22.00**	**8.89**	**30.89**	**22.00**	**8.89**	**30.89**
Sun Sensor	2.80	0.00	0.00	2.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Star Tracker #1	8.89		8.89	8.89	8.89	0.00	0.00	8.89		8.89	8.89		8.89	8.89
Star Tracker #2	8.89			8.89										
IMU	22.00		22.00	22.00	22.00	22.00	22.00	22.00	22.00		22.00	22.00		22.00
Propulsion	**281.26**	**4.50**	**23.57**	**23.57**	**36.65**	**119.57**	**124.77**	**23.57**	**4.50**	**19.07**	**23.57**	**4.50**	**19.07**	**23.57**
Thruster, AMBR 667N (150lbf) (1)	46.00					46.00								
AMBR Injector Heater	50.00					50.00								
Thruster, 22.24N (5lbf) (4)	101.20						101.20							
22.24N Cat. Bed Heaters (4 htrs, 4 primary e	13.08				13.08									
Thruster, 0.9N (0.2lbf) (12)	43.68		0.07	0.07	0.07	0.07	0.07	0.07		0.07	0.07		0.07	0.07
0.9N Cat. Bed Heaters (12 htrs, 12 primary e	22.80		19.00	19.00	19.00	19.00	19.00	19.00		19.00	19.00		19.00	19.00
Pressure Transducers (5)	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50	4.50		4.50	4.50		4.50
Thermal Required Loads	**10.57**	**3.57**	**3.57**	**3.57**	**3.57**	**10.57**	**10.57**	**3.57**	**0.00**	**3.57**	**3.57**	**0.00**	**3.57**	**3.57**
Tank Heaters	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00		0.00
Valve Heaters 35% Duty	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77		0.77	0.77		0.77	0.77
Line Heaters 45% Duty	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00		0.00	0.00
AMBR Valve Heater	2.80	2.80	2.80	2.80	2.80	2.80	2.80	2.80		2.80	2.80		2.80	2.80
Star Tracker Survival Heater	7.00		0.00		0.00	7.00	7.00	0.00	0	0		0	0	
Subtotal	695.89	43.55	143.51	170.20	156.59	237.62	242.82	108.51	115.47	48.54	164.01	106.97	51.55	158.53
Harness														
SC Harness (2.5% of Load)	17.40	1.09	3.59	4.25	3.91	5.94	6.07	2.71	2.89		2.89	2.67		2.67
Total Power Dissipation	**713.28**	**44.64**	**147.10**	**174.45**	**160.50**	**243.56**	**248.89**	**111.22**	**118.36**	**48.54**	**168.54**	**109.65**	**51.55**	**171.55**
Total Thermos Bottle losses (120 W)									**120.00**			**120.00**		
Internal Shunt Heaters (W)									**1.64**			**10.35**		
Total Load Power at PDU Output	**713.28**	**44.64**	**147.10**	**174.45**	**160.50**	**243.56**	**248.89**	**111.22**			**168.54**			**171.55**
ASRG Power Capability		**140.00**	**280.00**	**280.00**	**256.00**	**256.00**	**256.00**	**256.00**			**256.00**			**256.00**
Total Power Capability (at PDU Output)		**133.08**	**266.17**	**266.17**	**243.35**	**348.29**	**355.91**	**243.35**			**243.35**			**243.35**
Actual Margin for Study (MAX-CBE)/MAX		**66%**	**45%**	**34%**	**34%**	**30% ***	**30% ***	**54%**			**31%**			**30%**

Notes

Delta-V DSM assumes burn executed inertially while spinning (NOT turn and burn).

Delta-V Prep includes catbeds on for 5lb thrusters for TCMs, which would not be needed in prep for DSM.

RHUs added to thruster assembly plates to warm valves and lines, so less heater power drawn.

20 Ah LIO Battery used for Delta-V DSM and TCM.

Trojan Tour Decadal Survey Concepts Summary

(Presented on 13 May 2010)

Robert Gold, Andrew Rivkin,

Kenneth Hibbard, Marsha Schwinger

Trojan Tour Decadal Study: Appendix C

The Johns Hopkins University

APPLIED PHYSICS LABORATORY

Concept Science Trade

Concept	Diversity	Operations	Mission Length	Other
Chemical Solar	Prime rendezvous + pre-rendezvous flyby(s)	Battery -> Limited eclipses, no noon orbit	~11 years to primary target	Jupiter flyby with possible flyby science
Chemical 2 ASRG	Prime rendezvous + pre-rendezvous flyby(s)	No orbit restrictions. Potential for landing.	~11 years to primary target	Jupiter flyby with possible flyby science
REP 6 ASRG	Prime rendezvous + pre-rendezvous flyby(s) + possible 2nd rendezvous + post-rendezvous flyby(s)	No orbit restrictions. Potential for landing.	~8 years to primary target	Large propulsion capability enables 2nd rendezvous.

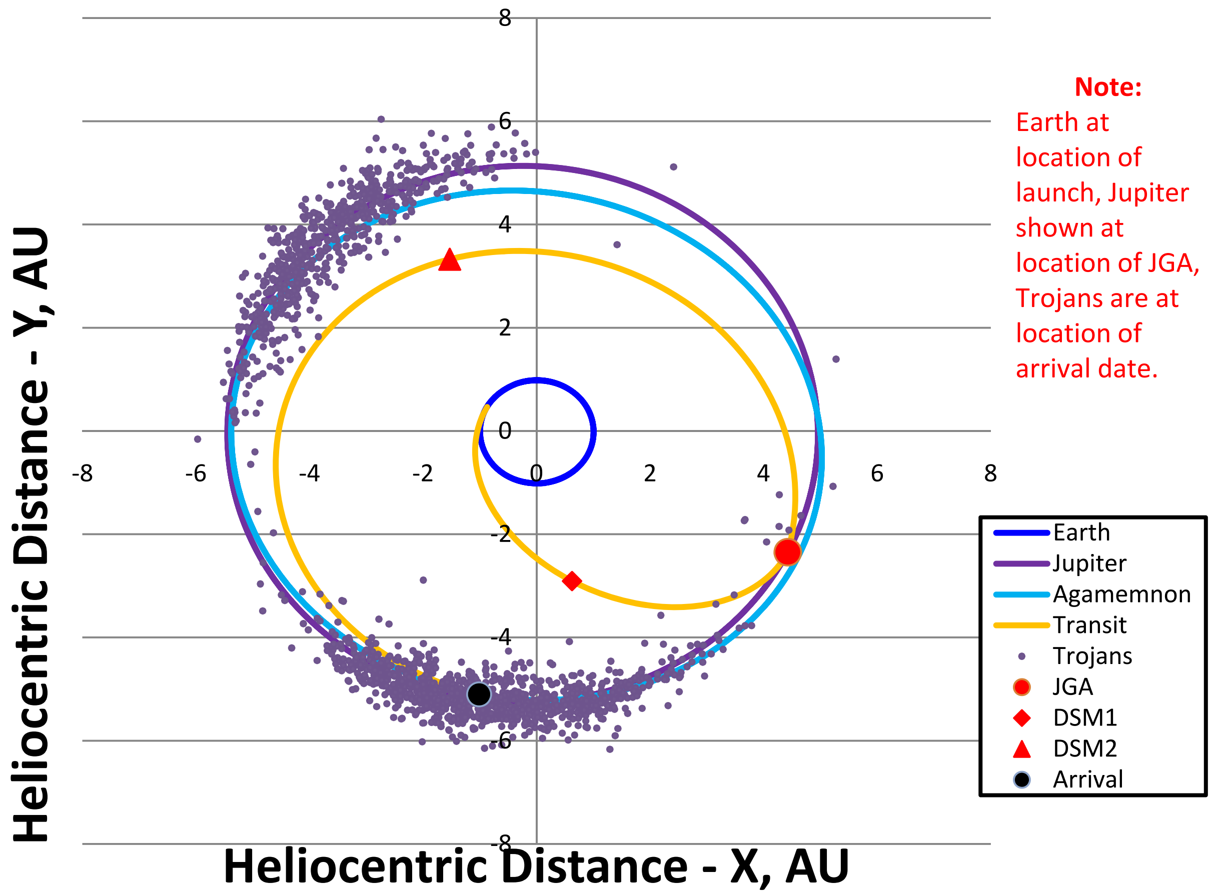
CHEMICAL CONCEPTS

Mission Design for Chemical Concepts

Provided by John Dankanich (GRC)

- **Primary Target Asteroid 911 Agamemnon**
  - C3: 73 km²/s²
  - Delta-V: 1633 m/s
  - Launch: Feb 2019
  - Cruise: 10 years

- **Backup Target Asteroid 4060 Deipylos**
  - C3: 75 km²/s²
  - Delta-V: 1600 m/s
  - Launch: Mar 2020
  - Cruise: 9.4 years



Note: Earth at location of launch, Jupiter shown at location of JGA, Trojans are at location of arrival date.

Chemical Concepts Overview

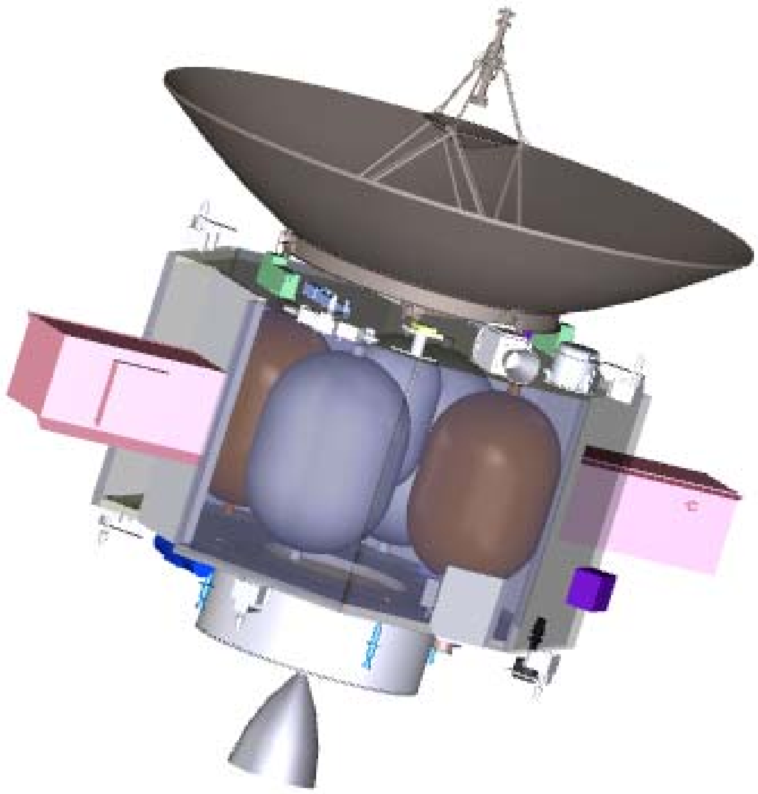
- **Science objectives do not require a landing**
- **Candidate payload from existing instruments**
  - Imager: Wide Angle Camera (WAC) / Narrow Angle Camera (NAC) – MESSENGER MDIS
  - Mapping IR Spectrometer – New Horizons RALPH LEISA
  - Gamma Ray Spectrometer – MESSENGER GRS
  - Neutron Spectrometer – MESSENGER NS
  - Thermal Imager – LRO DIVINER
  - UV Spectrometer – MESSENGER MASCS UVVS
  - LIDAR – NEAR
- **Trade between an ASRG versus Solar Array power system**
- **Both concepts include**
  - Pressure regulated dual-mode bipropellant/hydrazine propulsion system
  - Ka-band for nominal science return; X-band uplink and downlink
  - 2.5 m dish
  - Avionics consisting of integrated electronics module (IEM), TRIOs, and power distribution unit (PDU)
  - IMU and star trackers for attitude knowledge
  - Sun sensor for sun direction knowledge in contingencies

Instrument Data Return

Instrument	Instantaneous Data Rate	Data Per Day
Imager WAC/NAC (MDIS)	3 Mbps	120 Mbits/d
Mapping IR Spectrometer (Ralph-LEISA)	50 kbps	120 Mbits/d
Gamma Ray Spectrometer	4 kbps	13 Mbits/d
Neutron Spectrometer	4 kbps	13 Mbits/d
Thermal Imager	50 kbps	30 Mbits/d
UV Spectrometer	4 kbps	13 Mbits/d
LIDAR	4 kbps	10 Mbits/d

- **17W RF Ka-band TWTA provides 12.5 kbps average downlink rate**
- **Assume one 8-hour pass per day to a 34m antenna with 8 hours if actual data downlink**
- **270 day orbital phase**
- **Can return approximately 360 Mbits/day; 9.7 x 10^{10} bits over the entire mission**
  - 75% for the imaging instruments
  - 15% for the non-imaging instruments
  - 10% for housekeeping data

ASRG Concept

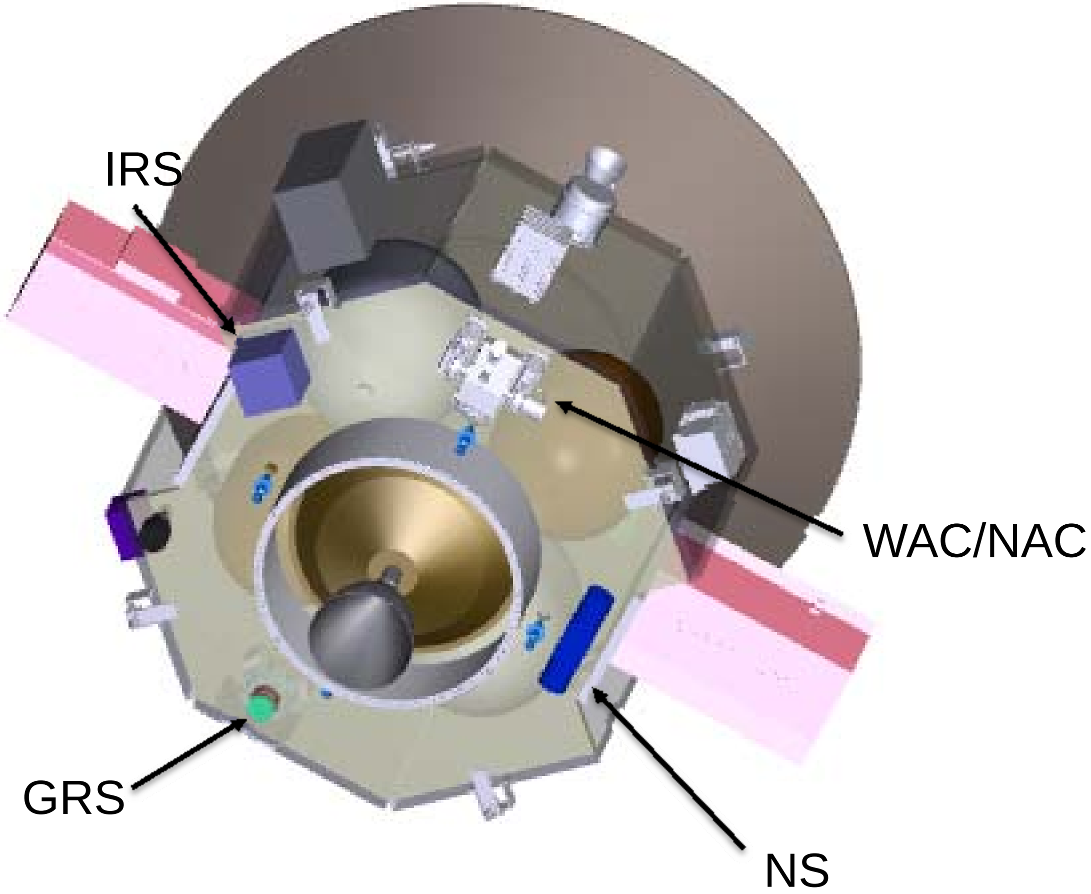


- **Updated ILION concept from DSMCE study**
- **Two ASRGs provide primary power**
- **20 Ah LIO battery to support Delta-V and peak power loads**
- **Attitude control via 0.2 lbf thrusters**
- **Thermal control passive “thermos bottle” design approach**
- **Fits in Atlas V 411 launch vehicle**

APL

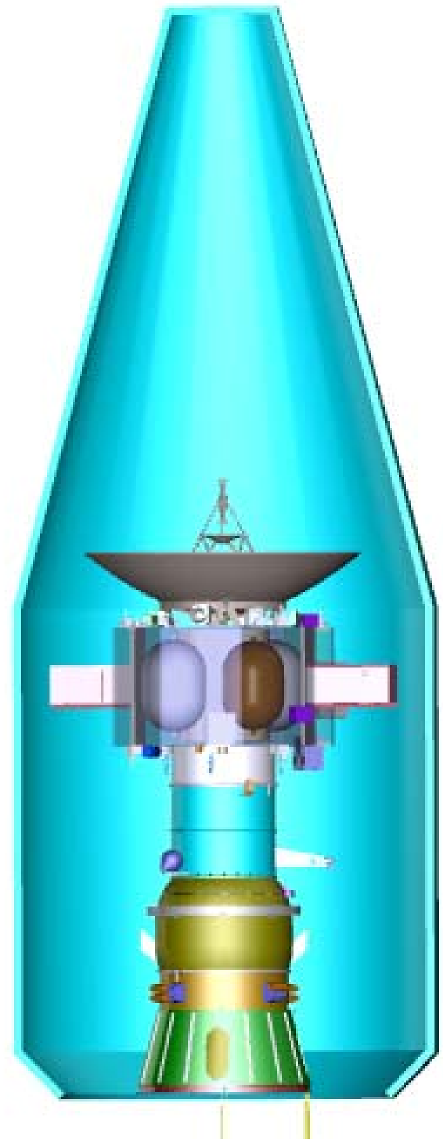
ASRG Concept Layout - Instruments

UV Spectrometer,
Thermal Imager,
LIDAR not shown



APL

ASRG Concept – Stack-up in 4m Fairing



ASRG Concept – Mass Summary

(refer to MEL/PEL for official numbers)

Trojan Tour ASRG Chemical Concept Mass Summary			
Subsystem	CBE Mass (kg)	Contingency	MEV Mass (kg)
Instruments	44.50	15%	51.18
Structures	85.94	15%	98.83
Propulsion	77.98	5%	82.03
Command & Data Handling (C&DH)	7.40	14%	8.47
Electrical Power (EPS)	88.12	10%	96.68
Guidance, Navigation, and Control	16.65	5%	17.48
Thermal Control (TCS)	37.32	14%	42.42
RF Communications	46.27	8%	50.09
Harness	24.25	15%	27.89
Subtotal Dry Mass	428.43	11%	475.06
Margin		32%	137.59
Total Dry Mass		43%	612.65
Useable Fuel			314.20
Useable Oxidizer			241.43
Residual Propellant			4.25
Helium			2.01
Total Consumables			561.89
Total Wet Mass			1174.54
Launch Vehicle Capability			1200.00
Contingency (kg)			46.63
Contingency %			11%
Margin above Contingency (kg)			137.59
Margin above Contingency (%)			32%
Total Margin above CBE %			43%
Unused launch mass (kg)			25.46

ASRG Concept – Power Summary

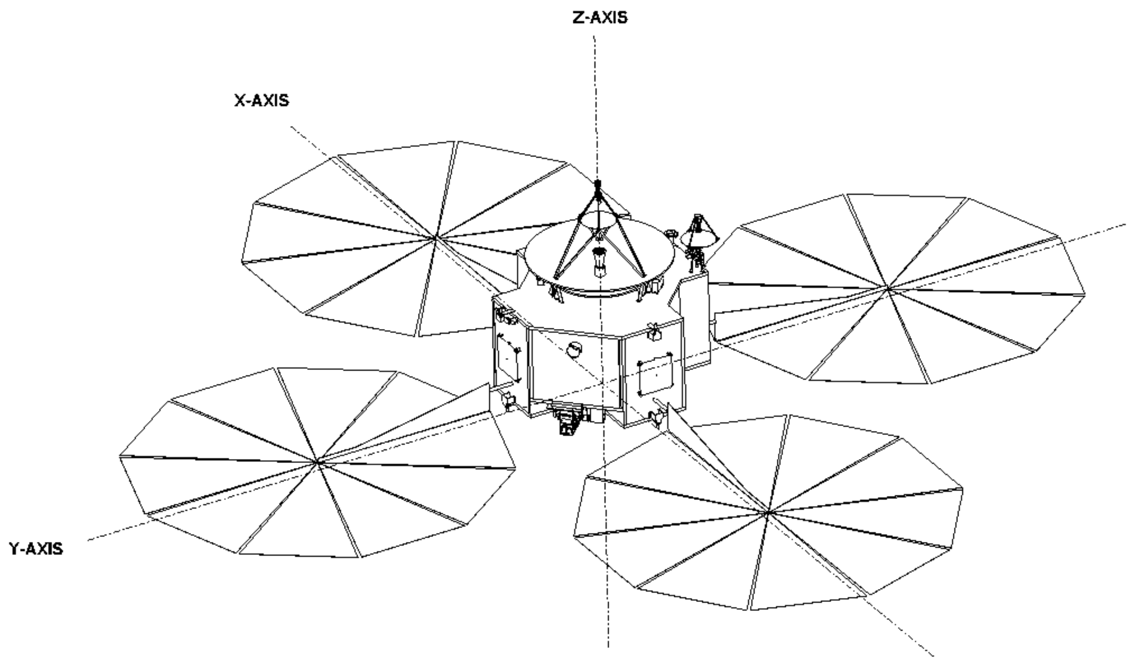
(refer to MEL/PEL for official numbers)

Trojan Asteroid ASRG Power Budget	CBE	Launch	Separation	Check-out	Delta-V Prep	Delta-V DSM	Delta-V TCM	Cruise	Orbit Science (inside)	Orbit Science (Outside)	Orbit Science Total	Orbit TX (inside)	Orbit TX (Outside)	Orbit TX Total
Payload	68.50	0.00	15.00	30.00	15.00	15.00	15.00	15.00	36.50	17.00	53.50	10.00	3.02	13.02
Spacecraft														
Command & Data Handling	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50	10.50	0.00	10.50	10.50	0.00	10.50
Electrical Power System	38.47	12.97	12.97	12.97	12.97	12.97	12.97	12.97	12.97	0.00	12.97	12.97	0.00	12.97
RF Communications	212.00	12.00	48.50	48.50	48.50	48.50	48.50	12.00	29.00	0.00	29.00	38.00	17.00	55.00
Guidance, Navigation, and Control	42.58	0.00	30.89	42.58	30.89	22.00	22.00	30.89	22.00	8.89	30.89	22.00	8.89	30.89
Propulsion	281.26	4.50	23.57	23.57	36.65	119.57	124.77	23.57	4.50	19.07	23.57	4.50	19.07	23.57
Thermal Required Loads	10.57	3.57	3.57	3.57	3.57	10.57	10.57	3.57	0.00	3.57	3.57	0.00	3.57	3.57
Subtotal	663.89	43.55	145.01	171.70	158.09	239.12	244.32	108.51	115.47	48.54	164.01	97.97	51.55	149.53
Harness														
SC Harness (2.5% of Load)	16.60	1.09	3.63	4.29	3.95	5.98	6.11	2.71	2.89		2.89	2.45		2.45
Total Power Dissipation	680.48	44.64	148.64	175.99	162.04	245.10	250.43	111.22	118.36	48.54	168.54	100.42	51.55	171.55
Total Thermos Bottle losses (120 W)									120.00			120.00		
Internal Shunt Heaters (W)									1.64			19.58		
Total Load Power at PDU Output	680.48	44.64	148.64	175.99	162.04	245.10	250.43	111.22			168.54			171.55
ASRG Power Capability		140.00	280.00	280.00	256.00	256.00	256.00	256.00			256.00			256.00
Total Power Capability (at PDU Output)		133.08	266.17	266.17	243.35	350.49	358.11	243.35			243.35			243.35
Actual Margin for Study (MAX-CBE)/MAX		66%	44%	34%	33%	30%	30%	54%			31%			30%

ASRG Concept Risks/Challenges

- **Meeting the 43% power margin is challenging, but achieved**
  - Considered optimized ASRGs
  - Considered adding a third ASRG
  - Added RHUs to decrease outside power loads
  - Design includes a battery for maneuvers
- **Approvals for nuclear power source**
- **Closing RF link during Jupiter burn**
  - Assume a 70m equivalent asset (most likely an array of four 34m antennas) available to allow use of the LGAs

Solar Array Concept



- UltraFlex solar arrays, 86 m^2 total area, for primary power
- 20 Ah LIO battery to support peak power loads
- Attitude control nominally via reaction wheels; thrusters used when spin stabilized
- Passive thermal design with individual radiators and heaters
- Fits in Atlas V 541

Solar Array Concept – Mass Summary

(refer to MEL/PEL for official numbers)

Trojan Tour Solar Chemical Concept Mass Summary			
Subsystem	CBE Mass (kg)	Contingency	MEV Mass (kg)
Instruments	44.50	15%	51.18
Structures	126.86	15%	145.88
Propulsion	86.95	5%	91.45
Command & Data Handling (C&DH)	7.40	14%	8.47
Electrical Power (EPS)	195.50	15%	224.35
Guidance, Navigation, and Control	52.25	5%	54.86
Thermal Control (TCS)	37.00	14%	42.05
RF Communications	46.27	8%	50.09
Harness	35.80	15%	41.17
Subtotal Dry Mass	632.53	12%	709.50
Margin		31%	195.02
Total Dry Mass		43%	904.52
Useable Fuel			463.81
Useable Oxidizer			356.44
Residual Propellant			6.28
Helium			2.92
Total Consumables			829.45
Total Wet Mass			1733.97
Launch Vehicle Capability			1800.00
Contingency (kg)			76.97
Contingency %			12%
Margin above Contingency (kg)			195.02
Margin above Contingency (%)			31%
Total Margin above CBE %			43%
Unused launch mass (kg)			66.03

Solar Array Concept – Power Summary

(refer to MEL/PEL for official numbers)

Trojan Asteroid Solar Power Budget	CBE	Launch	Separation	Checkout	Delta-V Prep	Delta-V DSM	Delta-V TCM	Cruise	Orbit Science	Orbit TX	Momentum Dump
Payload	**68.50**	**0.00**	**15.00**	**30.00**	**15.00**	**15.00**	**15.00**	**15.00**	**53.50**	**15.13**	**15.00**
Spacecraft											
Command & Data Handling	**10.50**	**10.50**	**10.50**	**10.50**	**10.50**	**10.50**	**10.50**	**10.50**	**10.50**	**10.50**	**10.50**
Electrical Power System	**31.50**	**25.50**	**31.50**	**31.50**	**31.50**	**25.50**	**25.50**	**31.50**	**31.50**	**31.50**	**31.50**
RF Communications	**212.00**	**12.00**	**48.50**	**48.50**	**48.50**	**48.50**	**48.50**	**12.00**	**29.00**	**55.00**	**48.50**
Guidance, Navigation, and Control	**122.58**	**0.00**	**110.89**	**122.58**	**30.89**	**22.00**	**22.00**	**30.89**	**110.89**	**110.89**	**110.89**
Propulsion	**279.46**	**2.70**	**2.70**	**2.70**	**34.85**	**117.77**	**122.97**	**21.77**	**2.70**	**2.70**	**21.77**
Thermal Required Loads	**73.35**	**66.35**	**66.35**	**66.35**	**66.35**	**73.35**	**73.35**	**66.35**	**66.35**	**66.35**	**66.35**
Subtotal	797.89	117.05	285.44	312.13	237.59	312.62	317.82	188.01	304.44	292.07	304.51
Harness											
SC Harness (2.5% of Load)	19.9	2.9	7.1	7.80	5.94	7.82	7.95	4.70	7.61	7.30	7.61
Total	**817.83**	**119.97**	**292.57**	**319.93**	**243.53**	**320.43**	**325.76**	**192.71**	**312.05**	**299.37**	**312.12**
Solar Array Output		**520.00**	**520.00**	**520.00**	**455.00**	**455.00**	**455.00**	**455.00**	**455.00**	**455.00**	**455.00**
Actual Margin (MAX-CBE)/MAX		**77%**	**44%**	**38%**	**46%**	**30%**	**28%**	**58%**	**31%**	**34%**	**31%**

Solar Array Concept Risks/Challenges

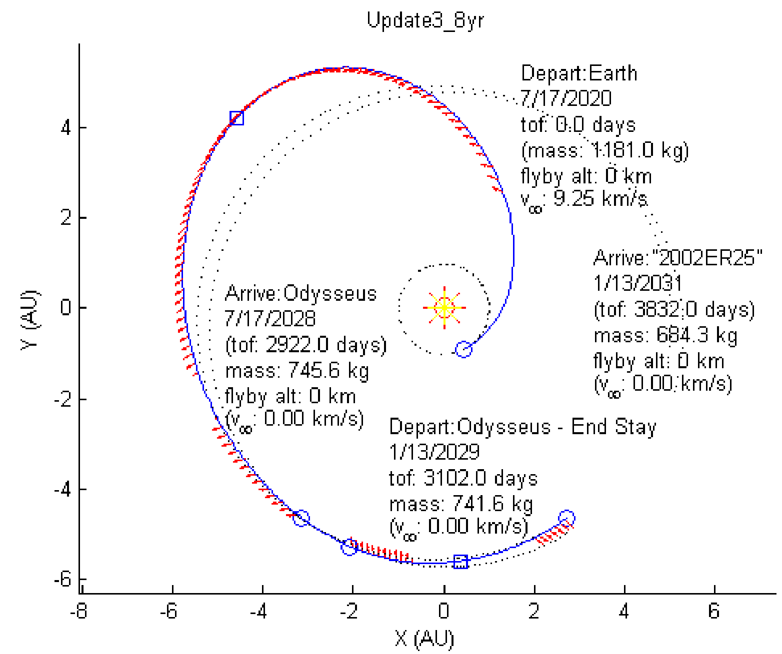
- **Packaging the four large solar array wings**
  - Additional deck for HGA dish to avoid interference with booms when stowed
- **Total wet mass exceeds capabilities of Atlas V 431 with Star 48 for this C3; require an Atlas V-541**
- **Larger bus does not allow for thermos bottle design approach, resulting in increased heater power**
  - Assumed 50W power for tank heaters
  - Further analysis needed; 60-80W could be required
  - Meeting power margins will be a challenge if this value is higher
- **LILT is a major challenge with solar arrays at the desired Sun distances**
  - Factored in lessons learned from Juno
  - Increased testing costs; can only test for LILT concerns and not design away issues
  - 40% of Juno solar cells not usable for the mission
  - Typical mechanical and manufacturing issues with very large arrays

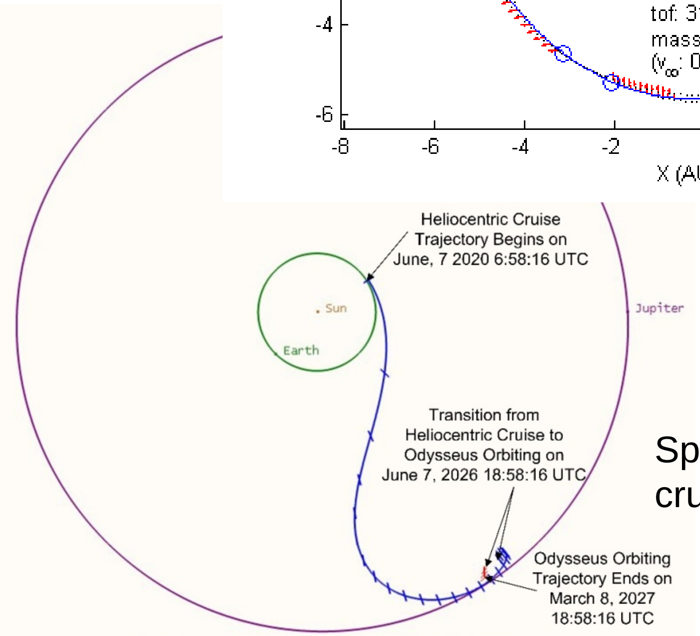
REP CONCEPT

Mission Design for REP Concept

Provided by John Dankanich (GRC)

- **Primary Target Asteroid 1143 Odysseus**
  - C3: 78.5 km^2/s^2
  - Launch: July 2020
  - Cruise: 8 years
- **Secondary Target Asteroid 2002ER25**
  - Depart Odysseus: Jan 2029
  - Arrive: Jan 2031
- **Target Wet Mass 1,181 kg for this mission design**
  - 535 kg Xenon required with margin
  - Allows for 646 kg dry mass with margin, 452 kg CBE
  - Current CBE dry mass is 482 kg (690 kg with margin)+ 25 kg hydrazine for ACS

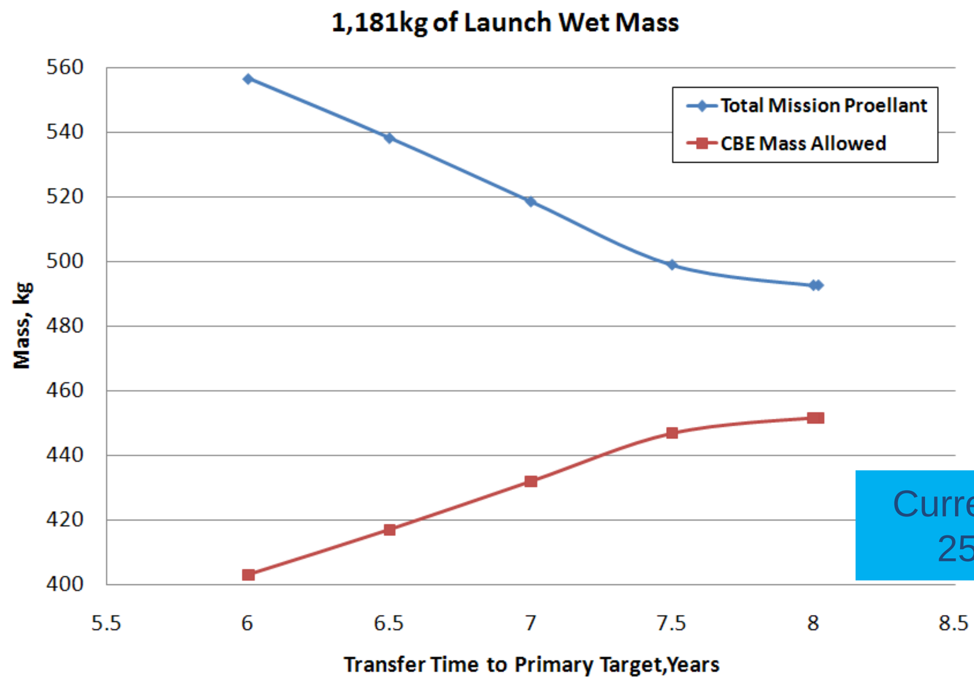




Sun-Centered, Jupiter-Sun-Fixed Frame
Time Ticks Every 3 Months

Spends last 5 years of cruise within Trojan cloud

Baseline Trojan Odysseus with 1,181 kg Wet Mass



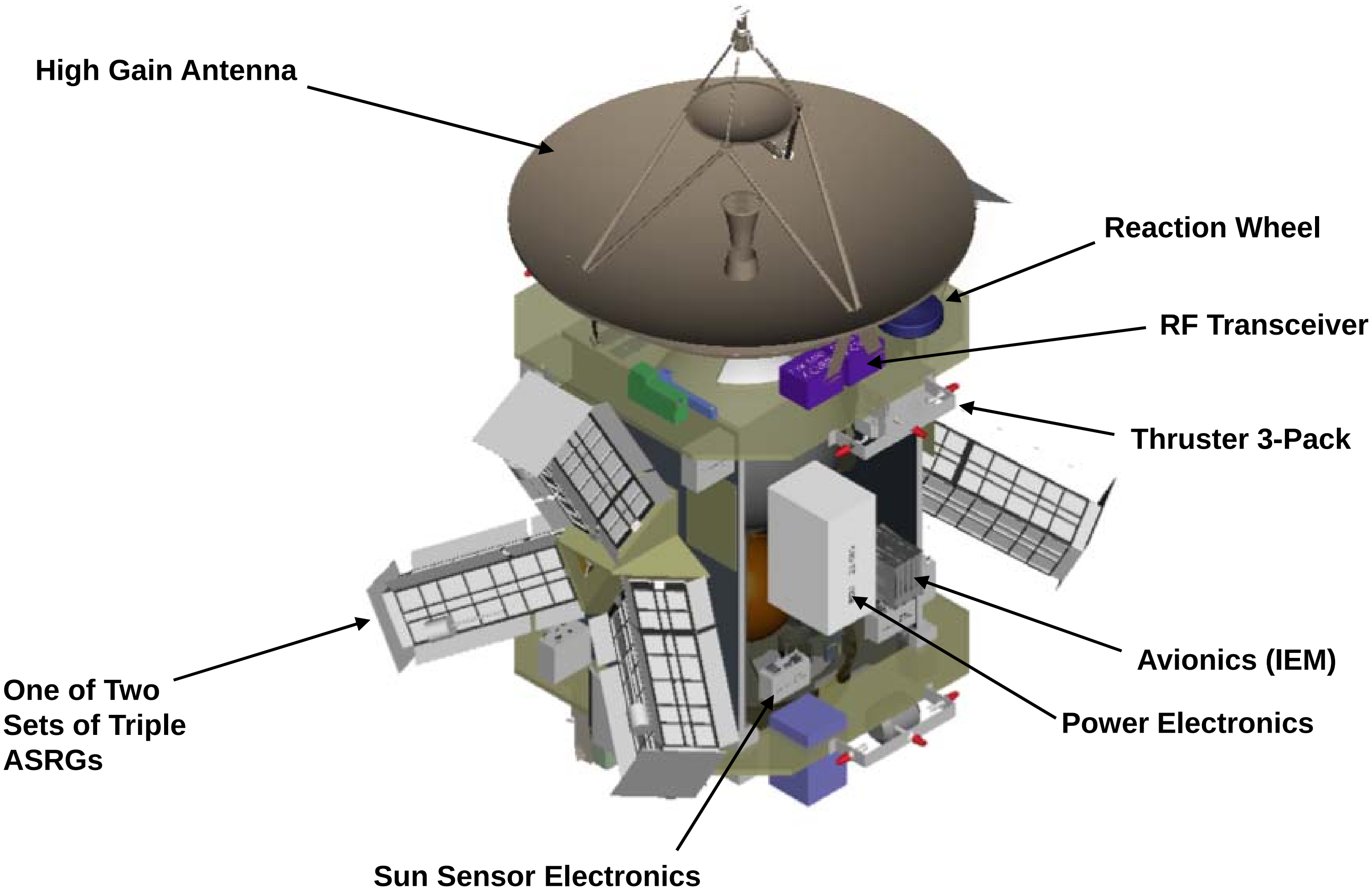
Current CBE mass = 482kg + 25kg Hydrazine for ACS

Trip time, yrs	Propellant Mass	w/ Margin	CBE Mass Allowed	Delivered at first	Mprop for 1 target	w/ Margin	CBE Mass allowed	CBE Delta to enable 2nd target
8.02	492.65	535.02	451.74	745.90	435.10	472.52	521.61	69.87
8.00	492.66	535.03	451.73	745.60	435.40	472.84	521.40	69.67
7.50	499.01	541.92	446.91	732.30	448.70	487.29	512.10	65.19
7.00	518.62	563.22	432.01	713.10	467.90	508.14	498.67	66.66
6.50	538.30	584.59	417.07	695.90	485.10	526.82	486.64	69.58
6.00	556.70	604.58	403.09	680.90	500.10	543.11	476.15	73.06

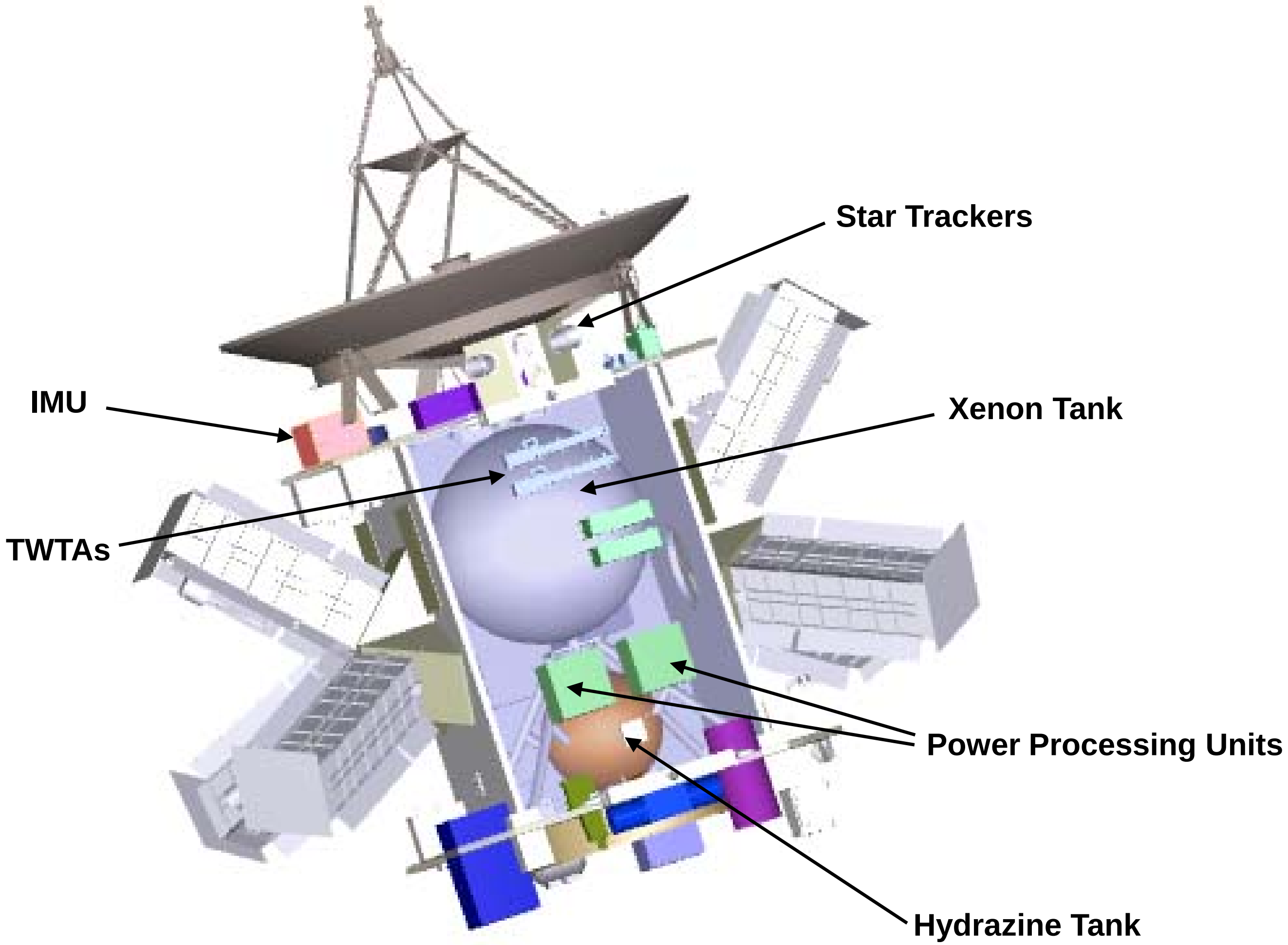
REP Concept Overview

- Fits on Atlas V 431 launch vehicle (1460 kg lift mass for C3=80 km^2/s^2)
- 6 ASRGs provide primary power (810 W at 7 years)
- Radioisotope Electric Propulsion (REP) for cruise and potential travel to a secondary target
- Blowdown monopropellant propulsion system for attitude control
- Single reaction wheel for compensation of swirl torques experienced with Hall thruster
- Ka-band for nominal science return; X-band uplink and downlink
- 1.7 m dish
- Avionics consisting of integrated electronics module (IEM) and TRIOs
- Power electronics for power distribution and shunt regulation
- Passive thermal control “thermos bottle” design approach
- Inertial Measurement Unit (IMU) and star trackers for attitude knowledge
- Sun sensor for sun direction knowledge in contingencies

REP Concept Layout (1/2)

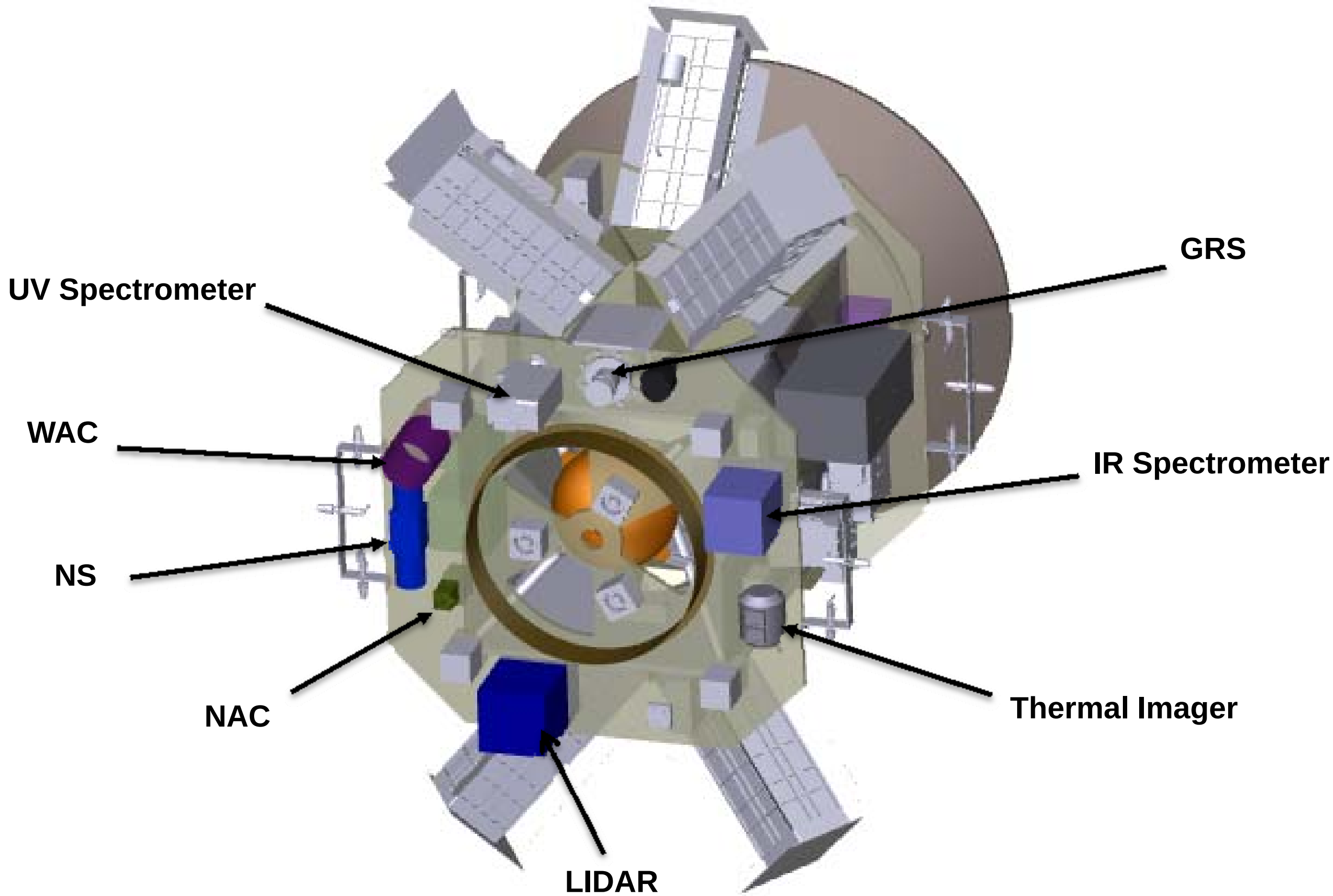


REP Concept Layout (2/2)



REP Concept - Instruments

- **Same instruments as chemical propulsion concepts**



REP Concept – Mass Summary

(refer to MEL/PEL for official numbers)

Trojan Tour ASRG REP Concept Mass Summary			
Subsystem	CBE Mass (kg)	Contingency	MEV Mass (kg)
Instruments	44.50	15%	51.18
Structures	85.18	15%	97.96
Propulsion	18.04	6%	19.09
Radioisotope Electric Propulsion	46.40	5%	48.72
Command & Data Handling (C&DH)	7.40	14%	8.47
Electrical Power (EPS)	168.00	6%	178.80
Guidance, Navigation, and Control	17.63	5%	18.51
Thermal Control (TCS)	33.32	13%	37.82
RF Communications	37.17	9%	40.64
Harness	24.67	15%	28.38
Subtotal Dry Mass	482.31	10%	529.56
Margin		33%	160.15
Total Dry Mass		43%	689.71
Useable Fuel			25.00
Residual Propellant			0.13
Pressurant			0.04
Useable Xenon			475.00
Total Consumables			500.17
Total Wet Mass			1189.88
Launch Vehicle Capability			1420.00
Contingency (kg)			47.25
Contingency %			10%
Margin above Contingency (kg)			160.15
Margin above Contingency (%)			33%
Total Margin above CBE %			43%
Unused launch mass (kg)			230.12

REP Concept – Power Summary

(refer to MEL/PEL for official numbers)

Trojan Asteroid REP Power Budget	CBE	Launch	Separation	Checkout	Checkout EP	Delta-V ACS Burn	Cruise (Inside)	Cruise (Outside)	Cruise Total	Orbit Science (Inside)	Orbit Science (Outside)	Orbit Science Total	Orbit TX (Inside)	Orbit TX (Outside)	Orbit TX Total
Payload	68.50	0.00	15.00	30.00	15.00	15.00	0.00	15.00	15.00	36.50	17.00	53.50	10.00	6.56	16.56
Spacecraft															
Command & Data Handling	10.50	10.50	10.50	10.50	10.50	10.50	10.50	0.00	10.50	10.50	0.00	10.50	10.50	0.00	10.50
Electrical Power System	101.00	125.78	125.09	124.79	106.04	123.14	105.38	0.00	105.38	123.08	0.00	123.08	123.05	0.00	123.05
RF Communications	244.00	12.00	47.00	47.00	47.00	47.00	12.00	0.00	12.00	12.00	0.00	12.00	47.00	17.00	64.00
Guidance, Navigation, and Control	62.00	0.00	54.00	62.00	54.00	54.00	47.00	7.00	54.00	37.00	7.00	44.00	37.00	7.00	44.00
Propulsion	68.28	1.80	20.87	20.87	20.87	20.87	1.80	19.07	20.87	1.80	19.07	20.87	1.80	19.07	20.87
Radioisotope Electric Propulsion	38.00	0.00	0.00	0.00	38.00	0.00	38.00	0.00	38.00	0.00	0.00	0.00	0.00	0.00	0.00
Thermal Required Loads	15.27	8.27	8.27	8.27	8.27	8.27	0.00	8.27	8.27	0.00	8.27	8.27	0.00	8.27	8.27
Subtotal (Thermal)	607.55	158.35	280.73	303.43	299.68	278.78	214.68	49.34	264.02	220.88	51.34	272.22	229.35	57.90	287.25
Subtotal (Electrical)	473.55	37.57	160.64	183.64	160.64	160.64	76.30	49.34	125.64	102.80	51.34	154.14	111.30	57.90	169.20
Harness															
SC Harness (2.5% of Load)	15.19	3.96	7.02	7.59	7.49	6.97	6.60		6.60	6.81		6.81	7.18		7.18
Thermos Bottle Heat load	235.00	235.00	235.00	235.00	235.00	235.00	235.00			235.00			235.00		
Internal Bus Heaters via PDU switches (W)		72.69	0.00	0.00	0.00	0.00	13.72			7.31			0.00		
Total Power Dissipation (electrical)	488.74	114.22	167.66	191.23	168.13	167.61	96.62	49.34	145.96	116.92	51.34	168.26	118.48	57.90	176.38
Total Load Power with 43% Study Margin		163.33	239.75	273.45	240.43	239.68			208.72			240.61			252.23
ASRG Power Capability		876.00	876.00	876.00	876.00	810.00			843.00			810.00			810.00
Unused ASRG Power		712.67	636.25	602.55	635.57	570.32			634.28			569.39			557.77
Power out of PPU (94% efficiency) to Engine					597.44				596.22						
Power heat (0.06%) (thermal only)					38.13				38.06						
Total External Shunt Heat (W)		712.67	636.25	602.55	0.00	570.32			0.00			569.39			557.77

REP Concept Risks/Challenges

- **Mass is a challenge**
  - Design closes for primary target, but not for secondary target.
    - Current concept is only 8 kg away from target wet mass, but only carries 475 kg Xenon
    - 435 kg needed for Odysseus & 493 kg for both Odysseus and 2002ER25 (without margin)
    - REP design closes with full margins for primary rendezvous target
  - As launch mass increases, the REP thruster efficiency drops (begin to only really push additional propellant needed).
  - With more time could optimize targets and/or decrease mass.
- **Additional complexity of the electric propulsion system**
- **Plutonium availability for 6 ASRGs**

Concept Selection Discussion

- **Now that we have three concepts reasonably defined, the question is which is the preferred concept to document and cost in detail for the study report**
  - Chemical/ASRG closes with required margins and achieves all of the primary science objectives, and enables potential secondary science objectives (e.g. landing)
  - Chemical/SA closes with required margins and achieves all of the primary science objectives with some notable technical challenges; does not appear to enable any secondary science objectives
  - REP closes for primary target but not for second target. We believe that a solution is certainly achievable within the next decade. REP achieves all of the primary science objectives, and enables secondary science objectives such as landing and probably a second rendezvous.
- **Cost estimates should also factor into the decision**
- **APL would like guidance from the science champions as to their preference on the mission concept**

Trojan Tour Decadal Survey Kick-off Science Slides

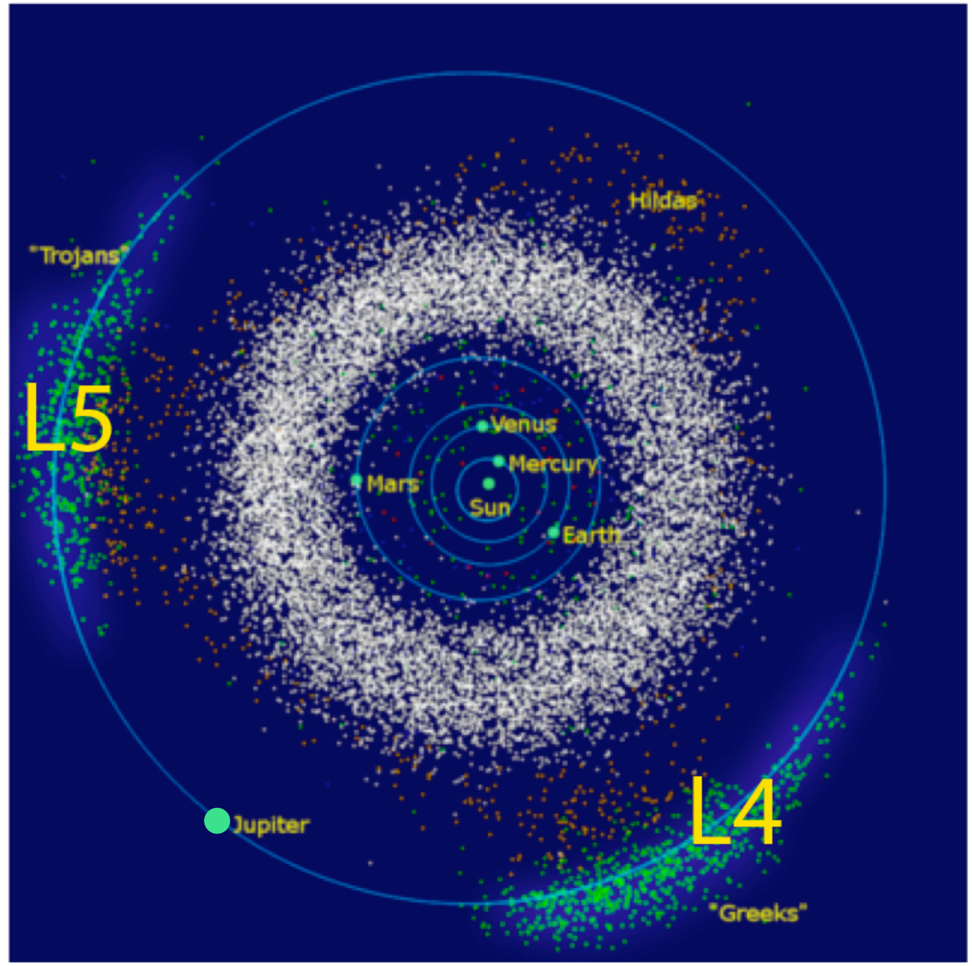
Andy Rivkin
Rob Gold

Trojan Tour Decadal Survey: Appendix D

APL
The Johns Hopkins University
APPLIED PHYSICS LABORATORY

Why Trojans?

- **Trojans are unexplored ancient objects**
- **More than 300,00 in stable orbits about L_4 & L_5 Lagrange points**
- **Spectral properties like cometary nuclei**
  - **Organics rich?**
  - **Icy interiors?**
- **Low albedo, difficult to observe from Earth**
- **Formed at 5 or 30 AU?**



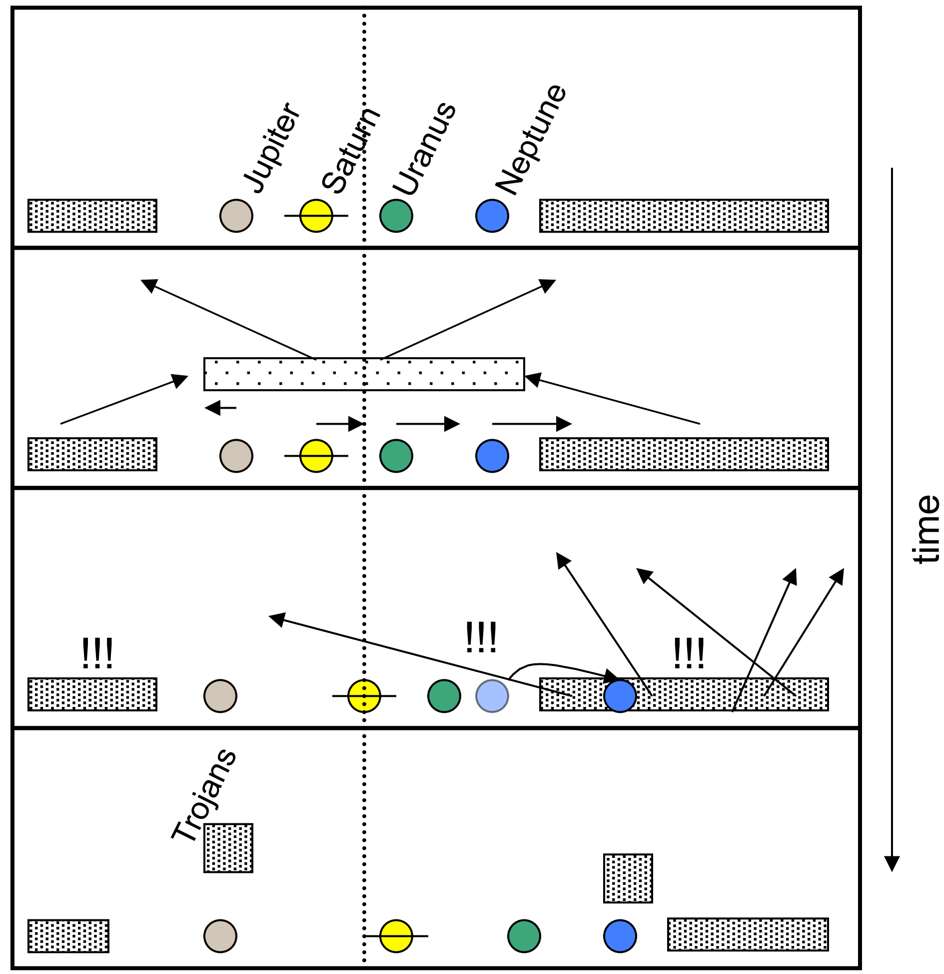
APL

Are Trojans Really TNOs?

- Are the Trojan asteroids *building blocks of Jupiter/ Galilean satellites* or are they *transported Trans-Neptunian Objects (TNOs) from 20+ AU?*

- Cartoon illustrates new simulations of outer planet migration in the early solar system

- What does this *unexplored population* tell us about the evolution of asteroids, comets, and icy satellites?



APL

What specific information do we want?

- Images over the entire surface capable of showing features like boulders, ponds, and small craters.
- Compositional information from targets sufficient to let us distinguish whether they are like any meteorites
- A measure of how much ice and organic material is present
- A density measurement precise enough to determine overall porosity

Appendix E- Mission Design Data for Ballistic Trajectory

Point Design Data for 911 Agamemnon

Heliocentric ephemeris in au and days

Earth Ecliptic and Equinox of J2000

Minimum delta-V

Trajectory 2.1.01 Search converged in 1 iterations

Minimum delta-V= 7.7861967 km/s Gradient norm= .27872425E-08

jdate tpb betb rcb tm1 tm2 xm2 ym2

zm2

51.141132 1021.9066 329.71350 2564840.9 319.22594 2139.3608 -1.5296769 3.3280853

0.95556014

-.30630605E-09 -.85080708E-09 -.12251610E-08 .17107226E-13 .16643906E-10 -.56904833E-09 -.20298862E-06 -.75195660E-08

5.16E-07

veq 7.7861967 vhl 8.5529362 vhp 1.1050051 dvt 7.7861967 dvmt .52752315 **dvpl 1.6325283**

dvl 6.1536684 **dvm1 .32293991** **dvb .0000000** **dvm2 .20458324** **dva 1.1050051**

adate 3701.1411 tend **3650.0000**

pta -.97025041E-03 ptend -.97025041E-03

Heliocentric state of ephemeris bodies and body centered equatorial parameters

Departure parameters: Earth (2,0) Feb 21, 2019 3:23:14 2458535.641

Heliocentric, Ecliptic J2000

x -.87260981 y .46520978 z -.16653040E-04 xd -.83737341E-02 yd -.15246401E-01 zd .68998104E-06

radi .98887210 theta 151.93682 phi -.96488606E-03 radot .21663868E-03 vthe .17393252E-01 vphi .69362933E-06

sma 1.0000002 ecc .16701116E-01 inc .24802870E-02 lan 174.83048 apf 288.17173 mean 47.503506

ea 48.217044 tru 48.934616 angmo .17199702E-01 hx .67087013E-07 hy .74153236E-06 hz .17199702E-01

Body centered Ecliptic, j2000

vhxo -4.1139767 vhyo -7.4985187 vhzo .11431252E-01 vhro .10265431 vhto 8.5523125 vhpo .11432980E-01

Body centered Planet equator and equinox of date

c3 73.152718 dla -20.389665 rla 239.41726 vhxo -4.0789316 vhyo -6.9018417 vhzo -2.9798685

phao 90.687694

Arrival parameters: 911 Agamemnon 1919 FD (2,0,2000911) Feb 18, 2029 3:23:14 2462185.641

Heliocentric, Ecliptic J2000

x -1.0138439 y -5.1035643 z -2.0426259 xd .68871437E-02 yd -.13865309E-02 zd .51631265E-03

radi 5.5898631 theta 258.76424 phi -21.433192 radot -.17189552E-03 vthe .70253036E-02 vphi .48719132E-03

sma 5.2604007 ecc .67199167E-01 inc 21.780211 lan 338.01852 apf 80.100276 mean 202.64423

ea 201.24883 tru 199.89438 angmo .39364801E-01 hx -.54671987E-02 hy -.13544398E-01 hz .36554707E-01

Body centered Ecliptic, j2000

vhxi -1.0535691 vhyi -.33215942 vhzi -.26431987E-01 vhri .50400915 vhti -.96865594 vhpi .16946021

Body centered Planet equator and equinox of date

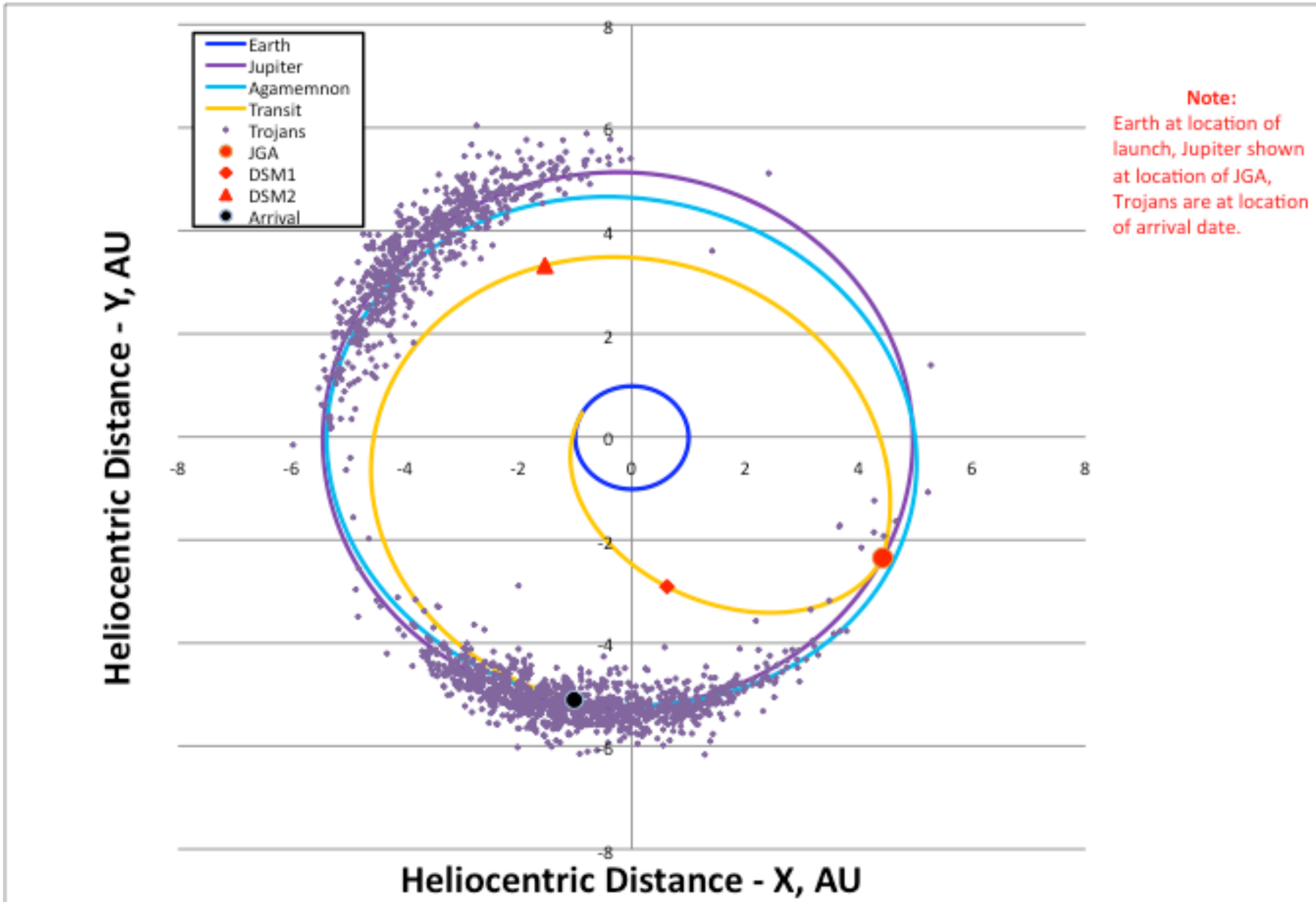
vhp 1.1050051 dap -1.3706595 rap 197.49853 vhxi -1.0535691 vhyi -.33215942 vhzi -.26431987E-01

phai 62.863317

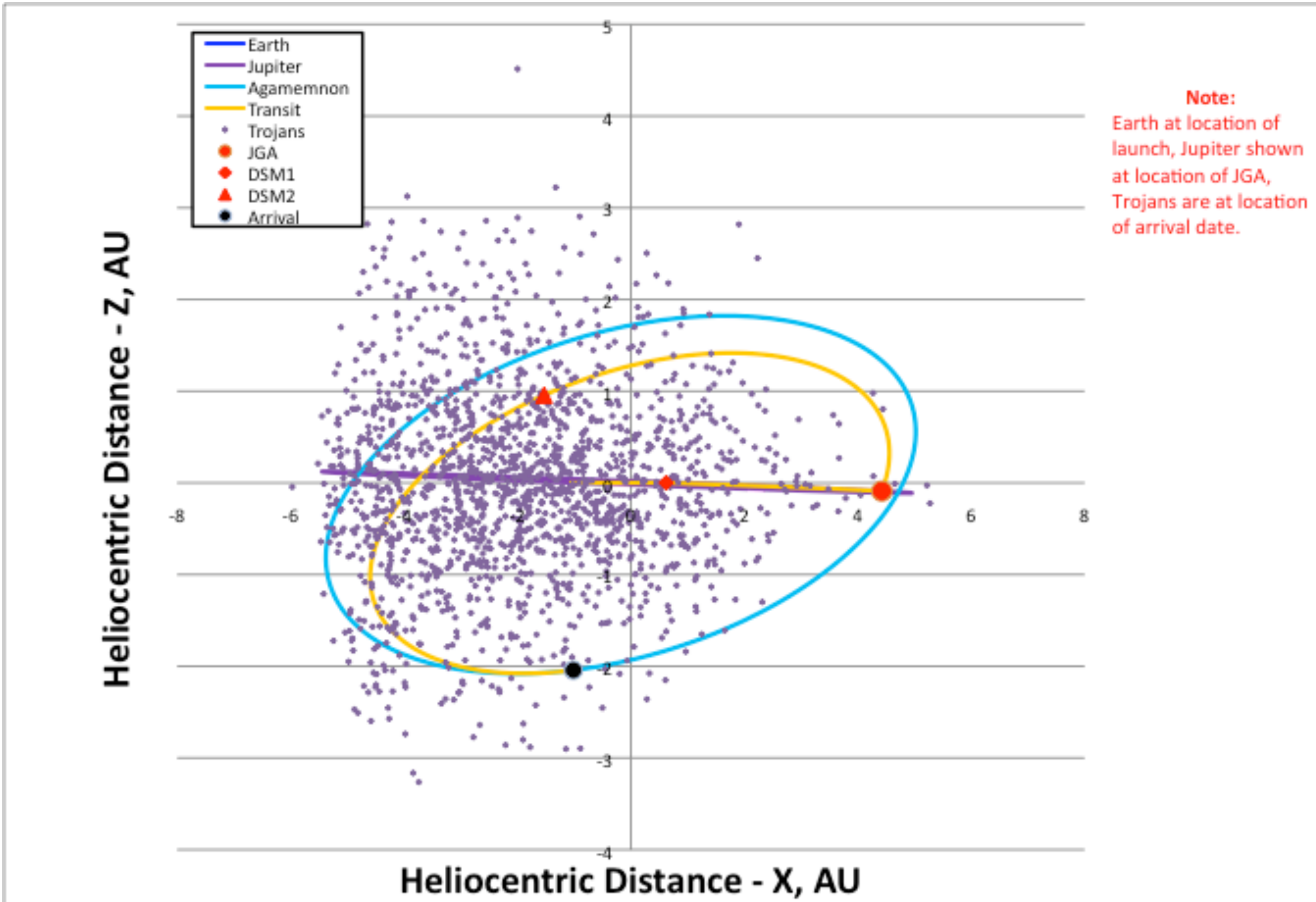
Appendix E- Mission Design Data for Ballistic Trajectory

```
 Gravity assist parameters: Jupiter (2,0)   unpowered                    Oct 18, 2021  21:45:32     2459506.407
                         Heliocentric, Ecliptic J2000
  x  4.4249966       y -2.3478038       z -.89529736E-01    xd  .34473573E-02    yd  .70253853E-02    zd -.10558256E-03
 radi  5.0100692     theta  332.05058      phi -1.0239278     radot -.24555129E-03   vthe  .78217048E-02   vphi -.10998812E-03
  sma  5.2028030      ecc  .48531593E-01   inc  1.3028457      lan  100.24987       apf  273.88308      mean  321.55252
  ea  319.75610      tru  317.92483    angmo  .39191156E-01    hx  .87686804E-03     hy  .15856149E-03    hz  .39181025E-01

                         Body centered Ecliptic, j2000
 vhxi -2.5940893     vhyi -5.2476089      vhzi  .69304493E-01   vhxo -2.9919551      vhyo -.43309511      vhzo  5.0131961
 vhri  .16672721     vhti -5.8513654      vhpi  .72295446E-01   vhro -2.5291864      vhto -1.7848847      vhpo  4.9687930

                     Body centered Planet equator and equinox of date
                   reference plane for b plane angle is Planet orbit plane
 vhxi -1.6649141     vhyi  5.6046545      vhzi  .29565273      vhxo  1.9676690      vhyo  2.1694338      vhzo  5.0688596
  vhi  5.8541867      vho  5.8541867      bend  72.366884       rca  2564840.9      beta1  117.55585      beta2  329.71350
  dvb   .0000000     thec  136.59952      phic -43.672716      inci  116.63069      lani  107.99749      apfi  309.42216
 dapb  2.8948278      rapb  106.54454      dlab  59.980142      rlab  47.792081      phai  88.367996      phao  64.403518

                          Heliocentric trajectory

 Departure: Earth                        time:  .000 days                  Feb 21, 2019   3:23:14     2458535.641
  x0 -.87260981       y0  .46520978       z0 -.16653040E-04   xd0 -.10749754E-01   yd0 -.19577157E-01   zd0  .72920813E-05
 radi  .98887210     theta  151.93682      phi -.96488606E-03  radot  .27592651E-03   vthe  .22332626E-01   vphi  .72967280E-05
  sma  2.9691601      ecc  .66701577      inc  .18745071E-01   lan  154.88738      apf  355.28029      tru  1.7691556
 elx0 -.29566390     ely0 -.53890468      elz0  .82154293E-03  eldx0  .76369300E-02  eldy0 -.40745513E-02  eldz0 -.92026142E-02
  x  .62319551       y -2.9074459       z  .77476736E-03    xd  .86556237E-02    yd -.49449129E-02    zd  .26305864E-06
 radi  2.9734854     theta  282.09799      phi  .14928912E-01  radot  .66491711E-02   vthe  .74270120E-02   vphi -.14694405E-05
  sma  2.9691601      ecc  .66701577      inc  .18745071E-01   lan  154.88738      apf  355.28029      tru  131.93032
  elx  .33229971      ely -.10186919      elz -.93765642      eldx  .65331927E-05   eldy  .11879763E-02   eldz -.12674915E-03

 Deep space maneuver (constrained)          time: 268.085 days                Nov 16, 2019   5:25:21     2458803.726
  x0  .62319551       y0 -2.9074459       z0  .77476736E-03   xd0  .87176021E-02   yd0 -.49639129E-02   zd0 -.17462243E-03
 radi  2.9734854     theta  282.09799      phi  .14928912E-01  radot  .66806933E-02   vthe  .74836317E-02   vphi -.17636315E-03
  sma  3.0082651      ecc  .66590658      inc  1.3500947       lan  102.73144       apf  48.360946       tru  131.00542
 elx0  .33229971     ely0 -.10186919      elz0 -.93765642      eldx0  .65331927E-05  eldy0  .11879763E-02  eldz0 -.12674915E-03
  x  4.4249966       y -2.3478038       z -.89529736E-01    xd  .19491454E-02    yd  .39946375E-02    zd -.65555870E-04
 radi  5.0100692     theta  332.05058      phi -1.0239278     radot -.14925827E-03   vthe  .44422585E-02   vphi -.68234005E-04
  sma  3.0082651      ecc  .66590658      inc  1.3500947       lan  102.73144       apf  48.360946       tru  180.96606
  elx  .13833250      ely  .27983421      elz -.36957286E-02   eldx -.41838568E-03   eldy  .21989203E-03   eldz  .18251804E-02

 Gravity assist: Jupiter                 time: 970.765 days                Oct 18, 2021  21:45:32     2459506.407
  x0  4.4249966       y0 -2.3478038       z0 -.89529736E-01   xd0  .17193587E-02   yd0  .67752519E-02   zd0  .27897804E-02
 radi  5.0100692     theta  332.05058      phi -1.0239278     radot -.17062787E-02   vthe  .67908476E-02   vphi  .27597300E-02
  sma  4.8128416      ecc  .23019945      inc  22.138817       lan  334.56840       apf  110.37021       tru  246.91186
 elx0  .15954911     ely0  .23095278E-01  elz0 -.26733388      eldx0  .34558309E-03  eldy0 -.55689947E-03  eldz0  .16969118E-03
  x -1.5296769       y  3.3280853       z  .95556014        xd -.90812767E-02    yd -.24802103E-02    zd -.24979110E-02
 radi  3.7853874     theta  114.68477      phi  14.621585      radot  .85860788E-03   vthe  .92872217E-02   vphi -.28055116E-02
  sma  4.8128416      ecc  .23019945      inc  22.138817       lan  334.56840       apf  110.37021       tru  27.574372
  elx  .86895911      ely  .17555648      elz  .46269858       eldx -.55614515E-03   eldy  .12431480E-02   eldz  .57278034E-03

 Deep space maneuver                      time: 2088.220 days               Nov  9, 2024   8:39:31     2460623.861
  x0 -1.5296769       y0  3.3280853       z0  .95556014       xd0 -.89786034E-02   yd0 -.24594671E-02   zd0 -.24432400E-02
 radi  3.7853874     theta  114.68477      phi  14.621585      radot  .84915558E-03   vthe  .91852678E-02   vphi -.27465449E-02
  sma  4.6446192      ecc  .20430575      inc  22.019414       lan  334.85632       apf  107.03180       tru  30.645972
 elx0  .86895911     ely0  .17555648      elz0  .46269858      eldx0 -.55614527E-03  eldy0  .12431480E-02  eldz0  .57278064E-03
  x -1.0138439       y -5.1035643       z -2.0426259        xd  .62786566E-02    yd -.15783690E-02    zd  .50104690E-03
 radi  5.5898631     theta  258.76424      phi -21.433192     radot  .11919412E-03   vthe  .64658580E-02   vphi  .58506279E-03
  sma  4.6446192      ecc  .20430575      inc  22.019414       lan  334.85632       apf  107.03180       tru  175.89698
  elx  .95345175      ely  .30059536      elz  .23920239E-01   eldx  .68972977E-03   eldy  .72938916E-03   eldz  .49144293E-04
 Arrival: 911 Agamemnon                   time: 3650.000 days               Feb 18, 2029   3:23:14     2462185.641
```

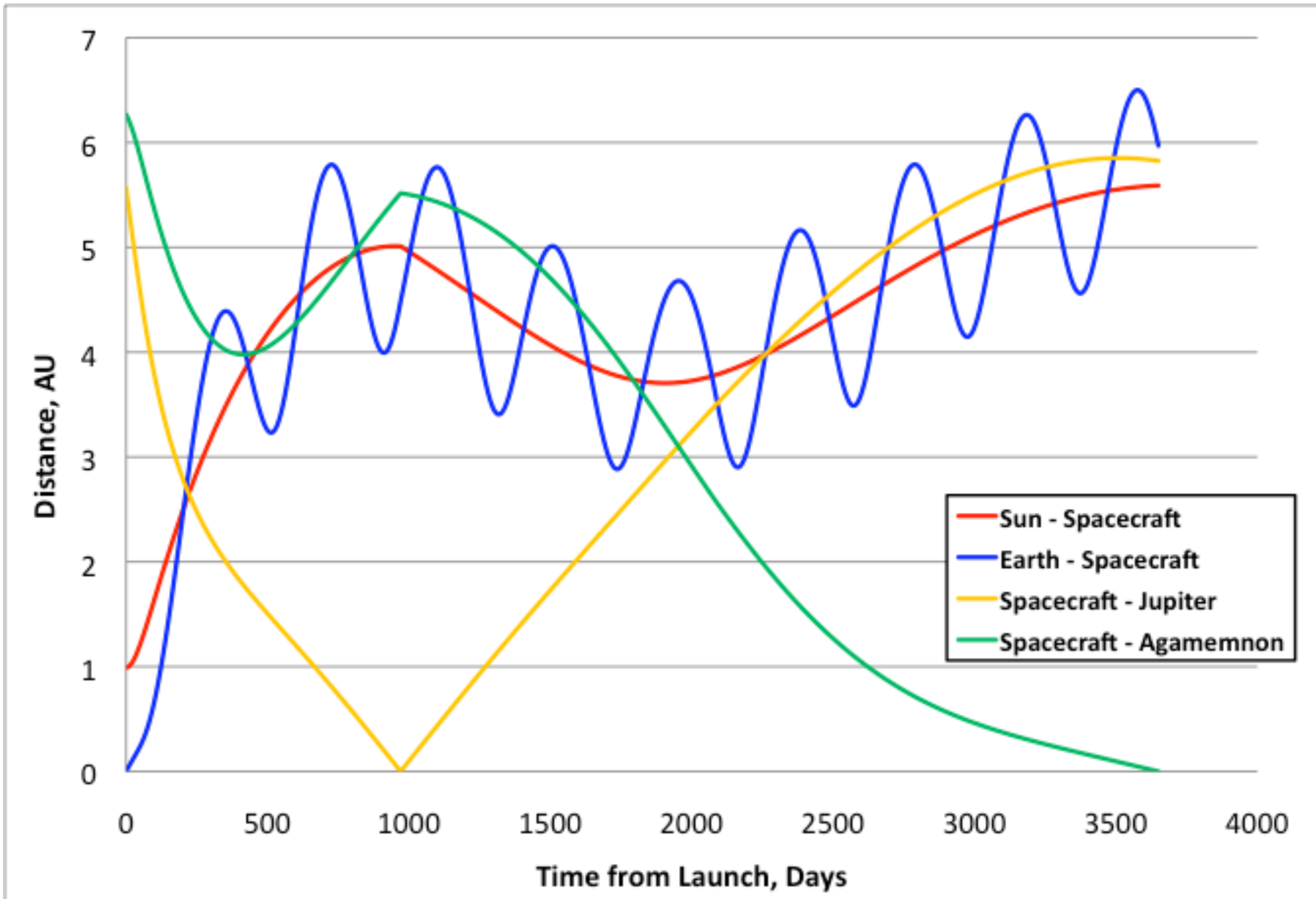
Baseline Trajectory Design in X-Y Heliocentric Plane



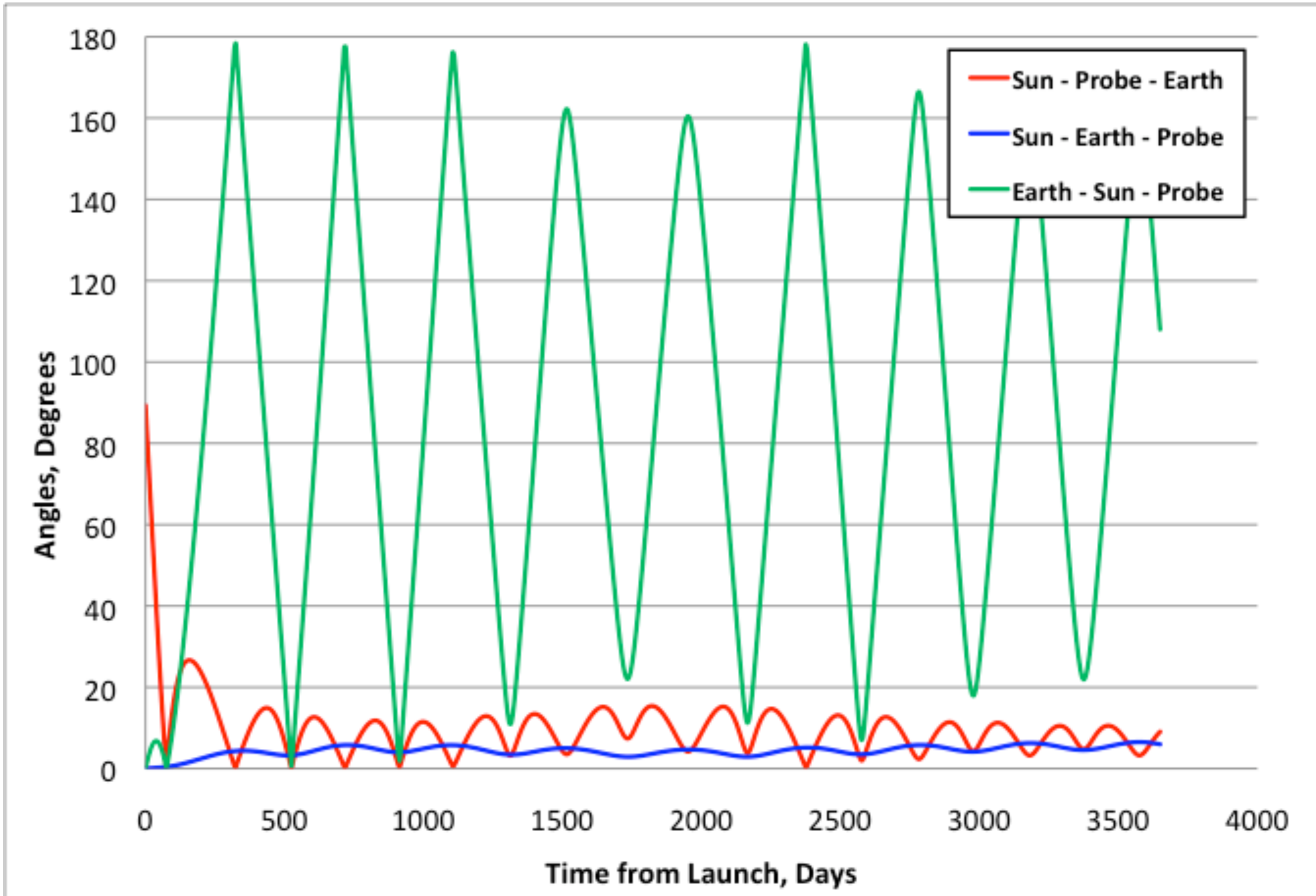
Baseline Trajectory Design in X-Z Heliocentric Plane



Appendix E- Mission Design Data for Ballistic Trajectory



Appendix E- Mission Design Data for Ballistic Trajectory



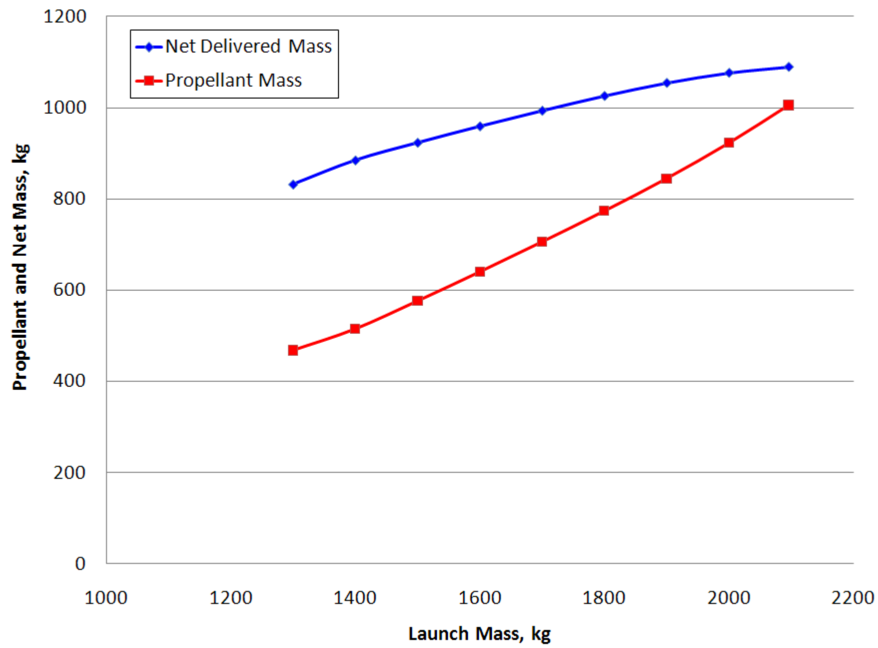
Trojan Tour Decadal Survey REP Trajectory

John Dankanich (NASA GRC)
Jim McAdams (JHU/APL)

Trojan Tour Decadal Survey: Appendix F

The Johns Hopkins University
APPLIED PHYSICS LABORATORY

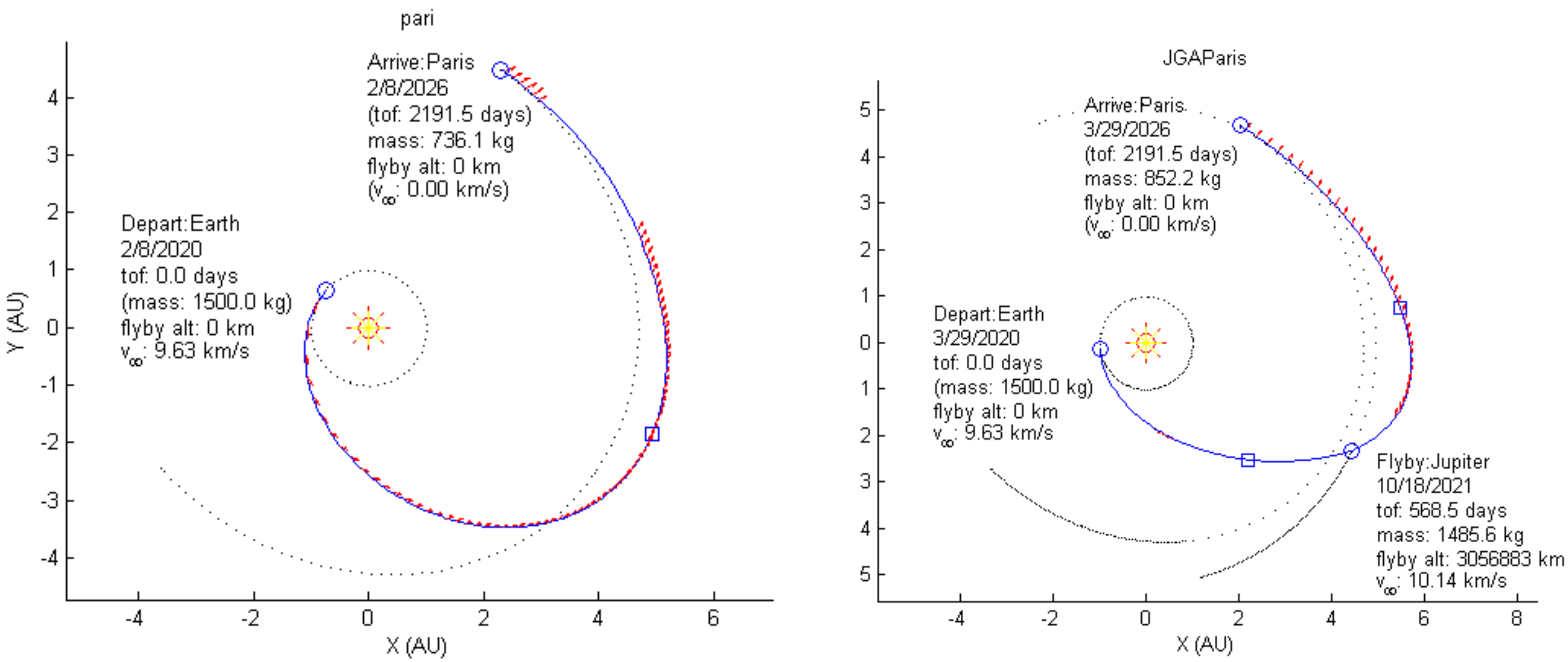
REP Mission to Trojans



REP mission performance is VERY sensitive to spacecraft alpha.

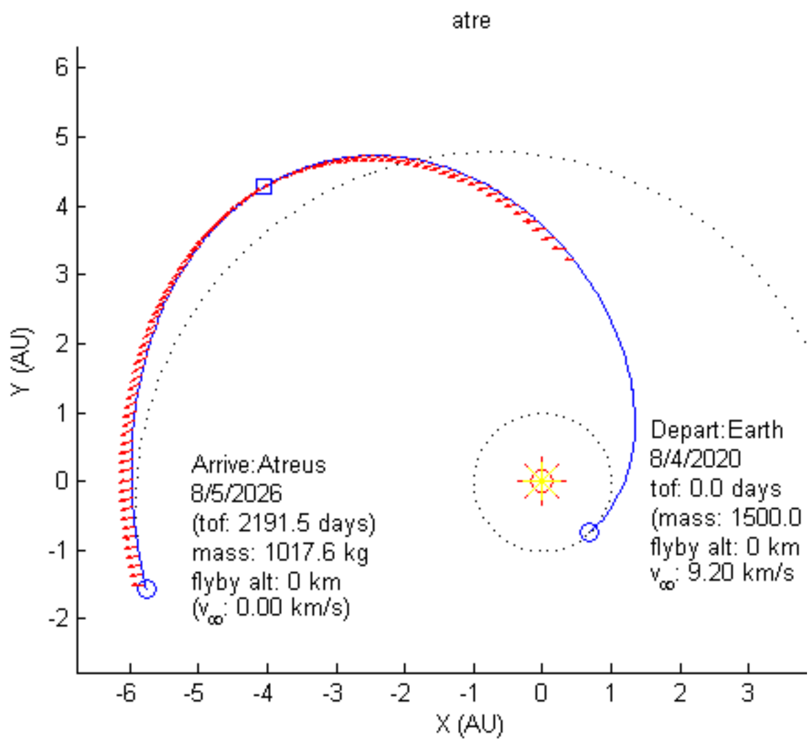
As the launch mass increases, the REP thruster begins to only push additional propellant.

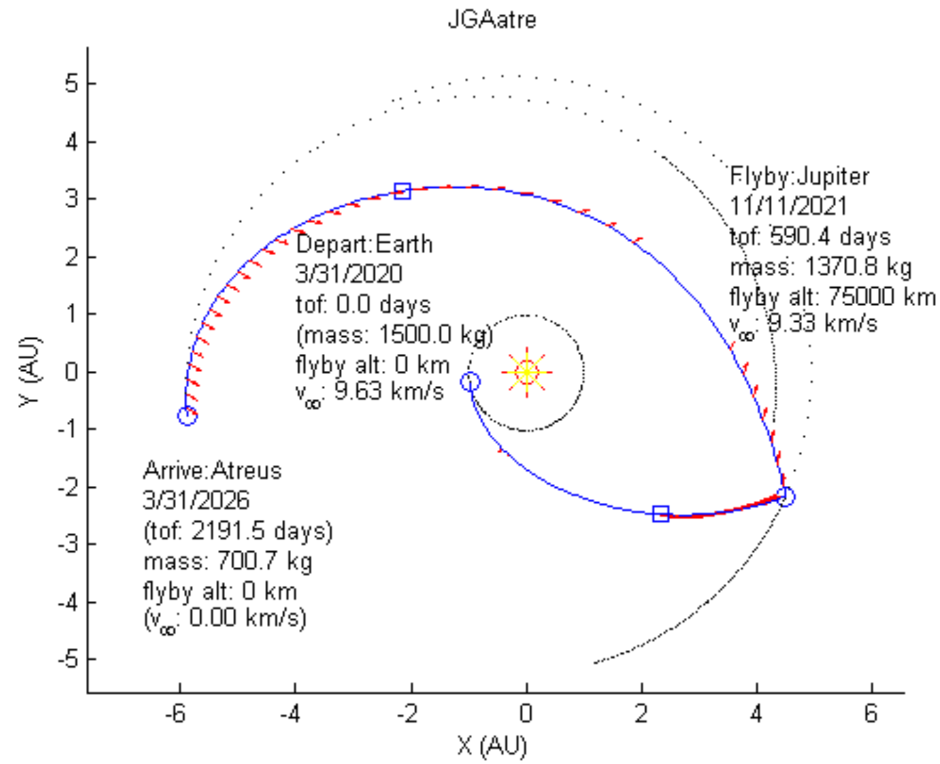
With or W/O JGA



Direct solutions with thrust arcs through Jupiter's orbit can benefit from a JGA.

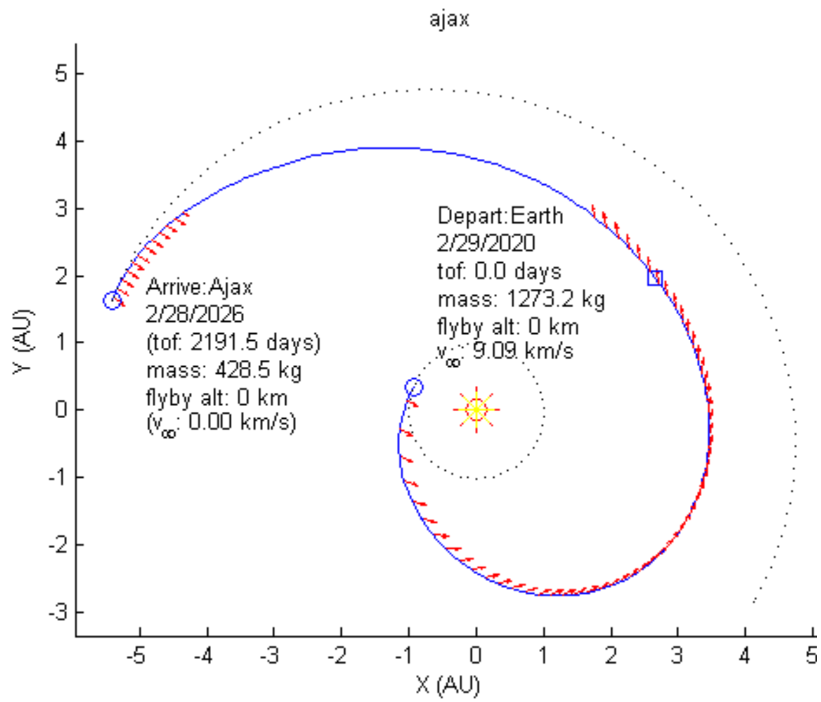
With or W/O JGA

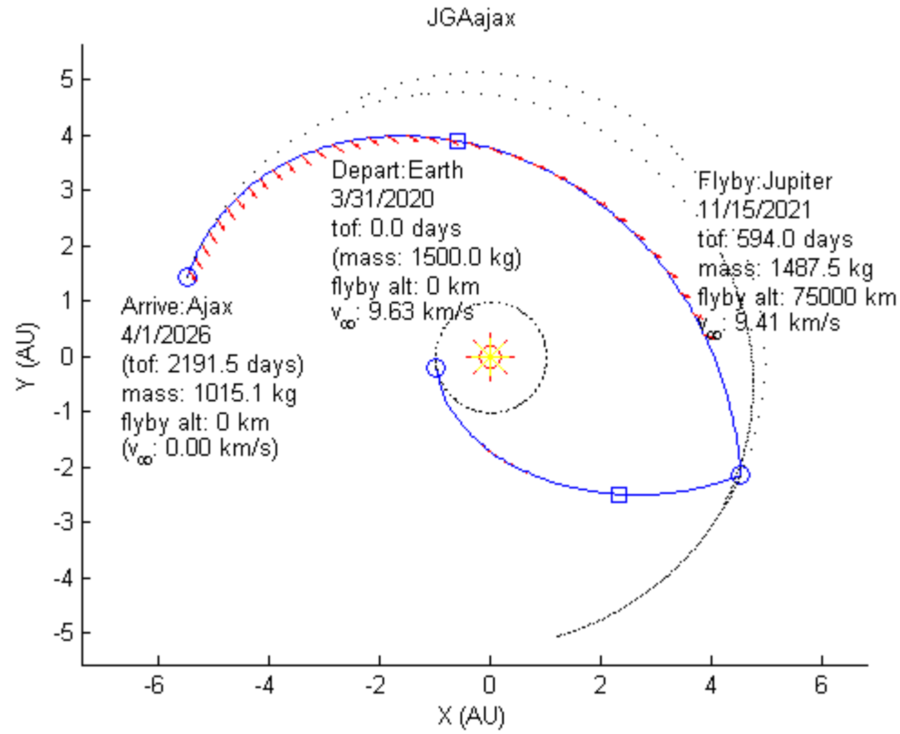




The JGA does not always help

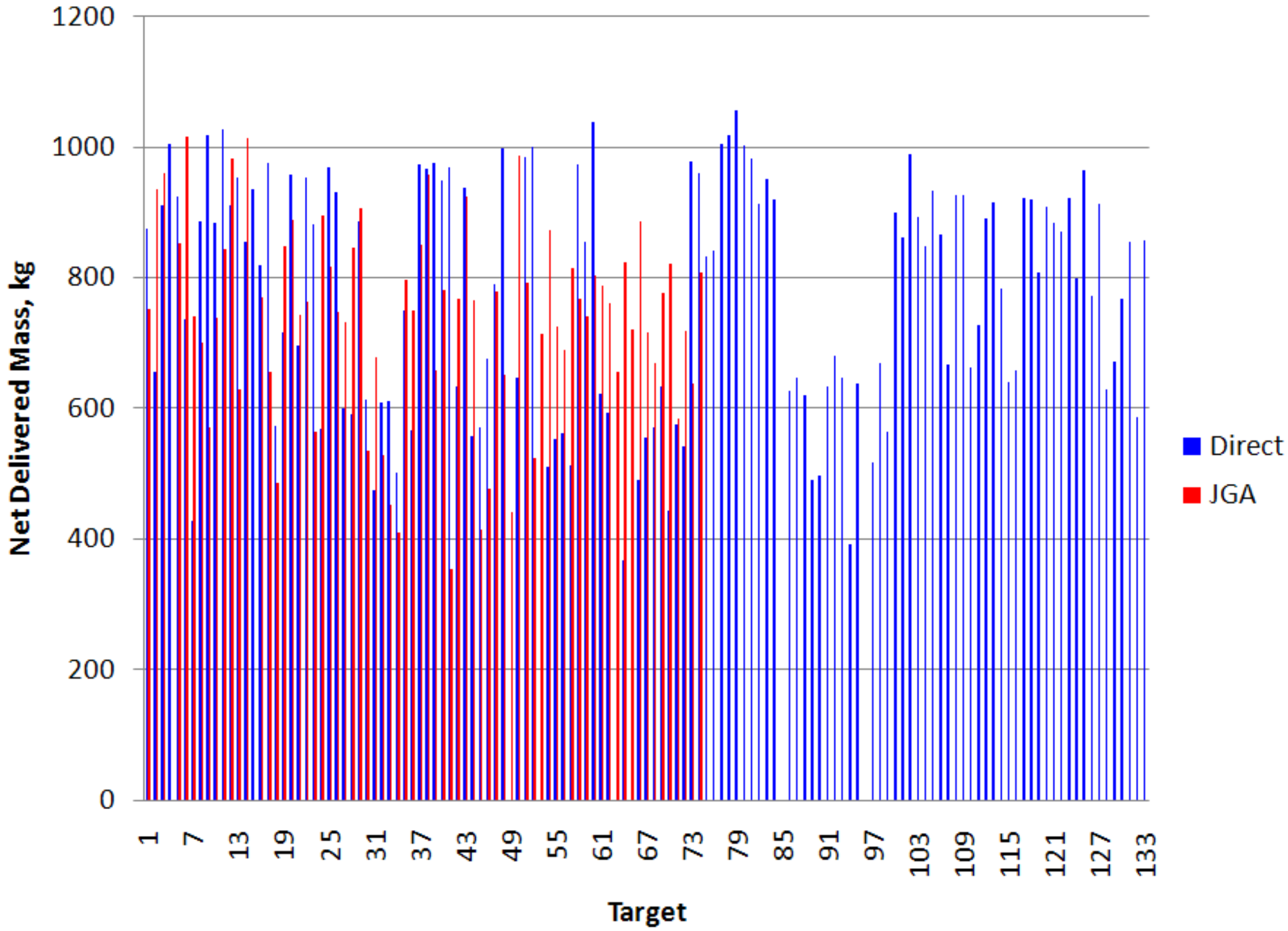
With or W/O JGA





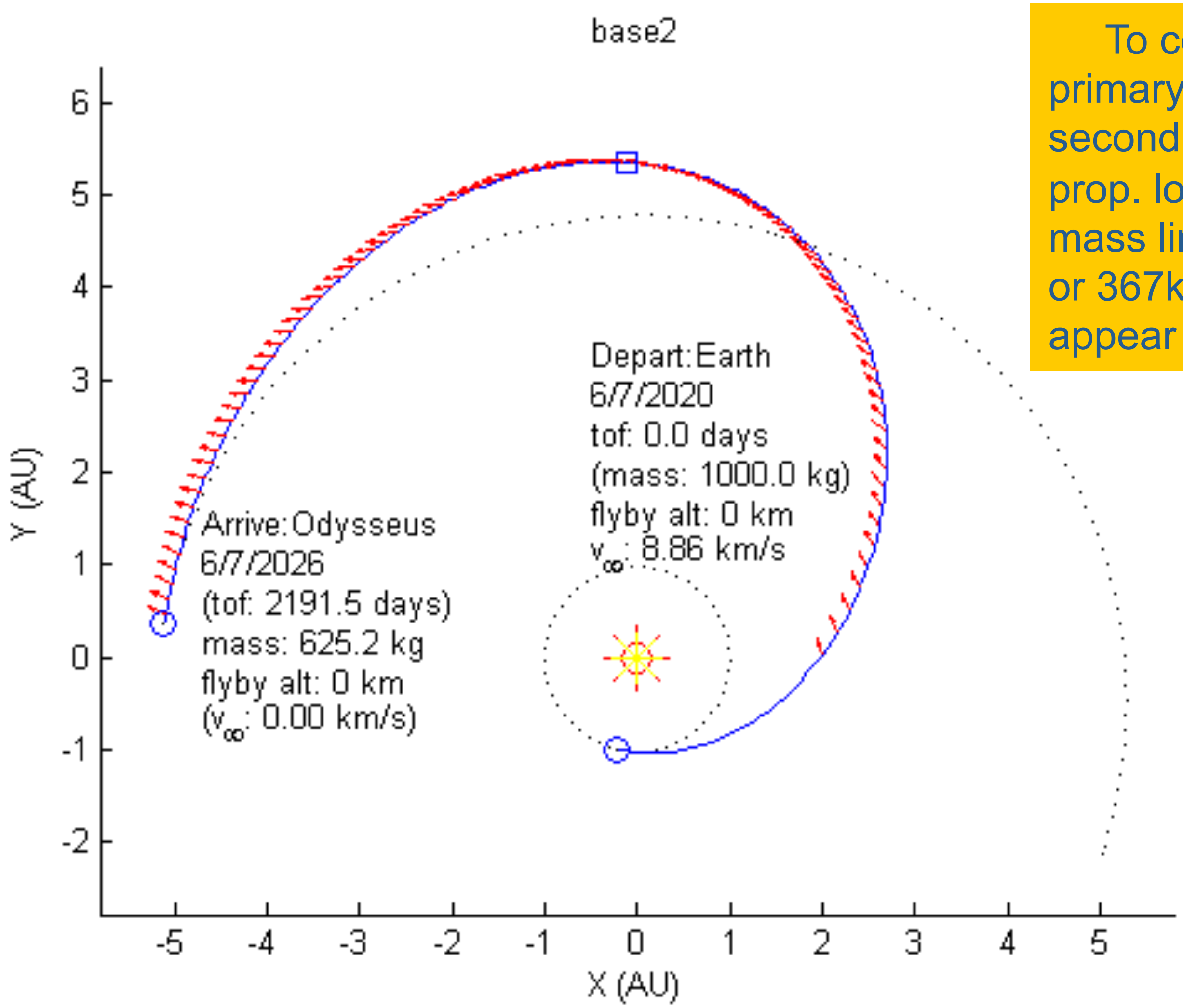
Some targets can be enabled by the JGA

Broad Search: 7 yr, 8 ASRG (total)



Constrained Launch Mass ≤ 1,500kg
Several solutions greater than 1,000kg delivered

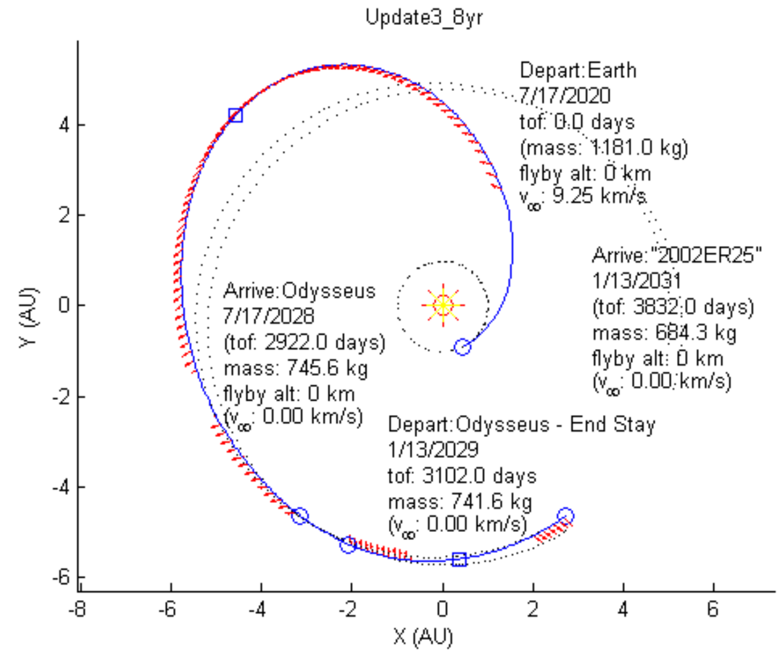
Baseline Trojan – Odysseus w/ 1000 kg Wet

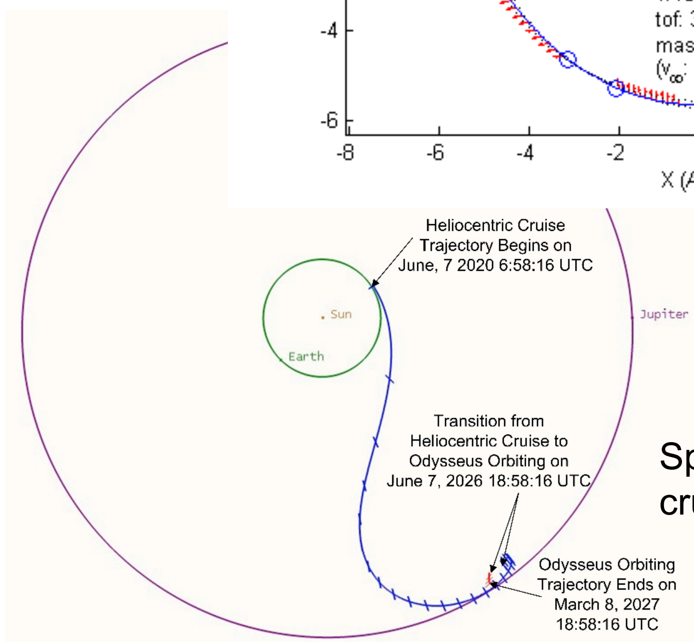


To complete the 6 years to the primary target and allow for a second target, both with a total prop. load of 475, we have a dry mass limit of 525kg with margin, or 367kg CBE. (This does not appear to be practical).

Baseline Trojan - 8yr to Primary Target
1,181 kg Wet Mass

- **Primary Target Asteroid 1143 Odysseus**
  - C3: 78.5 km^2/s^2
  - Launch: July 2020
  - Cruise: 8 years
- **Secondary Target Asteroid 2002ER25**
  - Depart Odysseus: Jan 2029
  - Arrive: Jan 2031
- **Target Wet Mass 1,181 kg for this mission design**
  - 535 kg Xenon required with margin
  - Allows for 646 kg dry mass with margin, 452 kg CBE
  - Current CBE dry mass is 482 kg (690 kg with margin) + 25 kg hydrazine for ACS

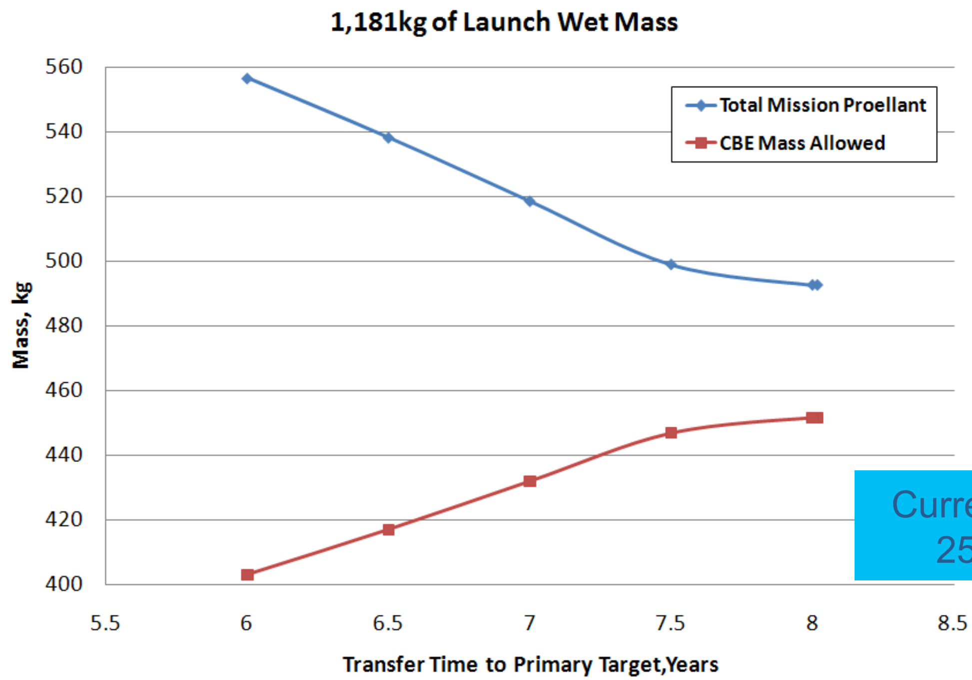




Sun-Centered, Jupiter-Sun-Fixed Frame
Time Ticks Every 3 Months

Spends last 5 years of cruise within Trojan cloud

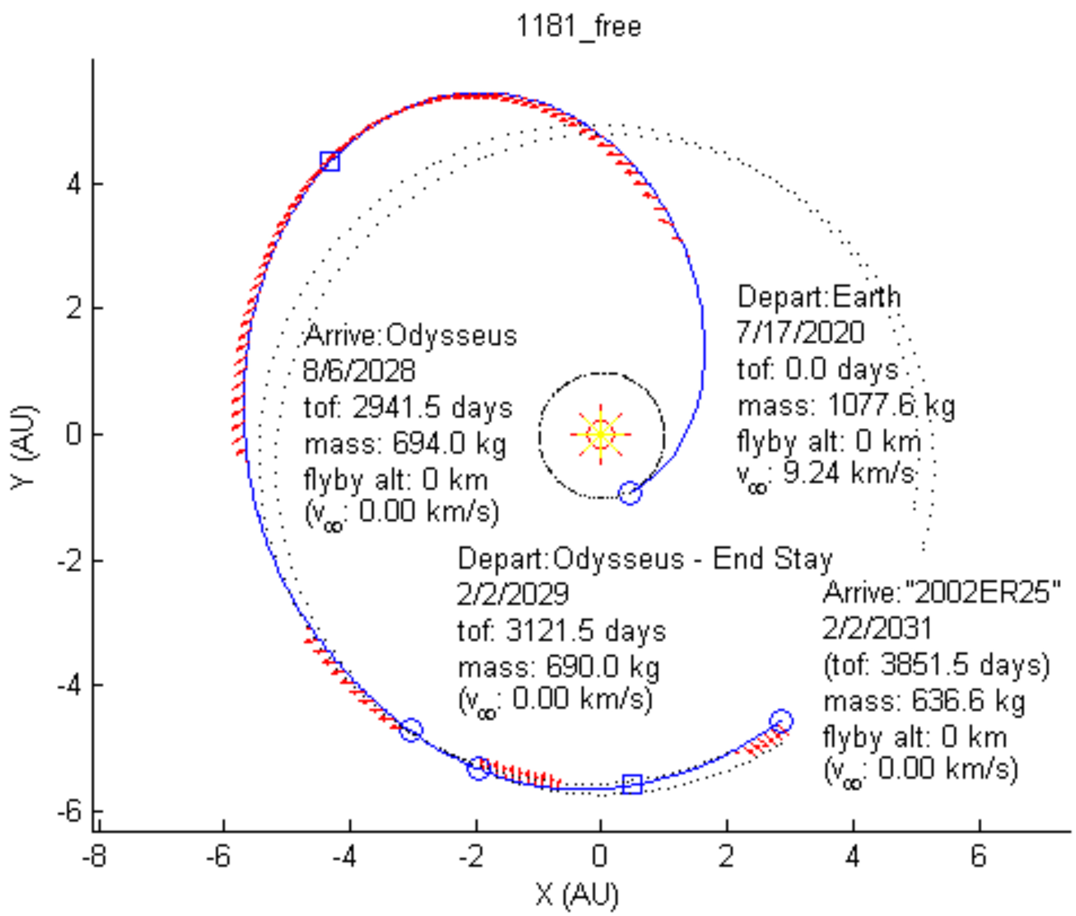
Baseline Trojan Odysseus with 1,181 kg Wet Mass



Current CBE mass = 482kg + 25kg Hydrazine for ACS

Trip time, yrs	Propellant Mass	w/ Margin	CBE Mass Allowed	Delivered at first	Mprop for 1 target	w/ Margin	CBE Mass allowed	CBE Delta to enable 2nd target
8.02	492.65	535.02	451.74	745.90	435.10	472.52	521.61	69.87
8.00	492.66	535.03	451.73	745.60	435.40	472.84	521.40	69.67
7.50	499.01	541.92	446.91	732.30	448.70	487.29	512.10	65.19
7.00	518.62	563.22	432.01	713.10	467.90	508.14	498.67	66.66
6.50	538.30	584.59	417.07	695.90	485.10	526.82	486.64	69.58
6.00	556.70	604.58	403.09	680.90	500.10	543.11	476.15	73.06

Max CBE Dry to close Mission w/ 475kg Prop Load

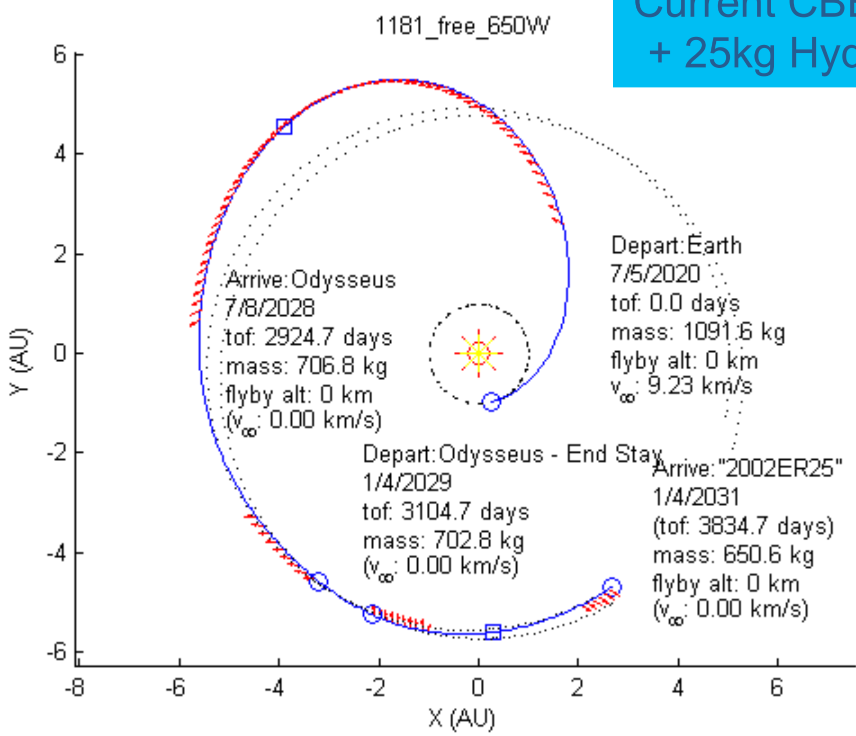


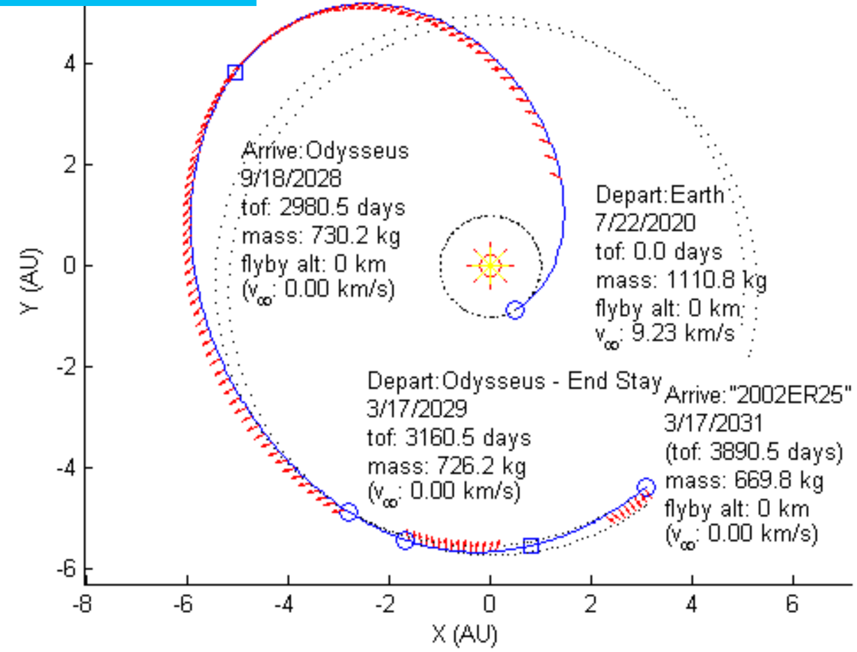
Fixing the propellant load. A transfer time of 8.05years, allows max wet mass of 1077.6kg for a Dry Mass of 602.6kg with margin or 421kg CBE.

Current CBE mass = 482kg + 25kg Hydrazine for ACS

With More Power and New Technology

Current CBE mass = 482kg
+ 25kg Hydrazine for ACS

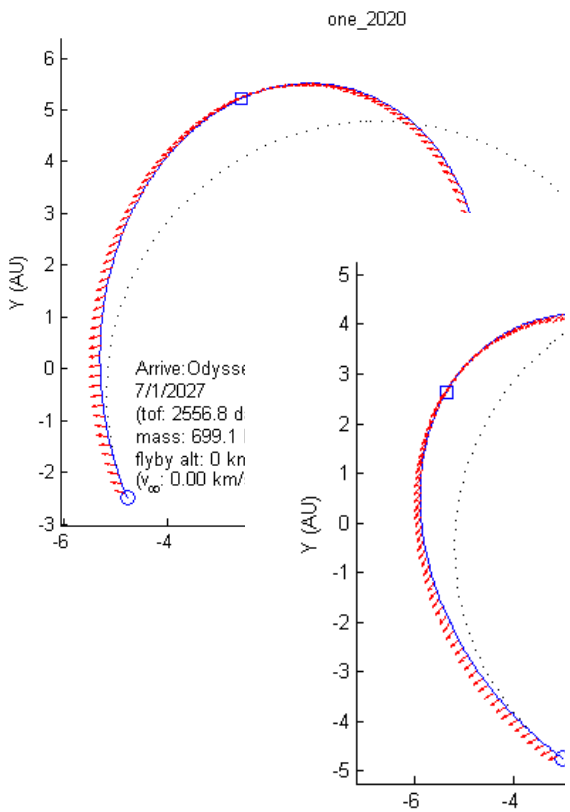


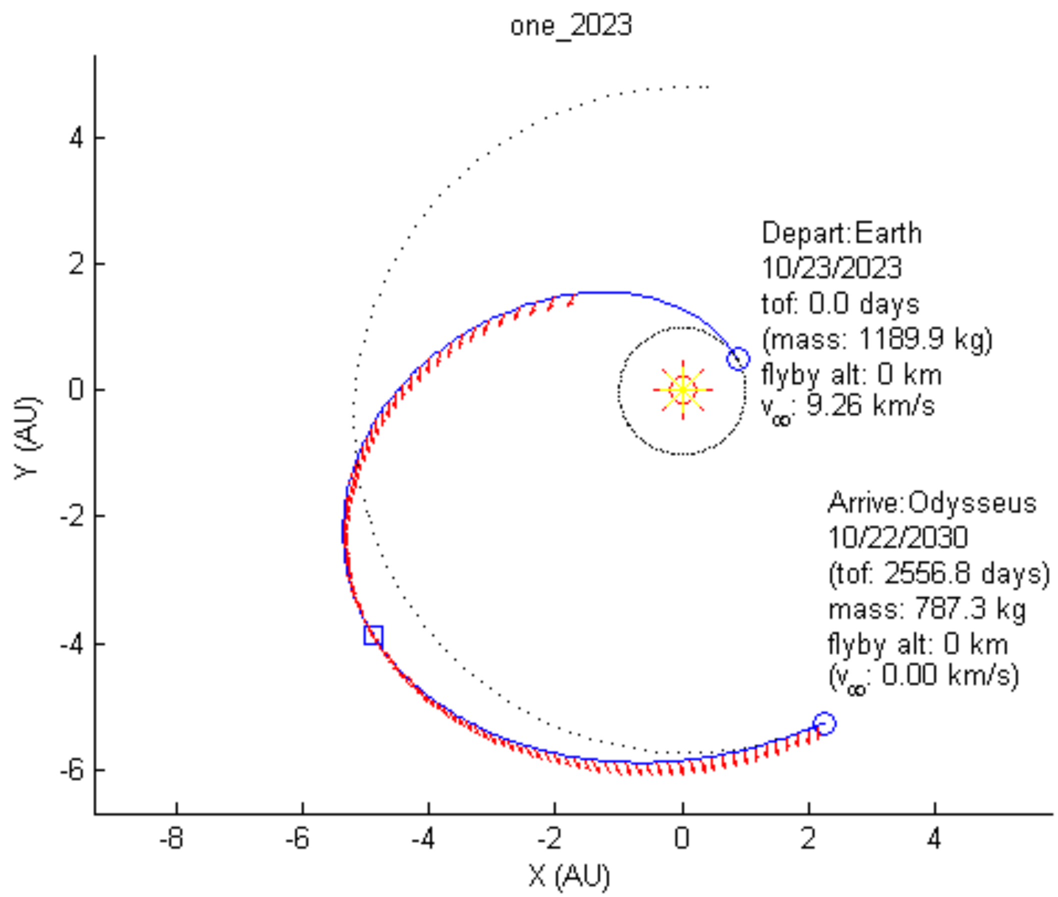


With 650W, A transfer time of 8.05years, allows max wet mass of 1091.6kg for a Dry Mass of 616.6kg (1kg for 2 Watts) with margin or 431kg CBE (1 kg per 3 Watts)

Allowing ~2000s Isp, A transfer time of 8.16years, allows max wet mass of 1110.8kg for a Dry Mass of 635.8kg with margin or 444.6kg CBE (11.5kg per 100s Isp)

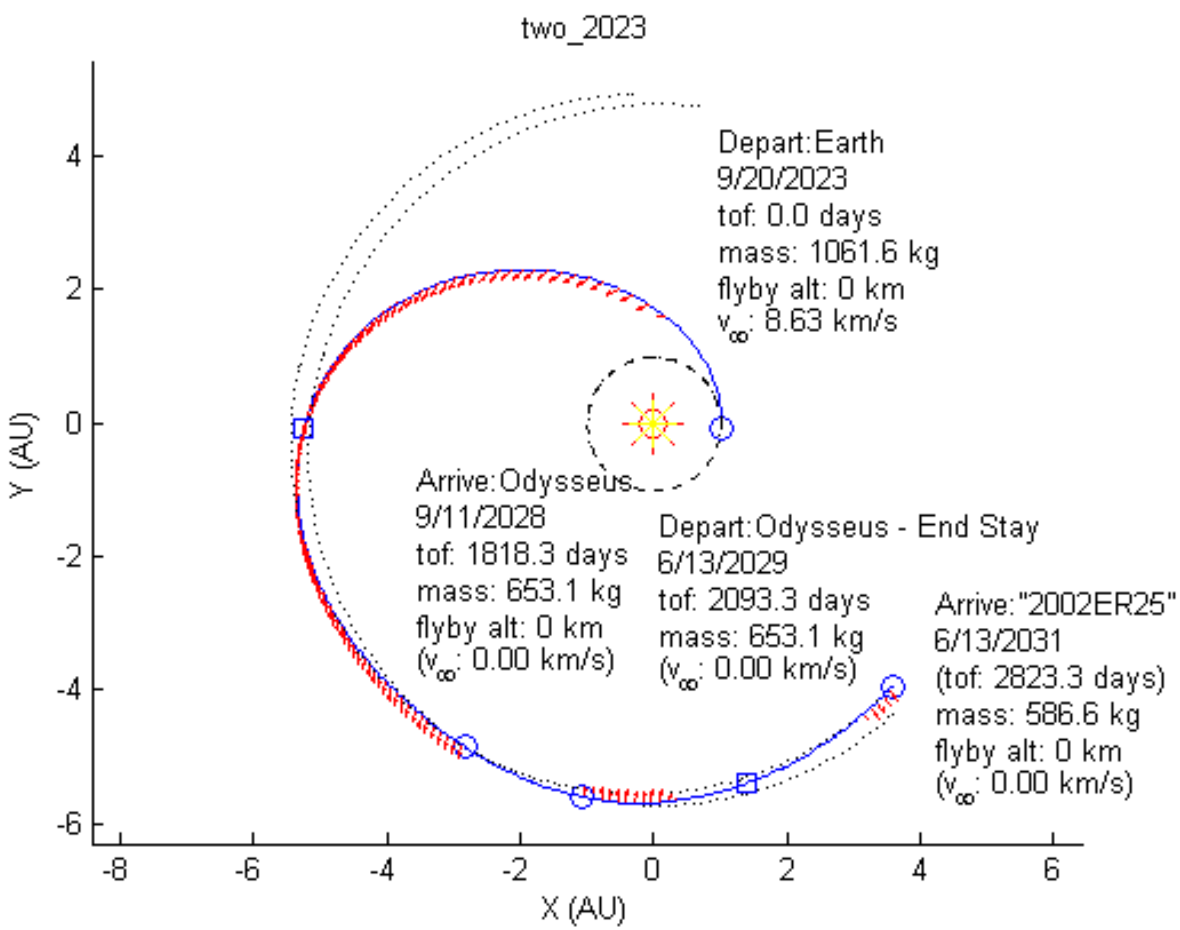
1189.88kg Wet Mass, 475kg usable Xenon





Solution gets better each year from 2019 – 2023. Closes easily, only requires 402.54kg usable Xenon

Best as is…Really close to closing two targets with 2023 launch. This also may not be the best 2nd target. (Wet mass of 1061.6 with 475kg of Xenon.)



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