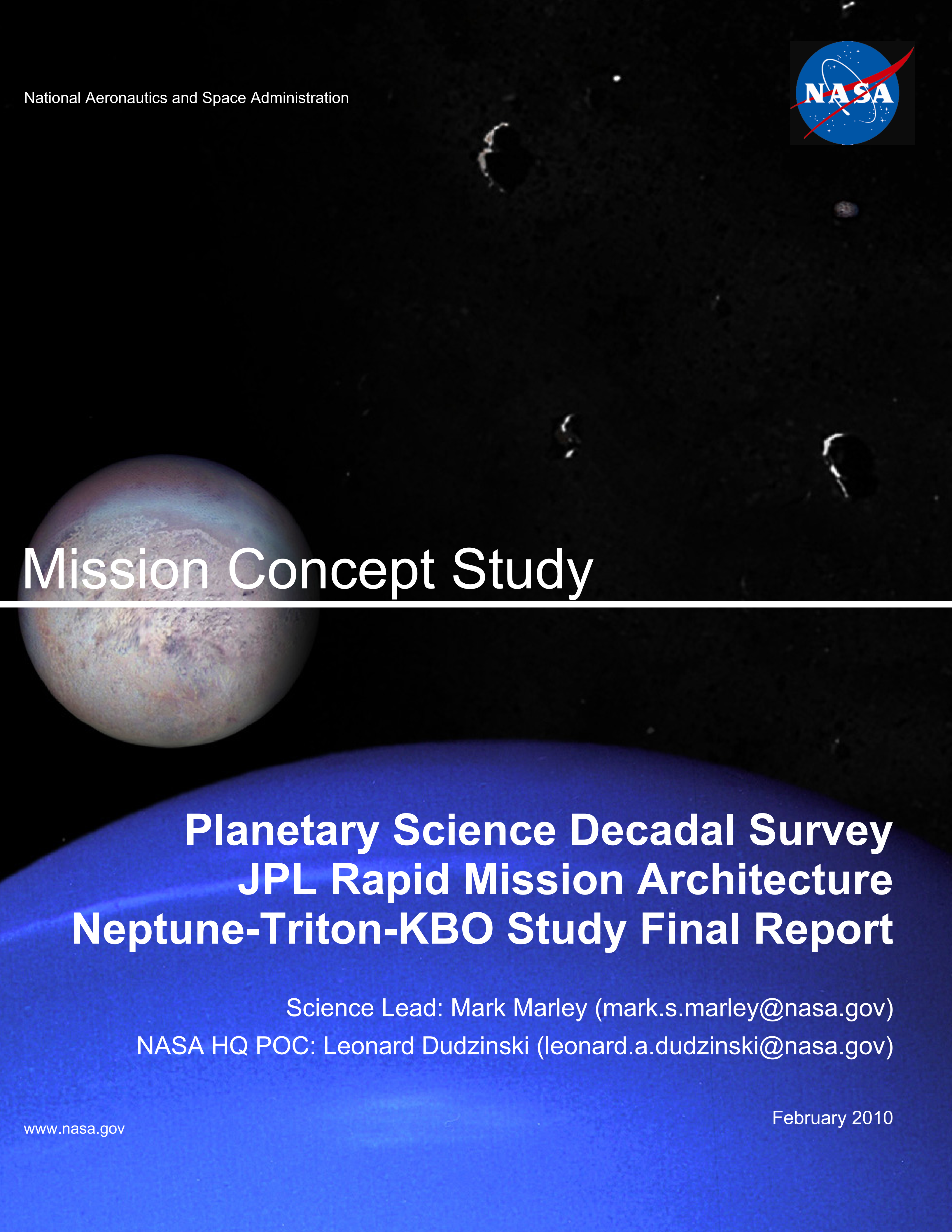

National Aeronautics and Space Administration

Mission Concept Study

Planetary Science Decadal Survey
JPL Rapid Mission Architecture
Neptune-Triton-KBO Study Final Report

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Data Release, Distribution, and Cost Interpretation Statements

This document is intended to support the SS2012 Planetary Science Decadal Survey.

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Cost estimates described or summarized in this document were generated as part of a preliminary, first-order cost class identification as part of an early trade space study, are based on JPL-internal parametric cost modeling, assume a JPL in-house build, and do not constitute a commitment on the part of JPL or Caltech. Costs are rough order of magnitude based on architectural-level input and parametric modeling and should be used for relative comparison purposes only. These costs are not validated for budgetary planning purposes.

Cost reserves for development and operations were included as prescribed by the NASA ground rules for the Planetary Science Decadal Survey. Unadjusted estimate totals and cost reserve allocations would be revised as needed in future more-detailed studies as appropriate for the specific cost-risks for a given mission concept.

Planetary Science Decadal Survey

Mission Concept Study Final Report

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Executive Summary

This JPL Rapid Mission Architecture (RMA) study was not a mission concept study of a single mission, but instead was an architectural-level study of a set of missions to the Neptune system and, for some, continued travel to a Kuiper Belt Object (KBO). It was commissioned by three Planetary Science Decadal Survey Panels: Giant Planets, Satellites, and Primitive Bodies, whose diverse sets of science priorities made tailoring architectures to the science priorities particularly challenging. The panels' intent is to use the results to compare key metrics of the architectures (including science value, cost, and risk) and decide which ones, if any, merit individual, more detailed study. The study science team, with members from each of the panels, emphasized lower-cost missions (e.g., potential candidate New Frontiers class missions or lower-cost flagship missions). As a result, a large fraction of both the science objectives and the selected architectures favor missions requiring the fewest resources.

The lowest-cost missions are flyby missions. The science team's consensus is that a flyby of Neptune provides sufficient new information about the Neptune system and Triton (relative to Voyager and Earth-based observations) to justify a second flyby through the system. New information arises from new instrumentation, different flyby geometry, and the evolution of Neptune over a 40-year hiatus of in-situ observations. Flyby trajectories exist that provide opportunities for good science at all three destinations (Neptune, Triton, and KBO). Adding a large KBO flyby, presumably the second-ever flyby of any KBO, enhances the value of the mission by adding significant progress toward primitive body goals, including comparison of a minimally processed KBO with Triton. The flyby missions were sized with a payload of approximately seven instruments (60 kg), predominantly based on New Horizons heritage. It should be noted that the science value relative to Voyager for a flyby mission drops dramatically if the payload is further reduced. Instruments added would have high value (e.g., dust, plasma wave, and a long wavelength, high resolution spectrometer); cost, not mass, is the critical issue. Further mission additions, such as free-flying instruments or atmospheric entry probes, also add significant science value.

Orbital missions enable many science opportunities in the Neptunian system unachievable by flyby architectures. The vastly greater time spent in the 1–2 years of orbital operations within 10^6 km of Neptune and 10^5 km of Triton (~5 and ~0.5 km imaging resolution, respectively) yields many obvious advantages, notably the ability to add or modify observations based on new discoveries. Orbital missions were sized with payloads both smaller and larger than the flyby payload, the smallest to study Neptune alone (even that yields significant science return) and the largest to have capability similar to Galileo or Cassini. A NASA Vision Mission study's extraordinarily rich 2-year tour of the Neptune-Triton system provides ~30 flybys/year of Triton and both low- and high-inclination orbits of Neptune. Flight-time limits make it impractical to leave Neptune orbit to fly by a KBO, but an option to send an enhanced, instrumented solar electric propulsion (SEP)/cruise stage onward to a KBO is feasible. SEP is found to be enabling or greatly enhancing for all orbiter architectures. Aerocapture is enabling for the two largest flagship-class architectures even with Jupiter gravity assists (JGAs), and aerocapture is enabling for all orbiter architectures that do not employ a Jupiter gravity assist.

This study used the JPL RMA team and process initially developed at JPL in 2007 as the approach for the architectural trade space assessment [1]. RMA team members referenced previous studies and relevant white papers submitted to the Planetary Sciences Decadal Survey to set the context for this RMA study [2–5]. Note that all mission concepts were studied at an architectural level, primarily for assessment of relative benefits and impacts. Specific mission concepts of interest should be examined and optimized in more detailed, follow-on point-design studies for more in-depth assessment of costs, resource requirements, and risks before any programmatic or budgetary planning decisions are made.

1. Scientific Objectives

Science Questions and Objectives

Three Decadal Survey panels sponsored this Rapid Mission Architecture (RMA) study of a set of mission architectures to Neptune, Triton, and a Kuiper Belt Object (KBO): Giant Planets, Satellites, and Primitive Bodies. The diverse sets of science priorities for the three panels (and targets) made fitting architectures to the science priorities particularly challenging. The joint panel placed emphasis on lower-cost missions, thus a large fraction of both the science objectives and the selected architectures favor missions requiring the fewest resources. While flyby mission architectures provide the lowest cost opportunities, orbiter mission architectures provide far better science opportunities with respect to range of time scales, variety of observational geometries, acquisition time and ability to adapt the mission to address new discoveries.

There is consensus within the science panel that a flyby of Neptune provides sufficient new information about the Neptune system (relative to Voyager and Earth-based observations) to justify a second flyby in the system. New information arises from new instrumentation, a more favorable flyby geometry (and over a different hemisphere), and the evolution of Neptune over a 40-year hiatus of in-situ observations. Nearly all aspects of Neptune detectable from Earth have changed significantly since the Voyager flyby in 1989: the Great Dark Spot (GDS) has disappeared, there has been significant evolution of the appearance of the atmosphere on time scales of less than 5 years, and there is (sub-millimeter) evidence for stratospheric heating as shown in Figure 1. It is expected that Neptune's magnetosphere will be very different from that measured by Voyager—the magnetic dipole is highly tilted and offset from the barycenter, so there are large changes associated with planetary rotation, as different parts of the field encounter the solar wind.

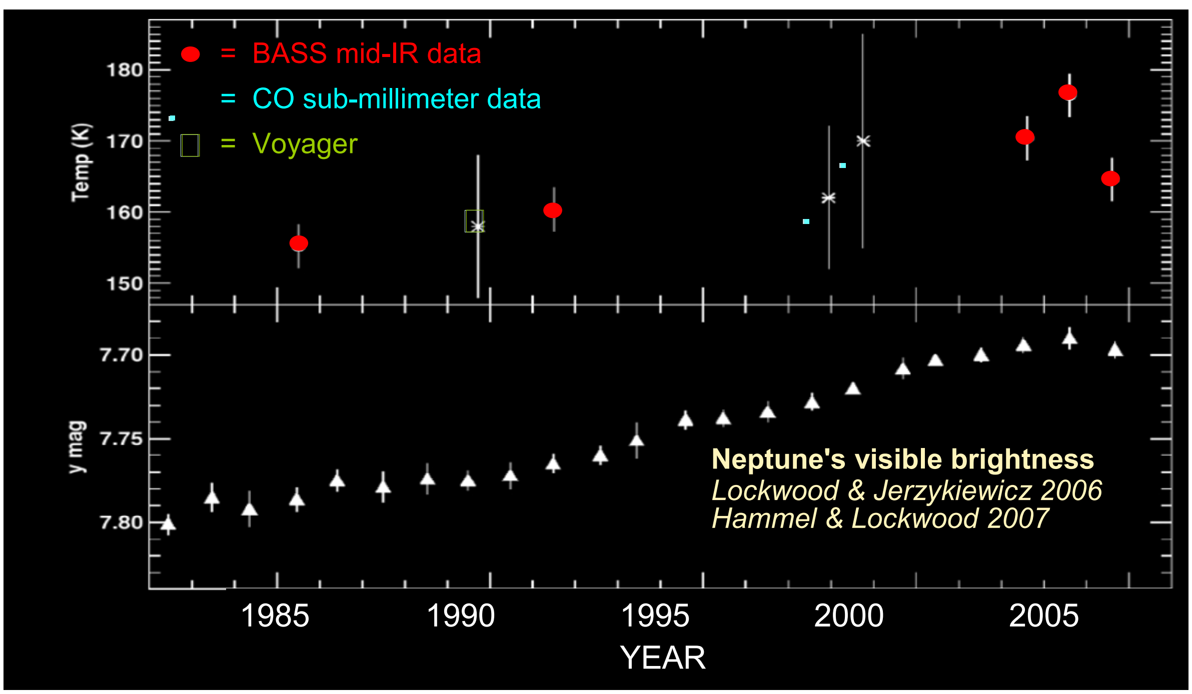


Figure 1. Neptune stratospheric heating.
Observations of Neptune at visible to sub-millimeter wavelengths show evidence for stratospheric heating since the Voyager encounter.

Table 1. Characteristics of Voyager Triton encounter.

A second flyby of Triton could greatly improve characterization of Triton. A Neptune orbital tour would provide opportunity to understand Triton and its volcanism on a global scale.

Closest approach	40,000 km
Subsolar latitude, longitude	~50 S, 0 W.
Imaged surface	~30% of surface imaged at ~2 km/pixel in multiple filters 0.4–0.6 μm
	~30% of surface imaged at ~1 km/pixel in clear filter
	~15% of surface imaged at ~0.5 km/pixel
Best plume resolution	~1 km/pixel
Best high-phase imaging	~2 km/pixel
Marginal detection in thermal IR	At ~45 microns, with spatial resolution ~500 km
UV solar occultation	

One side of Triton was seen only at a distance by Voyager ('terra obscura," ~60 km/pixel resolution) and more of the northern hemisphere would be illuminated in the arrival time period of the architectures studied (2029 for flybys). Near-global surface coverage would extend the post-capture cratering history and other modifications of Triton's surface. It can easily be seen from a summary of the characteristics of the Voyager flyby (Table 1) that a second flyby could provide the opportunity to dramatically improve our knowledge of Triton. A second flyby could provide the opportunity to view Triton at higher latitudes (Figure 2) and at ~100x better resolution (from a lower altitude, ~400 km), and to obtain complementary surface coverage. This would dramatically improve our understanding of mechanisms underlying Triton's volcanism, and the endo- and exogenic processes that shape Triton's unusual terrain.

Flyby missions could also provide a natural opportunity to encounter a KBO. The addition of a large KBO (nominally the second flyby of any KBO) would enhance the value of the mission through fulfilling both giant planet and primitive body goals and adding to measurements of Triton.

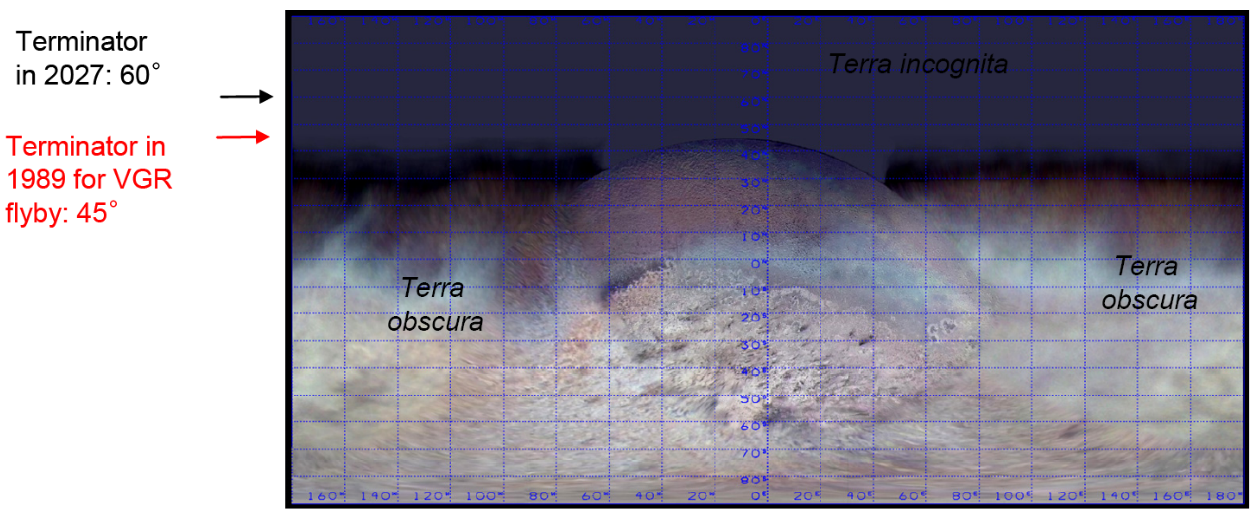


Figure 2. Triton's anti-Neptune hemisphere has been imaged at only 60 km/pixel.

For a 2027 encounter, more of the northern hemisphere would be in sunlight.

Orbital missions, though requiring more mission resources to achieve orbit, provide science opportunities that are unavailable to simple flybys. Orbital missions are better able to map the internal gravity and magnetic fields of Neptune and Triton, and thus fare better in addressing the related science objectives. A mission that orbits the Neptunian system is able to map both hemispheres of Triton. An orbital mission has significantly more time to adapt sequences to discoveries, achieves many more (~60–120) earth occultations for both Neptune and Triton, spends a factor of ~230 more time at altitude that yield the required resolution for observations of Neptune clouds and samples a wide range of spatial and temporal regimes in the Neptunian system. These observational advantages enable understanding how the Neptunian system works over a large range of time scales and focusing later observations on better understanding new results and interpretations.

Science Traceability

The science panel provided science objectives with tier 1 and tier 2 prioritization, which are shown in the left-hand columns of the top-level science traceability matrices, for each tier (Table 3, Table 4, and Table 5). The scientific objectives and the measurements required to fulfill these objectives are also summarized in the traceability matrices. During the study, measurement requirements associated with the traceability matrix were defined in more detail as needed to resolve selection of characteristics for particular architectural elements. This was captured in a “science linkages” matrix (see example in Appendix B), a matrix that links science objectives to measurement requirements to architectural requirements. As study analyses proceed, some of the assumptions entered in the initial science linkages matrix may be determined to be inaccurate, (e.g., an assumption that “one flyby trajectory could not address all target priorities well” was modified, after analysis, to “flyby trajectories exist that allow good trajectory geometries for all target objects for a modest propellant cost”).

The technical implementation of meeting the science objectives is associated with the 14 architectures described later in the architectures trade tree (Figure 5). Three sizes of payload were used to size the architectures: a minimal payload to support a minimal orbital mission, a simple payload of approximately seven instruments (used to support all flyby, and most orbital missions), and a high performance payload, similar in mass to that flown on Cassini.

Figure 3. KBO image.
KBOs are challenging to characterize from Earth. A flyby would provide fundamental information such as composition and collisional history.

It is difficult to satisfy, with a single mission, global mapping of Neptune’s fields and Triton’s surface (both of which would require orbital tours) in concert with the flyby of a KBO (Figure 3). A reasonable percentage of science objectives could be addressed with sufficient resolution to greatly advance our understanding of the Neptunian system using a flyby mission—a mission type that supports visits to all three targets. Orbital architectures provide an opportunity to study thoroughly the Neptune-Triton system, substantially addressing all related science objectives, but cannot reach a KBO. Architecture 3.4 provides an exception that requires two flight elements to deliver both a Neptune orbiter and KBO flyby staged spacecraft in a single mission architecture.

The science objectives and measurements led to the basic straw payload as shown in Table 2. There were variants of the payload (discussed in the Instrument Payload Description section) used to address specific science objectives.

The traceability matrix provided by the joint science panel served well in developing and evaluating mission architectures. The matrices, shown in Table 3, Table 4, and Table 5, provide links from the science objectives to the instrument and functional requirements. The quantitative measurement goals were not included in the traceability matrix in part for brevity and in part because the quantitative goals are inevitably linked to mission capability, and thus were appropriately treated as an iterative determination in the RMA process.

Quantitative measurements must meet high standards. For classes of measurements similar to those from Voyager, ground-based, or Earth-orbiting platforms, new measurements must provide significant advancements in fulfilling the scientific objectives. For Neptune, this includes repeated mapping of the atmosphere at 10 km or better and a pass close to Neptune's southern hemisphere to obtain complementary data on the magnetosphere. For Triton, this includes mapping a hemisphere at 0.25 km or better with selected imaging at 100 m or less. For a KBO, 100 m mapping and flight through the anti-sun wake is strongly desired. New measurements include near-IR mapping and thermal IR mapping, and, for some architectures, mass spectroscopy. Orbital architectures provide unique opportunities for observations over wide temporal and spatial ranges and a wealth of opportunities for stellar, solar, and earth occultations for both Neptune and Triton.

Table 2. Straw payload and function.

Instrument Type	Instrument Function
Narrow angle imager	Approach imaging at low resolution for multiple rotations of Neptune; high-resolution imaging of Triton and KBO
Medium angle imager	Color imaging of all targets
Near IR spectrometer (1–2.5 microns)	Composition of all targets
UV imaging spectrometer	Small particulate scattering (Rings, Neptune), composition, ions, and trace atmospheres (all targets)
Thermal Mapper	Thermal structure of Neptune atmosphere, surface temperatures (Triton, KBOs), and thermal inertia (Triton)
Magnetometer	Fields for all targets
Plasma spectrometer	Space weathering, low energy ions and electrons
Ultra-stable oscillator (USO)	Earth occultations for atmospheric structure, composition
Mass spectrometer	Atmospheric composition (Neptune, Triton)
Atmospheric probe	Atmospheric structure, noble gas, and isotopic composition for Neptune

Table 3. Tier 1 science traceability matrix.

Tier 1 Science Objective	Measurement	Instrument	Functional Requirement
Neptune - Determine how Neptune's clouds, atmospheric thermal structure, gasses, and winds vary over timescales of hours to months to seasons.	Global imaging on time scales from hours to months (seasons by linking to Voyager and Earth-based observations); thermal mapping; spatially-resolved spectroscopic information; radio occultation	Narrow and wide angle visible imagers; Thermal mapper; UV/vis/near-infrared mapping spectrometer; RSS link with USO; gimballed HGA	Flyby adequate; orbiter provides additional temporal coverage
Neptune - Understand the structure, dynamics, and composition of Neptune's magnetosphere.	Particles and field measurements	Magnetometer; Plasma spectrometer	Flyby adequate
Neptune - Measure the molecular composition, noble gas abundances, hydrogen ortho/para ratio, and isotopic adundances in Neptune's atmosphere.	In-situ measurements	Mass Spectrometer	Requires a single Neptune probe
Triton - Understand the geological processes that shape its surface and influence its composition, and constrain the ages of surface units. In particular, investigate whether geological activity is ongoing or dates largely from the time of Triton's capture by Neptune.	Imaging capability, surface reflectance spectroscopy	Narrow-angle visible imager; gimballed HGA; near-infrared mapping spectrometer;	Flyby adequate; orbiter provides global coverage of the surface
Triton - Understand the chemistry and structure of Triton's atmosphere and its interaction with the surface, including the seasonal volatile cycle and plume activity.	Imaging & spectroscopic mapping capability; radio occultation; UV stellar occultations; direct sampling of atmosphere via close flybys	Narrow and wide angle visible imagers; UV/vis/near-infrared mapping spectrometer; RSS link with USO; gimballed HGA; mass spectrometer for direct samples	Flyby adequate; orbiter provides global coverage of the surface, potential of direct atmospheric sampling, and possibility for direct observation of seasonal change on the surface and atmosphere
Triton - Understand the interior structure of Triton, particularly whether it is differentiated, and whether there is a subsurface ocean.	Magnetic field, gravity, shape measurements	Magnetometer; gimbaled HGA; visible imagers	Flyby adequate if sufficiently close and Triton has an internal liquid layer; orbiter preferred for magnetic induction and characterization of higher order gravity moments, or if Triton is not differentiated.
KBO - Understand the geological processes that shape its surface and influence its composition, and constrain the ages of surface units. In particular, investigate whether geological activity has ever occurred and relate that to its collisional history via the cratering record.	Imaging capability	Narrow-angle visible imager	Requires KBO flyby; excludes Neptune system orbiter
KBO - Understand the spatial distribution of surface composition and how the composition is coupled to geologic processes. Included in the surface composition investigation is the need to understand the nature and degree of space weathering on the surface.	Spectroscopic mapping capability	Uv/vis/near-infrared mapping spectrometer	Requires KBO flyby; excludes Neptune system orbiter

Table 4. Tier 2 science traceability matrix.

Tier 2 Science Objective	Measurement	Instrument	Functional Requirement
Neptune - Place new constraints on the internal structure of Neptune by refining and extending knowledge of the gravitational harmonics of the planet.	Higher order harmonics from orbiter	Main spacecraft	Orbiter
Triton – Understand the interaction between Triton and Neptune's magnetosphere.	Particles and field measurements	Magnetometer; Plasma spectrometer; mass spectrometer	Some data obtainable with flyby; orbiter preferred
Rings - Measure the composition, size, and dynamical properties of ring particles and associated small satellites, and determine how they interact to control structure and evolution.	Imaging and spectroscopic capability, occultations	Narrow and wide angle visible imagers; UV/vis/near-infrared mapping spectrometer; RSS link with USO	Flyby adequate
Small Neptune moons - Determine the surface composition, size and orbits of the small inner satellites and Nereid.	Imaging and spectroscopic capability	Narrow and wide angle visible imagers; UV/vis/near-infrared mapping spectrometer	Possible Nereid flyby.
KBO - Determine bulk properties such as the mass and volume, search for satellites, and measure the bolometric and Bond albedos and constrain or measure the surface temperature	Imaging capability; bolometric measurements	Narrow and wide angle visible imagers; Thermal mapper with far IR ensitivity	Requires KBO flyby; excludes Neptune system orbiter
KBO - Understand the interaction between the KBO and the solar wind, keeping in mind that the slightest presence of an atmosphere will have a profound effect on the structure and nature of the interaction region.	Particles and field measurements	Magnetometer; Plasma spectrometer	Requires KBO flyby; excludes Neptune system orbiter

Table 5. Triton expanded Tier 1 traceability matrix including quantitative requirements.

Tier 1 Science Objective	Measurement	Instrument	Functional Requirement	Flyby Geometry Constraint
Triton - Understand the geological processes that shape its surface and influence its composition, and constrain the ages of surface units. In particular, investigate whether geological activity is ongoing or dates largely from the time of Triton's capture by Neptune.	Imaging capability, surface reflectance spectroscopy. Hemispheric imaging at < 0.25 km/pixel with phase angle 20 – 70 degrees for good topography. Coverage of selected targets, especially plume sources, at < 100 m/pixel	Narrow-angle visible imager (best plausible resolution 4 μrad); near-infrared mapping spectrometer (best plausible resolution 30 μrad);	Flyby adequate; orbiter provides global coverage of the surface	• Solar phase angle 20 – 70 degrees at range between 10,000 and 60,000 km, for global imaging and NIR spectroscopy • View of latitudes < 45 S in sunlight at range < 10,000 km, for high-resolution plume imaging • C/A subsolar latitude >270 E or less than 90 E, so we can use Voyager images to target high-res images
Triton - Understand the chemistry and structure of Triton's atmosphere and its interaction with the surface, including the seasonal volatile cycle and plume activity.	Imaging & spectroscopic mapping capability 1 – 2.5 micron global spectra with <10 km resolution; radio occultation; UV stellar occultations; direct sampling of atmosphere via close flybys	Narrow and wide angle visible imagers; Near-infrared mapping spectrometer (best plausible resolution 30 μrad); UV spectrometer, RSS link with USO; gimballed HGA; mass spectrometer for direct samples	Flyby adequate; orbiter provides global coverage of the surface, potential of direct atmospheric sampling, and possibility for direct observation of seasonal change on the surface and atmosphere	• UV solar occultation for determination of atmospheric pressure and composition (stellar occultation might be an acceptable substitute, but probably not) • Earth radio occultation preferred but probably not essential Constraints for remote sensing: • C/A subsolar latitude >270 E or less than 90 E, for repeat imaging for post-Voyager change detection

2. High-Level Mission Concept

Overview

This JPL RMA study was not a mission concept study of a single mission, but instead an architectural-level study of a set of missions to Neptune, Triton, and for some, continued travel to a KBO. It was commissioned by three Planetary Science Decadal Survey Panels: Giant Planets, Satellites, and Primitive Bodies. The panels' intent is to use the results to compare key metrics of the architectures (including science value, cost, and risk) and decide which ones, if any, merit individual, more detailed study. The study science team, with members from each of the panels, emphasized lower-cost missions, so a large fraction of both the science objectives and the selected architectures favor missions requiring the fewest resources.

Architectures selected for the most detailed study include four primary classes of science missions, launch vehicle types consistent with the NASA ground rules for the study, and a variety of in-space propulsion methods for increasing the mass delivered to Neptune or performing a Neptune orbit insertion (NOI) maneuver. The four classes of science missions include flybys, a "minimal" Neptune orbiter, a set of "simple" Neptune orbiters, and a Cassini-class Neptune orbiter. Flybys visit all three primary destinations listed above. With one exception, Neptune orbital missions do not visit a KBO, but focus their investigations within the Neptune system. Secondary payload elements, such as atmospheric entry probes or free-flying instruments, were considered for architectures in all classes except the minimal Neptune orbiter. In-space propulsion methods used in the study range from those well in hand, such as gravity assists and chemical propulsion, to solar electric propulsion (SEP) that would need engineering development work, to aerocapture, a new technology yet to be used in a NASA science mission. For each architecture, mature technologies were used whenever they were sufficient to enable the mission. Only when mature technologies were insufficient would less mature technologies be considered.

Concept Maturity Level

This JPL RMA study is a concept maturity level (CML) level 3 trade space study, as defined in Table 6.

Table 6. Concept maturity level definitions.

Concept Maturity Level	Definition	Attributes
CML 6	Final Implementation Concept	Requirements trace and schedule to subsystem level, grassroots cost, 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

This study used the JPL RMA team and process initially developed at JPL in 2007 as the approach for the architectural trade space assessment. For a CML 3 JPL RMA study, the objective is to explore and evaluate a broad trade space of alternative mission and system architectures that respond to the science objectives, priorities, and constraints identified by the science panel members participating in the study. In conducting the study, the assessments complied with the ground rules established by NASA Headquarters to evaluate science value, cost, risk, and performance impacts; address programmatic issues (e.g., launch timing, cost class); and synthesize results and recommendations. The mission architectures selected for these JPL RMA CML-3-level assessments were evaluated at an architectural level of fidelity sufficient to allow relative assessment of key metrics and characteristics between mission architectures, to enable identification of promising mission candidates for follow-on point-design studies.

Technology Maturity

Instrument types studied were generally high technology readiness level (TRL), high-heritage instruments assessed as analogues from the New Horizons and Cassini missions. Additional information regarding the instruments can be found in the Instrument Payload Description section. Table 7 summarizes the estimated TRLs of various example instruments considered. It is natural to assume that by the time a Neptune/Triton mission were to be undertaken in the next decade, technology and instruments will have evolved. This study makes no assumptions about such evolution.

Out of the large number of spacecraft and ground system technologies that were considered and traded in the study, several specific key technologies and infrastructure elements were found to be enabling to accomplish the mission science and significantly enhancing to reduce cost for the mission architectures studied. Aerocapture, SEP, and advanced Stirling radioisotope generators (ASRGs) were identified as critical technologies and included amongst the set of mission architectures.

SEP was selected and used for all orbiter architectures. SEP is significantly enhancing to reduce launch vehicle (LV) costs (e.g., converging on the equivalent of an Atlas V class LV rather than Delta IV-Heavy class) and is enabling for some architectures to converge within the launch mass and time-of-flight constraints. These results are also driven by the mass increases for orbiters relative to the flyby architectures due to Neptune orbit insertion (NOI). SEP as a system-level technology has been flight demonstrated in deep space missions (DS-1, Dawn) and is at high TRL 8–9. However, specific improved component technologies already under development were assumed for the analyses in this study (e.g., “NEXT” ion thrusters under development by NASA and large “Ultraflex” solar arrays demonstrated or under development for several missions). These component technologies would likely be available in the mission timeframe of these mission concepts, but are currently below TRL 6.

Two architectures (3.4 and 4 as referenced later in the architectures trade tree [Figure 5]) would require the use of aerocapture for NOI to converge the architectures even with Jupiter gravity assists (JGAs). Without JGAs, aerocapture is enabling for all orbiter architectures. This was driven by the sensitivity of mass to orbit to NOI delta-V and time of flight to Neptune, even for launch vehicles up to the equivalent of a Delta IV-Heavy class. Aerocapture as a flight system represents a new system-level technology below TRL 6. However, many component technologies are at high TRL (6 or greater), including guidance, navigation, and control components and algorithms; aerodynamic modeling and simulation; and thermal modeling and simulation. Components such as the mid-L/D aeroshell (with a lift-to-drag ratio of 0.7 to 0.8, such as an “ellipsled” or other mid-L/D configuration) and thermal protection system (TPS) technologies were assessed below TRL 6 and would require further development and analyses.

Advanced Stirling radioisotope generators (ASRGs) were selected as the primary radioisotope power source (RPS) for all architectures. The use of an RPS would be required due to the power requirements and large distances from the sun. Multi-mission radioisotope thermoelectric generators (MMRTGs) were also considered, but plutonium availability was perceived as a major concern. Thus, the ASRG was selected to minimize the quantity of plutonium required by the architectures, with the added benefit of reduced mass and cost relative to the MMRTGs. ASRGs are currently at or nearly at TRL 6, and there is an ongoing specific NASA technology program supporting further development and lifetime testing of ASRGs for near-term mission infusion. ASRGs are at a high level of development maturity and would be ready for flight in the mission timeframe of these architectures.

Table 7. Estimated TRLs of example instruments.

Example Instrument	TRL
Wide angle imager	7+
Near-IR imaging spectrometer	7+
Magnetometer (includes boom)	8+
RSCM link	8+
USO	8+
Gimballed high-gain antenna	8+
Narrow angle imager	7+
UV imaging spectrometer	8+
Plasma spectrometer	7
Thermal mapper	5
Mass spectrometer	8+
Additional Flagship class mission instruments: RPWS, HEP, Dust, FTIR, GPR, etc.	Various, ranging 5–8

In addition to the spacecraft technologies, two key ground-based infrastructure elements were assumed in the study. Since RPSs would be enabling for these architectures, the study assumed sufficient availability of plutonium-238 for all architectures. This assumption would be dependent on the United States' ability to acquire and/or produce sufficient plutonium-238 to support space mission needs. Additionally, the study assumed support for up to four arrayed 34 m Deep Space Network (DSN) antennas and dual-polarization Ka band, as required to accommodate the nominal large data volumes. DSN arraying is a planned capability already in the DSN program operating plans, and new antennas are being built. Nevertheless, availability would be dependent on future DSN configuration and operational/programmatic decisions.

Key Trades

One primary goal and driving factor in a JPL RMA study is wide exploration of the trade space. In this study, the trade space was explored by examining factors such as cost drivers, and key emerging or new technologies, and by brainstorming various innovative solutions. These ideas were captured in a key trades matrix. The key trades matrix generated for this study is shown in Figure 4. The elements highlighted in blue are the trade dimension, and all items to the right represent tradable options within that trade dimension. The elements highlighted in gray were a product of the brainstorming sessions and were briefly assessed and filtered, but not analyzed in detail after the primary architectures were selected to proceed to integrated assessment. The white elements were analyzed further but were not selected in any of the architectures. Lastly, the orange elements were selected in at least one architecture. As shown, this matrix documents traded elements throughout the lifecycle of the study, from brainstorming to integrated assessment of architectures. The key trades matrix aided in developing and filtering the initial list of possible architectures.

Figure 5 illustrates the architectures trade tree. This tree summarizes the types of architectures first considered and the possible sub-options. The trade tree does not show every possible architectural combination, focusing instead on options of greatest interest.

All sub-options highlighted in green are architectures that were selected for integrated assessment. This set of 14 architectures encompasses the primary trades that the science team wanted to pursue in more detail. The architectures and their specifications will be discussed later in this report. In general, the rationale for not selecting a particular architecture involves, for example, high cost (e.g., exceeding a perceived cost target), lower science value for the cost (or similar science value for higher cost), higher risk (for similar science value), and constraint violation (e.g., multiple KBO flybys with a single spacecraft violate lifetime constraints). The selected architectures represent the science team's priorities and diversity in mission scope for the architectures selected.

Primary Flight Elements	Flyby S/C	Orbiter	Dual Orbiters			
Secondary Flight Elements	Neptune Probe (5 bar)	Neptune Probe (20 bar)	Combined N/T Probe	Dual Follower-Leader Probes	Staged Deep Probe	Skip Entry Probe
	Impactor	Free-Flying Magnetometer	Lander	Seperable KBO flyby S/C	Free-Flying Transponder/Mag.	
Primary Power	Solar Concentrators	MMRTG	ASRG			
Science Pointing and Ops	Body Fixed	Individual Instr. Scanning	Scan Platform	Gimballed HGA	Multiple Flybys w/Focused Objs	
Ops and Data Return Technology	Deployable Antenna	High Power Telecom	Dual Polarization	Arrayed 34m DSN	Optical Telecom	Autonomous Nav/Ops
Instruments	Altimeter	Accelerometer	TI	Press. Sensor	Mass Spec	Dust
	OPH	PWS	PLS	EPD	MAG	VI
	NIRI	Mapping Spec.	NAC	WAC	UVI	FTIR
	RSCM	USO	Sounding Radar	Transponder	Gravimeter	Microwave
Launch Vehicles/Options	Falcon 9 Heavy	Delta IV Heavy	Atlas V	Falcon 9	Added Centaur Cryostage w/in Fairing	Added Solid Upper Stage
Propulsion System	Chemical	SEP Stage	SEP Integrated	REP	NEP	REP&SEP
Cruise Approach	Chemical	JGA	Solar Sails	Low Thrust Inner System		
NOI Approach	Dynamic Tethers	Propulsive NOI	Neptune Aerocapture	Inflatable Aeroshell	Low Thrust Outer System	Long Term Cryogenics
	Triton AGA	Ballute	Flyby			
Neptune Trajectory	Flyby	Low Periapse Orbit	Triton Limited Tour	Full Tour		
Triton Trajectory	Flyby w/in 10,000 km	Flyby w/in 300-400 km	Multiple Flybys	Flyby as Possible		
KBO Trajectory	Large KBO	Smaller KBO	Mult. Flybys	Centaur Sub.		
Time of Flight to Neptune	11 years	12 years	13 years	14 years	15 years	
Tour Duration	1 year	2 years				
Primary Mission Duration	12 years	13 years	14 years	15 years	16 years	

Legend

Trade Dimension	**Allowable but not selected**	Selected	Provisionally rejected

Figure 4. Key trades matrix.

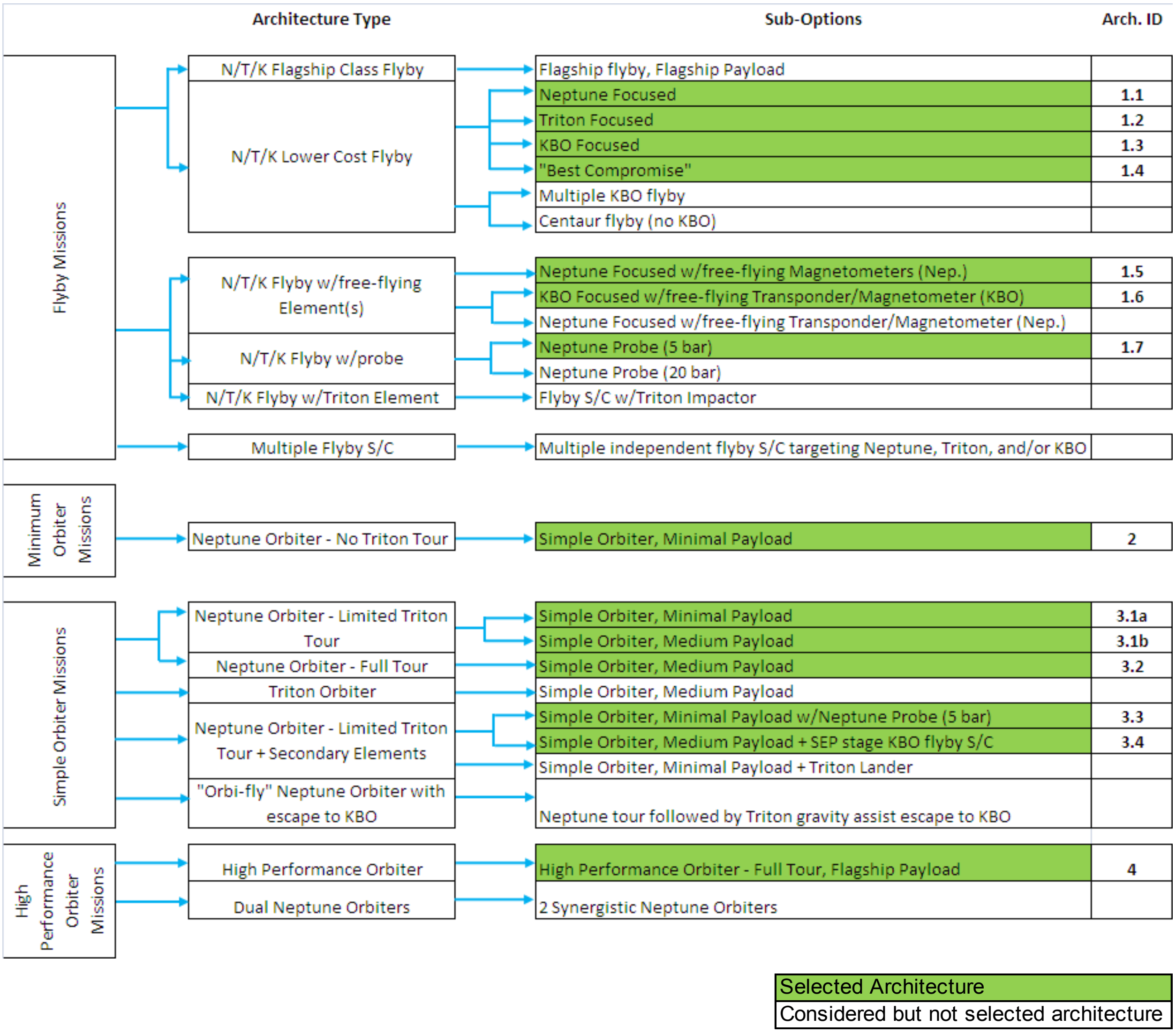


Figure 5. Neptune, Triton, KBO architectures trade tree.

There were two primary types of architectures considered in this study: flyby and orbiter. These architectures examined different areas of the trade space. The flyby architectures included variations in the Neptune, Triton, and KBO trajectories, and the more complex options included one of three secondary flight element types. However, since the primary payload suite for all the flyby options would be the same and trajectory variations had minimal impact on the flight system architecture, the trade decisions for the flyby architectures did not cause significant variations in the architectural results. The orbiter architectures do vary more significantly due to the broader trade space considered. The orbiter architectures traded different secondary flight elements, launch vehicles, payloads, tour durations, Neptune, Triton, and KBO trajectories (e.g., architecture 3.4), and the time of flight to Neptune.

The trades examined in this study were tuned to explore the driving parameters in this type of mission connected to cost (e.g., selection of simple payloads and operations), mass (such as payload and flight elements), and the trajectory (time of flight, mission duration, geometry about the objects). These areas and possible ways to impact them, such as launch vehicle or upper stage choice, instrument/component mass and lifetime, and propulsion systems/techniques, deserve further attention and analysis in future, more-detailed studies beyond this architectural-level study.

3. Technical Overview

Instrument Payload Description

Three classes of straw payload, designated “minimal,” “simple,” and “high-performance,” were used to assess the 14 architectures. The minimal payload concept was used for the “minimal orbiter” mission, a mission focused on collecting in-situ data on Neptune. This package consists of a magnetometer, an ultra-stable oscillator (USO), a combination camera/IR spectrometer, and telecom enhancements necessary for celestial mechanics experiments. The “simple” payload has approximately (depending on the grouping) seven instruments and was defined to meet the measurement requirements for most scientific objectives. There are minor variants of this payload, but all variants have roughly the same mass and power requirements. The “high-performance” payload is sized to use mass and power resources typical of a flagship mission (e.g., Cassini). The set of straw instruments in this payload were only partially defined. A fixed total mass, power and data rate allocation was used, as is, as appropriate for low-CML RMA trade space studies.

The instruments in the payloads are linked to the science objectives in the science traceability matrix. The implementation challenges for the payload include long mission duration and the high mass increases to achieve orbit at Neptune. Instruments used in Neptune missions would require special features, such as high redundancy, to achieve the necessary lifetimes. Extreme instrument mass reduction was less important for architectures using flyby or aerocapture, since those architectures are not highly sensitive to mass.

For missions which would use flyby trajectories, the number of rotations of Neptune observed at or below a given resolution would depend on the instantaneous field-of-view (IFOV). The strawman IFOV (5 microradians/pixel) would allow observation of two rotations at 10 km or better resolution (a resolution goal for atmospheric dynamics). IFOVs to 1 microradian would be practical for the flybys (e.g., the DI instrument, which includes a 1–5 micron spectrometer), allowing observation of 10 rotations at the required resolution. The wide angle camera would be combined with a near-IR spectrometer (e.g., New Horizons’ RALPH). The strawman implementation has a 6 cm aperture, leading to somewhat long integration times (0.75 seconds)—which is a limiting factor in the rate of data acquisition on approach to Neptune. There are no flight examples of the desired thermal imager (12 bands, 1–100 microns), though the Lunar Polar Orbiter’s Diviner instrument provides a reasonably close analog. A solid state recorder would be included with the flyby payloads to buffer acquisition duration, which is shorter than that available for an orbital mission (see Mission Design section).

The high performance payload includes instruments that provide important enhancements to the baseline simple payload. These include fields and particles instruments (plasma wave, high energy ions, dust), ground-penetrating radar, and a long-wavelength Fourier Transform Infrared spectrometer (FTIR) (e.g., CIRS).

In addition to the instrumentation shown in Figure 6, there are strawman payloads associated with the (small) atmospheric probes and free-flying magnetometers/transponders. The implementation of the latter is apparent in the name; the former includes a mass spectrometer (principally for measuring noble gases and isotopic ratios), USO, and an atmospheric structure package (to measure temperature, pressure, and Doppler winds).

	N/T/K flyby, Neptune focused	N/T/K flyby, Triton focused	N/T/K flyby, KBO focused	N/T/K flyby, "best compromise"	N/T/K flyby, Neptune focused w/Multiple Free-flying Magnetometers	N/T/K flyby, KBO focused w/ Single Free-flying Transponder/ Magnetometer	N/T(/K?) flyby w/Neptune probe	Simple orbiter: Neptune polar orbit	Simple orbiter: limited Triton tour, Minimum payload	Simple orbiter: limited Triton tour, Simple Payload	Simple orbiter: full tour	Simple orbiter: limited Triton tour w/ shallow atmospheric probe	Simple orbiter: limited Triton tour**, deploys KBO flyby S/C	Hi-perf. orbiter only	
Study option designator	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**2**	**3.1a**	**3.1b**	**3.2**	**3.3**	**3.4**	**4**	
Modeled Payload Mass	**60**	**60**	**60**	**60**	**60**	**60**	**60**	**25**	**25**	**60**	**60**	**25**	**60**	**300**	**Similar**
Instrument															**Instrument**
Wide angle imager	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Ralph
Near-IR imaging spectrometer	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Ralph
Magnetometer (includes boom)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	Mag
RSCM link	1	1	1	1	1	1	1	1	1	1	1	1	1	1	JUNO
USO	1	1		1	1	1	1	1	1	1	1	1	1	1	GLL
Gimballed High-Gain Antenna	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Narrow Angle Imager	1	1	1	1	1	1	1			1	1		1	1	Lorri
UV imaging spectrometer	1	1	1	1	1	1	1			1	1		1	1	Alice
Plasma spectrometer	1	1	1	1	1	1	1			1	1		1	1	Pepssi
Thermal mapper	1	1	1	1	1	1	1			1	1		1	1	Diviner
Mass spectrometer										1	1		1	1	INMS
RPWS, HEP, Dust, FTIR, GPR, etc														1	Cassini
SSR 256gbit	1	1	1	1	1	1	1							1	SEKR
Mass	61	61	59	61	61	61	61	27	27	56	56	27	56	300	
Power	63	63	61	63	63	63	63	14	14	61	61	14	61	300	

Figure 6. Payloads for the architectures fall into three mass classes: "minimal" (25 kg), "simple" (60 kg) and "high performance" (300 kg).
The 300 kg payload is only partially configured, with fixed allocations for total mass, power, and data rate.

Flight System Architectures

As discussed in earlier sections, flight system architectures were brainstormed and organized with qualitative methods. Quantitative analysis was then applied to those concepts that appeared to best meet study objectives. This analysis provides preliminary metrics for representative architectures that then provide insights into the contours of the trade space. Consistent with an architecture-level study, detailed design and optimization necessary to provide precise evaluations of subsystem-level properties has yet to be conducted.

The architectures characteristics matrix (Table 8) summarizes the 14 architectures selected by the science and JPL RMA teams to develop preliminary performance and resource (e.g., mass, cost) estimates. Appendix B contains the entire architectures characteristics matrix. The focus of this trade space is on relatively low-cost spacecraft, with a number of flyby missions and very simple orbiters examined. In order to provide an upper bound and relative fiducial point to the trade space in terms of concept scope, a flagship-class, high-performance Neptune orbiter was examined.

Within the matrix, each architecture is described by its core flight element, any secondary elements that it might carry, payload suite, and launch and time-of-flight information. The full architectures characteristics matrix in Appendix B also gives trajectory, launch, and time-of-flight information. The Mission Design section of this report describes in more detail the variety of trajectory types that are studied. The launch vehicles listed here are represented as analogues to the generic launch capabilities provided to the study team by the NASA Decadal Survey ground rules [6].

Table 8. Architectures characteristics matrix—flight element view.

Arch. # if Selected	Arch. Class	Sub-Options/Name	Launch Vehicle (Ground Rules)	Launch Vehicle Analogue	Cruise Stage (chem, YY kW SEP)	Arrival NOI Stage	Primary Flyby S/C	Primary Orbiter(s)	# ASRGs	Type of Secondary Element	Number of Secondary Elements	Primary Element Payload Mass (kg)	Primary Element Instruments List	Secondary Element Mass (kg)	Secondary Element Instruments List
	FLYBY														
1.1		N/T/K flyby, Neptune focused	Opt. 4b	Atlas V 521	Chem		x		4			60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, 256 Gbit SSR		
1.2		N/T/K flyby, Triton focused	Opt. 4b	Atlas V 521	Chem		x		4			60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, 256 Gbit SSR		
1.3		N/T/K flyby, KBO focused	Opt. 4b	Atlas V 521	Chem		x		4			60	WAC, NIRI Spec, MAG, RSCM link, NAC, UVI Spec, PLS, TI, 256 Gbit SSR		
1.4		N/T/K flyby, "best compromise"	Opt. 4b	Atlas V 521	Chem		x		4			60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, 256 Gbit SSR		
1.5		N/T/K flyby, Neptune focused w/ Free-flying Multiple Magnetometers	Opt. 4c	Atlas V 531	Chem		x		4	Free flying Magnetometers	3	60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, 256 Gbit SSR	15 (x3)	MAG
1.6		N/T/K flyby, KBO focused w/ Free-flying Transponder/Magneto meter	Opt. 4b	Atlas V 521	Chem		x		4	Free-flying transponder / magnetometer	1	60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, 256 Gbit SSR	15	Transponder, MAG
1.7		N/T/K flyby w/Neptune probe (5 bar)	Opt. 4c	Atlas V 531	Chem		x		4	Probe	1	60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, 256 Gbit SSR	100	MS, Temp. & Press., USO
	"MINIMAL" ORBITER														
2		Simple orbiter: Low periapse Neptune orbiter	Opt. 5	Atlas V 551	15kW SEP	Chem		x	3			25	WAC, NIRI Spec, MAG, RSCM link, USO		
	SIMPLE ORBITER														
3.1a		Simple orbiter: Limited Triton tour	Opt. 5	Atlas V 551	15 kW SEP	Chem		x	3			25	WAC, NIRI Spec, MAG, RSCM link, USO		
3.1b		Simple orbiter: Limited Triton tour	Opt. 5	Atlas V 551	15 kW SEP	Chem		x	3			60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, Mass Spec.		
3.2		Simple orbiter: Full tour	Opt. 6	Delta IV 4050H-19	25 kW SEP	Chem		x	3			60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, Mass Spec.		
3.3		Simple orbiter: Limited Triton tour w/ shallow atmospheric probe (5 bar)	Opt. 6	Delta IV 4050H-19	15 kW SEP	Chem		x	3	Probe	1	25	WAC, NIRI Spec, MAG, RSCM link, USO	100	MS, Temp. & Press., USO
3.4		Simple orbiter: Limited Triton tour, deploys KBO flyby S/C	Opt. 5	Atlas V 551	15 kW SEP	Aerocapture		x	3 + 3	KBO flyby S/C	1	60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, Mass Spec.	60 (payload)	WAC, NIRI Spec, MAG, RSCM link, NAC, UVI Spec, PLS, TI, 256 Gbit SSR
	HIGH-PERFORMANCE														
4		Hi-perf. orbiter only	Opt. 5	Atlas V 551	15 kW SEP	Aerocapture		x	5			300	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, Mass Spec, RPWS, HEP, Dust, FTIR, GPR, 256 Gbit SSR		

Core flight elements were developed by starting with data on the hardware subsystems for appropriate analogue spacecraft, and then rescaling them to the requirements imposed by their science objectives and mission trajectories. These were incorporated in architecture-level spacecraft models with propellant and dry masses adjusted as appropriate to their missions. The study assumed some selected areas of heritage from New Horizons for the flyby architectures, and also analogies with Cassini or the recent Titan Saturn System Mission (TSSM) Outer Planets Flagship Mission study for the orbiter architectures [7]. The TSSM mission concept study was a detailed mission study, but has not yet flown and is not currently in development. Where required to converge the architectures, these spacecraft were augmented by SEP stages and aerocapture systems, which were also scaled as necessary to meet mission demands.

Each of the core flight elements would carry ASRGs as the main power source. The number of ASRGs cited in the architectures characteristics matrix includes one spare (for single fault tolerance) for each independent flight element with onboard ASRGs. Every architecture has one spare total, except architecture 3.4 has one spare in both the main orbiter and the KBO flyby spacecraft. ASRGs require significantly less plutonium than their RTG or MMTRG counterparts. However, carrying a spare ASRG does require additional plutonium, which is a limited resource. This risk mitigation approach might be subject to change pending future additional reliability studies and lifetime testing for ASRGs.

Secondary flight elements were treated as allocations based on analogous previous studies or subject matter expert judgment, except for the separable KBO flyby stage of architecture 3.4. This spacecraft was designed in the same manner as the SEP stages, with additional dry mass allocated to account for instruments and independent flight subsystems (flight computer, attitude sensors, etc.).

There were two types of secondary elements considered: atmospheric entry probes and free-flying instrument packages. The science team specified “shallow” atmospheric probes descending to the 5-bar level within the Neptunian atmosphere to penetrate below the methane cloud level at Neptune. Two free-flying elements were designed, one to enable simultaneous multi-point magnetometer measurements at Neptune, and one to provide magnetometry and radio science on the opposite side of a KBO from the main spacecraft.

Figure 7 presents the results of the architecture-level spacecraft mass performance calculations, with masses broken out to show the relative scales of dry and wet masses needed to fly the mission profiles specified for each architecture. This chart also shows the highly beneficial impact of aerocapture in reducing the launch mass of high-performance spacecraft, serving as an enabling technology for the more ambitious missions. All architectures were nominally sized using JGAs. However, architectures 3.4 and 4 could not converge without aerocapture within time-of-flight constraints, even with a Delta IV-Heavy class launch vehicle and JGA. For those architectures, aerocapture would greatly simplify the primary orbiter, as it no longer required a large propulsion system for NOI. It should also be noted that the full Neptunian system tour in architectures 3.2 and 4 involve an increase in delta-V and associated propulsion system mass to accommodate the longer-duration 2-year tour to rotate from Triton’s orbital plane to a near-polar one for interior science. Although it is not explicitly shown in the mass results here, side trades demonstrated that aerocapture becomes an enabling technology for all orbiter architectures that do not employ a JGA.

An important finding is that high-duty cycle instruments drive power and telecom subsystem requirements and associated increases in dry mass, particularly for flyby missions. Furthermore, the most favorable of JGAs in the timeframe considered require a relatively large deep space maneuver to reach Neptune. The flyby architecture chosen requires a large deep space maneuver to fly the 2018 opportunity trajectory. This accounts for both the large propellant mass and associated spacecraft dry mass increase for the flyby architectures. This 2018 flyby trajectory opportunity was selected based upon the science targeting objectives and priorities for Neptune, Triton, and the KBOs as specified by the science team members. However, future studies might revisit trades available for later launch years, including 2019 (and possibly 2020) direct-to-Jupiter trajectories, albeit with increased Atlas V-class launch vehicle and a STAR motor upper stage. Trajectories without JGA would require SEP beyond these launch years (until the next JGA opportunity circa 2029). But such flyby trajectories would require SEP. Further aspects of the non-JGA trajectories are discussed in the Conclusions section.

Figure 8 gives the required delivered mass at Neptune for the various architectures. In accordance with the NASA ground rules for the Decadal Survey studies, each of the masses includes 30% margin. The increase in mass between architectures 3.1a, 3.1b, and 3.2 shows that the impact of the inclination change maneuver needed to achieve the full tour at Neptune is not limited to propellant. The mass comparison also highlights the significant propulsion and structural mass reduction benefit of aerocapture used in sizing architectures 3.4 and 4. Architectures 3.4 and 4 required aerocapture even with JGAs.

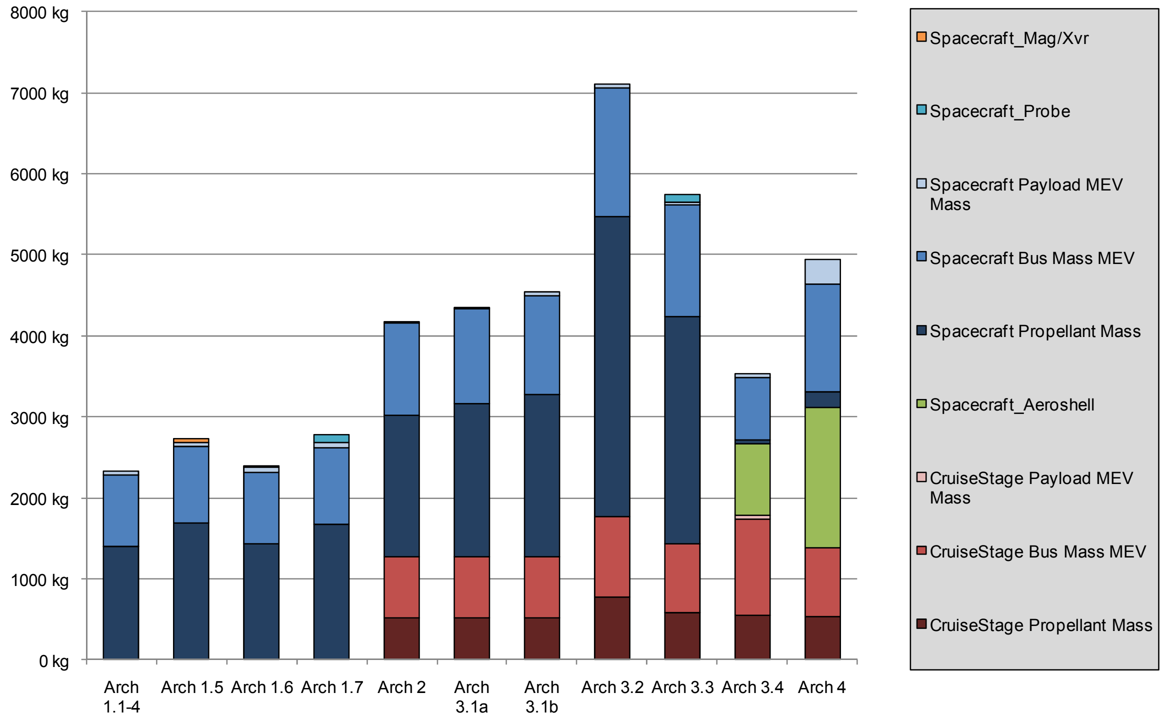


Figure 7. Architecture-level mass rollups.

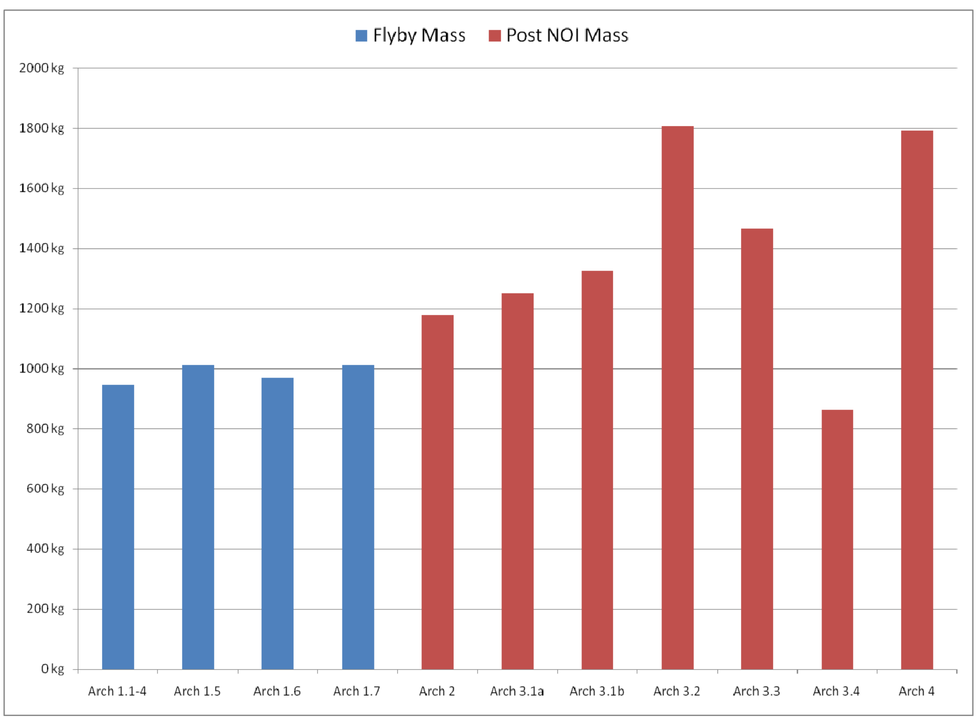


Figure 8. Delivered mass at Neptune.

Concept of Operations and Mission Design

An operations view of the Neptune-Triton-KBO RMA mission set provides four tour types—(1) single-pass flybys, (2) a low-periapsis, mid-inclination orbit of Neptune that does not involve Triton close flybys, (3) a "limited" 1-year, Triton-driven tour of the Neptune system, and (4) a "full" 2-year, Triton-driven tour of the Neptune system. The flyby type has four options, picking the best aim point for Neptune, Triton, or the KBO or a set of aim points that represent the best average return. The low-periapsis, mid-inclination orbit is the simplest tour type—a relatively fixed orbit orientation designed to map Neptune's internal fields and atmospheric activity. The orbit was applied to architecture 2 with either a 150° or 30° inclination to allow a low altitude (~3,000 km) NOI that avoids the rings. Orbit periapsis would start at ~3,000 km and be raised slowly (with maneuvers) to avoid the rings as Neptune's oblateness rotates the orbit. Orbit period could range from 20 days to several years, as apoapsis altitude may be arbitrarily chosen.

The limited and full tours arhcitectures provide rich science opportunities. The "limited tour" was used for architectures 3.1a, 3.1b, 3.3, and 3.4 and involves a tour in Triton's orbit plane followed by a short sequence of inclined Neptune orbits (between 130–157 degrees). The beginning of the limited tour alternates between two different Neptune orbits and two different Triton (equatorial) flybys. The end of the limited tour has the same Neptune orbital period at different inclinations, and flybys have consistent spacing. Limited-tour delta-V is ~1 m/s per Triton flyby in the planar phase and ~3 m/s in the inclined phase (~25 m/s total for 1 year tour). One Triton flyby is achieved every ~3 weeks. Twelve Triton flybys are equatorial and alternate between two groundtracks on opposite sides of Triton (~1,000–200 km alt). Four flybys are on the same side of Triton and inclined (~700 km alt). The Triton sub-solar point varies only for equatorial flybys. The limited tour assumes no close flybys of any moons other than Triton. Neptune periapsis is at >2.5 R_Neptune during the limited tour (limited by rings).

The "full tour" was used for architectures 3.2 and 4. This tour was developed by the NASA Vision Mission Study "Neptune Orbiter with Probes" and provides a very rich set of observation opportunities in the Neptune system [8]. Neptune orbit and Triton flyby geometry are highly varied to maximize science return per unit time, with inclinations between 90 and 180 degrees and periapsis altitudes ranging from ~3,000 km to 100,000 km. Full-tour delta-V is ~150 m/s per year, and 2 years long. Triton has 30+ flybys a year (sometimes as often as one a week). The full tour achieves a high diversity of Neptune orbits and Triton flybys. Several varied (day and night) Neptune and Triton occultations are possible. Neptune periapsis could go below 2.5 R_Neptune for certain orbits. A couple of close flybys of other moons is possible. Figure 9 shows a representative geometry for the full tour.

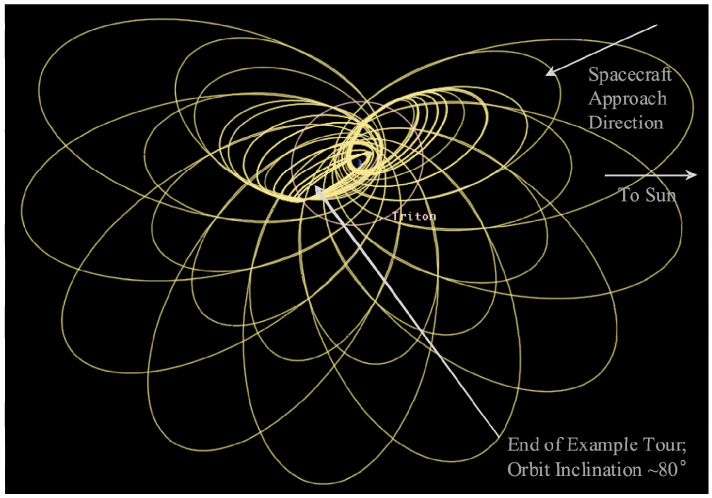
The mission operational phases for the flyby mission types would be launch, inner gravity assist, inner quiet cruise, JGA, outer quiet cruise, Neptune approach and flyby, Triton approach and flyby, quiet cruise and playback, KBO approach, KBO flyby, and KBO playback. The mission operational phases for orbiting missions without aerocapture would be launch, inner gravity assist, inner quiet cruise, JGA, outer quiet cruise, Neptune approach, NOI, Neptune tour, and Neptune tour termination. Architecture 3.4 has a staged KBO flyby spacecraft (in addition to the orbiter) that also undergoes KBO approach, KBO flyby, and KBO playback phases. Orbital missions with single flight elements cannot achieve a flyby of a KBO.

All mission architectures assume launch windows accommodating a JGA to greatly reduce mass and time of flight requirements. JGA is available only for specific launch dates. The potential timing issues related to these JGA launch windows and alternatives are discussed in the Conclusions section.

Example Tour from Neptune Vision Mission Study

- **2 year tour**
- **~300 m/s DV**
- **80º maximum inclination**
- **37 Triton Flybys**

- **Tours with Cassini-like diversity of geometries and observations are possible**



Neptune Tour From Visions Mission Study

Figure 9. Full tour, from NASA Vision Mission Study, "Neptune Orbiter with Probes," provides a wide range of observational geometries.

Operational Scenarios

The canonical mission timeline (variations are summarized in Figure 11) begins with an Earth-Earth gravity assist followed by a JGA (about 3 years after launch) and a cruise to Neptune leading to a Neptune encounter ~11 years after launch for flybys or NOI ~11–15 years after launch for orbiters. Figure 11 provides timelines corresponding to specific architectures. The flyby architectures follow the Neptune encounter with a Triton encounter (hours after the Neptune encounter) and a KBO flyby (~3 years later). The orbiter architectures follow NOI with one of the three tour types.

Cruise: The long cruise periods (JGA to Neptune, Neptune to KBO) utilize quiet cruise, with one track/month outside of the encounter/maneuver windows (of ~3 week duration). The encounter windows have one pass/day tracking, together with higher activity on the navigation and spacecraft engineering teams. First order effects of ramp-up and ramp-down times for the ops team have been taken into account. The post-Neptune and post-KBO cruises add playback to the quiet cruise paradigm.

Approach: Atmospheric probe release (for the relevant architectures) would occur up to 6 months prior to closest approach. All Neptune approach sequences (except for architectures utilizing aerocapture) would begin observations 5 months before Neptune closest approach. See Figure 10 for the data volume and operations timeline for Neptune closest approach. Neptune flyby (or orbit insertion) geometries are somewhat restricted due to the ring collision hazard. Tracking frequency is one pass per day until one month prior to encounter, then three passes/day starting one month prior to encounter and extending two weeks after the Triton encounter.

The missions using aerocapture could be limited in ability to observe Neptune on approach because the payload assets would be nominally within the aeroshell. This could also inhibit cruise science. However, engineering options exist that could allow configurations enabling some instruments visibility Two ways to circumvent this problem, both expensive and one fairly risky, include (1) carrying a separate set of instruments, outside the aeroshell, for observations before aerocapture and (2) providing a "door" in the aeroshell that could be opened to allow instruments inside the aeroshell to look outside the aeroshell. The latter involves a significant risk of failure of the door to close properly before the aerocapture maneuver, possibly causing loss of the entire mission from that point. Neither approach was adopted in the selected architectures.

Triton and KBO encounters: For flyby missions, Triton closest approach (CA) would occur a few hours after Neptune CA (this varies somewhat, depending on the approach V-infinity). The Triton sequence would last approximately 10 hours. The KBO encounter would require optical navigation and small maneuvers (<100 m/s total delta V) to ensure the CA altitude for the KBO is optimal. Tracking is three passes/day starting two weeks prior to encounter to one week after encounter. Table 9 provides the mission design parameters used to size the downlink.

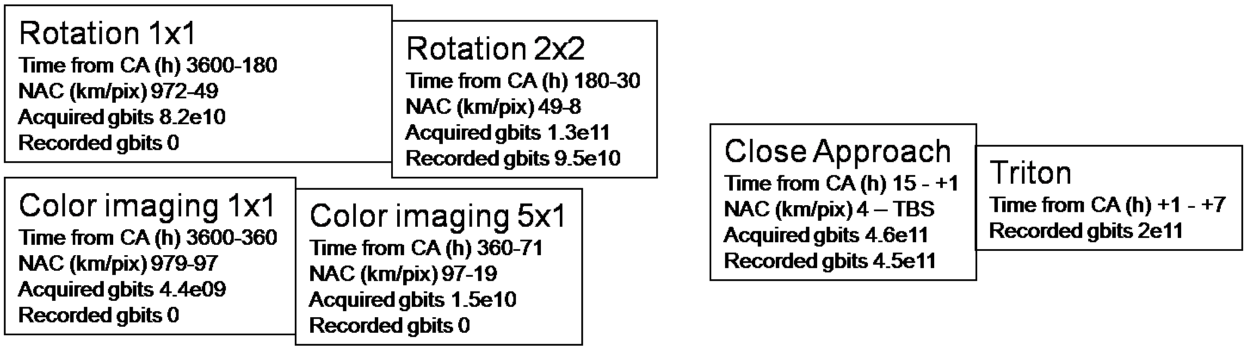


Figure 10. Nominal operations and data volume timeline for Neptune approach.

Figure 11. Nominal mission timelines.

Table 9. Mission operations and ground data systems.

Downlink Information	Gravity Assists	Cruise / Quiet Cruise	Approach and Encounter	Playback
Number of contacts per week	14	2 / 0.25	7	14
Number of weeks for mission phase, weeks (flyby/simple tour/full tour)	9	130 / 442	25/52/104	25
Downlink frequency band	Ka	Ka	Ka	Ka dual polarization
Telemetry data rate(s), kbps	1–6	1–6	30	30
Transmitting antenna type(s)	4 m HGA	4 m HGA	4 m HGA	4 m HGA
Transmitter peak power, Watts	100	100	100	100
Downlink receiving antenna	(34 m)	(34 m)	4x34	4x34
Transmitting power amplifier output, Watts	50	50	50	50
Total daily data volume, (MB/day)	**14**	**2**	**230/690**	**230**
Uplink Information				
Number of uplinks per day	0.05	0.05	0.2	0.05
Uplink frequency band	X	X	X	X
Telecommand data rate, kbps	1	1	1	1
Receiving antenna type(s) and gain(s), DBi	4 m HGA	4 m HGA	4 m HGA	4 m HGA

Data Volumes

The data volume is bounded (on the upper end) by telemetry capability and acquisition capability of the instruments and on the lower end by resolution requirements (driven by the goal that science return should add significant new information to the Voyager and Earth-based results). The NASA Decadal Survey studies ground rules document specifies nominally a Ka downlink (dual-polarization) to a single 34 m ground station, which yields 1-6 kbps at Neptune. It was difficult to fulfill the science objectives with reasonable compression with a single 34 m ground station; therefore, these studies used four arrayed 34 m antennas—a close equivalent to the 70 m DSN capability used by Voyager—under agreement with the NASA point of contact (POC) for this Decadal Survey study and consistent with existing NASA DSN capability plans for supporting arrayed 34 m antennas.

Data storage capability has changed significantly since the Voyager (1 Gbit) era. Currently, solid state recorders (SSRs) have the capacity to buffer a full 2-year data return (~1.3 Tbit for one pass/day, 64 kbps rate), which could allow flyby missions to achieve the same data return volume as an orbiter mission. However, modeling using reasonable observation scenarios and consideration of instrument throughput suggests that a flyby cannot fill a data volume equivalent to a 2-year orbital mission with data near the specified resolution (e.g.,10 km/pix for Neptune).

A very large SSR requires significant mass and power with today's catalog technology, but current developments promise a large improvement in required resources. For this reason, mass and power allocations for large SSRs are assumed to be insignificant drivers in the timeframe of the mission architectures studied (namely, launch ~2018 or later).

The limiting data volume (for a nominal 8-hour pass per day) is 1.8 Gbit for the four-antenna case (or 0.43 Gbit for the single antenna case). A strawman utilization plan is shown in Table 10, and the data flow (generation and return) timeline is annotated in Figure 11.

Table 10. Observations and data volumes for typical Neptune approach activities.
Approach activities acquire ~340 Gbit of which 160 Gbit is returned realtime.

Time from CA (hours)	Activity	Bits Acquired	Comments
3600–360	Color imaging	4.4e09	Single WAC frame + rest of payload
3600–180	Cloud circulation	8.2e10	Single frame NAC + rest of payload
360–71	Color imaging	1.5e10	WAC 5 frame
180–30	Cloud circulation	1.3e11	NAC 2x2 (10 km/pix goal at CA-37 hours)
15 – (+)1	Close encounter	4.6e11	Acquisition groups on 10 minute centers
+1 – +7	Triton encounter	2.0e11	Variety of observations

Data Products

The data products generated by these architectural options are typical for investigations of icy bodies and giant planets. Neptune approach observations would provide movies (in many bands) of cloud motion and composition. Thirteen rotations of Neptune would be observed at closest approach (50 km/pix) with two rotations at better than 10 km/pixel resolution (for the narrow angle camera). During encounters of both Neptune and Triton, Earth occultations would provide vertical profiles of atmospheric pressure and temperature; UV solar occultations would provide compositional and temperature profiles in the upper atmospheres. Remote sensing instruments would provide spatial and compositional maps and images of the Triton and KBO surfaces (as appropriate). Fields and particles measurements sample the magnetic field vectors and the distribution and composition of ions, which are projected with respect to the target bodies and the spacecraft trajectory. Orbiter missions would yield maps of the high order magnetic and gravity fields for both Neptune and Triton and, potentially, a spatially mapped vertical profile of Triton's subsurface and mass-spectroscopic observations of Triton's atmospheric composition.

Mission Design

This study examined a wide trade space that was bounded by feasible mass and time-of-flight constraints (set by ASRG lifetime and spacecraft (S/C) mechanism lifetime). Since low-cost options were emphasized, launch capability was traded against cruise duration, propulsion method, and orbit insertion approach (where needed). The team examined trajectory trades involving launch vehicle capability, gravity assist options, propulsion types, launch dates, and mission duration. Specific combinations were used in various architectures as annotated in the architectures characteristics matrix (Appendix B).

A JGA, when available, provides a large increase in mass capability. Favorable JGA opportunities are available for launch dates in 2016–2018 and starting again in 2029. Some limited JGA opportunities also exist for Neptune flyby architectures in 2019 and possibly 2020, but JGA opportunities for the orbiters end in 2018. The earlier launch dates, in particular, may be particularly challenging to meet programmatically, as is discussed in the Conclusions section. Flyby missions utilizing SEP can use other launch dates without JGA at added cost, and orbital missions are possible without JGA if using aerocapture and SEP.

Flyby missions, and orbital missions using aerocapture, are relatively insensitive to modest variations in flight system mass. Orbital missions utilizing chemical orbit insertion are very sensitive to delivered mass.

A broad set of many trajectories was examined for the set of architectures. Figure 12 shows a representative example trajectory for the flyby architectures and Figure 13 is a representative example trajectory for the orbiter architectures. Science priorities drove consideration of favorable trajectory characteristics (e.g., specific altitude, solar phase, or other geometry). For flyby trajectories, the JGA opportunities would require less delta-V but notably constrain flyby geometries. JGA trajectories were selected for nominal sizing of the architectures. However, side trades showed that SEP would enable an expanded range of flyby geometries, with launch opportunities available every year.

For orbiters on a given launch vehicle in the time frame specified for this decadal survey, the results point to some general conclusions: an Earth-Earth-Jupiter-Neptune (EEJN) sequence would deliver the largest mass for an ~14 year trajectory; SEP + chemical propulsion would deliver more net mass than chemical propulsion alone; windows for JGAs occur every 12 years; and aerocapture trajectories benefit from additional Earth gravity assist.

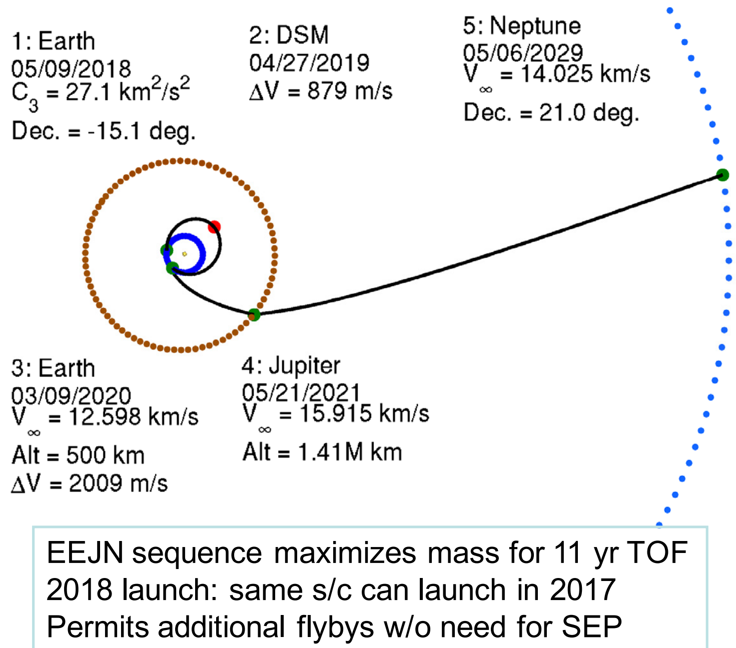


Figure 12. Representative trajectory for flyby architectures.

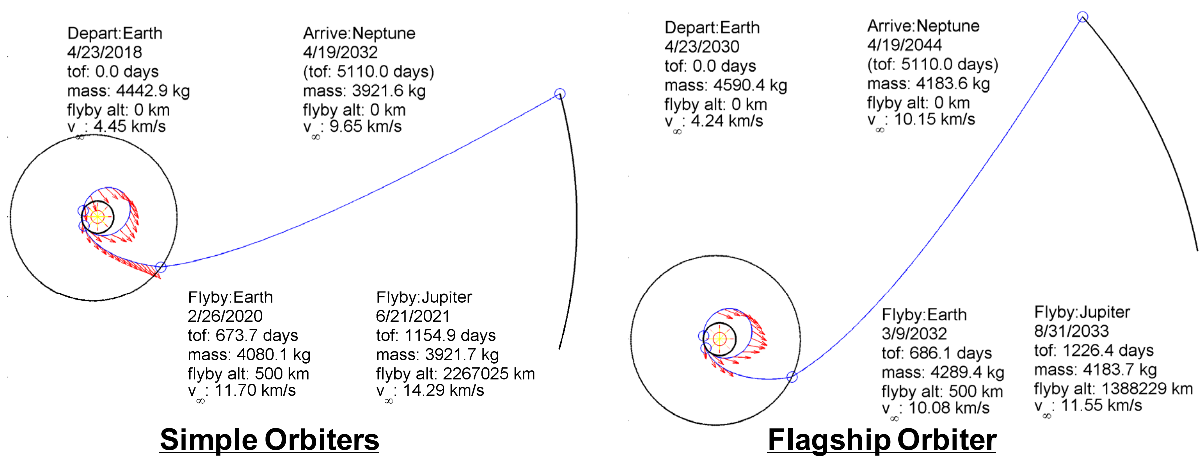


Figure 13. Representative trajectories for orbiter architectures.

Planetary Protection

Triton is the only object of planetary protection interest approached by the missions considered in this study. Unlike the expectation for KBOs, activity observed on Triton by Voyager 2 raises the *possibility* that Triton might not be entirely frozen. It is impossible at this time to predict what Triton's planetary protection classification would be at the time these missions might arrive there. Thus, none of the architectures considered attempt to orbit or land on Triton. Navigation margins for flybys preclude accidental collisions, and Neptune orbiter missions would dispose of the spacecraft in a way that precludes any future collision, such as impacting the spacecraft into Neptune's atmosphere. Free-flying instruments would be targeted to avoid Triton collisions, which is not a difficult task. After their brief science missions they would be on escape trajectories both from the Neptune system and from the solar system.

Risk List

During the course of the RMA study, team members identified risks that might impact the successful completion of one or more missions based on the architecture concepts. These risks were captured, reviewed, and evaluated for their likelihood of occurrence and impact. Risks were then aggregated at the architecture level for cross-comparison of relative risk levels across the architectures.

Risks were addressed from both an implementation and mission perspective. An implementation risk is defined as a risk involving a negative event that occurs prior to flight operations. Consequences of these risks involve the use of resource margins (i.e., mass, power, cost, schedule). A mission risk is defined as a risk involving a negative event that occurs during flight operations. Consequences of these risks involve reductions to mission science value (i.e., complete mission failure, loss of X% of science information, etc.).

Risks were associated with the individual architectures. For example, some risks might apply only to flybys, others only to orbiters. In some cases, a single risk applies to all concepts. Aggregated risk levels were generated for each architecture, and rankings were established.

As the study progressed, risks were identified during the concurrent group sessions. In some cases, a risk was judged to have a major impact that necessitated mitigating the risk immediately and updating the architecture accordingly (e.g., a change in trajectory). Since these mitigations became an inherent part of the mission concept, they are no longer identified as a major risk. The following examples illustrate this active risk management approach to mitigate potential red risks.

- Trajectories were modified to avoid crossing through the Neptunian rings. This removed the potentially red risk of collision with ring particles.
- Trajectories were modified to avoid very close KBO flybys. This removed the need for autonomous operations to complete science objectives and risks associated with navigation uncertainties in proximity of KBO.
- Trajectories were modified to avoid very close Triton flybys until later in the mission for orbiters. This removed the risks associated with uncertainties in navigation near Triton and Triton's atmosphere.
- Prime mission duration was kept to no more than 16 years because ASRG lifetime is uncertain. Guidelines were provided by NASA Headquarters POC Len Dudzinski to keep total ASRG lifetime less than 17 years from initial fueling (1 year for fueling and integration, plus 16 years post launch). This reduced the risk of data or mission loss resulting from insufficient power. Some (reduced) risks and uncertainties remain due to long mission duration.
- All architectures carry one spare ASRG to enable single fault tolerance in primary power subsystem. Architecture 3.4 actually carries two spares—one each for the orbiter and the separate KBO flyby stage. Future studies and lifetime testing might identify alternative risk mitigation approaches.

Two significant cross-cutting risks were identified that impacted all of the architectures—the impact on system reliability expectations due to long mission durations and the potential unavailability of plutonium, which could preclude future deep space missions requiring nuclear power.

The set of mission and implementation risks identified for each architecture are shown in Figure 14, Figure 15, and Figure 16. Red/yellow/green color indicators are based on estimates developed using the NASA 5x5 risk matrix and summarized to enable multiple architecture-level comparisons.

Potentially, some of these risks could be promoted to higher levels of risk as more is learned. For example, the risk of multiple ASRG failures could be possible during such long missions. Currently, reliability estimates for ASRGs are uncertain. Until ASRGs are used for long duration missions, further research into long-duration ASRG reliability is needed. As suggested in the Conclusions section, future studies and lifetime testing should be considered. Aerocapture technology also carries some uncertainty, which may be mitigated in the future with missions such as MSL (guided entry) and a potentially precursor technology flight demonstration mission. Additionally, potential plutonium unavailability remains an open programmatic issue for future NASA deep space missions.

The individual risks for each architecture were aggregated and sorted into risk groups and ranked lexicographically, as shown in Figure 17.

		1.1	1.2	1.3	1.4	1.5	1.6	1.7	2	3.1a	3.1b	3.2	3.3	3.4	4
Mission Risk ID	**Mission Risk Name**	**Flyby, Neptune focused**	**Flyby, Triton focused**	**Flyby, KBO focused**	**Flyby, "best compromise"**	**Flyby, Multiple Magnetometers**	**Flyby, KBO focused w/ Free-flying KBO Mag**	**Flyby w/Neptune probe**	**Minimum orbiter**	**Simple orbiter: limited Triton tour (min**	**Simple orbiter: limited Triton tour**	**Simple orbiter: full tour**	**Simple orbiter: limited Triton tour w/ probe**	**Simple orbiter: limited Triton tour w/ KBO S/C**	**Hi-perf. orbiter only, w/ full tour**
1	Failure of multiple ASRGs (insufficient power to operate spacecraft and instruments)	G	G	G	G	G	G	G	Y	Y	Y	Y	Y	Y	G
2	Spacecraft reliability risk due to long mission duration	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
3	Aerocapture fails NOI (due to failure of hardware, control software, or navigation)													Y	Y
4	Aerocapture system separation failure (aeroshell, backshell, etc.)													Y	Y
5	Data loss due to insufficient DSN (34m) availability	G	G	G	G	G	G	G	G	G	G	G	G	G	G
6	SEP stage release failure (arch 3.4, see #11)								G	G	G	G	G		G
7	Atmospheric probe enters a scientifically non-representative region of atmosphere							G					G		
8	Neptune free-flyer magnetometers failure					G									
9	KBO free-flyer magnetometer failure						G								
10	Neptune atmospheric probe release failure							G					G		

Figure 14. Mission risk by architecture.

Mission Risk ID	Mission Risk Name	1.1 Flyby, Neptune focused	1.2 Flyby, Triton focused	1.3 Flyby, KBO focused	1.4 Flyby, "best compromise"	1.5 Flyby, Multiple Magnetometers	1.6 Flyby, KBO focused w/ Free-flying KBO Mag	1.7 Flyby w/Neptune probe	2 Minimum orbiter	3.1a Simple orbiter: limited Triton tour (min	3.1b Simple orbiter: limited Triton tour	3.2 Simple orbiter: full tour	3.3 Simple orbiter: limited Triton tour w/ probe	3.4 Simple orbiter: limited Triton tour w/ KBO S/C	4 Hi-perf. orbiter only, w/ full tour
11	KBO spacecraft/SEP stage release failure													Y	
12	Atmospheric probe data loss during orbiter NOI												G		
13	Atmospheric probe data loss due to probe/spacecraft geometry							G					G		
14	Atmospheric probe failure after release (electronics, T/P sensors, etc.)							G					G		
15	Ka-band gravity science experiment data loss due to weather effects at DSN sites	G	G	G	G	G	G	G							
16	Large number of instruments may result in complicated operations and planning/targeting conflicts														G
17	Partial NOI failure using chemical insertion								G	G	G	G	G		
18	Triton data loss due to reduced sequence team (for limited Triton tour)									G	G		G	G	
19	SSR performance fails to sustain high data rate for flyby	G	G	G	G	G	G	G							
20	Spacecraft materials/design fails during close flyby near Triton's unknown atmosphere		G							G	G	G	G	G	G

Figure 15. Mission risk by architecture (continued).

Implementation Risk ID	Implementation Risk Name	1.1 Flyby, Neptune focused	1.2 Flyby, Triton focused	1.3 Flyby, KBO focused	1.4 Flyby, "best compromise"	1.5 Flyby, Multiple Magnetometers	1.6 Flyby, KBO focused w/ Free-flying KBO Mag	1.7 Flyby w/Neptune probe	2 Minimum orbiter	3.1a Simple orbiter: limited Triton tour (min payload)	3.1b Simple orbiter: limited Triton tour	3.2 Simple orbiter: full tour	3.3 Simple orbiter: limited Triton tour w/ probe	3.4 Simple orbiter: limited Triton tour w/ KBO S/C	4 Hi-perf. orbiter only, w/ full tour
101	Inability to execute mission due to plutonium unavailability	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
102	Unknown design and verification requirements for the KBO spacecraft/SEP stage design													G	
103	Aerocapture development and testing risk (TPS materials, L/D sufficient for Neptune, etc)													Y	Y
104	Large number of instruments may result in complicated/longer ATLO														G
105	Technology inheritance expectations for large (15kW and 25kW) solar array/SEP systems may be optimistic								G	G	G	Y	G	G	G
106	Highly constrained launch timeframe for Jupiter gravity assist may result in missing favorable gravity assist	G	G	G	G	G	G	G	Y	Y	Y	Y	Y	Y	G
107	SSR technology may not evolve as expected for low mass/power, large storage, high data rate	G	G	G	G	G	G	G							
108	Payload suite may not be able to acquire data fast enough to be commensurate with desired data volumes at associated flyby velocity	G	G	G	G	G	G	G							
109	Extended ASRG preparation/fueling lead time may result in launch date impact and reduced mission duration/reliability	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Figure 16. Implementation risk by architecture.

Mission Risk Architecture Ranking			
Arch	Red	Yellow	Green
3.4	0	5	3
4	0	3	5
3.3	0	2	10
3.1a	0	2	5
3.1b	0	2	5
3.2	0	2	4
2	0	2	3
1.7	0	1	8
1.2	0	1	5
1.5	0	1	5
1.6	0	1	5
1.1	0	1	4
1.3	0	1	4
1.4	0	1	4

Implementation Risk Architecture Ranking			
Arch	Red	Yellow	Green
3.4	0	4	2
3.2	0	4	0
4	0	3	3
2	0	3	1
3.1a	0	3	1
3.1b	0	3	1
3.3	0	3	1
1.7	0	2	3
1.6	0	2	3
1.5	0	2	3
1.4	0	2	3
1.3	0	2	3
1.2	0	2	3
1.1	0	2	3

Reduction in Mission Return/Consumption of Margin
Mission failure/Overrun
Significant
Moderate
Small to moderate
Minimal

Figure 17. Architectures ranked by mission and implementation risks.

The aggregated architecture-level risk rankings shown in Figure 17 indicate a range from small/moderate to significant (subject to further risk mitigation). There are no architecture-level risks identified as red since the architectures include major mitigations as part of the mission concepts developed. There are also no green (minimal) architecture-level risk rankings since all architectures involve small to moderate risks. Most of the flyby architectures have small to moderate risks. Architectures 3.4 and 4 (with aerocapture) are identified as having potentially significant mission and implementation risk. The results of the risk assessment are ordered highest- to lowest-ranking:

- Orbiters with aerocapture and major separations (e.g., a SEP stage separation late in the mission) (highest risk)
- Orbiters deploying secondary elements (e.g., atmospheric probes and free-flying magnetometers)
- Orbiters
- Flybys deploying secondary elements
- Flybys (lowest risk)

Primary implementation risks are associated with plutonium unavailability, constrained launch dates for orbiters, potential impact on launch date of ASRG fueling or processing delays, and aerocapture development and testing. Primary mission risks are associated with spacecraft reliability issues arising from long mission durations, ASRG failures that compromise required power, aerocapture, flight element separations occurring late in the mission, and deployments occurring late in the mission. The long mission duration is an underlying factor for the primary mission risks and is also the main cross-cutting risk for all architectures.

4. Development Schedule and Schedule Constraints

High-Level Mission Schedule

Notional mission schedules at the appropriate architectural level for a low-CML study are provided in Table 11 for the architectures considered during the RMA study. These schedules are based on JPL guidelines derived from previous, analogous missions and are based on expected mission complexity. The operations phase length is due to 11-year flight times to Neptune for flybys and 4 years beyond that in order to reach a highly desirable KBO. For orbiters, the time of flight is lengthened to 14–15 years to Neptune in order to increase in-orbit mass and decrease launch vehicle costs in some cases, with 1 year of operation for limited system tours and 2 years of operation for full tours.

Table 11. Key phase duration.

	Architecture Index													
Mission Phase Length	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**	**1.6**	**1.7**	**2.0**	**3.1a**	**3.1b**	**3.2**	**3.3**	**3.4**	**4.0**
A (months)	9	9	9	9	9	9	9	9	9	12	12	12	15	15
B (months)	9	9	9	9	9	9	9	9	9	12	12	12	15	15
C (months)	21	21	21	21	21	21	21	21	21	30	30	30	39	39
D (months)	19	19	19	19	19	19	19	19	19	20	20	20	22	22
E (months)	180	180	180	180	180	180	180	192	192	192	192	192	180	192
F (months)	6	6	6	6	6	6	6	6	6	6	6	6	6	6

Technology Development Plan

For the key technologies and infrastructure elements discussed in the Technology Maturity section, the general needs and status for technology development are as follows:

All technologies would need to be at TRL 6 by mission/instrument preliminary design review (PDR). Specifics of development and qualification schedule for the technology development plans are out of scope for a low-CML trade space RMA study. Such specifics would be generated upon selection of a particular mission architecture for further study as a point design. Table 12 illustrates technologies requiring development and their current status.

Table 12. Technology development needs and status.

Technologies	
Instruments	Limited development needed; mostly mission-specific engineering. Instruments are predominantly high-heritage from New Horizons and Cassini.
Aerocapture	The only technology requiring new mission-specific development. Already included in separate cost assessment for architectures 3.4 and 4 that required aerocapture. Particular need for development of mid-L/D aerostructure (“ellipsled” or alternative) and associated TPS. A technology demonstration precursor mission could also be considered for risk reduction.

Solar electric propulsion (SEP)	Limited development needed. Specific enhancements to particular thruster and solar array technologies are already under development and funded by NASA technology programs.
Advanced Stirling radioisotope generators (ASRGs)	Development and lifetime testing are ongoing, as funded by NASA technology program.
Infrastructure	
Plutonium-238 production or acquisition	Availability would be dependent on the United States' ability to acquire and/or produce sufficient plutonium-238 to support space mission needs.
Arrayed 34 m DSN antennas	Requires continued construction of additional 34 m antennas at DSN sites, per the projected DSN plans. Availability would be dependent on future DSN configuration and operational or programmatic decisions.

Development Schedule and Constraints

Since the current schedules are based on analogies to previous missions for this study, it is not possible to present detailed development schedules. It is appropriate to discuss constraints on possible schedules that arise from technical and programmatic factors.

The major constraint for the family of missions described in this report is the availability of a JGA to reduce the costs associated with launch and the size/requirements of the primary spacecraft. Near-term favorable launch opportunities for JGA are in ~2016–2018, and some reduced-performance opportunities are available until 2019 and possibly 2020 for flyby architectures. The next favorable JGA launch window begins in 2029. Architectures were nominally sized for a 2018 launch (2030 launch in the case of architecture 4), as driven by the science and targeting objectives. Furthermore, it is recommended to have at least one backup opportunity, which means that the last opportunity that can be planned for is in the middle of 2018. After this timeframe, analysis indicates that it will be necessary for flyby architectures (1.x) to incorporate SEP in order to deliver sufficient spacecraft mass to Neptune within time-of-flight constraints. Also, orbiter architectures would require aerocapture technology to deliver sufficient mass into Neptune orbit without JGA (after 2018). Follow-on studies should consider that the JGA timeframe might not be well-aligned with Decadal Survey and NASA schedules (i.e., the next likely opportunities for New Frontiers missions or a "small flagship" mission).

Another constraint on development schedule is the need for plutonium development or acquisition to support future missions and competing demand. This would tend to force missions to later launch dates as they may have to wait for existing demand to be satisfied.

5. Architecture-Level Cost

Since the RMA study considered multiple mission concepts within a single architecture-level study, the costs presented here are intended to give an impression of the range of potential missions to the Neptune system and KBOs. Costs are rough order of magnitude based on architectural-level input and parametric modeling and should be used for relative comparison purposes only. These costs are not validated for budgetary planning purposes. For example, it would be appropriate to think of costs for the various architectures as falling into cost bins (e.g., ~$1.0B, ~$1.5B, ~$2.0B, etc.), as appropriate for a low-CML study.

Cost Estimation Methodology and Basis of Estimate

The costs reported in this section have been developed using a JPL-internal parametric model. This model has been created and maintained with the purpose of generating preliminary estimates of cost at the early concept stage. It has been developed based upon the experiences and judgment of internal groups that have developed, built, and tested spacecraft hardware and software. The model is simplified in order to have a reduced number of inputs, as appropriate for low-maturity architectural-level trade space assessments.

Secondary flight elements have subject matter expert estimates as their basis of estimate. The free-flying magnetometers' rough costs were provided by Ames Research Center. Aerocapture hardware costs were estimated by JPL personnel. The costs for atmospheric probes were derived from analogous previous Team X study data.

All cited costs are consistent with the NASA-specified Decadal Survey ground rules. The NASA ground rules specified that all mission concept costs' would be stated in fiscal year 2015 (FY15) dollars and apply 50% reserves for Phases A–D and 25% reserves on Phases E–F. Additionally, where specific hardware or service costs relevant to the mission architectures studied were cited in the ground rules (e.g., for launch vehicles), those NASA-specified costs were used directly in the cost modeling.

For this study, the model was used with information developed during the RMA study for each of the architectures considered. Where required, selected additional information was compiled from previous study data or subject matter expert preliminary estimates.

Cost Estimates

The costs presented below are intended to provide a rough-order, architectural-level assessment of feasible mission costs rather than to provide detailed estimates for any given concept. The costs for the set of mission concepts are primarily used to understand the relative impacts of various architectural aspects.

Figure 18 provides cost estimates for each of the architectures considered in this study, with costs broken out by general project area. Note that costs shown in the figure include full cost of the KBO flyby phase of the mission (post-Neptune encounter) for all mission architectures with a KBO flyby (i.e., costs include the KBO flyby phase as part of the prime mission, not the extended mission). These costs should be used to associate each architecture to a cost bin (cost bins are in ~$0.5B increments). The $1.5B cost bin includes architectures 1.1–1.7, 2, 3.1a; the $2B cost bin includes 3.1b, 3.2, and 3.3; and the $2.5B+ cost bin includes architectures 3.4 and 4. The cost data should not be interpreted to an accuracy beyond this bin assessment, due to uncertainty in technical parameters, design strategies, implementation approach, and the preliminary nature of the cost estimates themselves.

A few properties of the trade space for Neptune/Triton/KBO and Neptune system missions should be considered. First, the long mission durations to Neptune or KBOs limit how far operational costs can be reduced. However, operations cost-savings measures (including quiet ops) were applied, where appropriate. For the lower cost flyby missions, operational costs approach the cost of the flight hardware. Second, given the relatively high base cost of these long duration missions, cost-effective improvements in science return could be achieved by adding additional flight elements, such as shallow atmospheric probes or small free-flying payloads. Another observation is that the missions at the highest-cost end of the trade space (architectures 3.4 and 4) are enabled by using aerocapture (in order to converge masses even with JGAs). Aerocapture adds some costs; however, aerocapture also results in a large size reduction and simplification of the primary orbiter (e.g., it no longer requires a large propulsion system for NOI).

The differences between the flyby missions (architectures 1.1–1.7) and architectures 3.1a and 3.1b also deserve some consideration. In terms of science payload, architecture 3.1b is the most similar to the flyby architectures, and so represents the cost increment incurred by placing this payload in orbit within the Neptune system. This increment is significant. The costs of 3.1a and the flyby architectures, however, are very close in magnitude (well within the uncertainty of the estimate). In order to realize this low cost bin, however, the orbiter has only a small modest instrument payload, trading extent of science data for persistence within the Neptunian system.

It should also be noted that Figure 18 does not include the costs of technology maturation to TRL 6. The costs of implementing the technology and testing it for the mission beyond TRL 6 for the project are included. Only architectures 3.4 and 4 utilize a technology that requires this degree of mission-specific maturation to TRL 6, namely a mid lift-to-drag ratio aeroshell for aerocapture (including structure, TPS, and aerothermodynamics). The cost of this pre-TRL 6 development has been estimated by JPL subject matter experts to be roughly $35M FY15 (without reserves). It should be noted that this is only a rough technology estimate and might vary greatly. If this technology cost is to be applied to the mission, then it should be added to estimates provided below. This estimate also does not include the cost of a potential technology precursor flight demonstration mission, which might not be necessary but is subject to NASA programmatic consideration.

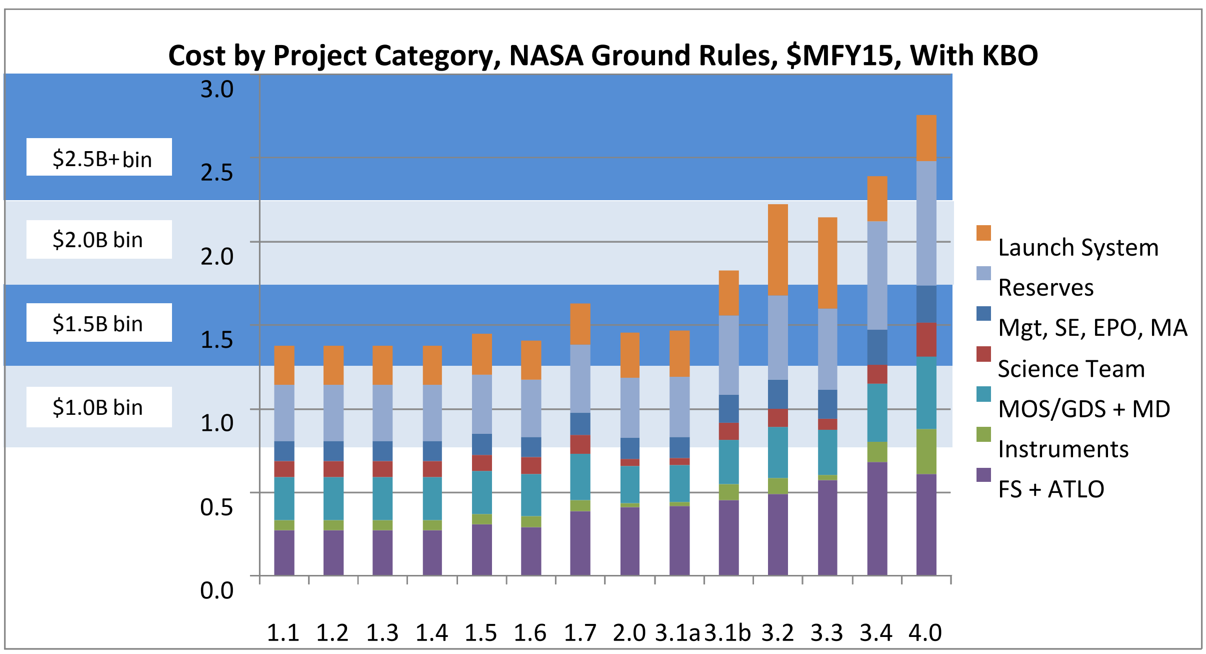


Figure 18. Costs of architectures with KBO, NASA ground rules.

6. Science Value

The traceability matrix provided by the joint science panel (Table 3, Table 4, and Table 5) served well for developing and evaluating mission architectures. The JPL RMA team worked with the science panel team to apply the JPL RMA Science Value Matrix approach. The objectives in the traceability matrix were grouped according to target, and the science team associated each group with both a group priority and a priority for each objective within each group (also provided by the panel). Architectures selected for more detailed study were rated by the panel on how well each of the architectures met each science objective. The ratings, summarized by the science representative, were weighted by their priorities and summed, then normalized to the ratings for one of the architectures (in this case, Voyager for Neptune/Triton science together with an estimate of how well a New Horizons type spacecraft would do flying by a KBO).

This approach is necessarily subjective, particularly in a low-CML study examining a broad architectural trade space. However, the approach represents a summary of the interests and priorities of the joint science panel. A consistent approach is applied across all architectures, and a single combined science team and RMA study team are used throughout to allow consistent assessment of architectures on a common basis of understanding. Nonetheless, it is important to note that science value ratings are the product of a particular set of reviewers, and may change if reviewed and assessed by a different science team in the future.

Intermediate constructs are used to achieve a group understanding of the architectures and how those architectures address the science objectives. An example of this is shown in Appendix B. This tool, known as a science linkages matrix, is intermediate in detail between a science traceability matrix (which traces the most important requirements for measurements) and a full mission requirements document (which links all implementation requirements for each measurement to one or more defined spacecraft and mission resource(s)). The tool is exercised in the JPL RMA process during early development of possible architectures—therefore, some of the (intermediate) assumptions used in developing the initial science linkages matrix may change after further assessment. For example, in this study an early assumption was that it was not possible to choose a flyby trajectory that met the encounter(s) requirements for all groups of objectives with acceptable performance. However, after further analysis, mission designers demonstrated that such a trajectory is achievable.

Three caveats should be noted when examining a science value matrix:

- The science value of the performance of the floor (in this case, Voyager for Neptune/Triton science plus New Horizons for KBO science) architecture is subjective (but consistently assessed with the same team and approach as the other architectures).
- The science value may be compressed at the ceiling, e.g., the high-performance orbiter (architecture 4) or similar high-performance architectures. This may arise from a natural reluctance to assign a lot of value to unknown unknowns.
- Some objectives groups may have different scale factors. For example, any data from a KBO provides a large increase in understanding those objects, while observations of Neptune must be fairly sophisticated to achieve a similar increase.

Science value estimates are best used as relative metrics, not absolute metrics. More detailed definition of both the science objectives and the architectures themselves would be required to achieve better estimates of the absolute magnitude of the differences in science value between architectures—using much higher CML studies and at the expense of the range of architectures that reasonably can be assessed.

The science value matrix produced by this study appears in Figure 19. The objectives, on the left, have been grouped as members of Neptune, Triton, or KBO groups and are preceded by the objective numbering (tier, sequence number) provided at the beginning of the study. The architectures, annotated across the top, can be traced to the architectures characteristics matrix with the architecture designator that appears below the description. The original architecture sequence number and the nominal payload mass also appear by each description. The science values are weighted (by objective priority) and summed by group; and the group sums are weighted (by group priority), summed, and normalized by a particular architecture. The (normalized) results are plotted in Figure 20.

Some features are immediately obvious. It is clear that orbital architectures (except architecture 3.4) cannot reach a KBO—resulting in significantly lower total value for those missions. The KBO rankings appear to have a scale factor different than the other groups—as mentioned above, arising from the fact that almost any information will greatly improve understanding of KBOs. The strong observational advantages of orbital missions are represented only weakly in the trend of valuation—a trend that is not well understood but that may arise from a compression of ratings toward the upper end of the scale. Trends that appear clearly in the science value matrix, and that reflect the analysis of the science panel, are that flyby missions can provide a very significant increase over our current measurement and understanding of Neptune, Triton, and KBOs and that an orbital mission would provide a superior approach to understanding the Neptunian system, when it is affordable.

Orignal Science Objective (Tier.Sequence)	Science value for architectural options - Values represent science assessment assuming the measurement goals are met for each architectural type.	Relative Category Science Value	Goal Science Value Relative in Category	Voyager (for reference)	N/T/K flyby, Neptune focused	N/T/K flyby, Triton focused	N/T/K flyby, KBO focused	N/T/K flyby, "best compromise"	N/T/K flyby, Neptune focused w/Multiple Free-flying Magnetometers	N/T/K flyby, KBO focused w/ Single Free-flying Transponder/ Magnetometer	N/T(/K?) flyby w/Neptune probe	Simple orbiter: Neptune polar orbit	Simple orbiter: limited Triton tour, Minimum payload	Simple orbiter: limited Triton tour, Simple Payload	Simple orbiter: full tour	Simple orbiter: limited Triton tour w/ shallow atmospheric probe	Simple orbiter: limited Triton tour**, deploys KBO flyby S/C	Hi-perf. orbiter only
	Study option designator			0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	2	3.1a	3.1b	3.2	3.3	3.4	4
	Sequential Option Number				2	3	4	1	13	11	5	6	7		15	10	9	8
	Nominal Payload Mass			300	60	60	60	60	60	60	60	25	25	60	60	25	60	300
	Science Goals, DSRMA_Neptune			Science Assessment - 0-10, 10 best relative to achieving goal														
	Neptune	9		1.3	4.3	2.5	2.5	2.6	4.9	2.5	6.0	6.4	5.6	6.3	7.1	7.1	6.3	8.0
1.1	Evolution of atmosphere structure, dynamics, clouds		10	3.0	6.0	5.0	5.0	5.5	6.0	5.0	6.0	8.5	8.0	9.0	9.0	8.0	9.0	10.0
1.2	Magnetosphere structure, dynamics, composition		8	1.0	6.0	3.0	3.0	3.0	8.0	3.0	6.0	7.0	7.0	8.0	9.0	7.0	8.0	10.0
1.3	Atmosphere composition, isotopes, noble gases		9	0.5	2.5	1.0	1.0	1.0	2.5	1.0	10.0	3.0	2.5	3.5	4.0	10.0	3.5	5.0
2.1	Internal structure, gravity		7	1.0	3.0	1.0	1.0	1.0	4.0	1.0	4.0	9.0	7.0	7.0	8.0	7.0	7.0	8.0
2.3	Ring Composition, particle size, dynamics		6	1.0	4.0	2.0	2.0	2.0	4.0	2.0	4.0	7.0	5.0	5.0	7.0	5.0	5.0	9.0
2.4	Moon composition, size orbits, esp. Nereid		5	1.0	4.0	2.0	2.0	2.0	4.0	2.0	4.0	3.0	3.0	4.0	5.0	3.0	4.0	5.0
	Triton	6		1.8	3.1	4.3	3.1	3.6	3.1	3.1	3.1	2.3	6.5	7.5	9.2	6.5	7.5	10.0
1.4	Geologic surface processes, composition, current activity		10	2.3	3.1	3.8	3.1	3.8	3.1	3.1	3.1	3.1	6.2	6.9	8.5	6.2	6.9	10.0
1.5	Atmosphere structure, chemistry, interaction w/ surface		8	2.5	3.3	4.2	3.3	4.2	3.3	3.3	3.3	3.3	5.8	7.5	9.2	5.8	7.5	10.0
1.6	Interior structure, differentiation, ocean		8	0.5	3.0	5.0	3.0	3.0	3.0	3.0	3.0	0.5	8.0	8.0	10.0	8.0	8.0	10.0
2.2	Magnetosphere interaction		4	2.0	3.0	4.0	3.0	3.0	3.0	3.0	3.0	2.0	6.0	8.0	9.0	6.0	8.0	10.0
	KBO	5		4.3	5.7	5.7	7.4	6.6	5.7	8.2	5.7	0.0	0.0	0.0	0.0	0.0	7.4	0.0
1.7	Geologic processes, ages, activity, cratering		10	5.0	7.0	7.0	9.0	8.0	7.0	9.0	7.0	0.0	0.0	0.0	0.0	0.0	9.0	0.0
1.8	Surface composition, space weathering		7	5.0	7.0	7.0	9.0	8.0	7.0	9.0	7.0	0.0	0.0	0.0	0.0	0.0	9.0	0.0
2.5	Bulk properties, satellites, radiometry, temperature		3	4.0	4.5	4.5	6.0	5.0	4.5	7.0	4.5	0.0	0.0	0.0	0.0	0.0	6.0	0.0
2.6	Solar wind interaction, role of atmosphere		5	2.0	2.0	2.0	3.0	3.0	2.0	6.0	2.0	0.0	0.0	0.0	0.0	0.0	3.0	0.0
	Category value by Architecture, summed			7.5	13.2	12.4	13.0	12.8	13.7	13.8	14.8	8.7	12.2	13.8	16.3	13.7	21.3	18.0
	Category Value-weighted, summed, normalized			1.48	2.88	2.55	2.61	2.60	3.03	2.73	3.37	2.38	2.99	3.40	3.97	3.44	4.64	4.40
	Normalized to Reference Architecture			1.00	1.94	1.72	1.76	1.76	2.04	1.84	2.27	1.61	2.02	2.29	2.68	2.32	3.13	2.97

Figure 19. Science value matrix shows the assessment of the relative science performance over the range of architectures.

The Voyager baseline "performance" ratings assume Voyager flying by Neptune and Triton and a New Horizons-class spacecraft flying by a KBO.

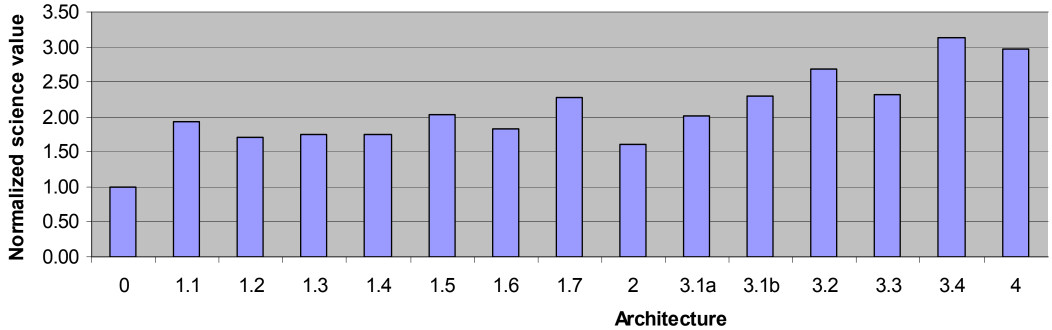


Figure 20. Science value relative to Voyager for Neptune/Triton science and New Horizons for KBO science (architecture index "0") shows the trend for assessments that include a KBO flyby.

7. Integrated Assessment and Conclusions

Integrated Assessment Findings

This section presents the synthesis of efforts by the RMA team to define a trade space, specify the breadth of its dimension by brainstorming architectural solutions, and bring its features into relief by evaluating select areas for cost, science value, and risk. Figure 21, Figure 22, and Table 13 provide an integrated view of these key figures of merit to enable assessment of relative benefits and impacts of the architectures. It should be noted again that all of the architecture-level cost estimates are cited using the NASA Decadal Survey ground rules (FY15 dollars, 50% Phase A–D reserves, 25% Phase E–F reserves) and cost bins are shown. The risks identified in the study were aggregated to provide both overall mission risk and implementation risk rankings represented as two color-coded symbols, as labeled in the figures. The plots display the results for both the case where the KBO mission phase is included as part of the prime mission and a separate case where the results were re-scored without the KBO mission phase to understand the relative impact and benefit of including the KBO science objectives. Note that this in effect re-normalizes the science value scores for each plot, so one should not directly compare absolute scores on one plot to scores on the other plot.

As seen in these results, there is a cluster of lower relative cost options that include simple flybys (no secondary payloads) and the simplest of orbiters. These architectures included the flybys, flybys with small secondary payloads, and minimal-payload orbiters. The range of science values in this cluster is largely a function of the priorities placed on the destinations and associated science objectives. Most of the variability in this lower-cost cluster is in science value rather than in cost or risk.

Some of the flyby architectures appear to be viable lower relative-cost mission concepts. These flyby architectures achieve significant scientific progress beyond Voyager 2 and potential new KBO science, while representing the lowest-cost alternatives in the set of selected architectures. The simplest flyby architectures (architectures 1.1, 1.2, 1.3, and 1.4) might be potential candidates for New Frontiers class missions, subject to further cost reduction approaches. Note that these architectures would need to be re-costed using previous New Frontiers Announcements of Opportunity (AO) cost guidelines and reserves (current year dollars and lower-cost reserves than provided by the NASA Decadal Survey ground rules), but are subject to potential changes in future AOs. However, in applying cost reductions, ramifications for science value must be considered.

Minimal-payload orbiters (architectures 2 and 3.1a), in the ~$1.5B cost class, are the lowest-cost orbiter options in the study set. Architecture 2 provides interesting Neptune interior science not available to near-equatorial orbital missions. Architecture 3.1a provides compelling Triton science and increased relative-science value in this cost class. There are fewer cost reduction avenues available for these orbiters than for the flybys. It is unlikely that there is a New Frontiers class solution for these types of orbiters unless the resource constraints for New Frontiers are expanded in the future.

Table 13 is a combined summary of key architecture characteristics with their cost, risk, and science value as evaluated by the RMA study team. Note that these cost numbers are rounded to the nearest $0.5B. Therefore, they represent a cost “bin” for these concepts. These results should not be interpreted beyond this bin assessment, due to uncertainty in technical parameters, design strategies, implementation approach, and the preliminary nature of the cost estimates themselves.

Mid-cost mission concepts (roughly $1.5B to $2.5B) provide enhanced payloads for simple orbiters and missions with atmospheric entry probes. Architecture 1.7 yields higher science value by achieving the combined science from both a Neptune atmospheric probe and the KBO flyby. Architecture 3.4 is an interesting standout at the higher cost class. Architecture 3.4 is a simple-payload orbiter where the SEP stage is enhanced to be a fully independent spacecraft that separates from the orbiter prior to NOI to become a separate KBO flyby spacecraft. Architecture 3.4 could accomplish both orbital science at Neptune/Triton and the KBO flyby science for a cost less than two independent missions. Architecture 4, the high performance orbiter with full payload, yields a modest increase in estimated science value for its increase in cost and is one of the highest science value architectures.

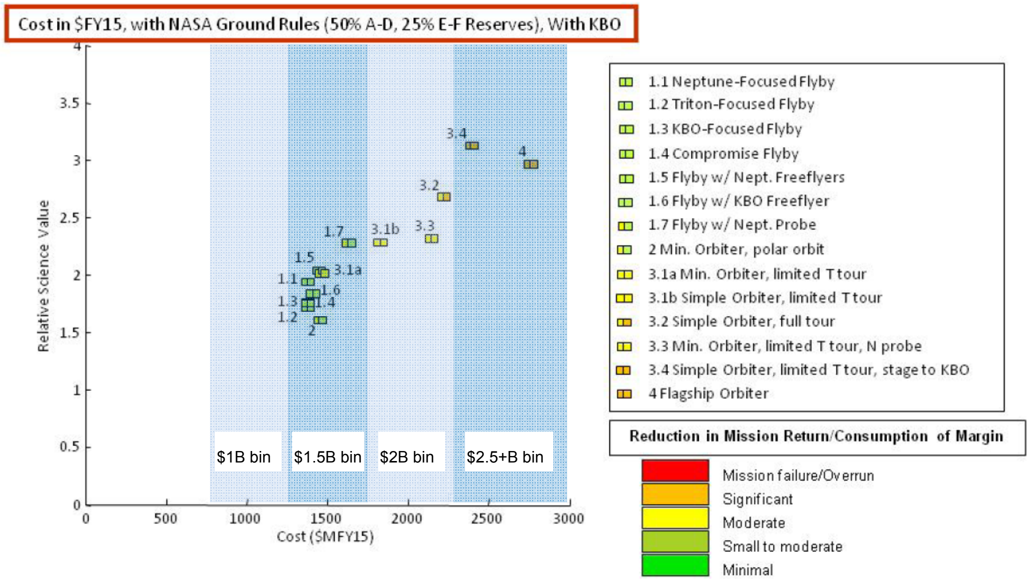


Figure 21. Integrated assessment (<u>with</u> KBO) of science value vs. cost with risk indicators (left hand box is mission risk, right hand is implementation risk).

Here the KBO mission phase is included, and science value is normalized to 1.0 for the scores with Voyager + New Horizons KBO science.

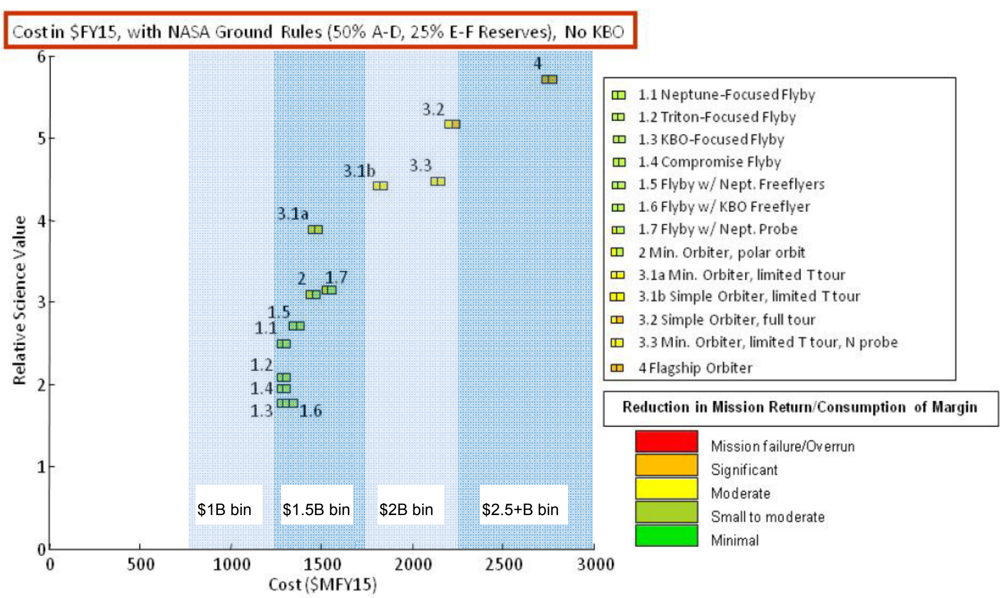


Figure 22. Integrated assessment (<u>without</u> KBO) of science value vs. cost with risk indicators (left hand box is mission risk, right hand is implementation risk).

Here the KBO mission phase is <u>not</u> included, and science value is normalized here to 1.0 for the scores with Voyager science only. Also, architecture 3.4 is not shown as it would not be a relevant mission without a KBO phase.

Table 13. Architecture parameters and results summary (with KBO).

The cost numbers shown represent $0.5B bins and should not be interpreted beyond this bin assessment.

	Architecture Summary	Architecture Parameters										Results			
		Trajectory	Primary Element	Secondary Element (s)	Primary Payload Suite	# ASRGs	Launch Year	Launch Vehicle	Prop. Systems	Neptune Arrival (years)	KBO Arrival (years)	Science Value	Cost Bin (FY15$B)	M Risk	I Risk
Flybys	**1.1** N/T/K flyby, Neptune focused	N/T/K Flyby (N focus)	Flyby S/C		Medium	4	2018	Atlas V 521	Chem	11	15	1.9	1.5		
	1.2 N/T/K flyby, Triton focused	N/T/K Flyby (T focus)	Flyby S/C		Medium	4	2018	Atlas V 521	Chem	11	15	1.7	1.5		
	1.3 N/T/K flyby, KBO focused	N/T/K Flyby (K focus)	Flyby S/C		Medium	4	2018	Atlas V 521	Chem	11	15	1.8	1.5		
	1.4 N/T/K flyby, "best compromise"	N/T/K Flyby (compromise)	Flyby S/C		Medium	4	2018	Atlas V 551	Chem	11	15	1.8	1.5		
	1.5 N/T/K flyby, Neptune focused w/ Free-flying Multiple Magnetometers	N/T/K Flyby (N focus)	Flyby S/C	Free-flying Magnetometers (3)	Medium	4	2018	Atlas V 531	Chem	11	15	2.1	1.5		
	1.6 N/T/K flyby, KBO focused w/ Free-flying Transponder/Magnetometer	N/T/K Flyby (K focus)	Flyby S/C	Free-flying Transponder-Magnetometer	Medium	4	2018	Atlas V 521	Chem	11	15	1.8	1.5		
	1.7 N/T/K flyby w/Neptune probe (5 bar)	N/T/K Flyby (N focus)	Flyby S/C	Neptune Shallow Probe	Medium	4	2018	Atlas V 531	Chem	11	15	2.3	1.5		
Orbiters	**2** Simple orbiter: Low periapse Neptune orbiter	Low Periapse Orbit- 1 yr	Orbiter S/C		Small	3	2018	Atlas V 551	15 kW SEP, Chem	15		1.6	1.5		
	3.1a Simple orbiter: Limited Triton tour	Limited Triton Tour - 1 yr	Orbiter S/C		Small	3	2018	Atlas V 551	15kW SEP, Chem	15		2	1.5		
	3.1b Simple orbiter: Limited Triton tour	Limited Triton Tour - 1 yr	Orbiter S/C		Medium	3	2018	Atlas V 551	15 kW SEP, Chem	15		2.3	2		
	3.2 Simple orbiter: Full tour	Full System Tour - 2 yr	Orbiter S/C		Medium	3	2018	Delta IVH	25kW SEP, Chem	14		2.7	2		
	3.3 Simple orbiter: Limited Triton tour w/ shallow atmospheric probe (5 bar)	Limited Triton Tour - 1 yr	Orbiter S/C	Neptune Shallow Probe	Small	3	2018	Delta IVH	15kW SEP, Chem	15		2.3	2		
	3.4 Simple orbiter: Limited Triton tour, deploys KBO flyby S/C	Limited Triton Tour - 1 yr	Orbiter S/C	KBO flyby S/C	Medium	6	2018	Atlas V 551	15kW SEP, Aerocapture	11	15	3.2	2.5		
	4 Hi-perf. orbiter only	Full System Tour - 2 yr	Orbiter S/C		Large	5	2030	Atlas V 551	15kW SEP, Aerocapture	14		3	2.5+		

Architectures 1.5, 1.7, and 3.4 appear to provide estimated science values above the general trend. All three use deployed secondary payloads to accomplish significant science measurements not possible with a single platform. Augmenting a Neptune flyby with an atmospheric probe or free-flying magnetometers appears to notably increase science value for a low-cost increment. In particular, the atmospheric probes provide unique in-situ science not achieved by other platforms.

Including KBO science as part of the prime mission (for applicable architectures) was found to significantly increase the estimated science value of the mission, for relatively small increase in cost. This finding is further strengthened if the relative science weighting for the KBO is increased from its current value of 5 (compared to 9 for Neptune science). However, considering the KBO phase as an extended mission is a potential cost-saving approach. Table 13 illustrates a comprehensive summary of the architecture parameters studied and their key results.

It should be noted that the selected science objectives are most appropriate for lower-cost mission concepts. Thus, science value estimates for higher-performance architectures might have been compressed to some extent.

This study verified that a single flyby trajectory could provide good science at all three destinations (Neptune, Triton, KBO). While some compromises would be made, no destination suffers severe science degradation from prioritizing another destination's science.

Science priorities given in the study drove the flyby architectures to higher science values with associated cost impacts. For example, preferred trajectory geometries and launch dates increased overall mass and launch vehicle selected. Also, the desired high instrument duty cycles and high data rates at encounters increased operations, telecom, and power costs. However, as previously indicated, there is related potential for cost savings with further refinement. Such cost savings measures are discussed later as future considerations.

Risk Findings

Two key risks are identified as inherently cross-cutting for all architectures. The potential unavailability of plutonium-238 for the RPSs is a concern. Plutonium-238 availability for future missions is an issue NASA needs to address in its programmatic and policy decisions. Additionally, the long total mission durations could be an issue for overall reliability and testing, particularly since initial primary science observations do not occur until Neptune encounters 11–15 years after launch.

In addition, two natural transitions occur in the risk assessmefnt within the set of architectures. There is an increase in relative risk associated with transition from single-element (e.g., flyby only) architectures to multi-element architectures with critical events and deployments (e.g., flybys with deployed secondary payload elements and orbiters). There is also an increase in relative risk observed for architectures 3.4 and 4 because of the use of aerocapture.

There are no red risks in the risk results since mitigation of major risks became an inherent part of the mission concepts evaluated (e.g., trajectories were modified to avoid crossing through the Neptunian rings, removing the potentially red risk of collision with ring particles).

Technology Findings

All of the selected architectures are enabled by a nuclear primary power source (RPS such as ASRG or MMRTG).This study assumed an ASRG lifetime of 16 years post-launch and 1 year pre-launch for fuel loading, per agreement with the NASA HQ Decadal Survey study POC. Previous studies had assumed 14 year lifetime post-launch and up to 3 years pre-launch for fuel loading. However, this study identified that longer mission durations were enabling for non-aerocapture architectures using JGA. ASRG reliability and lifetime assessment should be a topic of future study. Additionally, it is important to again emphasize that the potential unavailability of sufficient plutonium-238 in the future is a major programmatic concern.

The increase in performance provided by SEP is greatly enhancing (and enabling in some cases) for the orbiter architectures. SEP greatly increases the delivered mass for the orbiter architectures within the time-of-flight constraints. SEP also helps to converge the architectures in launch timeframes when JGAs are unavailable, as discussed below under the Mass Sensitivities section.

Availability of validated aerocapture technology would potentially benefit all orbiter options. Aerocapture reduces sensitivity to delivered mass, time of flight, and launch date. This could result in a reduction of the class of launch vehicle required or some reduction in risks due to long mission duration. Architectures 3.4 and 4 identify aerocapture as an enabling technology to converge their masses even with a JGA. Those architectures would not converge without aerocapture even if choosing the larger Delta IV-Heavy or equivalent class launch vehicle. Without aerocapture, the architectures would require greater than 16 years total mission duration to converge. However, such increased mission durations violates the NASA ground rules for RPS lifetime and increase various subsystem reliability risks. Furthermore, aerocapture is enabling for orbiters in launch years when JGAs are not available.

There is potential for the science value of KBO flybys to be greatly enhanced by mitigating ephemeris uncertainties with autonomous onboard sequence and pointing updates. This capability was not assumed in the selected architectures, but it could be an excellent candidate for future consideration.

Mass Sensitivities

For the set of Neptune mission architectures studied, mass performance is highly sensitive to time-of-flight and JGA opportunities. Delta-Vs are greatly increased as time of flight is reduced or as trajectories depart from favorable launch years. JGAs were used in the nominal architectures' sizing, but the timing of favorable JGAs (circa 2016–2018 and 2029–2031 launch) might not be well-aligned with Decadal Survey and NASA schedules (i.e., the next likely opportunities for New Frontiers missions or a "small flagship" mission). ASRG lifetime was already maximized in some architectures up to the NASA-provided guideline of 16 years post-launch plus 1 year for fueling and integration.

Orbiter architectures using chemical propulsion for NOI (i.e., without aerocapture) are also highly sensitive to mass growth due to large delta-Vs required for orbit insertion within time-of-flight constraints. Flyby architectures do not have this particular mass sensitivity, but flybys were still sensitive to significantly reduced delivered mass without the JGA.

Though not used in the selected architectures, a side trade demonstrated that flybys with SEP and orbiters with aerocapture and SEP do not require JGA. Incorporating such technologies would thus provide launch opportunities in almost any year, albeit at some added cost. However, if NASA technology development programs were to independently develop system-level technologies that could benefit multiple missions and destinations such as a modular SEP stage or aerocapture system technology, the cost impact directly to specific missions could be greatly mitigated.

Future Considerations

Potential cost savings might be achieved in future, more detailed studies, particularly for the flybys. Cost savings may include science, performance, and operational trades resulting in:

- Additional trajectory optimization and alternative KBO targets (e.g., smaller KBOs)
- Reduction in payload and telecom duty cycles to reduce telecom and power (ASRGs) costs
- Mass optimization to a smaller launch vehicle (at the expense of increased flight time)
- Possible further reductions in ops costs and reduced DSN requirements
- Possible allocation of the KBO flyby phase as an extended mission phase

Given the long mission duration prior to primary science and critical events late in long missions, future work should examine approaches and modeling to reduce risk associated with long-life mission reliability. These analyses should address uncertainties in the cost impacts due to long duration mission reliability and testing. Additional studies should examine the potential implications and benefits (e.g., mass, time of flight, cost, and risk) of long-duration operation of ASRGs and other lifetime-critical subsystem components. These studies should attempt to address the mission sensitivities to long total mission durations to define required component lifetimes across a suite of science destinations (e.g., outer planets and satellites, primitive bodies, etc.).

Compelling mission concepts were studied with 2018 launch dates (and 2030 for architecture 4) allowing JGAs. While launch dates allowing JGAs yield dramatically larger delivered mass for a given launch vehicle, they might not be well-aligned with expected NASA program schedules. Favorable JGA seasons for transfer to Neptune occur approximately 2 years out of every 12 years. One such season is 2016–2018 and the next is 2029–2031. If an architecture is selected to proceed to a point-design study of a potential New Frontiers mission concept, that study should also examine post-2018 launch dates without JGA (using SEP for flybys or SEP and aerocapture for orbiters). Also, some trajectories for Neptune flybys launching in 2019 and possibly 2020 could be used, subject to an increase in launch vehicle and STAR motor upper stage. Orbiter architectures launching after 2018 cannot achieve the beneficial JGA. Launching in the next JGA window (2016–2018) does not fit the expected schedule for the next New Frontiers Program AO, which anticipates launches in 2021–2023, when JGAs are not available. Because of the less efficient transfer trajectories without JGAs, missions based on any of the selected architectures and launched in intermediate years without JGA opportunities incur additional costs to enable the missions with SEP for flybys and aerocapture plus SEP for orbiters.

All missions potentially risk ^{238}Pu unavailability, unless the United States soon establishes its own production capability, acquires additional resources from Russia, or re-allocates ^{238}Pu to future missions.

Potential low-maturity technologies and advanced capabilities for further consideration or trades include:

- Falcon 9 Heavy launch vehicle as a potential cost-saving high-performance LV
- New/modified Centaur-class LOX/LH2 upper stage to increase delivered mass in either Atlas V or Delta IV-Heavy class LVs
- Long-storage cryogenic propulsion, which could prove promising to save significant mass for NOI relative to conventional propulsion if a small cryo-propulsion system is feasible
- Long-life critical spacecraft components, including ASRGs

If carried forward to point-design studies, specific designs should be studied in more detail to reduce cost and risk uncertainties, including general configuration and packaging design (particularly for multi-element architectures), atmospheric entry probe design, designs for free-flying magnetometers and magnetometers with radio transponders, aerocapture system aeroshell design, and aerothermal modeling for aerocapture.

Note that all mission concepts were studied at an architectural level, primarily for assessment of relative benefits and impacts. Specific mission concepts of interest should be examined and optimized in more detailed, follow-on point-design studies for more in-depth assessment of costs, resource requirements, and risks before any programmatic or budgetary planning decisions are made.

Appendix A. References

[1] Moeller, R.C., and C.S. Borden. “Rapid Mission Architecture (RMA) Overview.” Presentation to Planetary Science Decadal Survey Science Panels. Washington, DC. 24–28 August 2009.

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[4] Jet Propulsion Laboratory. *Titan and Enceladus $1B Mission Feasibillity Study Report*. 30 January 2007.

[5] The National Academies. “Planetary Science Decadal Survey White Papers.” 2010. http://www8.nationalacademies.org/ssbsurvey/publicview.aspx

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[8] Ingersoll, A.P., and T.R. Spilker. “A Neptune Orbiter with Probes Mission with Aerocapture Orbit Insertion,” in *Progress in Astronautics and Aeronautics: NASA Space Science Vision Missions*, **224**, 81–113, AIAA, Reston, VA. June 2008.

Appendix B. Specific Architectural Analyses and Assessments

Table B-1. Full architectures characteristics matrix—flyby architectures.

Arch. # if Selected	Arch. Class	Sub-Options/Name	Launch Vehicle (Ground Rules)	Launch Vehicle Analogue	Cruise Stage (chem, YY kW SEP)	Arrival NOI Stage	Primary Orbiter(s)	# ASRGs	Type of Secondary Element	Number of Secondary Elements	Mission Sequence	Launch Year	Time to Neptune (years)	Time for Science Phase	Time to KBO (years)	Total Mission Duration (years)	Mission Implementation & Sequence Comments	Primary Element Payload Mass (kg)	Primary Element Instruments List	Secondary Element Mass (kg)	Secondary Element Instruments List	When Secondary Element Deployed
	FLYBY																					
1.1		N/T/K flyby, Neptune focused	Opt. 4b	Atlas V 521	Chem			4			Launch/xfer to Neptune; gravity-assist(s) during cruise; Neptune/Triton flybys, with an eye to an acceptable KBO flyby (trajectory constraints); short downlink cruise; quiet cruise to KBO; KBO flyby, with choice of KBO constrained by desire for excellent Neptune and acceptable Triton flyby characteristics; short downlink cruise. Payload emphasizes Neptune science.	2018	11	9 months	15	15.2	Need Earth occultation by Neptune, prefer ingress & egress angles near vertical (within ~45 deg) - KBO's (5% w/Triton)	60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, 256 Gbit SSR			
1.2		N/T/K flyby, Triton focused	Opt. 4b	Atlas V 521	Chem			4			Launch/xfer to Neptune; gravity-assist(s) during cruise; Neptune/Triton flybys, with an eye to an acceptable KBO flyby (trajectory constraints); short downlink cruise; quiet cruise to KBO; KBO flyby, with choice of KBO constrained by desire for acceptable Neptune and excellent Triton flyby characteristics; short downlink cruise. Payload emphasizes Triton science.	2018	11	9 months	15	15.2	Triton flyby less than 700km, Solar occultation	60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, 256 Gbit SSR			
1.3		N/T/K flyby, KBO focused	Opt. 4b	Atlas V 521	Chem			4			Launch/xfer to Neptune; gravity-assist(s) during cruise; Neptune/Triton flybys, with an eye to an excellent KBO flyby (trajectory constraints); short downlink cruise; quiet cruise to KBO; KBO flyby, with choice of KBO only loosely constrained by desire for acceptable Neptune/Triton flyby characteristics; short downlink cruise. Payload emphasizes KBO science.	2018	11	9 months	15	15.2	KBO> 100km, 5% of KBO's available	60	WAC, NIRI Spec, MAG, RSCM link, NAC, UVI Spec, PLS, TI, 256 Gbit SSR			
1.4		N/T/K flyby, "best compromise"	Opt. 4b	Atlas V 521	Chem			4			Launch/xfer to Neptune; gravity-assist(s) during cruise; Neptune/Triton flybys, with an eye to an acceptable KBO flyby (trajectory constraints); short downlink cruise; quiet cruise to KBO; KBO flyby, with choice of KBO constrained by desire for acceptable Neptune/Triton flyby characteristics; short downlink cruise. Payload chosen for "best compromise".	2018	11	9 months	15	15.2	Triton flyby less than 10,000km; 50 km < KBO (req.); 100 km > KBO (desired) - 5% of desired KBO's possible	60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, 256 Gbit SSR			
1.5		N/T/K flyby, Neptune focused w/ Free-flying Multiple Magnetometers	Opt. 4c	Atlas V 531	Chem			4	Free flying Magnetometers	3	Launch/xfer to Neptune; gravity-assist(s) during cruise; free-flyer targeting & deployment upon Neptune approach, each free-flyer requiring at least 1 targeting maneuver and then release, with a final orbiter retargeting maneuver after the last release; free-flyer data reception at the flyby S/C for a TBD period around C/A; Neptune/Triton flybys, with an eye to an acceptable KBO flyby (trajectory constraints); short downlink cruise; quiet cruise to KBO; KBO flyby, with choice of KBO constrained by desired Neptune and Triton flyby characteristics; short downlink cruise.	2018	11	9 months	15	15.2	Free-flyers released near Neptune	60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, 256 Gbit SSR	15 (x3)	MAG	L + 11
1.6		N/T/K flyby, KBO focused w/ Free-flying Transponder/Magnetometer	Opt. 4b	Atlas V 521	Chem			4	Free-flying transponder / magnetometer	1	Launch/xfer to Neptune; gravity-assist(s) during cruise; Neptune/Triton flybys, with an eye to an excellent KBO flyby (trajectory constraints); short downlink cruise; quiet cruise to KBO; KBO flyby, with choice of KBO only loosely constrained by desire for acceptable Neptune/Triton flyby characteristics; upon approach to KBO (aided by optical nav and maneuvers), S/C targets and releases a free-flying transponder-magnetometer, then performs a retargeting maneuver; short downlink cruise after flyby. Payload emphasizes KBO science.	2018	11	9 months	15	15.2	Until KBO approach, same as Architecture 1.3, @ KBO fly through the plasma wake	60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, 256 Gbit SSR	15	Transponder, MAG	L + 15
1.7		N/T/K flyby w/Neptune probe (5 bar)	Opt. 4c	Atlas V 531	Chem			4	Probe	1	Launch/xfer to Neptune; gravity-assist(s) during cruise; Probe targeting & deployment upon Neptune approach, 1 to 6 months out, flyby S/C retargeting maneuver afterward; Neptune/Triton science observations before closest approach (C/A); probe entry and data relay near flyby S/C C/A; continued Neptune/Triton science observations after C/A; short downlink cruise; quiet cruise to KBO; KBO flyby, with choice of KBO constrained by desire for acceptable probe relay & Neptune/Triton flyby characteristics; short downlink cruise. Non-probe payload emphasizes Neptune science.	2018	11	9 months	15	15.2	Probe atmosphere-relative entry angle should be - 8 +/- 1.5 deg at 1000 km above the 1-bar level. Track probe for 40 minutes.	60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, 256 Gbit SSR	100	MS, Temp. & Press., USO	L + 11

Table B-2. Full architectures characteristics matrix—orbiter architectures.

Arch. # if Selected	Arch. Class	Sub-Options/Name	Launch Vehicle (Ground Rules)	Launch Vehicle Analogue	Cruise Stage (chem, YY kW SEP)	Arrival NOI Stage	Primary Flyby S/C	Primary Orbiter(s)	# ASRGs	Type of Secondary Element	Number of Secondary Elements	Mission Sequence	Launch Year	Time to Neptune (years)	Time for Science Phase	Time to KBO (years)	Total Mission Duration (years)	Mission Implementation & Sequence Comments	Primary Element Payload Mass (kg)	Primary Element Instruments List	Secondary Element Mass (kg)	Secondary Element Instruments List	When Secondary Element Deployed
	"MINIMAL" ORBITER																						
2		Simple orbiter: Low periapse Neptune orbiter	Opt. 5	Atlas V 551	15kW SEP	Chem		x	3			Launch/xfer to Neptune; gravity-assist(s) during cruise; chemical propulsive insertion into a quasi-polar, high-eccentricity orbit with low periapse, no targeted Triton flybys; orbit evolves naturally until EOM.	2018	15	1 year		16	Periapsis < 10,000km, inclination: 30 or 150 degrees. Triton seen from afar	25	WAC, NIRI Spec, MAG, RSCM link, USO			
	SIMPLE ORBITER																						
3.1a		Simple orbiter: Limited Triton tour	Opt. 5	Atlas V 551	15 kW SEP	Chem		x	3			Launch/xfer to Neptune; gravity-assist(s) during cruise; chemical propulsive insertion into a quasi-equatorial, medium-eccentricity orbit with Triton encounters; Triton encounters crank orbit into Triton's orbit plane, then further encounters rotate the orbit petal until EOM.	2018	15	1 year		16	~ 20 Triton flybys with altitudes ranging from 300-1000 km. Neptune periapsis @ 100,000 km and inclinations ranging from 130-157 degrees. Some occultations achieved at both bodies.	25	WAC, NIRI Spec, MAG, RSCM link, USO			
3.1b		Simple orbiter: Limited Triton tour	Opt. 5	Atlas V 551	15 kW SEP	Chem		x	3			Launch/xfer to Neptune; gravity-assist(s) during cruise; chemical propulsive insertion into a quasi-equatorial, medium-eccentricity orbit with Triton encounters; Triton encounters crank orbit into Triton's orbit plane, then further encounters rotate the orbit petal until EOM.	2018	15	1 year		16	~ 20 Triton flybys with altitudes ranging from 300-1000 km. Neptune periapsis @ 100,000 km and inclinations ranging from 130-157 degrees. Some occultations achieved at both bodies.	60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, Mass Spec.			
3.2		Simple orbiter: Full tour	Opt. 6	Delta IV 4050H-19	25 kW SEP	Chem		x	3			Launch/xfer to Neptune; gravity-assist(s) during cruise; chemical propulsive insertion into a quasi-equatorial, medium-eccentricity orbit with Triton encounters; full Triton-driven tour a la Vision Mission tour.	2018	14	2 years		16	Full Visions Mission Tour: ~ 35 Triton flybys per year with altitudes ranging from 300-2000km. Neptune periapsis ranging from 3,000-100,000km with inclinations from 90-180 degrees. Both bodies achieve several varied occultations.	60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, Mass Spec.			
3.3		Simple orbiter: Limited Triton tour w/ shallow atmospheric probe (5 bar)	Opt. 6	Delta IV 4050H-19	15 kW SEP	Chem		x	3	Probe	1	Launch/xfer to Neptune; gravity-assist(s) during cruise; Probe targeting & deployment upon Neptune approach, 1 to 6 months out, orbiter retargeting maneuver afterward; probe entry and data relay before (or after?) closest approach (C/A); around C/A orbiter does orbit insertion manuever into a quasi-equatorial, medium-eccentricity orbit with Triton encounters; Triton encounters crank orbit into Triton's orbit plane, then further encounters rotate the orbit petal until EOM (same tour as Architecture 3.1).	2018	15	1 year		16	~ 20 Triton flybys with altitudes ranging from 300-1000 km. Neptune periapsis @ 100,000 km and inclinations ranging from 130-157 degrees. Some occultations achieved at both bodies.	25	WAC, NIRI Spec, MAG, RSCM link, USO	100	MS, Temp. & Press., USO	
3.4		Simple orbiter: Limited Triton tour, deploys KBO flyby S/C	Opt. 5	Atlas V 551	15 kW SEP	Aerocapture		x	3 + 3	KBO flyby S/C	1	Launch/xfer to Neptune; gravity-assist(s) during cruise; during Neptune approach (1 to 6 months out), orbiter targets and deploys a KBO flyby S/C, either a dedicated spacecraft or one built into a SEP stage, then performs a retargeting maneuver. The KBO S/C does the Neptune flyby targeting a high-priority KBO, while the orbiter undergoes an aerocapture insertion into a quasi-equatorial, medium-eccentricity orbit with Triton encounters; Triton encounters crank orbit into Triton's orbit plane, then further encounters rotate the orbit petal until EOM (same tour as Architecture 3.1)**.	2018	11	1 year (orbit) 3 months (flyby)	15	15.2	~ 20 Triton flybys with altitudes ranging from 300-1000 km. Neptune periapsis @ 100,000 km and inclinations ranging from 130-157 degrees. Some occultations achieved at both bodies.	60	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, Mass Spec.	60 (payload)	WAC, NIRI Spec, MAG, RSCM link, NAC, UVI Spec, PLS, TI, 256 Gbit SSR	L +11
	HIGH-PERFORMANCE																						
4		Hi-perf. orbiter only	Opt. 5	Atlas V 551	15 kW SEP	Aerocapture		x	5			Launch/xfer to Neptune; gravity-assist(s) during cruise; aerocapture insertion into a quasi-equatorial, medium-eccentricity orbit with Triton encounters; full Triton-driven tour a la Vision Mission tour.	2030	14	2 years		16	Full Visions Mission Tour: ~ 35 Triton flybys per year with altitudes ranging from 300-2000km. Neptune periapsis ranging from 3,000-100,000km with inclinations from 90-180 degrees. Both bodies achieve several varied occultations.	300	WAC, NIRI Spec, MAG, RSCM link, USO, NAC, UVI Spec, PLS, TI, Mass Spec, RPWS, HEP, Dust, FTIR, GPR, 256 Gbit SSR			

Table B-3. Science Linkages Matrix provides a useful tool for capturing salient architectural issues associated with each science objective.
This matrix is intermediate between a science traceability matrix and a full spacecraft requirements matrix. Only relevant matrix cells are filled. In some cases, alternative implementations cause branching (added rows) that may propagate cell entries to the right, left, or both directions. For this study, rows were added and cells populated on an ad-hoc basis. There are three panels for this figure addressing objectives for KBOs, Neptune, and Triton.

Note: Some science objectives have been branched - this is labeled in the branch label column, all instruments in ( ) are desired but not required, all wording in [ ] are more specific comments

							Requirements and preferences					
Science Objective	**Branch Label**	**Target or Objective Priority**	**Historic Implementation**	**Observation Approach**	**Key Desirable Attributes**	**Measurements**	**Instruments**	**Flyby Geometry Constraints**	**Mission design**	**Flight system**	**New Technology**	**Prospective Mission Concepts**
KBO		5										
Surface processes, ages, activity, cratering		10	Visible mapping	VIS mapping	Flyby ok, autonomous boundary targeting routine [Low Flyby (<1.5 radii)]	General contrast: 100m/pixel Dynamics: 1m-5m/pixel	NAC + MAC/WAC, (Dust, MS)	Light side flyby, Low Flyby (<1.5 radii)		Pointing and slew rates reqs		
Surface composition, space weathering	Flyby Geometry 1	7	NIR mapping	Multiband mapping	Flyby ok	Spectral Mapping (UV, VIS, NIR): 0.5-1km/pixel Thermal Emission (LWIR): 5-10km/pixel	UVI, VI, NIRI, (CIRS), PLS, MS, TI	Spectral: Light side Thermal: Dark side		Pointing and slew rates reqs		
	Flyby Geometry 2							Fly on the anti-sun side of the KBO to sample the plasma wake [this is likely contrary to the other science objectives nb. Further analysis says ok]				
	Impactor			Targeted Imaging						Impactor	Autonomous target selection	
Bulk properties, satellites, radiometry, temperature	Measurement Method 1	3	Navigation, Imaging, Thermal measurements	Mapping, Photometry, Navigation	Flyby OK	Volume: visible imaging Navigation: RSCM	NAC, WAC, TI (~100μ), RSCM			Pointing and slew rates reqs Ka-band Coherrent Transponder		
	Measurement Method 2				Drop a repeater		Transponder			USO on S/C	Transponder, Could use optical	
Interior structure								Very close		Gravimetric, Test mass w/ laser tracking	Free flying test mass w/ laser tracking	
Space weathering, atmosphere		5	Spectroscopy (??)	Multiband mapping	Flyby OK		UVI, VI, NIRI,	Make pointing and slew rates reqs consistent with instruments		Pointing and slew rates reqs		

Note: Some science objectives have been branched - this is labeled in the branch label column, all instruments in ( ) are desired but not required, all wording in [ ] are more specific comments

							Requirements and preferences					
Science Objective	**Branch Label**	**Target or Objective Priority**	**Historic Implementation**	**Observation Approach**	**Key Desirable Attributes**	**Measurements**	**Instruments**	**Flyby Geometry Constraints**	**Mission design**	**Flight system**	**New Technology**	**Prospective Mission Concepts**
Neptune		9										
Atmosphere structure, dynamics, composition	Flyby	10	Camera, LWIR, many rotations, prefer view of both equator and pole	Global vis mapping (hours to months), thermal mapping; spatially resolved spectra, radio occultation	Flyby OK (returns about half the science value of an orbiter); Atmospheric dynamics gets some improvement from flyby relative to Jupiter due to NIR and higher resoltuion; additional improvement from Thermal imagery	UV occultation for upper atmosphere [Low altitude required - will make KBO pass difficult for flyby]	WAC, NAC, TI, UVI, VI,NIRI,USO, antenna gimbal, MS, (CIRS, Microwave), [Filtered IR, 8 to 100 microns (~12 filters)]; [MassSpec requires low passes to get useful data, Prefers an orbiter - good complement to Microwave]	Speed of collection for lower frequencies of light	Flyby			
	Orbiter				Orbit supports temporal coverage; Twice the science value of a flyby		Same instrument set as flyby; Orbiter allows longer integration times, shorter focal lengths, and opportunities to add other instruments		Orbital observations for dynamics - ~1-2 years for dark spot formulation and change [prefer both equatorial and polar orientations]			
Magnetosphere structure, dynamics, composition	Flyby	8	Magnetometer, [EPD], PWS, Varying apoapse radius, position; close approach to satellites	Particles and fields measurements; Particularly Triton-Neptune connection	Flyby ok;		MAG, PLS	Inclination (southern hemisphere) will limit access to KBOs; pretty much guaranteed a different sample of magnetosphere than Voyager	Flyby			
	Orbiter				Low Neptune orbit required for higher order harmonics; Tour preferred for temporal and spatial sampling		MAG, Plasma wave (PLS + PWS) preferred to mag if choosing one, LENAP [neutral torus]		Orbiter [prefer different altitudes of apoapse and rotate the line of apsides]			
Atmosphere isotopes, noble gases	Flyby + probe	9	Probe	In Situ measurements	Flyby ok, probe required [Want to be below methane layer @ 3 bar, want isotopic info on methane, "low end" probe at 5 bar, "high end" at ~20 bar]		MS, Altimeter, accelerometer, pressure sensor, temperature sensor (for probe), Ortho-para hydrogen	High flyby for probe release		Probe		
	Orbiter + Low Periapse (atmosphere)					Sampling at TBD pressure [assume on the order of 1 microbar]		Low periapse - within upper atmosphere	Orbit			
	Orbiter + Aerocapture					Sampling behind TPS?		Sampling during aerocatpure				
Internal structure, gravity	Measurement Method 1	7	Dual band radio, Low altitude, near-circular orbit, USO	High order harmonics from near-circular orbit, precision navigation	Low , near orbit required, preferably polar:: significant DSN tracking	Orbital displacement to [TBS radial accuracy] to derive 12th order harmonics	Dual Band radio, UUSO	NA	Must have Polar Orbit	Could use multiple jpasses to target science objectives or utilize a scan platform or gimballed HGA	UUSO	3 instrument orbiter, low mass, low power
	Measurement Method 2						Precision Gradiometer					
	Measurement Method 3						Grace-like [consider using a different sized s/c - one with a beacon]			Dual spacecraft		
Ring composition, particle size, dynamics,		6	Imaging	Vis Mapping, spectra; range of temporal scales desired	Flyby ok		WAC, NAC, UVI, VI, NIRI, (PWS, Microwave, Dust)		High phase angle - rings illuminated from behind			
Moon composition, size orbits,		5	Imaging, Navigation	Mapping (VIS, IR)	Flyby ok, Low Neptune periapse preferred		WAC, NAC, UVI, VI, NIRI, TI	Close flyby required to get Nereid science - will bend trajectory and compromise KBOs				

Note: Some science objectives have been branched - this is labeled in the branch label column, all instruments in ( ) are desired but not required, all wording in [ ] are more specific comments

							Requirements and preferences					
Science Objective	**Branch Label**	**Target or Objective Priority**	**Historic Implementation**	**Observation Approach**	**Key Desirable Attributes**	**Measurements**	**Instruments**	**Flyby Geometry Constraints**	**Mission design**	**Flight system**	**New Technology**	**Prospective Mission Concepts**
Neptune		9										
Atmosphere structure, dynamics, composition	Flyby	10	Camera, LWIR, many rotations, prefer view of both equator and pole	Global vis mapping (hours to months), thermal mapping; spatially resolved spectra, radio occultation	Flyby OK (returns about half the science value of an orbiter); Atmospheric dynamics gets some improvement from flyby relative to Jupiter due to NIR and higher resoultion; additional improvement from Thermal imagery	UV occultation for upper atmosphere [Low altitude required - will make KBO pass difficult for flyby]	WAC, NAC, TI, UVI, VI,NIRI,USO, antenna gimbal, MS, (CIRS, Microwave), [Filtered IR, 8 to 100 microns (~12 filters)]; [MassSpec requires low passes to get useful data, Prefers an orbiter - good complement to Microwave]	Speed of collection for lower frequencies of light	Flyby			
	Orbiter				Orbit supports temporal coverage; Twice the science value of a flyby		Same instrument set as flyby; Orbiter allows longer integration times, shorter focal lengths, and opportunities to add other instruments		Orbital observations for dynamics - ~1-2 years for dark spot formulation and change [prefer both equatorial and polar orientations]			
Magnetosphere structure, dynamics, composition	Flyby	8	Magnetometer, [EPD], PWS, Varying apoapse radius, position; close approach to satellites	Particles and fields measurements; Particularly Triton-Neptune connection	Flyby ok;		MAG, PLS	Inclination (southern hemisphere) will limit access to KBOs; pretty much guaranteed a different sample of magnetosphere than Voyager	Flyby			
	Orbiter				Low Neptune orbit required for higher order harmonics; Tour preferred for temporal and spatial sampling		MAG, Plasma wave (PLS + PWS) preferred to mag if choosing one, LENAP [neutral torus]		Orbiter [prefer different altitudes of apoapse and rotate the line of apsides]			
Atmosphere isotopes, noble gases	Flyby + probe	9	Probe	In Situ measurements	Flyby ok, probe required [Want to be below methane layer @ 3 bar, want isotopic info on methane, "low end" probe at 5 bar, "high end" at ~20 bar]		MS, Altimeter, accelerometer, pressure sensor, temperature sensor (for probe), Ortho-para hydrogen	High flyby for probe release		Probe		
	Orbiter + Low Periapse (atmosphere)					Sampling at TBD pressure [assume on the order of 1 microbar]		Low periapse - within upper atmosphere	Orbit			
	Orbiter + Aerocapture					Sampling behind TPS?		Sampling during aerocatpure				
Internal structure, gravity	Measurement Method 1	7	Dual band radio, Low altitude, near-circular orbit, USO	High order harmonics from near-circular orbit, precision navigation	Low , near orbit required, preferably polar:: significant DSN tracking	Orbital displacement to [TBS radial accuracy] to derive 12th order harmonics	Dual Band radio, UUSO	NA	Must have Polar Orbit	Could use multiple jpasses to target science objectives or utilize a scan platform or gimballed HGA	UUSO	3 instrument orbiter, low mass, low power
	Measurement Method 2						Precision Gradiometer					
	Measurement Method 3						Grace-like [consider using a different sized s/c - one with a beacon]			Dual spacecraft		
Ring composition, particle size, dynamics,		6	Imaging	Vis Mapping, spectra; range of temporal scales desired	Flyby ok		WAC, NAC, UVI, VI, NIRI, (PWS, Microwave, Dust)		High phase angle - rings illuminated from behind			
Moon composition, size orbits,		5	Imaging, Navigation	Mapping (VIS, IR)	Flyby ok, Low Neptune periapse preferred		WAC, NAC, UVI, VI, NIRI, TI	Close flyby required to get Nereid science - will bend trajectory and compromise KBOs				