

NEPTUNE POLAR ORBITER WITH PROBES*

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Bernard Bienstock⁽¹⁾, David Atkinson⁽²⁾, Kevin Baines⁽³⁾, Paul Mahaffy⁽⁴⁾, Paul Steffes⁽⁵⁾,
Sushil Atreya⁽⁶⁾, Alan Stern⁽⁷⁾, Michael Wright⁽⁸⁾, Harvey Willenberg⁽⁹⁾, David Smith⁽¹⁰⁾,
Robert Frampton⁽¹¹⁾, Steve Sichi⁽¹²⁾, Leora Peltz⁽¹³⁾, James Masciarelli⁽¹⁴⁾, Jeffrey Van Cleve⁽¹⁵⁾

⁽¹⁾Boeing Satellite Systems, MC W-S50-X382, P.O. Box 92919, Los Angeles, CA 90009-2919,
bernard.bienstock@boeing.com

⁽²⁾University of Idaho, PO Box 441023, Moscow, ID 83844-1023, atkinson@ece.uidaho.edu

⁽³⁾JPL, 4800 Oak Grove Blvd., Pasadena, CA 91109-8099, kbaines@pop.jpl.nasa.gov

⁽⁴⁾NASA Goddard Space Flight Center, Greenbelt, MD 20771, paul.r.mahaffy@nasa.gov

⁽⁵⁾Georgia Institute of Technology, 320 Parian Run, Duluth, GA 30097-2417, ps11@mail.gatech.edu

⁽⁶⁾University of Michigan, Space Research Building, 2455 Haward St., Ann Arbor, MI 48109-2143, atreya@umich.edu

⁽⁷⁾Southwest Research Institute, Department of Space Studies, 1050 Walnut St., Suite 400, Boulder, CO 80302,
astern@boulder.swri.org

⁽⁸⁾NASA Ames Research Center, Moffett Field, CA 94035-1000, mjwright@mail.arc.nasa.gov

⁽⁹⁾4723 Slalom Run SE, Owens Cross Roads, AL 35763, harvey@willenbergs.com

⁽¹⁰⁾ Boeing NASA Systems, MC H013-A318, 5301 Bolsa Ave., Huntington Beach, CA 92647-2099,
david.b.smith8@boeing.com

⁽¹¹⁾ Boeing NASA Systems, MC H012-C349, 5301 Bolsa Ave., Huntington Beach, CA 92647-2099
robert.v.frampton@boeing.com

⁽¹²⁾ Boeing Satellite Systems, MC W-S50-X382, P.O. Box 92919, Los Angeles, CA 90009-2919,
stephen.f.sichi@boeing.com

⁽¹³⁾ Boeing NASA Systems, MC H013-C320, 5301 Bolsa Ave., Huntington Beach, CA 92647-2099,
leora.peltz@boeing.com

⁽¹⁴⁾Ball Aerospace & Technologies Corp., P.O. Box 1062, Boulder, CO 80306-1062 jmasciar@ball.com

⁽¹⁵⁾Ball Aerospace & Technologies Corp., P.O. Box 1062, Boulder, CO 80306-1062 jvancllev@ball.com

ABSTRACT

The giant planets of the outer solar system divide into two distinct classes: the ‘gas giants’ Jupiter and Saturn, which consist mainly of hydrogen and helium; and the ‘ice giants’ Uranus and Neptune, which are believed to contain significant amounts of the heavier elements oxygen, nitrogen, and carbon and sulfur. Detailed comparisons of the internal structures and compositions of the gas giants with those of the ice giants will yield valuable insights into the processes that formed the solar system and, perhaps, other planetary systems. By 2012, Galileo, Cassini and possibly a Jupiter Orbiter mission with microwave radiometers, Juno, in the New Frontiers program, will have yielded significant information on the chemical and physical properties of Jupiter and Saturn. A Neptune Orbiter with Probes (NOP) mission would deliver the corresponding key data for an ice giant planet.

Such a mission would ideally study the deep Neptune atmosphere to pressures approaching and possibly exceeding 1000 bars, as well as the rings, Triton, Nereid, and Neptune’s other icy satellites. A potential source of power would be nuclear electric propulsion (NEP). Such an ambitious mission requires that a number of technical issues be investigated, however, including: (1) atmospheric entry probe thermal protection system (TPS) design, (2) probe structural design including seals, windows, penetrations and pressure vessel, (3) digital, RF subsystem, and overall communication link design for long term operation in the very extreme environment of Neptune’s deep atmosphere, (4) trajectory design allowing probe release on a trajectory to impact Neptune while allowing the spacecraft to achieve a polar orbit of Neptune, (5) and finally the suite of science instruments enabled by the probe technology to explore the depths of the Neptune

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atmosphere. Another driving factor in the design of the Orbiter and Probes is the necessity to maintain a fully operational flight system during the lengthy transit time from launch through Neptune encounter, and throughout the mission.

Following our response to the recent NASA Research Announcement (NRA) for Space Science Vision Missions for mission studies by NASA for implementation in the 2013 or later time frame, our team has been selected to explore the feasibility of such a Neptune mission.

SECTION 1: INTRODUCTION, OUTLINE/OVERVIEW, BACKGROUND

Solar system exploration has historically been divided into three overlapping stages – Reconnaissance, Exploration, and In-Depth Study [1]. Since the advent of outer planetary exploration in the 1970s, an initial reconnaissance of the gas giants Jupiter and Saturn has been completed by the Pioneers 10 and 11, Voyagers 1 and 2, and Ulysses spacecraft. Exploration of the Jupiter and Saturn Systems is in its early stages, initiated by the multiyear encounters of the Galileo spacecraft and the Cassini / Huygens spacecraft, respectively. However, the Ice Giant planets Uranus and Neptune have only been visited once each, by Voyager 2 in 1986 and 1989, respectively. Comparative exploration of one or both of the Ice Giants is the natural next step in the continuing progression of outer solar system exploration.

Although sharing a number of characteristics, each of the Gas and Ice Giant Planets is a unique system. Not only is each a miniature planetary system in its own right, with moons and rings, dynamic atmospheres and magnetospheres, but the outer planets contain a physical and chemical record of conditions at the time of solar system formation that is complementary to but different from the record encoded in the terrestrial planets.

Jupiter and Saturn are dominated by H and He. However, conditions change markedly as we move beyond the inner outer solar system to the regions where the Ice Giants Uranus and Neptune reside. Both Uranus and Neptune contain much higher levels of condensed refractories and volatile ices such as nitrogen, oxygen, sulfur, and carbon [2]. Careful examination and comparison of the compositions and internal structures of the Ice and Gas Giants will provide important clues regarding the mechanisms by which the solar system and, by extension, extra-solar planetary systems formed.

Hammel (2001) [3] points out that previous studies of planetary atmospheres have stressed the identification of physical and chemical processes underlying many of

the phenomena observed in planetary atmospheres. However, now that preliminary studies of individual atmospheres in the outer solar system have been completed, more detailed comparative studies of the atmospheres, satellites, rings, and magnetospheres of the Gas and Ice Giants are needed.

Although quite diverse, the terrestrial planets and the Gas Giants share a number of characteristics. The similarities and differences between the moons, atmospheres, geology, chemistry, and magnetospheres of the inner and outer solar system provide a natural laboratory for identifying and understanding conditions favorable for enabling and supporting biological activity, understanding and controlling the effects on the Earth's atmosphere of human activity, as well as interpreting observations of extra-solar planetary systems.

The overall justification for the Neptune Orbiter with Probes (NOP) mission therefore derives from the importance of continuing comparative studies of the Gas and Ice Giants, as well as between bodies in the inner and outer solar system, to address questions of planetary origins, and to help discriminate between possible theories of solar system formation and evolution. The NOP mission provides an opportunity to contribute to these goals by exploring a member of the family of Ice Giants.

The proposed NOP mission directly addresses a number of common goals, objectives, and themes in the National Academy of Science Decadal Survey, NASA's Solar System Exploration theme, and the Solar System Exploration Roadmap.

Solar System Exploration Roadmap, 2003

The Solar System Exploration (SSE) Roadmap, 2003 [4] lists possible mid-term and long-term flagship missions that should be selected to build on results of earlier investigations. One of the high priority missions listed is the NOP mission. Of the 8 primary objectives enumerated in the Roadmap, the first two contain elements that are directly addressed by the Neptune Orbiter with Probes mission:

How did planets/minor bodies originate. Understand the initial stages of planet and satellite formation, and study the processes that determined the original characteristics of the bodies in our solar system

How solar system evolved to current state. Determine how the processes that shape planetary bodies operate and interact, understand why the terrestrial planets are so different from one another, and learn what our solar system can tell us about extra solar planetary systems.

Furthermore, the SSE Roadmap indicates that “comprehensive exploration of the Ice Giant Neptune will permit direct comparison with Jupiter and more complete modeling of giant planet formation and its effect on the inner solar system.” The Roadmap also provides the Neptune Orbiter with Probes mission as an example of a high priority Flagship mission that would provide major scientific advances.

National Academy of Science Decadal Survey for Solar System Exploration

The National Academy of Science Decadal Survey for Solar System Exploration [5] has recommended that in-depth studies of the Neptune system be given high priority. Additionally, the Primitive Bodies Panel lists a Neptune/Triton mission among its highest priorities for Medium Class, and the Giant Planets Panel lists a Neptune Orbiter with multiple entry Probes as its highest priority in the next decade. The Decadal Study emphasizes that it is only through a comparison of composition and interior structure of the giant planets in our solar system that we can advance our understanding of how our planetary system formed. Additionally, detailed study of the giant planets can help us extrapolate to planetary systems around other stars. All three of the themes developed in the Decadal Study Report: 1) Origin and evolution; 2) Interiors and atmospheres; and 3) Rings and plasmas are addressed by a Neptune Orbiter with Probes mission.

“The primary probe science goal is the use of composition and temperature data in the Neptune atmosphere from the stratosphere to hundred/kilobar pressures to advance the understanding of solar system formation. Complementary probe measurements of winds, structure, composition and cloud particle size and lightning are also suggested. Critical measurements are CH₄, NH₃, H₂S, H₂O, PH₃, and the noble gases He, Ne, Ar, Kr, and Xe. Although the average atmospheric O abundance is not likely to be measured by 100 bar, C in methane and the noble gases will reveal the elemental abundance that can constrain models of Neptune’s formation when analyzed in the context of data from other giant planets such as Jupiter and Saturn.” 2003 NASA Strategic Plan and the more recent report of the President’s Commission on Implementation of United States Exploration Policy provides the broad motivation for a Neptune mission. The Strategic Plan places the outer planet exploration program in the context of the study of the origin of the solar system and the building blocks of life. The President’s Commission Report describes the same themes in its National Science Research Agenda organized around the themes Origins, Evolution, and Fate. Neptune exploration is further motivated by sub-

themes described in the NASA Strategic Plan, including formation of the solar system, comparative planetology, and solar controls on climate .

Solar System Exploration Theme

NASA’s Solar System Exploration theme also lists a Neptune mission as one of its top priorities for the mid-term (2008-2013) [6,7]. In a recent NASA study, a Neptune mission was highly ranked for its connections to astrophysical problems beyond the Solar System, including geology, ring systems and ring dynamics, atmospheric dynamics and structure, magnetic field structure and generation, Triton pre-biotic chemistry, and as an analog for local extrasolar planets. The Neptune mission is described as “almost Cassini-like in scope, near Discovery-like in cost” [8].

SECTION 2: SCIENCE

Very little is known about the overall composition, structure, and dynamics of Neptune’s deep atmosphere. It is proposed that multiple entry Probes be used to sample the composition, cloud and energy structure, and atmospheric dynamics of the Neptune atmosphere at several latitudes. Voyager and ground-based observations have revealed in Neptune’s atmosphere the presence of hydrogen, helium (indirectly), methane (and only two of its photochemical products, acetylene and ethane), hydrogen cyanide, carbon monoxide, and H₃⁺. This list is sparse when compared to the 28 (neutral) molecules, one ion, and multiple important isotopes that have been measured in the atmosphere of Jupiter [9]. Moreover, even for the species detected in Neptune’s atmosphere, the actual mixing ratio measurement is either highly uncertain or just not available.

To understand the formation of Neptune and Neptune’s atmosphere, detailed knowledge of atmospheric composition is crucial. Composition measurements in the region of 10-1000 mbar (lower stratosphere to upper troposphere) can offer valuable information on dynamical and photochemical processes in these regions. Elemental abundances of the heavy elements, at least C and S, as well as helium and the other noble gases, Ne, Ar, Kr, Xe, in the well-mixed atmosphere below the cloud layers, are needed to constrain the formation models of Neptune, as well as the origin and evolution of its atmosphere. The O/H and N/H ratios in the well-mixed atmosphere are desirable but not required. Supporting composition measurements on disequilibrium species, PH₃, GeH₄, AsH₃; isotope ratios, ¹⁵N/¹⁴N, and D/H, primordial molecules, N₂ together with CO and HCN, are also highly desirable.

Based on the known composition, the deepest (probe accessible) cloud on Jupiter is expected to be water (ice

and droplets) at approximately 5 bars for 3 x solar O/H and at 10 bars for 10 x solar O/H (10 times the solar value of O/H) [10,11]. Similarly, the deepest cloud on Neptune is also expected to be water. Thermochemical equilibrium calculations predict a water “ice” cloud base at approximately 100-bar level (273 K), with a cloud of water/ammonia droplets – aqueous solution – forming below this level. The base of the water cloud could therefore be as deep as approximately 370 bar (460 K) for 30x solar O/H or 500 bar (500 K) for 50x solar [11,12].

Models of formation of Jupiter and the other giant planets predict that heavy elements become increasingly enriched from Jupiter to Neptune [9]. This indeed appears to be the case, as the C/H ratio, 3x solar at Jupiter, is found to increase to 20-30x solar at Uranus and 30-50x solar at Neptune. Icy planetesimal models [9] predict that other heavy elements including O (as in water) would also be similarly enhanced in the atmosphere of Neptune [11]. This implies that to ensure the measurement of O/H on Neptune, a Probe would have to make measurement of water vapor to depths well below the water cloud, i.e. to >500 bar level.

However, a theorized deep water-ammonia ionic ocean would prevent water and ammonia from being well-mixed at pressures less than 10-100 kilobars [11]. Although no Probe in the foreseeable future can access these pressure levels, the elements C, S, He, Ne, Ar, Kr, and Xe (same as Jupiter except for O and N) can easily be reached at pressures of 50-100 bar. Combining mixing ratios of these elements with the isotopic data on D/H and $^{15}\text{N}/^{14}\text{N}$, along with the available elemental information on Jupiter from Galileo and Juno (if selected following the on-going Phase A study), along with C, $^{15}\text{N}/^{14}\text{N}$, and He at Saturn by the Cassini orbiter, will be adequate for constraining the models of formation of Neptune and its atmosphere. It is also important to recognize that even though the O/H and N/H will not be accessible at Neptune, measurement of the NH_3 and H_2O profiles to the maximum attainable depths are still valuable for gaining insight into the interior processes including the existence of the purported ionic ocean.

Neptune does possess an internal heat source, and, similar to Jupiter, we would expect to find that this is variable from equator to pole, resulting in variable convective processes and latitude-dependent winds with depth. For purposes of studying global atmospheric dynamics, as well as possible variability in composition, the proposed NOP mission therefore targets entry Probes to multiple latitudes.

TRITON, RINGS, MAGNETOSPHERE AND ICY SATELLITES

A mission to the Neptune system has strong connections to astrophysical problems beyond the Solar System, including geology, ring systems and ring dynamics, atmospheric dynamics and structure, magnetic field structure and generation, possible pre-biotic chemistries, and as an analog for local extrasolar planets.

Triton

Triton is perhaps the key element to selecting Neptune over Uranus as the prime representative of the Ice Giants for exploration. The largest satellite of Neptune, Triton is in a high inclination, retrograde orbit, and appears to be a captured object. Imaging from Voyager 2 showed a marked disparity between different regions on Triton’s surface suggesting significant differences in the dynamic and impact history of these regions. Additionally, it is suspected that Triton may be related to Charon and Pluto, and possibly to comets and Kuiper Belt Objects (KBOs), although it is unknown how the composition and inventory of volatiles of Triton compares with these objects. Key science questions include the composition of the surface ice, the abundance of N_2 , CO, hydrocarbons, nitriles, and noble gases on Triton’s surface and in Triton’s atmosphere, and the distribution and sources of aerosols.

Satellites and Rings

The properties of Neptune’s system of satellites are largely unknown, including overall densities and composition, whether they are mostly silicate or icy. Are the dark surfaces siliceous or carbonaceous? What is the dynamic / collision history of these objects? The relationship between the satellites and Neptune’s rings is also unknown. Do the satellites contribute to the generation and maintenance of the rings, and if so – how? What is the composition of the rings, what are their ages and dynamical evolutionary history? Can the overall structure of the rings, including ring arcs be explained?

Magnetic Field

Neptune’s magnetic field is unique in the solar system; it mainly consists of a dipole field that is offset and highly inclined with respect to Neptune’s center. What is the mechanism by which the magnetic field is generated? How does the structure of the field affect interactions with the solar wind, and the structure and properties of the magnetosphere? Does the magnetosphere change over a Neptune year? Additionally, Neptune’s aurora can be used as a partial diagnostic and probe of the magnetic field. What are the

processes of the auroral emission, and how do these compare to those on Saturn and Jupiter, as well as the Earth?

The complexity and scientific richness of the Neptune systems requires a well-defined list of science and measurement goals and objectives, and a highly integrated suite of remote sensing and in situ instruments. A detailed discussion of the specific goals and required instrumentation is beyond the scope of this paper. However, a listing of important science goals and issues in the Neptune system can be found in [2]. The NOP Science Goals and Objectives are listed in Table 1a, and specific measurement objectives are provided in Table 1b.

Table 1a. Science Goals and Objectives

1. <u>Origin and evolution of Ice Giants</u> – Neptune atmospheric elemental ratios relative to Hydrogen (C, S, He, Ne, Ar, Kr, Xe) and key isotopic ratios (e.g., D/H, ¹⁵ N/ ¹⁴ N), gravity and magnetic fields.
2. <u>Planetary Processes</u> – Global circulation, dynamics, meteorology, and chemistry. Winds (Doppler and cloud track), cloud structure, microphysics, and evolution; ortho/para hydrogen ratio; Photochemical species (C-H hydrocarbons, HCN); tracers of interior processes such as N ₂ , and disequilibrium species, CO, PH ₃ , GeH ₄ , AsH ₃).
3. <u>Triton</u> – Origin, Plumes, Atmospheric composition and structure, surface composition, internal structure, and geological processes
4. <u>Rings</u> – Origin and evolution, structure (waves, microphysical, composition, etc.)
5. <u>Magnetospheric and Plasma Processes</u>
6. <u>Icy Satellites</u> – Origin, evolution, surface composition and geology Neptunian magnetosphere.

Table 1b. Measurement Goals and Objectives

<ul style="list-style-type: none"> <u>Neptune</u> – Measurement of profiles of N₂, HCN, H₂S, NH₃, CH₄, H₂O, PH₃ and other disequilibrium species, hydrocarbons, noble gases and their isotopic ratios, D /H, ¹⁵N/¹⁴N; Profiles of atmospheric temperature, pressure, and density; atmospheric dynamics; radiative balance and internal heat; Cloud particle size/density, microphysical properties; storm evolution, lightning, stratospheric emissions, nightside thermal imaging; Interior: Gravitational field measurements <u>Triton</u> – Geological mapping, surface composition/roughness and thermal mapping, topography, subsurface mapping and interior/seismometry <u>Rings</u> – Composition, waves, dynamics <u>Magnetosphere</u> – Magnetic field; Plasma composition and electric fields

In the following tables of instruments (Tables 2a and 2b) the numbers in parentheses following each Measurement Goal refer to a Science Goal in Table 1a.

Table 2a. Probe Instruments

Instrument	Measurements*	Heritage
Gas Chromatograph Mass Spectrometer (GCMS)	<ul style="list-style-type: none"> Profiles of N₂, CO, HCN, H₂S, NH₃, CH₄, H₂O, etc.: Stratosphere to deep atmosphere (1,2) D/H (1) ¹⁵N/¹⁴N (1) Disequilibrium species (2, 1) Hydrocarbons (1,2) Noble gases (He, Ne, Ar, Kr, Xe) (1) Isotopic ratios (1) 	Stand-alone GC and MS experiments have been flown on the Pioneer Venus Probes. An MS was flown on the Galileo Jupiter Probe. A GCMS is now flying on the Huygens Probe as part of the Cassini-Huygens mission.
Atmospheric Structure Instrument (ASI), including 3-axis accelerometers: x, y, z and redundant z	<ul style="list-style-type: none"> Density (2) Temp/pressure profile (2) Wind dynamics (2) 	Used in many planetary Probe missions to Venus, Mars, and Jupiter
Net Flux Radiometer (NFR)	<ul style="list-style-type: none"> Radiative balance and internal heat (1,2) 	Used on Jupiter and Venus Probes
Nephelometer	<ul style="list-style-type: none"> Cloud particle size/density, microphysical properties (2) 	Flown on Pioneer Venus Probes.
Helium Abundance Detector (HAD)	<ul style="list-style-type: none"> Detailed helium measurements (1) 	Some redundancy with the GCMS. Flown on Galileo Probe.
Ortho/Para H ₂ Experiment	<ul style="list-style-type: none"> Vertical atmospheric transport (2) 	First flight for this instrument.
Lightning Detector	<ul style="list-style-type: none"> Lightning (2) 	Flown on Galileo Probe.
Doppler Wind Experiment (DWE)	<ul style="list-style-type: none"> Vertical Profile of zonal winds, atmospheric waves (2) 	Flown on Galileo and Huygens Probes
ARAD (Analog Resistance Ablation Detector)	<ul style="list-style-type: none"> TPS recession as a function of time, allows for determination of flight aerodynamics and aerothermal loads (1,2) 	Provides science and engineering data. Flown on the Galileo Probe. A must for planetary entry Probes.

* Numbers in parentheses refer to a Science Goal in Table 1a

Table 2b. Orbiter Instruments

Instrument	Measurements*	Heritage
High Resolution UV Spectrometer	<ul style="list-style-type: none"> • Neptune thermospheric and auroral emissions, occultation number density profiles (2) • Triton: atmospheric emissions, occultation number density profiles, surface composition (3) • Rings: composition (4) 	Galileo UVS Cassini UVIS New Horizons/ ALICE
High Resolution IR Spectrometer	<ul style="list-style-type: none"> • Atmospheric composition (1, 2) • Triton and icy satellite surface composition/roughness and temperature (3, 6) 	Imaging experiment included as part of Galileo (NIMS) and Cassini (VIMS) orbiter payloads.
High Resolution Camera	<ul style="list-style-type: none"> • Triton Surface, geological mapping (3) • Rings: waves, structure and dynamics (4) • Neptune Atmosphere, meteorology, dynamics, storm evolution, and lightning (2) • Icy Satellites (6) 	Voyager/ ISS Galileo/SSI Cassini/IS
Mid and far IR spectrometer	<ul style="list-style-type: none"> • Neptune: detailed atmospheric composition, thermal mapping (3-D wind fields) (1,2) • Triton: surface thermal mapping (3) • Rings: particle size and thickness (4) 	Voyager/IRIS Cassini/CIRS
Plasma wave instrument	<ul style="list-style-type: none"> • Plasma composition and electric fields (5) 	Galileo/PWS, Cassini/RPWS
Ion / neutral mass spectrometer (INMS)	<ul style="list-style-type: none"> • Protons, heavier ions, neutral particles/atoms (3,5) 	Cassini/INMS

Instrument	Measurements*	Heritage
Ka/X/S-band radio science	<ul style="list-style-type: none"> • Atmospheric pressure, temperature profile, density (2) • Abundance profiles of PH₃, H₂S, and NH₃ (1,2) • Gravitational field measurements (interior structure) (1,2) • Ring occultations for particle size and ring thickness (4) 	Flown on Cassini Orbiter for studies of Saturn/Titan atmospheres. Earlier Voyager heritage.
Uplink radio science	<ul style="list-style-type: none"> • Neptune and Triton atmospheric pressure, temperature profiles, density (2) 	Developed and ready for launch as part of New Horizons mission to Pluto.
Bistatic radar	<ul style="list-style-type: none"> • Triton and possibly other satellite surface texture, mapping (3) 	Uses incumbent radio science system. Demonstrated on Mars Global Surveyor Mission
Magnetometer	<ul style="list-style-type: none"> • Magnetic fields (1,5) 	Galileo/Magnetometer, Cassini/Magnetometer
Laser altimeter	<ul style="list-style-type: none"> • Triton topography (3) 	Mars MOLA, NEAR
Microwave radiometer	<ul style="list-style-type: none"> • Neptune deep atmosphere composition (1,2) • Triton composition (3) • Neptune, Triton, icy satellite brightness temperatures (1, 2, 3, 6) 	Demonstrated with both Magellan and Cassini RADAR systems operating in passive modes
Bolometer Array	<ul style="list-style-type: none"> • Triton, icy satellite, and possibly ring surface temperature distribution (3, 4, 6) 	
Penetrating radar	<ul style="list-style-type: none"> • Triton subsurface mapping, altimetry, surface emissivity/roughness (3) 	Magellan/ RADAR Cassini/RADAR under development for JIMO.

* Numbers in parentheses refer to a Science Goal in Table 1a

Candidate Instrument Payloads

As illustrated in Table 2b, the Orbiter is the core of the Neptune mission, providing a remote sensing platform and in-situ instruments for the study of Neptune’s magnetic field, and primary data links. A key element of the Orbiter instrument payload would be an integrated imaging package comprising multiwavelength imagers and spectrometers and a microwave radiometer. Space physics detectors might include a magnetometer and a plasma wave detector. An Ion and Neutral Mass Spectrometer could obtain chemical and isotopic measurements from the atmosphere of Triton. Radio science investigations would be enhanced by including an uplink capability enabled by ultrastable oscillators. Multiple entry Probes and Triton Lander(s) are also an essential part of the atmospheric and surface structure and chemistry on Neptune and Triton, respectively. Probe instrumentation, listed in Table 1a, is similar to that flown on Galileo and Huygens, including a Gas Chromatograph/Mass Spectrometer (GCMS), sensors for measuring temperature, pressure and acceleration, solar and IR radiometers, and a nephelometer.

SECTION 3: PROMETHEUS ARCHITECTURE; CAPABILITIES, ADVANTAGES, BENEFITS

Use of Prometheus technology, while providing great flexibility in mission planning, has several liabilities, including long mission duration and the necessity for extremely long burns from a 2-3 N thruster system to accomplish the required ΔV. A comparison of typical chemical operating parameters with the nuclear electric propulsion (NEP) performance is provided in Table 3. At present the Jupiter Icy Moons Orbiter (JIMO) NEP system is not qualified for a Neptune mission, although this technology is expected to be qualified in time for incorporation into a Neptune Orbiter mission.

Table 3. Thrust Characteristics of NEP and Chemical Propulsion Systems

Parameter	Chemical Propulsion	Nuclear Electric Propulsion
Isp (sec)*	320	7000
Thrust (N)	100	2-3

* Isp, or specific impulse, is a measure of fuel efficiency

Using thrust constraints imposed by NEPP, the transit time for a Neptune mission will be approximately 16 years. This extremely long time can be shortened somewhat by using higher thrust NEP, which should be available in the 2015 to 2018 time frame. In addition, a Jupiter gravity assist will also shorten the mission, although this constraint affects the launch period and in fact limits the launch opportunities to once every 12 years. This fact alone may negate the advantages of

planning a Neptune mission that requires a Jupiter gravity assist.

Additional advantages of NEP result from the nature of a low thrust, highly efficient system. Although NEP requires that thrusters be fired for long periods of time (on the order of months), this continuous thrust provides the ideal situation for on-board navigation. Midcourse corrections are not required since they can be incorporated during the long thrust periods. In addition, the high Isp affords great flexibility in mission planning at Neptune, although careful planning is required to begin the thrusting at the proper time to execute the desired ΔV maneuver.

The use of the highly efficient NEP on the Prometheus platform also results in considerable mass available for the science payload. On JIMO, that mass is specified at 1500 kg. But the mass estimate for shielding of electronic components from the intense radiation at Europa is on the order of 1000 kg. The radiation fields at Neptune, and its moon Triton, are significantly lower than those at Jupiter. Thus, it is expected that the Neptune Orbiter could support a payload mass of nearly 2500 kg.

Since the Neptune Orbiter payload consists of three planetary entry Probes, with a relatively low mass allocated for Orbiter science payload, the mass allocation for the Neptune Probes will be significant. Assuming a Probe design goal of approximately 300 kg, or close to the Galileo Probe mass of 339 kg, the 3 Neptune Probes consume only 36%, or 900 kg of the available 2500 kg payload mass. Allocating 100 kg for the Neptune Orbiter science payload still leaves 1500 kg of mass available for other science within the Neptune planetary system. A tantalizing use for this mass is to fly two Triton Landers, at 750 kg each, for a detailed evaluation of a moon that is nearly the scientific equal of Titan and Europa. A summary of the payload mass allocations for the Neptune Orbiter with Probes mission is given in Table 4.

Table 4. Payload Mass Allocations

Element	Unit Mass (kg)	Count	Total Mass (kg)
Probe	300	3	900
Orbiter	100	1	100
Triton Lander	750	2	1500
Total			2500

The use of nuclear electric power, the second “P” in NEPP, also enhances the NOP mission. The continuously available, high level of electrical power permits simultaneous operation of all science instruments on the Orbiter and a high-power transmitter

for high data rate transmissions to Earth. Thus, high power science, such as a Triton radar imager, can operate simultaneously with other instruments. This is in marked contrast to previous outer planet missions, where the relatively low power generated by Radioisotope Thermoelectric Generators (RTGs) necessitated cycling of the science instruments to remain within the total science power allocation.

SECTION 4: MISSION DESIGN ISSUES

Defining a robust strategy for multiple Probe release, Lander operations, and the Orbiter mission (over and above serving as the communications link for the Probes and Landers) at Neptune and Triton is a challenging task. As is common for complex missions of this type, optimization of each mission element must be balanced with the science requirements and mission design constraints of the other elements. Ideally, the selected design will provide a balanced mission that achieves all the science goals for each element. A discussion of the considerations for each element is presented below.

Probe Mission

The current concept includes three identical Probes that will sequentially enter the Neptune atmosphere at three different latitudes. The well-mixed nature of the Neptune atmosphere and the desire to study the atmospheric dynamics drives the Probe entry to three widely spaced latitudes. In addition, other than possible slight seasonal effects, the Neptune atmosphere is postulated to be symmetric about the equator so that a Probe entering at 15° north latitude would sense the same atmosphere as a Probe entering at 15° south latitude. For planning purposes, the three Probes should be targeted to high (60° - 90°), mid (30° - 60°) and low (0° - 30°) latitudes. Entry at 90° and 0° latitude should be avoided, since the atmosphere at these locations will undoubtedly have singularities not representative of low and high latitude atmospheric dynamics.

Probe depth is another mission design driver. For a Neptune atmospheric entry Probe, it is desirable to descend to a depth of 200 bars. Descent to this depth may require up to 4 hours assuming reasonable ballistic coefficients and the current model of the Neptune atmosphere. Thus a constraint on the Orbiter trajectory is to maintain the Probe in radio view for at least 5 hours, a duration that allows margin should a Probe descend deeper than the baseline depth by operating beyond its design life.

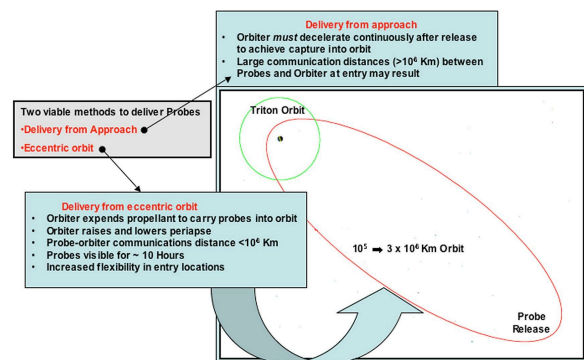
An additional science consideration for the Orbiter is dictated by science mission requirements for long-term observations of Neptune, and Neptune's rings and icy satellites. Although Orbiter science will be conducted

throughout the Probe and Lander segments of the Neptune encounter, it is expected that long-term observations of Neptune, the rings, and the icy satellites will continue during a post-Probe, post-Lander extended mission.

The Orbiter must allocate sufficient resources to support the three Probe missions, including payload mass, ΔV (fuel), power, and relay link communication system design. Probe release strategy is also a significant mission driver for the Orbiter. Figure 1 indicates two options for Probe release. Separation of the first Probe as the Orbiter approaches Neptune is a strategy that optimizes the first Probe mission only. The subsequent two Probes will be released from an elliptical orbit, at apoapsis, in order to allow the Orbiter to perform a deflection mission to avoid following the same planetary entry trajectory as the Probe.

A possible Probe release strategy is to complete the first Probe mission, complete a preliminary analysis of the Probe data, and to then have the option of modifying the second (and third) Probe missions based on the initial data reduction/analysis from the first (and second) Probes. Following each release, the Orbiter must execute an inclination change to allow the next vehicle to enter at a different latitude. Thus a possible strategy is to select a sequence with a low latitude change requirement. Finally, long term observations of Triton are an essential component of the NOP mission and must also be factored into the mission design. The phasing of the Orbiter Triton mission must be factored into the Orbiter mission planning. A long-term observation of Triton is required, that in turn drives the Orbiter to continue to orbit Triton after completion of the Probes mission support.

Figure 1. Neptune Mission Design



Technology and Engineering

A host of technology issues exist in the Neptune Orbiter with Probes mission design. These include the following:

Pressure Vessel Design. Even at 200 bars, the pressure vessel design is a challenge. Remember that the Pioneer Venus Probes were designed for 100 bars [13]. The question here is what type of technologies enable the fabrication of a 200 bar pressure vessel and penetrations (windows, inlets, feedthroughs, etc.). At the conference, a titanium alloy with carbon nanotubes was discussed as a potential light-weight pressure vessel material. This would, of course, save tremendous mass.

The Probe thermal design is also a challenge. Heaters will likely be required to maintain Probe temperatures above minimum limits from Orbiter separation to atmospheric entry. After entry, the thermal design must maintain electronics and science instrument temperatures within their operating ranges as thermal input increases due to atmosphere heating and energy dissipation within the Probe. The use of carbon nanotube passive heat pipes might prove useful since conventional heat pipes are not viable in a high-G Probe mission.

Deceleration Module. Significant work is required to define, design, develop and test materials appropriate for a high speed Neptune entry. High latitude entries will result in increased atmosphere-relative entry speeds, requiring high capability thermal protection system (TPS) materials.

Staging Systems. Although parachutes have been used successfully on the previous Probe and Probe/Lander missions (Pioneer Venus, Viking, Galileo, MER, etc.), they have required extensive development. Due to the inherent unreliability of parachutes, other staging techniques (separation of the Probe from the deceleration module) should be considered.

RF Link Design. The Radio Frequency (RF) link design, including frequency, power, and data rate, is dependent on the atmosphere model and the depth. Once the link is designed, there will be a need to design RF electronics with high efficiencies to limit thermal dissipation and provide the necessary power to allow reception of the Probe signal by the Orbiter.

Battery Design. The Probe battery design is of great concern in determining the total Probe electrical power budget. A primary consideration includes the power required during Probe coast (the period between Probe separation from the Orbiter and Probe pre-entry warm-up). The need for heaters may require batteries with high energy densities. The use of RHUs (radioisotope heater units), as were used on the Galileo and Huygens Probes, would help alleviate the electrical power requirement for heaters prior to Probe entry. The Probe battery requirements will also be driven by the depth to which the Probe must operate, the time to depth as dictated by the descent system, and the mass and power

requirements of the Probe science and engineering payload.

Electronic Design. The use of low power electronic devices that can operate over a wide temperatures range should be considered. These devices should be used throughout the Probe, within both housekeeping and science electronics, to ease the thermal control requirements.

Probe Miniaturization. The deployment of multiple Probes into the Neptune atmosphere is likely to be realized only with considerable Probe miniaturization. This can be accomplished not only through the continued miniaturization of the required instruments and sensors, but also by integrating all Probe elements. Power, mass and volume efficiencies can be achieved by, for example, using a single processor for all Probe elements and by mounting most of the Probe subsystems in a common vacuum or pressurized vessel. Of course, multiple processors, with appropriate, autonomous switching logic, must be included in the design to guarantee the highest probability of mission success. An aggressive program to develop and test highly integrated miniature Probes capable of obtaining the required measurements is essential for this mission.

Entry Environment and TPS Testing

The Galileo Probe entered Jupiter at a velocity of about 47 km/s, and experienced a peak net heat flux (including the effects of ablation) of nearly 30 kW/cm². This was by far the most energetic planetary entry attempted in the history of spaceflight. Direct entry at Neptune will not be as stressing, but entry velocities will be in the range of 23-30 km/s, depending on the interplanetary trajectory and desired entry latitude. At these conditions peak heat fluxes of several thousand W/cm² will be encountered. By comparison the Shuttle Orbiter experiences heat fluxes on the order of 40 W/cm².

Barring significant advances in TPS technology, there are few materials that can withstand these heat fluxes effectively. The only material ever used in such an environment is fully dense carbon phenolic of the kind used on the Pioneer Venus and Galileo Probes. Unfortunately, heritage carbon phenolic can no longer be produced, since the heritage Rayon fabric is no longer manufactured. The Air Force is currently qualifying a new carbon phenolic material for ballistic missile applications. Once this qualification is complete, the new material can readily be adapted to planetary entry Probes.

However, even when a suitable material is created, the performance characteristics of the material will be different and must be characterized *in a relevant*

environment to ensure that the TPS system will perform as expected. Arc jet facilities provide the best test environment for planetary TPS, and such facilities have been used to flight-qualify the thermal protection materials for every NASA planetary Probe to date, including Mars Pathfinder, MER, Pioneer Venus, and Galileo. The environment experienced by a giant planet entry Probe is very different from that seen by Probes entering the inner planets. For example, 50% or more of the aerothermal heating will be due to radiation produced in the hot shock layer. Furthermore, the atmosphere of all giant planets consists primarily of hydrogen and helium, much different than the N₂/O₂/CO₂ atmospheres of the inner planets. Therefore, in order to test materials in flight relevant conditions, a facility is required that can provide a combination of convective and radiative heating in a H₂/He environment.

During the Galileo program an arc jet facility known as the Giant Planet Facility (GPF) was constructed at NASA Ames Research Center specifically for material testing. However, this facility was shut down and dismantled soon after the conclusion of Galileo testing. No facility currently exists that can meet the requirements for giant planet TPS qualification. But, since the net heat fluxes encountered at Neptune are likely much lower than those seen by Galileo, the full capabilities of the GPF may not be required. One alternative is to conduct much of the testing in existing facilities using air as the test gas, and supplement this with limited testing in the correct gas in the presence of radiative heating. This could be accomplished either via a reconstruction of the GPF, or with a (lower cost) subscale option, such as the Developmental Arc Facility (DAF) currently under construction at NASA Ames. Both options will be explored during the development of this mission concept. In any case, development of a suitable facility will take some time and must be accommodated in any giant planet entry Probe mission timeline.

Parachuteless Entry Option

Parachutes are used during atmospheric Probe entries for three main reasons: (1) to separate the hot aeroshell from the payload, (2) to provide stability in the subsonic regime, and (3) to slow descent through the atmosphere to enable science objectives. For this mission, it is desired to reach atmospheric pressures of 100 bars or greater. Preliminary studies have shown that it will take many hours to reach this depth with a parachute, which is undoubtedly too long to maintain radio contact with the Orbiter. For this reason it would be desirable to eliminate the parachute if possible. In order to do this, a design must be chosen that is unconditionally stable from the hypersonic to subsonic flow regimes. This can

be done; for example, by a sphere-cone with a spherical base and a cone angle of 45° or less.

Another concern is separation of the aeroshell from the payload. This is important both to permit scientific instrument access to the atmosphere and to eliminate the aeroshell before the heat absorbed during the hypersonic entry is conducted into the payload. There have been other methods of aeroshell separation proposed, including shaped charges that split the aeroshell into “petals” that are then shed, but a high drag device is by far the best option. This study will look at several descent options, but at this point the most attractive option is to use a parachute only for aeroshell separation. Once separation is achieved the parachute would be cut free and the payload would continue its descent.

CONCLUSIONS

A complex Neptune Orbiter with Probes mission, that includes Triton Landers, will benefit considerably from development now under way to develop a nuclear electric power and propulsion capability for solar system exploration. Challenges abound in the development of the technologies necessary to support this ambitious mission. In addition, the extremely long mission duration, while daunting, must be viewed as path to completing a comprehensive study of Neptune, Triton and the other Neptunian moons. The time required to transverse nearly the entire solar system in order to complete a comprehensive Neptune study should be considered as an investment in a mission that will undoubtedly be conducted only once in this century or perhaps in the centuries to come.

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