# JPL Rapid Mission Architecture (RMA) Neptune Study Report Executive Summary

**Presentation to Solar System 2012 Giant Planets Panels**

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# Purpose of the Study

- **Identify & assess architecture options for multiple Neptune system mission concepts**
  - The previous Decadal Survey placed a high priority on Neptune system exploration
    - Judged to be at a lower state of technological readiness than Europa and Titan mission concepts
  - Consider a variety of platform types and their scientific utility

# Use of the Study Results

- **Perform preliminary analyses of trajectory, architecture, and flight system options**
  - Prepare for (anticipated) Planetary Science Decadal Survey (PSDS) Panel request for such a study
  - Fine-tune procedures and tools for an anticipated similar study
- **Identify high-value mission architecture concepts and elements for future studies**
- **NOT for determining "sweet spot" mission candidates for the PSDS**
  - Must have actual PSDS Panel science direction for credible (among the planetary science community) science value assessments
  - Study payloads not initially constrained by specific S/C resource allocations

# Study Objectives

- **Identify high-value architectural concepts and elements**
  - Especially if applicable to a wide range of scientific investigations
- **Identify architectural elements of lower relative value**
- **Look across the spectrum of New Frontiers and Flagship mission candidates**

# Neptune Science Opportunities

## Why Go To Neptune?

1. Things unique to Neptune and the Neptune system
   - It's an Ice Giant (and the solar system has only 2 of those) with a large, possible former KBO orbiting it
   - It's an Ice Giant with significant atmospheric convective activity and strong zonal winds
   - Of the Ice Giants it is the one with a significant interior heat source
   - A diagnostic species (CO) appears to transport from deep in the atmosphere (>1000 bars?) to the stratosphere
   - Neptune's ring system has no close analog elsewhere in the solar system
   - Triton has an unexpectedly dense (electron concentrations) ionosphere

2. Things that provide context to the unique measurements
   - Interior composition
   - Interior structure
   - Dynamo field
   - Atmospheric composition
   - Atmospheric structure
   - Clouds and haze layers
   - Composition of Neptune's inner satellites
   - Magnetospheric interaction with Triton
   - Magnetospheric interaction with Neptune's atmosphere (aurora)
   - Relationship of Neptune's inner satellites to the rings
   - Dust environment, relationship to ring composition
   - Seasonal variations

3. Things of interest that could be measured at various other locations in the solar system
   - Interstellar dust composition, trajectories
   - Magnetospheric structure (could be done at Uranus? Or does Triton change things too much?)
   - Magnetospheric interaction with the solar wind
   - Other satellites

# Science Goals

## Neptune & System Science Goals

1. Understand the processes by which, and from what material, the Neptune system formed

2. Understand how the Neptune system influenced the formation of the rest of the solar system, and its evolution since formation

3. Understand the evolution of the Neptune system since formation, and into the future

4. Understand how knowledge of the Neptune system informs us about extrasolar planetary systems

## KBO Science Goals

1. Understand the processes by which, and from what material, KBOs form

2. Understand how the materials that formed KBOs might have influenced the formation of the rest of the solar system

3. Understand the evolution of the Kuiper belt since formation

# Guiding Science Questions

These science questions, expressed as objectives, formed the global basis of science objectives for all architectures in the trade space to attempt to address. Later, these science questions were prioritized and multiple mission architectures were assessed relative to these priorities.

1. **What is the elemental composition and structure of Neptune's interior?**
2. **What processes control the three-dimensional distribution of gaseous composition, clouds, temperatures, and winds in Neptune's atmosphere?**
3. **What processes control the internal structure of Triton?**
4. **What processes control the surface morphology of Triton? What is happening on the unexplored half of Triton?**
5. **What are the composition of Triton and its atmosphere, and the global distribution of volatiles?**
6. **What are the size, composition, morphology, and orbital histories of Neptune's small satellites?**
7. **What are the composition, size, and dynamical properties of ring particles and associated small satellites, and how do they interact to control structure and evolution?**
8. **What processes control the structure, composition, density, and dynamics of the magnetosphere, and how does the magnetosphere interact with other elements of the Neptune system?**
9. **What are the sources of interplanetary dust particles in the Neptune system, what are their compositions, and what processes control their orbital histories?**
10. **How did KBOs form and evolve, and how did they influence the rest of the solar system?**

# Top-Level Mission Requirements and Constraints

- **Launch timeframe**
  - Nominally 2022-2035
  - For New Frontiers opportunities, prefer options launching 2022+ but allow examination of options ~2018+ recognizing the constrained timeframe for Jupiter gravity assist opportunity
  - Assume earliest flagship launch date ~2025 (nominally ~2030 for favorable Jupiter gravity assist opportunity)
- **Launch vehicles**
  - Allowed in assessments: Atlas V, Delta IV-Heavy, Ares V
    - Examine Ares V in specific selected architecture options
    - Multiple launches are OK, if required

# Top-Level Mission Assumptions

- **Primary electric power sources**
  - Assume Advanced Stirling Radioisotope Generator (ASRG) and Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) are available
    - Assume 14-year (after launch) RPS lifetime
    - Assume plutonium is available
  - Assume nuclear (fission) reactors are not available
- **Assume aerocapture at Neptune is allowed**
  - Examine aerocapture only where driven to use the technology, but identify risks
  - Examine non-aerocapture orbiter options, where reasonable
- **DSN capabilities**
  - Assume equivalent of 70 m capability
  - Also examine 34 m capability
- **Science representatives provided the science priorities for the study. Higher priority was given to the Neptune science. KBO science was assumed to be lower priority for this study.**

# "Tall Tentpoles"

- **Neptune's large heliocentric distance (30 AU) yields a challenging delivered-mass vs. mission-duration trade**
  - Precise trade parameters (and thus degree of challenge) are influenced by:
    - Choice of transfer trajectory type and launch date
    - Choice of launch vehicle
    - Type and magnitude of post-launch propulsion augmentation
    - Method used for Neptune Orbit Insertion (if applicable)
  - There are practical limits on which parts of the trade space are useful
    - Practical masses of current or foreseen S/C components and science instruments
    - Lifetime limits of critical S/C components
    - Deployments after 12-13 year cruise (e.g., entry probes, lander, aerocapture aeroshell)
    - Time required for a scientifically justifiable investigation and return of the necessary data
    - Programmatic reticence to engage in very long-duration missions
- **Large heliocentric distance yields a challenging power problem**
  - Solved by RPS technology (no other practical choice) -- but we must have the $^{238}Pu$!
- **Large heliocentric distance yields a challenging telecommunications problem**
  - Pushes the limits of radio-telecommunications and power technologies
    - Neptune-to-Earth link is the primary data bottleneck
- **Landing on Triton suffers from uncertainty in surface conditions**
  - Accommodation of a wide range of surface conditions is expensive and risky
    - Risk mitigation requires detailed mapping and characterization of a few candidate landing sites to verify acceptable sites exist

# Addressing the Tall Tentpoles

- **Neptune's large heliocentric distance (30 AU) yields a challenging delivered-mass vs. mission-duration trade**
  - Choosing a launch vehicle, trajectory type and launch date specifies a delivered-mass vs. trip-time curve
    - If delivered mass is sufficient for an acceptable transfer time, no further analysis is needed
  - Used a hierarchical approach for dealing with delivered-mass shortfall
    - Includes trajectory type, launch date, propulsion system type, launch vehicle, and aerocapture
  - Selected approaches:
    - Constrained all missions to ~14 years total duration
    - Chose 12-13 year trajectories on Atlas V or Delta IV-Heavy. Ares V only studied as a delta-option to 2 specific architectures to get to Neptune in 10 yrs. If using Ares V, also assume an all-chemical biprop staged architecture for cruise and orbit insertion.
    - Make minimizing delta-Vs a high priority to reduce the mass of propellant required
    - Attempt to avoid aerocapture where possible; use only if required to get the payload desired and system masses required to Neptune without an Ares V

# Addressing the Tall Tentpoles (cont'd)

- **Neptune's large heliocentric distance (30 AU) yields a challenging delivered-mass vs. mission-duration trade (cont'd)**
  - Some approaches have significant ramifications for cost and risk
    - Aerocapture has many associated risks
      - New technology (mid L/D aeroshell)
      - Aeroshell packaging and waste heat
      - Testing and validation -- flight demonstration needed?
    - Ares V launch vehicle
      - Availability during the launch time frame is uncertain
      - New launch vehicles are more risky
        - Ares V carries both technical and programmatic risk
      - Could reduce cruise time and/or increase mass delivered to Neptune
        - 2 extra years of primary science tour (4 yrs total) possible with 10 yr flight to Neptune using Ares V
    - Developing new propulsion stages (chemical or SEP) is expensive
      - Source of funds for development is uncertain -- could be up to the flight project
      - Introduces schedule risk
  - Mass sensitivity greatly influences launch vehicle and post-launch approach
    - Each additional kg delivered to Neptune orbit requires launching 3-4 kg more mass
    - Architectures that deliver the same mass to Neptune orbit with less mass delivered to Neptune approach yield less challenging launch and post-launch requirements
      - *Makes aerocapture attractive despite the associated risks*

# Addressing the Tall Tentpoles (cont'd)

- **Large heliocentric distance yields a challenging power problem**
  - Selected approach: Assume an RPS similar in performance to current proposed ASRG spec is available
    - >14-yr RPS lifetime would involve a significant new development task; not ready for some early launch dates
- **Large heliocentric distance yields a challenging telecommunications problem**
  - "Standard" radio system (e.g., 50 W RF Ka-band, 3-m HGA to 34-m DSN) yields 9 kbps
    - Significantly impacts the science return for nearly all architectures
  - Assuming a 70-m equivalent Ka-band ground station yields more Cassini-like rates (~30 kbps)
  - Selected approach:
    - Data volume and return estimates were generated assuming 70-m equivalent capability
    - However, due to the uncertain future regarding DSN capabilities, it is not appropriate to select a specific ground system architecture
- **Landing on Triton suffers from large uncertainties in surface conditions**
  - Selected approach:
    - For the few lander-bearing architectures, we assumed:
      - Propulsive soft landers with autonomous hazard avoidance
      - Existence of suitable landing sites on Triton, to be verified by early-mission, pre-landing observations
    - Filtered out other variants such as rough landers and impactors early on

# Science Payloads

- **Several typical strawman payloads were defined:**
  - A minimum payload for a simple Neptune orbiter
    - Implements Neptune science reasonably well
    - Mass = 36 Kg
  - A small flyby payload for a New Frontiers-class flyby
    - This payload is also used for the options with the additional KBO flyby S/C as a modified cruise stage
    - Mass = 40 Kg
  - A full payload for a Flagship-class flyby
    - Mass = 186 Kg
  - A high-capability orbiter payload addressing all Neptune objectives
    - For simplicity (and redundancy), same high capability for all relevant architectures
    - Mass = 202 Kg
  - A carrier payload (specifically for mapping Triton prior to landing)
    - Mass = 62 Kg
  - A soft-lander payload for Triton
    - Mass = 29 Kg
  - An atmospheric probe payload for Neptune
    - Mass = 17 Kg

# Mission design solutions enable high value science at Neptune

- **The interplanetary trajectory designs enabled significant delivered mass to the Neptune system**
  - New interplanetary trajectories were generated for this study
  - Enabled by various combinations of gravity assists coupled with alternative launch vehicles, upper stages, solar-electric propulsion (SEP), and aerocapture (where required)
- **A Neptune system tour with Triton as the gravity assist engine provides significant science over the entire Neptune system**
  - 2-yr tour derived from the aerocapture-based Neptune Vision Mission study

# Architectures Considered

| | Architecture Type | Sub-Options | Arch. ID |
|---|---|---|---|
| Flyby Options | Neptune flyby only | No KBO flyby | |
| | Neptune/KBO NF-class flyby | Include KBO flyby. Target New Frontiers class mission and simpler payload | 1 |
| | | Deliver free-flying instruments or impactor | |
| | Neptune/KBO flagship-class flyby + probe(s) | Target Flagship class payload + Neptune entry probes (2) | 2 |
| | | Deliver Triton Impactor | |
| Simple Orbiter Options | Simple Neptune orbiter | Interior structure & atmospheric science focus. Orbiter only. Likely aerocap. | 3 |
| | | Variant w/all-chem + upper stage on Delta 4-H LV | 3.2 |
| | | Interior structure only | |
| | | Deliver Neptune entry probes | |
| High-Performance Orbiter Options | Hi-perf Neptune orbiter | Orbiter only (no entry probes). Flagship class payload. Likely aerocapture. | 4 |
| | | Variant w/30 kW SEP/chem + upper stage on Delta 4-H LV | 4.2 |
| | | Variant w/all-chem + upper stage on Delta 4-H LV | 4.3 |
| | | Neptune orbiter with full flagship class payload, but without Triton flyby tour | |
| | Hi-perf Neptune orbiter + probe(s) | Deliver Neptune entry probes (2) | 4.a |
| | | Deliver Neptune deep atmospheric probe | |
| | | Deliver impactor(s) to Triton, other satellites | |
| | | Deliver subsat or freeflying instruments | |
| | | Deliver Triton hard lander(s) or penetrator(s) | |
| | Hi-perf Neptune orbiter + probes + Triton soft lander | Deliver Triton soft lander | 4.b |
| | | Variant with Ares V, shorter 10 yr cruise, plus 4 year tour | 4.b.2 |
| | Hi-perf Neptune orbiter + KBO flyby S/C | Deliver Neptune entry probes (2) along w/add'l KBO flyby S/C | 4.c |
| | | No entry probes; only add'l KBO flyby S/C | 4.d |
| | | Alternative using completely separate KBO S/C (not modified cruise stage) | |
| | Hi-perf Neptune/Triton orbiter | Orbiter transitions from Neptune orbit then later into Triton orbit | 4.e |
| | | Variant with Ares V, shorter 10 yr cruise, plus 4 year tour | 4.e.2 |
| | | Deliver Neptune entry probes | |
| | | Deliver impactor(s) to Triton, other satellites | |
| | | Deliver Triton hard lander(s) or penetrator(s) | |
| | | Deliver Triton soft lander | |
| | | Deliver subsat or freeflying instruments | |
| | Triton orbiter direct | Direct insertion to Triton orbit from approach to Neptune system | |
| Dual Orbiters Options | Dual Orbiters: Neptune orbiter + Triton orbiter | Deliver 2 S/C: Neptune orbiter + separate Triton orbiter | 5 |
| | Dual Orbiters: Neptune magnetospheric orbiter + Neptune remote sensing orbiter | Deliver 2 S/C: Neptune magnetospheric orbiter + Neptune remote sensing orbiter | 5.a |
| | Dual Orbiters: Neptune magnetospheric orbiter + Neptune/Triton orbiter | Deliver 2 S/C: Neptune magnetospheric orbiter + Neptune/Triton orbiter | |
| | Dual Orbiters: Neptune orbiter + Triton "orbi-lander" | Deliver 2 S/C: Neptune orbiter + Triton "orbi-lander" | 5.b |

# Selected Architectures: Flight Systems

| | | Flight Systems List | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Arch. # if Selected** | **Arch. Name** | **Launch Vehicle (Atlas V, Delta IV-H, Ares 5)** | **LV Upper Stage (if required for Delta IV-H or Ares V options)** | **Cruise Stage (chem, 15 kW SEP, 30 kW SEP)** | **Arrival NOI Stage (chem, aerocapture)** | **Primary Flyby S/C** | **Primary Orbiter(s)** | **Atmospheric Probe(s)** | **Lander(s) (soft/propulsive lander, rough lander, penetrator)** | **Lander Deceleration Stage (chem/ballute)** |
| 1 | Neptune/KBO NF-class flyby | Atlas V-401 | | | | 1 | | | | |
| 2 | Neptune/KBO flagship-class flyby + probes | Atlas V-401 | | | | 1 | | 2 probes | | |
| 3 | Simple Neptune orbiter (chem/aero) | Atlas V-551 | | Chem | Aero | | 1 | | | |
| 3.2 | Simple Neptune orbiter (chem/chem + upper stage) | Delta IV-Heavy + Upper Stage | Add'l LOX/LH2 upper stage | Chem | Chem | | 1 | | | |
| 4 | Hi-perf Neptune orbiter (chem/aero) | Atlas V-551 | | Chem | Aero | | 1 | | | |
| 4.2 | Hi-perf Neptune orbiter (30kW SEP/chem + upper stage) | Delta IV-Heavy + Upper Stage | Add'l LOX/LH2 upper stage | 30kW SEP | Chem | | 1 | | | |
| 4.3 | Hi-perf Neptune orbiter (chem/chem + upper stage) | Delta IV-Heavy + Upper Stage | Add'l LOX/LH2 upper stage | Chem | Chem | | 1 | | | |
| 4.a | Hi-perf Neptune orbiter + probes | Atlas V-551 | | Chem | Aero | | 1 | 2 probes | | |
| 4.b | Hi-perf Neptune orbiter + probes + Triton lander | Delta IV-Heavy | | 15kW SEP | Aero | | 1 | 2 probes | Soft Lander | Ballute |
| 4.b.2 | Hi-perf Neptune orbiter + probes + Triton lander (10 yr Ares V) | Ares V w/Jupiter assist | Integral upper stage | Chem | Chem | | 1 | 2 probes | Soft Lander | Ballute |
| 4.c | Hi-perf Neptune orbiter + KBO flyby S/C + probes | Delta IV-Heavy | | Chem | Aero | | 1 | 2 probes | | |
| 4.d | Hi-perf Neptune orbiter + KBO flyby S/C | Atlas V-551 | | Chem | Aero | | 1 | | | |
| 4.e | Hi-perf Neptune/Triton orbiter | Atlas V-551 | | 15kW SEP | Aero | | 1 | | | |
| 4.e.2 | Hi-perf Neptune/Triton orbiter (10 yr Ares V) | Ares V w/Jupiter assist | Integral upper stage | Chem | Chem | | 1 | | | |
| 5 | Dual Orbiters: Neptune orbiter + Triton orbiter | Delta IV-Heavy | | 15kW SEP | Aero | | 2 orbiters | | | |
| 5.a | Dual Orbiters: Neptune magnetospheric orbiter + Neptune remote sensing orbiter | Delta IV-Heavy | | Chem | Aero | | 2 orbiters | | | |
| 5.b | Dual Orbiters: Neptune orbiter + Triton "orbi-lander" | Delta IV-Heavy | | Chem | Aero | | 1 (but with separate orbi-lander) | | "Orbi-Lander" | Chem |

# New technologies identified for the selected architectures

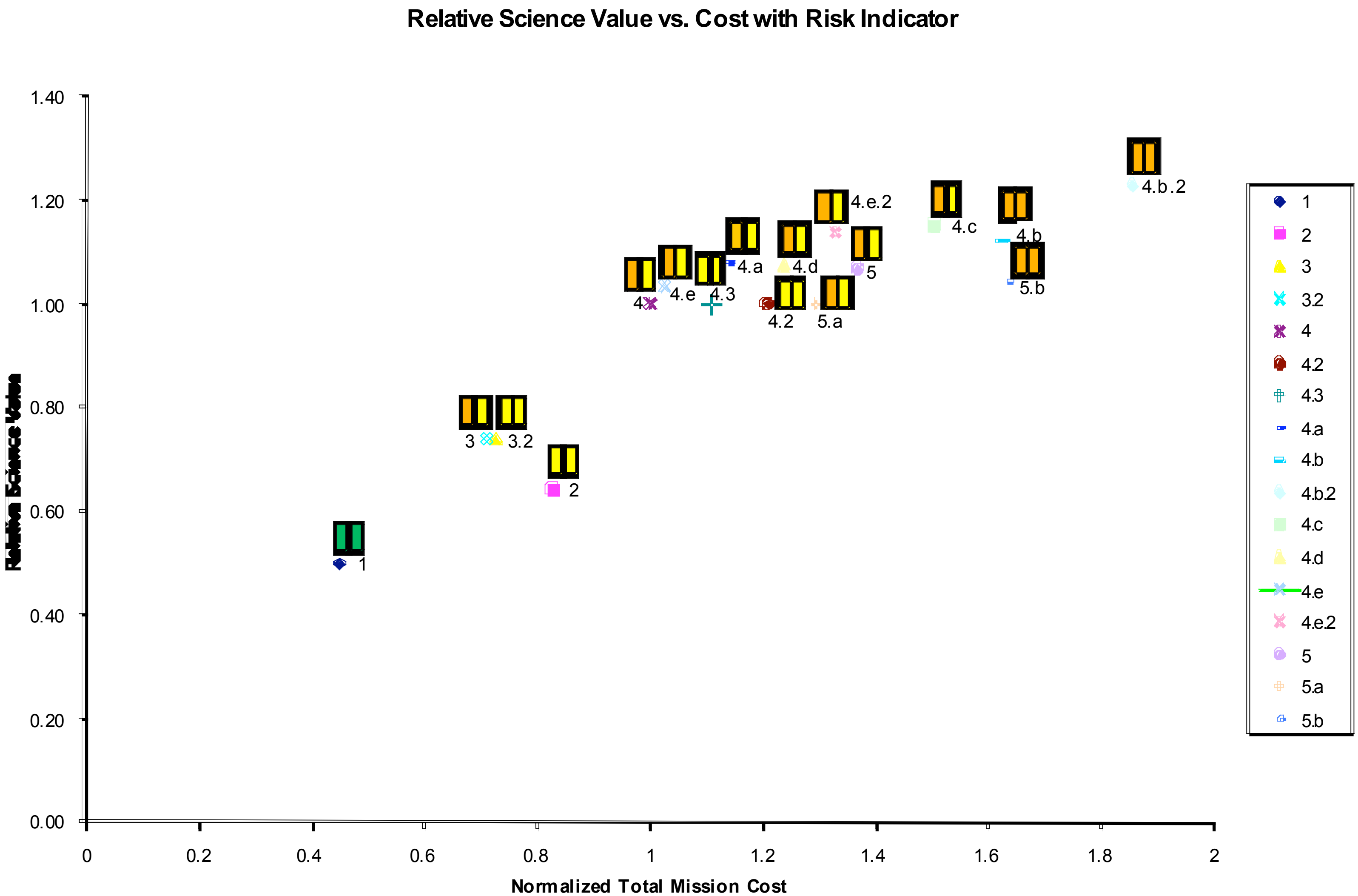
| | Type or Readiness of Technology | | | Potential Impacts of Technology | | | Potential Benefits of Technology | | | Mission Benefit Potential? | Architecture types benefitted | Selected architectures benefitted |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Existing/High-TRL | Emerging/Mid-TRL | New/Low-TRL | Increase mass-to-target or decrease launch | Increase data scope, rate, or volume | Reduce cruise/ops duration | Improved performance | Reduce cost | Reduce risk | | | |
| **Launch Vehicles** | | | | | | | | | | | | |
| Ares V or similar heavy-lift-class LV | | | x | x | | | x | | | x | Large launch mass systems and | 4.b2, 4.e2 |
| New/modified Centaur-class LOX/LH2 upper stage | | x | | x | | | x | | | x | Large launch mass systems and faster trajectories | 3.2, 4.2, 4.3 (note 4.b2 and 4.e2 on Ares V also effectively have an Ares V cryo upper stage) |
| **Instruments** | | | | | | | | | | | | |
| Icy-body lander instruments | | | x | x | | | x | | | | Large Icy Satellite Landers | 4.b, 4.b2, 5.b |
| Atmospheric entry probe instruments | | | x | x | | | x | | | x | Probe Missions to Giant Planets/ | 2, 4.a, 4.b, 4.b2, 4.c |
| **Flight Systems & Operations** | | | | | | | | | | | | |
| Soft lander hazard avoidance | | x | | x | x | | x | | x | x | All soft landers in potentially hazardous | 4.b, 4.b2, 5.b |
| Advanced Stirling Radioisotope Generator (ASRG) | | x | | x | | | x | | | x | All outer planet missions | All |
| High-density, low-temperature energy storage | | x | | x | | | x | | | x | All entry probes and short-lived landers | 2, 4.a, 4.b, 4.b2, 4.c |
| Autonomous spacecraft operations | | x | | | x | x | | | x | x | All outer planet missions | 4.b, 4.b2, 5.b |
| **Propulsion & Mission Design** | | | | | | | | | | | | |
| Ballute | | | x | x | | | x | x | | x | Triton lander; *possibly* Triton | 4.b, 4.b2 |
| Aerocapture | | | | x | | | x | | | x | Any orbiter for a body with a significant | 3, 4, 4.a, 4.b, 4.c, 4.d, 4.e, 5, 5.a, 5.b |
| Modelling | | x | | | | | | x | x | x | All Aerocapture/Aeroentry missions | 3, 4, 4.a, 4.b, 4.c, 4.d, 4.e, 5, 5.a, 5.b |
| Mid-L/D aeroshell TPS (aerocaptured orbiter) | | | x | x | | | | | x | | Very Large (Manned) Mars Missions | 3, 4, 4.a, 4.b, 4.c, 4.d, 4.e, 5, 5.a, 5.b |
| Aeroshell TPS (atmospheric entry probe) | | x | | x | | | x | | x | x | Any outer planet atmospheric entry | 2, 4.a, 4.b, 4.b2, 4.c |
| Solar electric propulsion (SEP) | x | | | x | | x | x | | | x | All outer planet missions | 4.2, 4.b, 4.e, 5 |
| **Telecom and Ground Systems** | | | | | | | | | | | | |
| Ground network of large antenna arrays | | | x | | x | x | x | x | | x | All missions | All |

# Neptune System Science Value Matrix

| **Science value for architectural options -** Values represent science assessment assuming the measurement goals are met for each architectural type. *Note: If a science value is below a corresponding Voyager value, the option does not improve on Voyager's results.* | Relative Category Science Value | Goal Science Value Relative in Category | Neptune/KBO NF-class flyby | Neptune/KBO flagship-class flyby + probes | Simple Neptune orbiter | Hi-perf Neptune orbiter (with Triton flybys, no probes) | Hi-perf Neptune orbiter + probes | Hi-perf Neptune orbiter + probes + Triton lander | Hi-perf Neptune orbiter + probes + Triton lander (10 yr Ares V) | Hi-perf Neptune orbiter + KBO flyby S/C + probes | Hi-perf Neptune orbiter + KBO flyby S/C | Hi-perf Neptune/Triton orbiter | Hi-perf Neptune/Triton orbiter (10 yr Ares V) | Dual Orbiters: Neptune orbiter + Triton orbiter | Dual Orbiters: Neptune magnetospheric orbiter + Neptune remote sensing orbiter | Dual Orbiters: Neptune orbiter + Triton "orbi-lander" | Voyager (for reference) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Study option number (Arch. ID) | | | 1 | 2 | 3 | 4 | 4a | 4b | 4b2 | 4c | 4d | 4e | 4e2 | 5 | 5a | 5b | |
| Sequential Option Letter | | | A | B | C | D | E | F | G | H | I | L | N | J | K | L | Z |
| **Science Goals, Neptune Prototype** | 4 | 8 | Science Assessment - 0-10, 10 best relative to achieving goal | | | | | | | | | | | | | | |
| **Neptune** | 10 | | 3.5 | 4.0 | 6.5 | 7.5 | 9.0 | 9.0 | 10.0 | 9.0 | 7.5 | 7.5 | 8.5 | 7.5 | 7.5 | 7.5 | 2.0 |
| Structure and composition of the interior | | 10 | 3.0 | 3.0 | 7.0 | 8.0 | 9.0 | 9.0 | 10.0 | 9.0 | 8.0 | 8.0 | 9.0 | 8.0 | 8.0 | 8.0 | 2.0 |
| Atmosphere - composition, clouds, winds, temps | | 10 | 4.0 | 5.0 | 6.0 | 7.0 | 9.0 | 9.0 | 10.0 | 9.0 | 7.0 | 7.0 | 8.0 | 7.0 | 7.0 | 7.0 | 2.0 |
| **Triton** | 8 | | 3.6 | 4.3 | 6.0 | 7.0 | 7.0 | 8.0 | 8.7 | 7.0 | 7.0 | 8.6 | 9.5 | 8.6 | 7.0 | 8.0 | 2.9 |
| Internal structure | | 10 | 3.0 | 3.0 | 6.0 | 7.0 | 7.0 | 7.0 | 7.5 | 7.0 | 7.0 | 9.0 | 10.0 | 9.0 | 7.0 | 7.0 | 2.0 |
| Surface morphology | | 8 | 4.0 | 5.0 | 6.0 | 7.0 | 7.0 | 8.0 | 8.5 | 7.0 | 7.0 | 9.0 | 10.0 | 9.0 | 7.0 | 8.0 | 5.0 |
| Composition (including atmosphere) | | 10 | 4.0 | 5.0 | 6.0 | 7.0 | 7.0 | 9.0 | 10.0 | 7.0 | 7.0 | 8.0 | 8.5 | 8.0 | 7.0 | 9.0 | 2.0 |
| **Neptune System** | 7 | | 2.7 | 4.9 | 3.9 | 8.5 | 8.5 | 8.5 | 9.2 | 8.5 | 8.5 | 7.5 | 8.0 | 8.5 | 8.5 | 8.5 | 2.5 |
| Small satellite characterization (size, composition, etc) | | 10 | 3.0 | 3.0 | 3.0 | 8.0 | 8.0 | 8.0 | 8.5 | 8.0 | 8.0 | 7.0 | 7.5 | 8.0 | 8.0 | 8.0 | 2.0 |
| Ring structure and particle characterization | | 8 | 3.0 | 3.0 | 6.0 | 8.0 | 8.0 | 8.0 | 8.5 | 8.0 | 8.0 | 7.0 | 7.5 | 8.0 | 8.0 | 8.0 | 4.0 |
| Interplanetary dust environment (sources, velocities etc) | | 7 | 0.0 | 8.0 | 0.0 | 9.0 | 9.0 | 9.0 | 10.0 | 9.0 | 9.0 | 8.0 | 8.5 | 9.0 | 9.0 | 9.0 | 2.0 |
| Magnetic field | | 10 | 4.0 | 6.0 | 6.0 | 9.0 | 9.0 | 9.0 | 10.0 | 9.0 | 9.0 | 8.0 | 8.5 | 9.0 | 9.0 | 9.0 | 2.0 |
| **KBOs** | 2 | | 6.0 | 7.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 7.0 | 7.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Characterize KBOs | | 10 | 6.0 | 7.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 7.0 | 7.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Category value by Architecture, summed | | | 15.8 | 20.1 | 16.4 | 23.0 | 24.5 | 25.5 | 27.9 | 31.5 | 30.0 | 23.6 | 26.0 | 24.6 | 23.0 | 24.0 | 7.3 |
| Category Value-weighted, summed, normalized | 0.5 | 0.8 | 0.35 | 0.45 | 0.52 | 0.71 | 0.76 | 0.79 | 0.87 | 0.81 | 0.76 | 0.73 | 0.80 | 0.75 | 0.71 | 0.73 | 0.22 |
| | 1.5 | 2.2 | 0.50 | 0.64 | 0.74 | 1.00 | 1.08 | 1.12 | 1.23 | 1.15 | 1.07 | 1.03 | 1.14 | 1.07 | 1.00 | 1.04 | 0.32 |
| Sum | | h23 | | | Key= | Low | Mid | High | | | | | | | | | |

- **Science value matrix results from science lead representative**
- **Note: Architectures 3.2, 4.2, and 4.3 not shown, as they are the same science value as the base arch.'s 3 & 4**

# RMA team integrated science value, cost, and risk analyses to assess the trade space




- Risk indicator: Left color=Implementation risk, Right color=Mission risk
- Color spectrum: Green=low, Light Green=low-med, Yellow=med, Orange=med-high, Red=high

For planning and discussion purposes only

# Principal Conclusions

- **The Neptune system provides a rich, largely-unexplored environment that supports scientifically interesting architecture options spanning candidate New Frontiers, small flagship, and flagship missions**
  - Failure of a flagship mission to achieve any one of the objectives does not greatly impact the mission science return, i.e. no single objective or instrument appears to "make or break" the mission
- **This study identified the following promising candidates for further study:**
  - A scientifically interesting candidate New Frontiers mission (Arch. 1)
  - A "simple orbiter" (Arch. 3 or 3.2) in the "small flagship" cost class (under $2B)
    - Scientific progress well beyond Voyager 2, but only limited additional science at Triton
  - There are multiple scientifically interesting flagship mission architectures
    - The scientific investigations can be approached in a variety of ways, all of which yield scientifically viable flagship missions (e.g., combinations of remote sensing and in-situ combinations)
    - Architecture 4 ("high performance Neptune orbiter") forms the basis for a set of flagship mission variants (Architectures 4, 4.2, 4.a, 4.d, 4.e, 4.e.2, 5, 5.a) that form a cluster of cost-effective, scientifically viable flagship mission options
      - Individual architectures had specific advantages and disadvantages discussed in the full report
- **Candidate architectures can deliver probes and landers through combinations of larger launch vehicles, upper stages, SEP and aerocapture (where required)**
  - Addition of Neptune atmospheric entry probes (Arch. 4.a) appears scientifically worthwhile
  - Addition of a Triton lander (Arch. 4.b) adds science value but is also accompanied by significant increases in cost and risk

# Principal Conclusions (cont'd)

- **Unique, high priority measurements can be made at a KBO, but it was not highly valued by the scientists representing the interests of a proxy Giant Planets Panel**
  - However, inclusion of KBOs helps to engage a wider scientific community
  - For any flyby of a giant planet, it is worthwhile to consider going on to a KBO flyby
- **Identified some architectures as having lower science-to-cost performance**
  - Flagship flyby (Arch. 2) yields lower-value science than a lower-cost simple orbiter (Arch. 3)
  - Dual orbiter architectures 5, 5.a, and 5.b yield only modest increases in science value for relatively large cost increases needed to accommodate the additional flight systems
- **Availability of Jupiter gravity assists are a major aspect of performance of Earth-to-Neptune transfers**
  - Jupiter flybys are primarily effective for launch windows in 2016–2018 and 2028–2030
  - Ares V launch vehicle may open up the trade space for launch opportunities between Jupiter gravity assist windows
- **Opportunities for collaborations and contributions**
  - In places where there are clean interfaces (e.g., individual flight system elements or payloads), there are good opportunities to reduce effective cost to NASA via contributions by other organizations (e.g., academia, industry, other U.S. government agencies, foreign agencies)
- **Some new technologies enhance mission value, but with associated risks**

# Follow-on study: What will change?

- **Science value assessments**
  - Science objectives and their priorities will be updated by Decadal Survey Science Panels
- **Driving assumptions and constraints**
  - Ground rules established by NASA HQ for the Decadal Survey will change some technical and cost assumptions
- **More emphasis on potential New Frontiers and lower-cost flagship class mission options**
  - Payloads and flight elements will likely change

**Next Step:**

- **Science panels to provide prioritized science objectives integrated across those science panels participating in the Neptune/Triton RMA study**

# Questions?