National Aeronautics and Space Administration

... Mission Concept Study • Planetary Science Decadal Survey ...

# SATURN ATMOSPHERIC ENTRY PROBE MISSION STUDY

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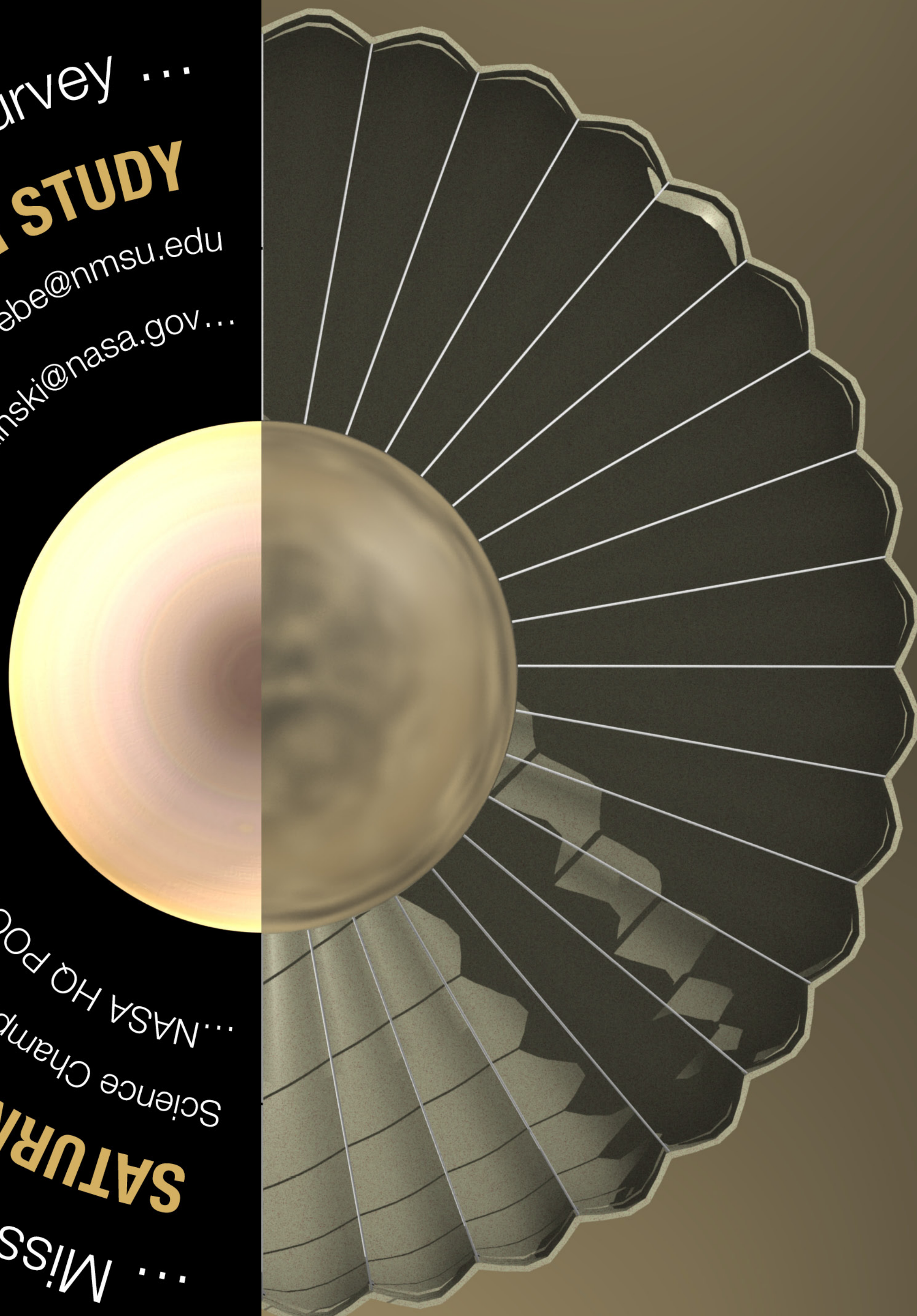

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# Data Release, Distribution, and Cost Interpretation Statements

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

The data contained in this document may not be modified in any way.

Cost estimates described or summarized in this document were generated as part of a preliminary concept study, are model-based, assume a JPL in-house build, and do not constitute a commitment on the part of JPL or Caltech. References to work months, work years, or FTEs generally combine multiple staff grades and experience levels.

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

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# Executive Summary

The science objectives of the Saturn Atmospheric Probe Mission Study are divided into two groups: "Tier 1," the science floor objectives that would need to be addressed to make the mission worthwhile, and "Tier 2," the next highest priority level, with objectives that prospective Principal Investigators could reasonably add, given sufficient resources. By request from the science team, this study addressed only the Tier 1 objectives:

- Determine the noble gas abundances and isotopic ratios of hydrogen, carbon, nitrogen, and oxygen in Saturn's atmosphere
- Determine the atmospheric structure at the probe descent location(s)

The primary study objective was to determine if any probe mission to accomplish these science objectives could fit within the resource constraints of NASA's New Frontiers Program. A secondary objective was to determine if a single mission delivering two entry probes to different locations at Saturn might fit within these constraints, although this was judged unlikely.

The mission concept, which resulted from a previous Decadal Survey–sponsored study (see "Saturn Atmospheric Entry Probe Trade Study Report" [1]), is fairly straightforward and in many ways resembles a simpler version of the Galileo probe mission. There would be three main phases: launch and transfer (cruise) to Saturn; approach and targeting; and the science mission. Launch would be to a trajectory with a single Earth gravity-assist after a deep-space maneuver of 449 m/s. For this study the opportunity of August 30, 2027 was used, arriving at Saturn June 22, 2034.

The flight system would consist of a carrier-relay spacecraft and a probe. The carrier-relay spacecraft would release the probe into Saturn's atmosphere and act as a relay for probe data. The approach and targeting phase would begin about 8 months before arrival. The approach V-infinity for the study trajectory is ~7.1 km/s, steered via trajectory-correction maneuvers to the probe entry point. As a stressing case, probe spin-up (for attitude stability) and release was chosen to be 1 month before entry. This choice requires ~55 m/s of delta-V for the divert maneuver that would place the carrier-relay spacecraft on the proper trajectory to perform its data-relay task. Earlier release would decrease the required delta-V, yet still provide sufficient delivery accuracy.

Hours before the probe entry, the science mission phase would begin. An event timer on the probe would initiate the "wake-up" activities, while the carrier-relay spacecraft would power-up its relay radio receiver and turn to point its probe relay antenna to the entry site. The probe would enter at an atmosphere-relative velocity of ~27 km/s, significantly less than the Galileo probe's 47.4 km/s. After the entry heating and deceleration phase, it would deploy a drogue parachute that would assist in jettison of the aeroshell and would open the main parachute near the 0.1-bar pressure level, when primary data acquisition and radio relay to the carrier-relay spacecraft would begin. At the 1-bar level the parachute would be released, and the descent module would continue either freefalling or descending under a small drogue parachute to the nominal end of mission at the 5-bar level, some 55 minutes later and 250 km deeper than the beginning of transmissions. The carrier-relay spacecraft would continue to point at the entry site for some time after the nominal end of mission, continuing to store data in onboard memory, since the descent module would be designed for the 10-bar level and would most likely survive longer than required.

Downlink of the data is predicted to be completed a short time after the end of the data relay. The entire probe data set would be expected to be only ~2 Mb, so at a downlink rate of 1.6 kbps the entire data set could be transferred to the ground in slightly more than 20 minutes. Multiple copies could be downlinked in the Deep Space Network pass immediately after the probe descent. The carrier-relay spacecraft would be on a flyby trajectory, so, unlike the Galileo spacecraft, it would need no orbit insertion maneuver, continuing on a solar system escape trajectory for spacecraft disposal.

This mission would require no new technology developments. It would rely on the Galileo probe's carbon-phenolic heatshield technology, and continued development to flight-readiness of the Advanced Stirling

Radioisotope Generator (ASRG). The pathways and schedules for the use of these technologies are well understood.

This is a relatively low-risk mission concept. Most of its primary risks would be programmatic rather than technical. The main programmatic risks would involve availability of ASRGs and appropriate carbon-phenolic materials. The main technical risks would involve the probe's entering a nonrepresentative region in Saturn's atmosphere, and a critical deployment after nearly seven years of soak in deep space. Because the science objectives would not require measuring the deep absolute abundances of oxygen and nitrogen, the risk of entering a nonrepresentative region would be significantly lower than that of the Galileo mission.

# 1. Scientific Objectives

## Science Questions and Objectives

See Atkinson, D.H., et al., "Entry Probe Missions to the Giant Planets" [2].

### *Abstract*

In situ probe missions to the outer planets are designed to satisfy three needs:

- To constrain models of solar system formation and the origin and evolution of atmospheres
- To provide a basis for comparative studies of the gas and ice giants
- To provide a valuable link to extrasolar planetary systems

The gas and ice giants offer a laboratory for studying the atmospheric chemistries, dynamics, and interiors of all the planets, including Earth. It is within the deep, well-mixed atmospheres and interiors of the giant planets that pristine material from the epoch of solar system formation might be found, providing clues to the local chemical and physical conditions existing at the time and location at which each planet formed. Although planetary entry probes sample only a small portion of a giant planet's atmosphere, probes provide data on critical properties of atmospheres that cannot be obtained by remote sensing, such as measurements of constituents that are spectrally inactive, constituents found primarily below the visible clouds, and chemical, physical, and dynamical properties at much higher vertical resolutions than can be obtained remotely. The Galileo probe, for instance, returned compositional data at Jupiter that have challenged existing models of Jupiter's formation. To complement Galileo in situ explorations of Jupiter, an entry probe mission to Saturn would be needed. To provide for comparative studies of the gas giants and the ice giants, additional probe missions to either Uranus or Neptune would be essential.

### *Current State of Knowledge*

#### *Background*

The atmospheres of the giant planets hold clues to the chemical nature of the refractory materials from which the original planetary cores formed, the surrounding protosolar nebula, and the subsequent formation and evolution of atmospheres. These clues could be derived from the composition, dynamics, and structure of giant planet atmospheres. There exist a number of different theories of planetary formation that attempt to explain observed patterns of enrichments across volatiles and noble gases. In at least two theories, the enrichment of heavy elements (amu >4) in the giant planets was provided in the form of solids. The core accretion model predicts that the initial heavy element cores of the giant planets formed from grains of refractory materials in the protosolar nebula. Once these cores grew to 10–15 Earth masses, hydrogen and helium, enriched with heavy elements, gravitationally collapsed from the surrounding nebula onto the central core. Additional heavy elements were subsequently delivered by primordial planetesimals (solar composition icy planetesimals [SCIPs]). However, this theory suffers from the fact that these planetesimals are not seen today. In the clathrate-hydrate (C-H) model, heavy elements are delivered to the giant planets in icy clathrate-hydrate "cages." Although the C-H theory can account for some of the abundances observed at Jupiter, such as the low abundance of neon (the only noble gas not easily trapped in clathrates), other observed abundances such as water do not closely match the predictions of the C-H model. Another theory suggests that heavy elements were incorporated into the gas accumulated by Jupiter, not in the solids. Guillot and Hueso [3] suggest a scenario comprising a sequence of refinement by settling of grains and loss of gas from the near-Jupiter nebula. To help establish the relative validity of these theories, measurements of heavy element abundances in the deep, well-mixed atmospheres of the giant planets would be needed.

## *Composition*

Some models of planetary formation predict that the central core mass of the giant planets should increase with distance from the Sun, with a corresponding increase in the abundances of the heavier elements from Jupiter outwards to Neptune. Carbon, in the form of methane, is the only heavy element that has been measured on all the giant planets. As predicted, Voyager, Galileo, Cassini, and ground-based remote sensing have shown that the ratio of carbon to hydrogen increases from three times solar at Jupiter to 30× solar or greater at Neptune. In addition to carbon, of particular importance to constraining and discriminating between competing theories of giant planet formation are the deep atmosphere abundances of the heavy elements, particularly nitrogen, sulfur, oxygen, and phosphorus; helium and the other noble gases and their isotopes; and isotope ratios of hydrogen, helium, nitrogen, oxygen, and carbon. Also, abundances of disequilibrium species such as carbon monoxide, phosphine, germane, and arsine can provide insight into the nature of convection and other not easily observable dynamical processes occurring in a planet's deep atmosphere. Table 1-1 shows the known and suspected abundances of the heavy elements and several key isotopes at Jupiter, Saturn, Uranus and Neptune. The suspected increase in heavy element abundances for the outer planets is based on the measured increase in carbon and the predictions of the icy planetesimal model of nearly equal enrichment of heavy elements (relative to solar) in the giant planets. However, the specifics of how all the elements vary relative to each other—especially how these relative abundances might vary from Jupiter to Saturn to the ice giants—would be diagnostic of accretionary processes because of the range of volatility of their parent molecules.

***Table 1-1. Elemental (relative to H) and Isotopic Abundances*** [4]

| Element | Sun | Jupiter/Sun | Saturn/Sun | Uranus/Sun | Neptune/Sun |
|---|---|---|---|---|---|
| **He** | 0.1 | 0.8 ±0.0 | 0.6–0.9 | 0.92–1.0 | 0.9–1.0 |
| **Ne** | $2.1 \times 10^{-4}$ | 0.59 ±0.0 | ? | 20–30 (?) | 30–50 (?) |
| **Ar** | $1.7 \times 10^{-6}$ | 5.34 ±1.1 | ? | 20–30 (?) | 30–50 (?) |
| **Kr** | $2.1 \times 10^{-9}$ | 2.0 ±0.4 | ? | 20–30 (?) | 30–50 (?) |
| **Xe** | $2.1 \times 10^{-10}$ | 2.1 ±0.4 | ? | 20–30 (?) | 30–50 (?) |
| **C** | $2.8 \times 10^{-4}$ | 3.8 ±0.7 | 9.3 ±1.8 | 20–30 | 30–50 |
| **N** | $6.8 \times 10^{-5}$ | 4.9 ±1.9 | 2.7–5.0 | 20–30 (?) | 30–50 (?) |
| **O** | $5.1 \times 10^{-4}$ | 0.5 ±0.2 (a) | ? | 20–30 (?) | 30–50 (?) |
| **S** | $1.6 \times 10^{-5}$ | 2.9 ±0.7 | ? | 20–30 (?) | 30–50 (?) |
| **P** | $2.6 \times 10^{-7}$ | 4.8 (b) | 5.0–10.0 | 20–30 (?) | 30–50 (?) |
| **Isotope** | **Sun** | **Jupiter** | **Saturn** | **Uranus** | **Neptune** |
| **D/H** | 2.1 ±0.5E-5 | 2.6 ±0.7E-5 | 2.3 ±0.4E-5 | 5.5(+3.5,-1.5)E-5 | 6.5(+2.5,-1.5)E5 |
| **$^3$He/$^4$He** | 1.5 ±0.3E-5 | 1.7 ±0.0E-5 | — | — | — |
| **$^{15}$N/$^{14}$N** | $\leq 2.8 \times 10^{-3}$ | $2.3 \pm 0.3 \times 10^{-3}$ | — | — | — |

(a) Jupiter hotspot meteorology

(b) [5], relative to solar composition of [6]

## *Structure and Dynamics: Transport, Clouds and Mixing*

Giant planet atmospheres are by no means static, homogeneous, isothermal layers. High-speed lateral and vertical winds are known to move constituents through the atmospheres' complex structures, creating the strongly banded appearance of zonal flows modulated by condensation (clouds) and by vertical and lateral compositional gradients. Foreknowledge of structure and dynamics, even if incomplete, would allow better understanding of local fractionation of atmospheric constituents, which is necessary to interpret the local abundances in terms of the physical conditions under which the inferred constituents could have formed and, thus, point to the locations within the solar system where they originated.

Measurements of structure, dynamics, and composition, in addition to providing understanding of the fundamental processes by which giant planets operate and evolve, help to verify that composition measurements are made under the proper conditions. As temperatures decrease with increasing distance from the Sun, the expected depths of the cloud layers should also increase. At the warmer temperatures of Jupiter, equilibrium models predict three cloud layers: an upper cloud of ammonia ($NH_3$), a second, slightly deeper cloud of ammonium hydrosulfide ($NH_4SH$), and deeper still cloud(s) of water-ice and/or water-ammonia mixture. At Jupiter, water is the deepest cloud expected, with a cloud-base location predicted to be at depths of 5 to 10 bars for O/H ranging between 1 and 10× solar. In the colder environs of Saturn, Uranus, and Neptune, water-ice and water-ammonia clouds are expected to form at much greater depth. Thermochemical equilibrium calculations suggest that the base of water ice and ammonia-water solution clouds at Saturn may be at pressures of 10 bars and 20 bars, respectively, for 10× solar O/H. Although atmospheric chemistry and diffusion and condensation processes affect the location and composition of clouds and tend to fractionate constituents above the clouds, the well-mixed state is expected well beneath the clouds.

## *Key Science Questions*

To unveil the processes of outer planet formation and solar system evolution, detailed studies of the composition, structure, and dynamics of giant planet interiors and atmospheres would be necessary. To constrain the internal structure of gas giants, a combination of both in situ entry-probe missions and remote-sensing studies of the giant planets would be needed. Although some important measurements addressing Saturn's composition, structure, and dynamics are being accomplished by the Cassini mission, other critical information is impossible to access solely via remote-sensing techniques. This is the case when constituents or processes of interest, at depths of interest, have no spectral signature at wavelengths for which the atmospheric overburden is optically thin. Additionally, when remote-sensing measurements are made it is often difficult to ascertain the precise depth. Entry probes circumvent such limitations by performing in situ measurements, providing precise vertical profiles of key constituents that could be invaluable for elucidating chemical processes such as those in forming clouds (like $NH_3$ and $H_2S$ producing $NH_4SH$ clouds), and for tracing vertical dynamics (e.g., the $PH_3$ profile, where the competing processes of photochemical sink at altitude and supply from depth could give a variety of profiles, depending, for example, on the strength of vertical upwelling). The key science measurements for entry probes therefore focus on those measurements best addressed utilizing in situ techniques. This data set, combined with Cassini data (in particular, the end-of-life scenario) could be contrasted with the Jupiter Galileo probe and Juno data to constrain current models of gas giants and solar system formation and more clearly define the required remote and in situ measurements of ice giants (Neptune and Uranus) to more fully constrain formation of planets and solar systems in general. Of particular value would be measurements of the vertical profile of temperatures, preferably at multiple latitudes, although preliminary measurements at a single latitude would be the first step toward more complete characterization in the future. It is not understood how energy is distributed within the atmosphere of the giant planets, how the solar energy and internal heat flux of Saturn contribute to the dynamics of the atmosphere, to what depth the zonal wind structure penetrates, and whether the zonal winds increase with depth as on Jupiter. The key science questions to be addressed by giant-planet entry-probe missions are listed in the science traceability matrix, Table 1-2.

In addition to these in situ measurements to satisfy the probe goals, knowledge of the core size and mass would be needed. The Cassini end-of-life scenario and the Juno mission should obtain detailed measurements of variations in the gravitational field of Saturn and Jupiter that could be used to constrain the internal mass distribution. These results would be highly complementary to the anticipated results of an in situ Saturn probe and the Galileo probe data. Together these data would provide robust constraints for models and for the evolution of the gas giants Jupiter and Saturn.

### *Giant Planet Probe Missions*

Jupiter is the only giant planet to have been studied in situ. To provide improved context in the results of the Galileo probe studies of Jupiter, and to provide for additional discrimination among theories of the formation and evolution of the gas giants and their atmospheres, it would be essential that the Galileo Jupiter probe studies be complemented by similar studies at Saturn and the ice giants Neptune and Uranus. For an understanding of the formation of the family of giant planets, both ice giants and gas giants, and, by extension, the entire solar system, probe missions to the ice giants Uranus and Neptune would also be essential. Both observationally (measured carbon abundances) and theoretically (atmospheres forming from some combination of accreting nebula gas, degassing of core material, and influx of SCIPs, etc.), there is every reason to expect the atmospheric composition of the ice giants to be greatly different from that of Jupiter or Saturn. It is recognized that all the giant planets could represent excellent targets for future probe explorations, and if special opportunities should be presented, the order in which specific giant planets are explored would be of lesser importance than the value of the science that could be returned from missions to any of these targets; however, the fact that acquisition of in situ data for Saturn would complete a comparative data set for Jupiter and Saturn promises potentially high value return for this proposed mission.

### *Saturn Probe*

Although multiple shallow probes and multistage deep probes would be desirable, this study addresses the implementation of a proposed single shallow probe capable of determining isotopic ratios and elemental abundances as well as the temperature, pressure and density structure of the entry site. If such a mission were selected, inclusion of additional instruments or possibly a second probe would be desirable. However, the science floor of the mission defined in this study could acquire highly significant fundamental data. The proposed requirements for this mission are summarized in the science traceability matrix, Table 1-2.

Flying multiple probes would enhance the science considerably and could reduce mission risk, but to minimize cost, a single probe could be used. Even though measurements of disequilibrium species (a Tier 2 goal) change with latitude, the abundance of the noble gases and isotopic ratios are expected to be relatively insensitive to entry location. A simple probe with two instruments, an atmospheric structure instrument (ASI) and a mass spectrometer (MS), would fulfill the Tier 1 science goals and address substantially the Tier 2 goals. The nominal penetration depth would be the 5-bar level to accomplish the oxygen isotopic ratio measurements, the most demanding of the Tier 1 objectives.

The proposed probe might descend in a region not representative of the average Saturnian atmosphere. This could compromise compositional goals, but would be unlikely to affect measurements of isotopic ratios. Thus, Tier 1 science would not be sensitive to this possibility.

Tier 1 science objectives have driven the mission and flight system design. Tier 2 objectives are addressed only to the extent that the Tier 1 measurements would be applicable.

## Science Traceability

***Table 1-2. Science Traceability Matrix***

| Science Objective | Measurement | Instrument | Functional Requirement |
|---|---|---|---|
| **Tier 1** | | | |
| Determine the noble gas abundances and isotopic ratios of H, C, N, and O in Saturn's atmosphere | Bulk composition to ±20%<br>Helium/solar (±2%)<br>Ne, Ar, Kr, Xe, S, N ±20%<br>Isotopes ±10%<br>O profile above clouds | Mass spectrometer | Descent to 5 bar<br>70-minute relay<br>Sample interval ≤250 meters |
| Determine the atmospheric structure at the probe descent location acceleration | Acceleration<br>Temperature<br>Pressure | Atmospheric structure instrument (ASI) | Descent to 5 bar<br>70-minute relay<br>Sample interval ≤100 meters |
| **Tier 2** | | | |
| Determine the vertical profile of zonal winds as a function of depth at the probe descent location(s) | — | ASI | Doppler tracking |
| Determine the location, density, and composition of clouds as a function of depth in the atmosphere | — | ASI, MS | — |
| Determine the variability of atmospheric structure and presence of clouds in two locations | — | ASI (MS helpful) | — |
| Determine the vertical water abundance profile at the probe descent location(s) | — | MS (difficult measurement) | 20 bar |
| Determine precision isotope measurements for light elements such as S, N, and O found in simple atmospheric constituents | — | MS | — |

# 2. High-Level Mission Concept

## Overview

The mission concept, which resulted from a previous Decadal Survey–sponsored trade study [1], is fairly straightforward and in many ways resembles a simpler version of the Galileo probe mission. A proposed atmospheric entry probe is the central science element of the flight system, supported by the other proposed element, a carrier-relay spacecraft that would deliver the probe to Saturn's atmosphere and would provide data relay from the probe to Earth.

Science objectives requiring measurements of isotopic ratios of key atmospheric constituents drive the need to penetrate Saturn's thick atmosphere to the 5-bar level. This drove the requirement for the entry probe's descent module to survive to at least that depth. The need for margin on that design, to handle uncertainties in the atmosphere actually encountered, motivated designing to the 10-bar level. This is not a particularly challenging task compared to the Galileo probe design. But compared to Jupiter, Saturn's much larger atmospheric scale height, coupled with its smaller gravitational acceleration, yield a longer descent time than the Galileo probe. Those differences also drive a somewhat different descent strategy: releasing the main parachute at some point (approximately the 1-bar level) to permit faster descent to the deeper levels. This would accomplish descent to the 10-bar level in about 70 minutes, with margin in the trajectory design to accommodate (with data relay) even lengthier descents if necessary. Instrumentation to make the required science measurements is covered in Section 3.

The design of the carrier-relay spacecraft is straightforward, but is driven by the critical need to use the most cost-effective solutions possible to fit within a New Frontiers Program paradigm. Some design decisions were not driven directly by science requirement thresholds. For instance, the telecommunications system for data relay from the probe to the carrier-relay spacecraft would have significantly more capability than the science floor requires, but would use standard, cost-effective components, while a lower-rate system that just meets the science floor would be a custom build. Regarding power systems, although it might be possible to use solar arrays for the carrier-relay spacecraft's primary electric power system, operating at 10 AU would push the very limit of current solar cell technology, requiring large margins and an expensive parts selection program for the solar cells. For the mission time period studied, a radioisotope power source (RPS) is less expensive and lower risk for this mission than a solar array system, and would perform well in all mission phases.

There are three main mission phases: launch and transfer (cruise) to Saturn; approach and targeting; and the science mission. For this study a launch opportunity centered on August 30, 2027, was used, with the spacecraft arriving at Saturn on June 22, 2034. The cruise trajectory would use a single Earth gravity-assist after a deep-space maneuver (DSM) of 449 m/s.

The approach and targeting phase would begin about 8 months before arrival. The approach V-infinity for the study trajectory would be ~7.1 km/s, steered via trajectory-correction maneuvers (TCMs) to the probe entry point. Probe spin-up (for attitude stability) and release was chosen to be 1 month before entry as a stressing case. This choice raises to ~55 m/s the delta-V for the subsequent carrier-relay spacecraft divert maneuver, the maneuver that would place the carrier-relay spacecraft on the proper trajectory to perform its data-relay task. Earlier release would decrease that delta-V, roughly inversely proportionally to the release-to-entry time, yet would still provide sufficient delivery accuracy. For comparison, the Galileo probe was released 5 months before entry.

Hours before the probe entry the science mission phase would begin. An event timer on the probe would initiate the "wake-up" activities, while the carrier-relay spacecraft would power up its relay radio receiver and turn to point its probe relay antenna to the entry site. The probe would enter at an atmosphere-relative velocity of ~27 km/s, significantly less than the Galileo probe's 47.4 km/s. After the entry heating and deceleration phase, the probe would deploy a drogue parachute that would help to jettison the aeroshell and open the main parachute near the 0.1-bar pressure level, when primary data acquisition and radio relay to the carrier-relay spacecraft would begin. At the 1-bar level the parachute would be released and the descent module would continue either freefalling or descent under a small drogue parachute to the nominal end of mission at the 5-bar level, some 55 minutes later and 250 km deeper than the beginning of transmissions. The carrier-relay spacecraft would continue to point at the entry site for some time after the nominal end of mission, continuing to store data in onboard memory, since the proposed descent module is designed for the 10-bar level and would most likely survive longer than required.

Downlink of the data would be completed a short time after the data relay ends. Since the entire probe data set would be only ~2 Mb, at the downlink rate of 1.6 kbps the entire data set could be transferred to the ground in slightly more than 20 minutes. Multiple copies would be downlinked in the Deep Space Network (DSN) pass immediately after the probe descent. The carrier-relay spacecraft would be on a flyby trajectory, so unlike the Galileo spacecraft it would need no orbit insertion maneuver, continuing on a solar system escape trajectory for spacecraft disposal.

The previously mentioned probe entry speed of ~27 km/s is important. Where the Galileo probe pushed carbon-phenolic thermal protection system (TPS) technology to the limit, Saturn entry conditions are much more in-family with carbon-phenolic's "comfort zone." Notably, existing facilities can test carbon-phenolic TPS materials under conditions appropriate to entry into a hydrogen-helium atmosphere at up to 30 km/s, sufficient for prograde Saturn entries. Since NASA ARC's Giant Planets Facility has been dismantled, the ability to test under Jupiter entry conditions no longer exists in the US (or elsewhere), but that does not impact this mission concept.

# Concept Maturity Level

The Advanced Projects Design Team (Team X) study conducted in support of this report assembled JPL experts in mission design, science, instrumentation, ground operations, and spacecraft subsystems. These experts made recommendations on appropriate approaches for achieving mission objectives according to the science team's posture for cost and risk. The study performed quasi-grassroots cost estimation down to work breakdown structure level 3 for the proposed project, and level 4 for the proposed spacecraft. Mass, power, and performance estimates of proposed spacecraft subsystem components were developed along with durations for major project phases (A–F). Mission and implementation risks were collected from the study team and evaluated. The sum of this information places the concept described in this report at concept maturity level (CML) 4, using the CML definitions in Table 2-1.

***Table 2-1. Concept Maturity Level Definitions***

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

# Technology Maturity

The only technology below TRL 6 is the Advanced Stirling Radioisotope Generator (ASRG), but per the NASA ground rules, we have assumed that maturation of this technology is funded by a separate NASA program.

# Key Trades

The principal trades conducted in the course of this study involved the primary electric power source (solar vs. nuclear), and trades involving trajectories, especially Earth-to-Saturn transfer trajectories. The current design used the results of some trades examined in previous studies, such as the superiority (for this mission) of science data relay from the probe through the carrier-relay spacecraft to Earth, instead of data transmission from the probe directly to Earth [7].

Unexpectedly, the solar vs. nuclear trade study concluded that the nuclear option, specifically the use of ASRGs, would provide significant cost savings and risk reduction relative to the solar option. There are multiple reasons. Despite using no RPS, the solar option would nonetheless require radioisotope heater units (RHUs), some in the proposed probe and some in the proposed carrier-relay spacecraft. Thus it would incur some costs associated with nuclear payloads anyway, nullifying one potential cost-saving advantage of the solar option. Solar cells from a production process are not all exactly the same, and differences that are small under normal illumination conditions could be greatly magnified under the low-intensity, low-temperature (LILT) conditions in the outer solar system. For a mission to Saturn, selecting acceptable solar cells from production batches would require a significant program of testing and screening, increasing the cost per cell. Because such testing does not always guarantee expected performance, the solar arrays would need to be designed with somewhat larger margins, increasing the size, cost and risk of producing and flying already-large arrays. These large arrays would have masses far greater than the mass of ASRGs producing similar power. Solar array size and mass influenced the proposed launch vehicle selection and subsequent spacecraft operations: The dimensions and mass of the arrays would require a larger launch vehicle and significant operational constraints, contributing significantly to the total cost and risk difference.

Earth-to-Saturn trajectories were also evaluated partly on the basis of their fit with smaller launch vehicles. Other metrics include trip time and operational complexity. The study found that trajectories arriving at Saturn in the 2026–2027 time frame would suffer the effects of having Saturn near its greatest excursion away from Earth's ecliptic plane, which would require a significant out-of-ecliptic component to the final departure trajectory. This in turn would require more complex trajectories, with either more gravity-assist flybys of Venus and Earth (adding to total trip time) or multiple, sizeable DSMs requiring a large, expensive bipropellant propulsion system. Trajectories arriving at Saturn within a year or two of late 2033 would find Saturn near its ecliptic-plane crossing, reducing the out-of-ecliptic component of the departure trajectory and simplifying it, with fewer gravity-assists and/or greatly decreased delta-V requirements that would allow using much less-expensive monopropellant propulsion systems. Note that an exhaustive search for transfer trajectories has not been conducted, since it far exceeds the scope of the study. There might be trajectories that would perform better than the ones considered here, even outside of the near-2033 arrivals. Further development of this mission concept would involve a more thorough investigation of trajectory options and would consider a larger range of trajectory types. Also note that no trajectories involving Jupiter gravity-assists were considered. Two-year (approximately) windows for Jupiter gravity-assists to Saturn occur on 20-year centers. For example, the Cassini-Huygens mission made use of the gravity-assist in 1997. The next opportunity is in 2016–2017, too early for consideration under the first New Frontiers AO that is anticipated to be within this Decadal Survey's time frame (2013–2022). Following that, the window in 2036–2037 is far beyond that time frame.

# 3. Technical Overview

## Instrument Payload Description

The instrument payload would consist of two instruments: a mass spectrometer (MS) and an atmospheric structure instrument (ASI). The estimated capabilities and requirements for these proposed instruments are given in Tables 3-1 and 3-2, respectively. The MS would determine the noble gas abundances and isotopic ratios of H, C, N, O, and Ar in Saturn's atmosphere; these data would complement Cassini science findings. This MS would be a simpler version of (i.e., would measure fewer chemical species than) the mass spectrometer flown on the Galileo mission, and so would have a strong heritage. It would cover 2 amu (atomic mass unit) to 150 amu with an accuracy of 0.3 amu. The proposed MS would use 25 watts and have a mass of only 8 kg. It would be mounted near the apex of the probe with inlets exposed to a free stream of gas flow. After the probe heatshield deployment, the inlet break-off cap would be actuated (one-time pyrotechnic), and the MS would take data continuously during probe descent until the end of mission. The compressed data rate for the MS could be as low as 80 bps, but increased data rates could yield additional useful science information.

The ASI, based on the Galileo mission probe design, would consist of three sensors for measuring temperature, pressure, and density. Data from these sensors would also be used to properly contextualize other instrument measurements. The data streams from all three sensors would be controlled by a sensor-signal conditioning circuit board for further command and data handling (C&DH). The first sensor subsystem would be an inertial measurement unit (IMU), which would consist of a 3-axis accelerometer mounted at the center of mass of the probe to an accuracy of ±1 cm. It would be sampled at a rate of 5 Hz, and would be operational when the probe first enters the atmosphere at hypersonic speeds. The second sensor would be a thermocouple for temperature measurements and would be mounted on a fixed boom extending beyond the proposed probe boundary layer by at least 3 cm. It would be sampled at 2 Hz and would begin operating only at subsonic speeds. The third sensor would measure pressure, would be mounted on a fixed boom that extends beyond the probe boundary layer, and would provide data only at subsonic probe speeds. Overall, the ASI would use 5.7 watts and would have an estimated total mass of 1.2 kg (assuming the signal-conditioning board shares the probe avionics case). The uncompressed data rate could be up to 370 bps. These data could easily be compressed by a factor of 3 to 5.

The total data rate allotted for both proposed instruments would be 450 bps. The equivalent rate for the Galileo probe was less than 120 bps. At 450 bps, a full 70-minute descent mission would generate slightly less than 1.9 Mbits of data. Future studies would define the optimum allocation of data (and thus compression) for the MS, ASI, and any other instruments a PI might want to add.

The calibration and reduction of ASI and MS data are well understood and have been demonstrated in previous missions (e.g., Galileo and Pioneer Venus).

Mass and power parameters for the payload instruments are summarized in Table 3-3. The high level of heritage for these instruments prompts a lower contingency posture as shown in the table.

## *Table 3-1. Mass Spectrometer*

| Item | Value | Units |
|---|---|---|
| Type of instrument | MS | |
| Number of channels | 1.0 | |
| Size/dimensions (for each instrument) | 3000.0 | $cm^3$ |
| Instrument mass **without** contingency (CBE*) | 8.0 | kg |
| Instrument mass contingency | 15.0 | % |
| Instrument mass **with** contingency (CBE+Reserve) | 9.2 | kg |
| Instrument average payload power **without** contingency | 25.0 | W |
| Instrument average payload power contingency | 43.0 | % |
| Instrument average payload power **with** contingency | 35.8 | W |
| Instrument average science data rate^ **without** contingency | 0.1 | kbps |
| Instrument average science data rate^ contingency | 8.0 | % |
| Instrument average science data rate^ **with** contingency | 0.1 | kbps |
| Instrument fields of view (if appropriate) | N/A | degrees |
| Pointing requirements (knowledge) | N/A | degrees |
| Pointing requirements (control) | N/A | degrees |
| Pointing requirements (stability) | N/A | deg/s |

*CBE = Current best estimate

^Instrument data rate defined as science data rate prior to onboard processing

#Mass contingency based on Galileo heritage

## *Table 3-2. Atmospheric Structure Instrument (ASI)*

| Item | Value | Units |
|---|---|---|
| Type of instrument | ASI | |
| Number of channels | 3.0 | |
| Size/dimensions (for each instrument) | <~300.0 | $cm^3$ |
| Instrument mass **without** contingency (CBE*) | 1.2 | kg |
| Instrument mass contingency | 15.0 | % |
| Instrument mass **with** contingency (CBE+Reserve) | 1.3 | kg |
| Instrument average payload power **without** contingency | 5.7 | W |
| Instrument average payload power contingency | 43.0 | % |
| Instrument average payload power **with** contingency | 8.1 | W |
| Instrument average science data rate^ **without** contingency | <= 0.3 | kbps |
| Instrument average science data rate^ contingency | 8.0 | % |
| Instrument average science data rate^ **with** contingency | <= 0.4 | kbps |
| Instrument fields of view (if appropriate) | N/A | degrees |
| Pointing requirements (knowledge) | N/A | degrees |
| Pointing requirements (control) | N/A | degrees |
| Pointing requirements (stability) | N/A | deg/s |

*CBE = Current best estimate

^Instrument data rate defined as science data rate prior to onboard processing

## *Table 3-3. Payload Mass and Power*

| | Mass | | | Average Power | | |
|---|---|---|---|---|---|---|
| | CBE (kg) | % Cont. | MEV (kg) | CBE (W) | % Cont. (Carried at System Level) | MEV (W) |
| Mass Spectrometer | 8.0 | 15 | 9.2 | 25.0 | 43 | 35.8 |
| ASI | 1.2 | 15 | 1.3 | 5.6 | 43 | 8.1 |
| **Total Payload Mass** | **9.2** | **15** | **10.5** | **30.6** | **43** | **43.9** |

# Flight System

The proposed flight system design would be straightforward. The mass capability of the launch vehicle would provide a large mass margin, so no light-weighting would be needed. However, future reductions in power consumption might yield cost savings and risk reductions. No proposed subsystem would need space qualification. Accommodation for the science instruments would be similar to that of the Galileo probe. Mass and power properties for the carrier-relay spacecraft and probe are summarized in Tables 3-4, 3-5, and 3-6 with additional detail included in Appendix C. High-level characteristics of the carrier-relay spacecraft and probe are summarized in Tables 3-7 and 3-8, respectively.

The proposed flight system would be composed of two major flight elements: the carrier-relay spacecraft and the atmospheric probe. The proposed carrier-relay spacecraft would serve to transfer the probe from launch to an impact trajectory at Saturn and then would relay communications back to Earth until it lost the radio link with the probe. The carrier-relay spacecraft would finish its mission by playing back all probe data multiple times to ensure its reception on the ground.

The proposed carrier-relay spacecraft was designed to be low cost but to accommodate a long-duration mission to Saturn. Its subsystems would have redundancy in the most critical components only. The performance characteristics of both carrier-relay spacecraft and probe would be such that high-heritage hardware could be used to reduce both cost and mission risk. A more detailed description of the subsystems for the proposed carrier-relay spacecraft is given in the following pages.

## *ACS*

The proposed spacecraft would be 3-axis-stabilized. Precision inertial attitude determination would be achieved using redundant star trackers and IMUs, and Sun sensors would be used for safing. Attitude control would be provided by coupled thrusters. The attitude-control subsystem (ACS) design would use high-heritage hardware and algorithms.

## *Propulsion*

The proposed propulsion subsystem would be a monopropellant system using four 22-N main thrusters and eight 0.9-N ACS thrusters. A bipropellant system was considered, but the initial trade showed this option to be too expensive and ultimately unnecessary. The propulsion subsystem hardware would have high heritage, with no need for development or delta qualification.

## *Power*

The proposed power subsystem would consist of two ASRGs that would provide a total of 262 W of power 7 years after launch. There would be dual-string power electronics and two Li-ion batteries with a total capacity of 32 A-hr included for energy balancing. The second electronics string would be “cold,” i.e., it would not be brought on-line unless there were a fault in the primary string. The system would include a third battery to meet single-fault tolerance requirements.

The ASRGs would be used to power the flight system during cruise and to keep the batteries charged. During encounter and data downlink, the ASRGs and the batteries would be used to power the carrier-relay spacecraft. One side of an ASRG could fail, and power would still be sufficient to recharge batteries in quiet cruise. It is assumed that the ASRGs will be flight proven by the 2027 launch date. The remainder of the proposed power subsystem would consist of high-heritage components. The probe would be powered by battery alone.

### *Mechanical*

The proposed carrier-relay spacecraft would consist of a simple cubic frame that would house the central monopropellant fuel tank and avionics. The only mechanisms would be the spin table and probe-release mechanism. The mechanical design has high flight heritage.

The proposed probe would consist of the descent module, which would house avionics and instruments. The descent module would be embedded within the aeroshell, which would house the thermal shield and descent parachutes. The probe design is based on Galileo heritage.

### *Thermal*

Thermal protection for the proposed carrier-relay spacecraft would be accomplished through a capillary-pumped heat-pipe that would use the waste heat from the ASRG units to warm the avionics and propulsion. This heat-pipe would be supplemented by additional electric heaters and passive elements, such as multi-layer insulation (MLI) blankets and RHUs. The thermal design consists of high-flight-heritage components.

The proposed probe thermal-protection subsystem would consist of high-heritage passive thermal components, such as MLI blankets and RHUs.

### *Telecom*

The proposed carrier-relay spacecraft telecom subsystem would be a direct-to-Earth (DTE) link using standard redundant X-band design for deep-space missions. DTE communication would use a 1.5-m fixed high-gain antenna (HGA). X-band would satisfy the low data rates (1.6 kbps down, 1 kbps up). To reduce cost, the proposed telecom system would not include a Ka-band system. The relay link would use a patch-array medium-gain antenna (MGA) and the Electra proximity radio (UHF). The proposed patch-array MGA would require a straightforward engineering development, while the rest of the telecom system would be high heritage.

The probe telecom system would be a reduced-functionality Electra UHF radio transmitting from a patch antenna. The probe would require the use of the carrier-relay spacecraft for data relay to Earth.

### *C&DH and Flight Software*

The proposed command and data handling (C&DH) subsystem would consist of high-flight-heritage components and would be a fairly simple design. A trade study was performed to examine use of a simple, custom design versus a multimission architecture with flight software (FSW) build included. It was concluded that the simplicity of the custom designs of C&DH and FSW would make a custom-designed C&DH subsystem more cost-efficient for the same functionality than the more elaborate multimission architecture. The proposed carrier-relay spacecraft and probe would share the same C&DH, except that the carrier-relay spacecraft would have full block-redundancy, and the probe would be single-string. The baseline C&DH architecture would consist of a processor, memory board, telecom/probe interfaces, and chassis.

**Table 3-4. Carrier-Relay Spacecraft Mass**

| | Mass | | |
|---|---|---|---|
| | **CBE (kg)** | **% Cont.** | **MEV (kg)** |
| Structures and mechanisms | 106.7 | 23 | 138.7 |
| Thermal control | 32.6 | 27 | 41.4 |
| Propulsion (dry mass) | 43.4 | 7 | 46.3 |
| Attitude control | 9.9 | 10 | 10.9 |
| Command & data handling | 10.3 | 14 | 11.8 |
| Telecommunications | 28.3 | 14 | 32.2 |
| Power | 86.8 | 30 | 112.8 |
| Carrier-Relay Spacecraft Systems contingency | — | 13 | 64.5 |
| Entry Probe (including instruments) | 151.3 | 30 | 216.4 |
| **Total Carrier-Relay Spacecraft Dry Mass** | **469.3** | **30** | **675** |

## *Table 3-5. Carrier-Relay Spacecraft Power*

| | Mode 1 Pwr (W) Launch | Mode 2 Pwr (W) Cruise w/ Telecom | Mode 3 Pwr (W) Cruise w/o Telecom | Mode 4 Pwr (W) Instr Ckout during Cruise | Mode 5 Pwr (W) Main Engine Mnvrs | Mode 6 Pwr (W) Probe Rels | Mode 7 Pwr (W) Data Acq from Probe | Mode 8 Pwr (W) Primary Data D/L | Mode 9 Pwr (W) Eclipse | Mode 10 Pwr (W) Safe |
|---|---|---|---|---|---|---|---|---|---|---|
| **Power Mode Duration (hrs)** | **3** | **8** | **24** | **0.2** | **1** | **1** | **1.5** | **1** | **1** | **24** |
| Instruments | 0 | 0 | 0 | 31 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Spacecraft Bus** | | | | | | | | | | |
| Attitude control | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 |
| Command & data handling | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 |
| Power | 21 | 26 | 21 | 31 | 26 | 22 | 22 | 26 | 21 | 22 |
| Propulsion | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 |
| Telecommunications | 12 | 97 | 12 | 12 | 97 | 30 | 30 | 97 | 12 | 33 |
| Thermal control | 11 | 11 | 11 | 11 | 8 | 11 | 11 | 11 | 11 | 11 |
| **Bus Total** | 122 | 211 | 122 | 131 | 208 | 141 | 141 | 211 | 122 | 144 |
| Flight System Total | 122 | 211 | 122 | 162 | 208 | 141 | 141 | 211 | 122 | 144 |
| System contingency | 53 | 91 | 53 | 70 | 90 | 61 | 61 | 91 | 53 | 62 |
| **Flight System w/ Contingency** | **175** | **302** | **175** | **232** | **298** | **202** | **202** | **302** | **175** | **206** |

## *Table 3-6. Probe Power*

| | Mode 1 Pwr (W) Probe Cruise (Standby) | Mode 2 Pwr (W) Preentry Wake-Up | Mode 3 Pwr (W) Aeroshell Entry | Mode 4 Pwr (W) Probe Parachute Deployment | Mode 5 Pwr (W) Probe Descent |
|---|---|---|---|---|---|
| **Power Mode Duration (hrs)** | **24** | **2** | **0.1** | **0.0** | **1.2** |
| Instruments | 0 | 10 | 16 | 31 | 31 |
| Attitude control | 0 | 0 | 0 | 0 | 0 |
| Command & data handling | 27 | 27 | 27 | 27 | 27 |
| Power | 11 | 14 | 15 | 15 | 15 |
| Telecommunications | 0 | 65 | 65 | 65 | 65 |
| Thermal control | 3 | 3 | 3 | 3 | 3 |
| **Total** | 41 | 120 | 126 | 142 | 142 |
| System contingency | 18 | 52 | 54 | 61 | 61 |
| **Probe with Contingency** | **59** | **172** | **180** | **203** | **203** |

## *Table 3-7. Carrier-Relay Spacecraft Characteristics*

| Flight System Element Parameters (as appropriate) | Value/ Summary, units |
|---|---|
| **General** | |
| Mission life, months | 82 |
| **Structure** | |
| Structures material | Aluminum/titanium/ composite |
| Number of articulated structures | 0 |
| Number of deployed structures | 1 |
| **Thermal Control** | |
| Type of thermal control used | Capillary-pumped heat pipe (closed-loop w/ ASRG heat) |
| **Propulsion** | |
| Estimated delta-V budget, m/s | 675 |
| Propulsion type(s) and associated propellant(s)/oxidizer(s) | Blowdown hydrazine monopropellant |
| Number of thrusters and tanks | Four 22-N engines<br>Eight 0.9-N engines<br>Single fuel tank |
| Specific impulse of each propulsion mode, seconds | 230 |
| **Attitude Control** | |
| Control method | 3-axis |
| Control reference | Inertial |
| Attitude control capability, degrees | 0.25 |
| Attitude knowledge limit, degrees | 0.125 |
| Agility requirements | N/A |
| Articulation/#–axes | N/A |
| Sensor and actuator information | Star tracker, IMU, Sun sensors, 0.9-N thrusters |
| **Command & Data Handling** | |
| Carrier-relay spacecraft housekeeping data rate, kbps | 0.0005 |
| Data storage capacity, Mbits | 384 |
| Maximum storage record rate, kbps | 2 |
| Maximum storage playback rate, kbps | 2 |
| **Power** | |
| Type of power source | Radioisotope (ASRG) |
| Number of power sources | 2 |
| Expected power generation at beginning of life (BOL) and end of life (EOL), watts | BOL = 280<br>EOL = 264 |
| On-orbit average power consumption, watts | 175 |
| Battery type | Li-ion |
| Battery storage capacity, amp-hours | 32 |

**Table 3-8. Probe Characteristics**

| Flight System Element Parameters (as appropriate) | Value/ Summary, units |
|---|---|
| **General** | |
| Design Life, months | 82 (<1 month active, 81 months dormant) |
| **Structure** | |
| Structures material | Aluminum/titanium/ composite |
| Number of articulated structures | 0 |
| Number of deployed structures | 1 |
| Aeroshell diameter, m (probe) | ~1 |
| **Thermal Control** | |
| Type of thermal control used | Passive |
| **Command & Data Handling** | |
| Probe housekeeping data rate, kbps | 0.0005 |
| Data storage capacity, Mbits | 384 |
| Maximum storage record rate, kbps | 2 |
| Maximum storage playback rate, kbps | 2 |
| **Power** | |
| Type of power source | Primary battery |
| Number of active power sources | 2 |
| Number of on-orbit spare power sources | 1 |
| Expected power generation at beginning of life (BOL) | BOL = 203 |
| On-orbit average power consumption, watts | 185 |
| Battery type | Li-SOCl2 |
| Battery storage capacity, amp-hours | 24 |

# Concept of Operations and Mission Design

## *Mission Design*

The proposed trajectory would have a relatively brief transit time to Saturn (under 7 years), arriving when Saturn is close to the ecliptic plane, thus minimizing postlaunch delta-V. Launch to a C3 of 49 $km^2/s^2$ on August 30, 2027 would yield a 3-year Earth-return trajectory, with a DSM at aphelion that would set up the Earth gravity-assist. The Atlas V 401 launch capacity to that C3 is 1135 kg.

The proposed trajectory is illustrated in Figure 3-1. The timeline and delta-V budget are shown in Table 3-9 for an August 30, 2027 launch and June 22, 2034 arrival.

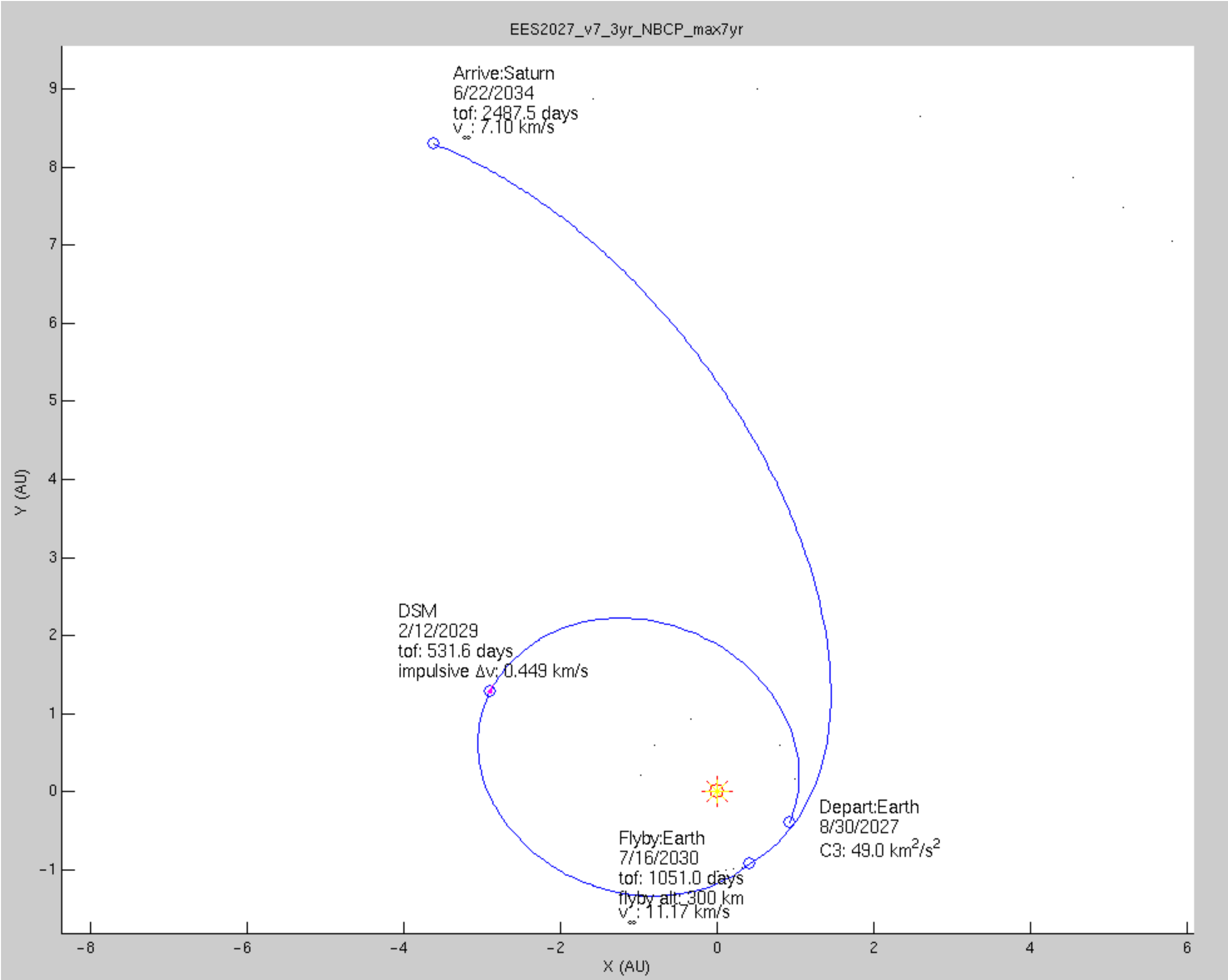


***Figure 3-1. Baseline Trajectory***

***Table 3-9. Timeline and Delta-V Budget***

| Event | L + days | ΔV (m/s) |
|---|---|---|
| Launch | 0 | 15 (TCM-1) |
| Deep-space maneuver | 531 | 450 |
| Earth flyby | 1051 | 30 |
| Approach navigation | ~2400 | 5 |
| Probe release | 2467 (Arrival –30 days) | 55 |
| Unallocated margin | | 50 |
| **Total** | | **590** |

While this study included some trajectory trades, the proposed baseline certainly does not represent an optimized trajectory. With a single Earth gravity-assist, launch opportunities to fly similar missions would repeat annually, but when Saturn is significantly out of the ecliptic plane there could be significant increases in C3 and delta-V requirements. Building margin into the design to accommodate that possibility is beyond the scope of this study. Instead, when Saturn is significantly out of the ecliptic plane, other trajectory types would be more appropriate. While this might change the proposed probe entry latitude and certain details of the approach trajectory, it would not significantly affect the probe release, entry, or relay support strategies.

The probe release would occur at 30 days prior to entry; the carrier-relay spacecraft would then perform a 55-m/s divert maneuver to place itself on a relay-supporting flyby trajectory. No mission requirement drives the 30-day release; it was chosen as a “stressing case” and could be significantly longer by choice. For example, the Galileo probe release occurred 5 months before entry. Since the proposed carrier-relay spacecraft divert delta-V is roughly inversely proportional to the time between the divert maneuver and encounter, an earlier release could save propulsive delta-V. Table 3-10 summarizes the proposed probe/carrier-relay spacecraft entry and flyby characteristics. Figure 3-2 shows the relay geometry and trajectory. Table 3-11 provides parameters for key elements of the mission design.

***Table 3-10. Representative Trajectory Characteristics***

| | |
|---|---|
| Carrier-relay spacecraft divert | −30 days |
| Probe entry latitude | −22.4° |
| Probe entry velocity | 26.9 km/s |
| Probe entry flight path angle | −8° (atmosphere-relative) |
| Probe ring-plane crossing | 150,000 km, within gap between F ring and G ring (F/G) |
| Carrier-relay spacecraft periapse altitude | 49,500 km |
| Carrier-relay spacecraft ring-plane crossing | 147,000 km (F/G gap) incoming, 538,000 km outgoing |

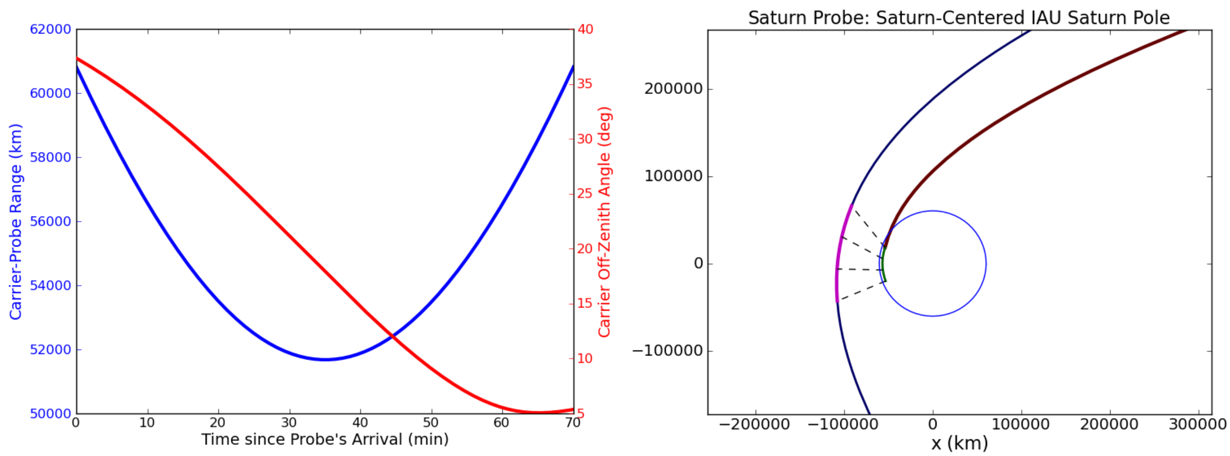


***Figure 3-2. Relay Geometry and Trajectory***

## *Table 3-11. Mission Design*

| Parameter | Value | Units |
|---|---|---|
| Orbit parameters (apogee, perigee, inclination, etc.) | See trajectory plot in Figure 3-1 | — |
| Mission lifetime | 82 | mos |
| Maximum eclipse period | 60 (assumed) | min |
| Launch site | KSC | |
| Total carrier-relay spacecraft mass **with** contingency (no instruments) | 458.6 | kg |
| Total probe mass **with** contingency (includes instruments) | 216.4 | kg |
| Propellant mass **without** contingency | 251.7 | kg |
| Propellant contingency | 7 | % |
| Propellant mass **with** contingency | 269.3 | kg |
| Launch adapter mass (S/C side) **with** contingency | 12.8 | kg |
| Total launch mass | 957.1 | kg |
| Launch vehicle | Option 1 | Type |
| Launch vehicle lift capability | 1135 | kg |
| Launch vehicle mass margin | 177.9 | kg |
| Launch vehicle mass margin (%) | 16 | % |

## *Ground Systems*

From a ground systems perspective, this mission would be simple on nearly every level. The one area of potential operational complexity is the proposed probe deployment and relay of communications from the probe to the carrier-relay spacecraft. There would be no unusual viewing or pointing constraints.

The sequence on the probe would be developed during cruise, uplinked to the probe, and would require no interaction from the ground. The proposed DSN contact schedule would provide for two staffing levels. The flight team would need to be staffed at normal levels only from launch to the first Earth flyby. Staffing could be reduced to quiet levels after Earth flyby and during the cruise to Saturn. Cruise staffing would be comparable to other New Frontiers missions. The science phase and data volumes for this mission would both be very small. As a result, science planning and sequencing could be scaled back for the proposed mission, and science requirements for DSN passes would be limited. The study identified no unusual constraints or requirements on tracking or ground support.

The proposed mission DSN tracking is shown in Table 3-12. The most critical aspects of the mission would occur during the deep-space maneuver, Earth flyby, probe release, and data downlink. The mission study assumed an 8-hour DSN track for every communication link opportunity.

Telecommunications information for the proposed mission operations and ground data systems is given in Table 3-13. Data would be transmitted from the carrier-relay spacecraft to the 34-m DSN stations. An average of 5 kilobytes/day would be downlinked during the spacecraft transit to Saturn, with increased volume during critical activities like the DSM, Earth flyby, and probe release. After the probe has relayed its data to the carrier-relay spacecraft, there would be a brief period of continuous tracking of the spacecraft as it sends back multiple sets of data. During this time the spacecraft would be downlinking at 1.6 kbps in intervals determined by the recharge rate of the batteries. With a total probe data volume of only ~2 Mbits, downlink of one entire copy would take slightly over 20 minutes, so a single 8-hour DSN pass could relay more than 20 copies. Spacecraft uplinks would be essentially driven by the number of tracks per week, resulting in an average of one uplink per week over the course of the mission (with the exception that there would be increased uplinks before and after critical events).

### *Table 3-12. DSN Tracking*

| Support Period | | Hours per Track (hours) | No. Tracks per Wk (# tracks) | No. Weeks Reqd (# weeks) | Total Time Reqd (hours) |
|---|---|---|---|---|---|
| No (#) | Name (description) | | | | |
| 1 | Launch and Operations | 8 | 21.0 | 2.0 | 378.0 |
| 2 | Launch and Operations | 8 | 14.0 | 2.0 | 252.0 |
| 3 | Cruise to Deep Space Maneuver-Cruise | 8 | 1.0 | 58.0 | 522.0 |
| 4 | Cruise to Deep Space Maneuver-TCMs | 8 | 7.0 | 1.0 | 63.0 |
| 5 | Deep Space Maneuver-Cruise | 8 | 1.0 | 17.0 | 153.0 |
| 6 | Cruise to Earth Flyby-Cruise | 8 | 1.0 | 56.0 | 504.0 |
| 7 | Cruise to Earth Flyby-TCMs | 8 | 7.0 | 1.0 | 63.0 |
| 8 | Earth Flyby- Cruise | 8 | 1.0 | 15.0 | 135.0 |
| 9 | Earth Flyby-TCMs | 8 | 7.0 | 2.0 | 126.0 |
| 10 | Cruise to Saturn-Cruise | 8 | 0.3 | 175.0 | 393.8 |
| 11 | Cruise to Saturn-TCMs | 8 | 7.0 | 3.0 | 189.0 |
| 12 | Cruise to Saturn-annual health checks | 8 | 7.0 | 2.0 | 126.0 |
| 13 | Probe Deploy/Encounter-init encounter | 8 | 7.0 | 19.0 | 1197.0 |
| 14 | Probe Deploy/Encounter-extended enctr | 8 | 21.0 | 4.0 | 756.0 |

### *Table 3-13. Mission Operations and Ground Data Systems*

| Downlink Information | Values |
|---|---|
| Number of contacts per week | Table 3-12 |
| Number of weeks for mission phase, weeks | Table 3-12 |
| Downlink frequency band, GHz | 8.40 |
| Telemetry data rate(s), kbps | 1.6 |
| Transmitting antenna type(s) and gain(s), dBi | HGA<br>MGA<br>2x LGA |
| Transmitter peak input power, watts | 97 W |
| Downlink receiving antenna gain, dBi | DSN 34-m |
| Transmitting power amplifier output, watts | 35 W |
| **Uplink Information** | |
| Uplink frequency band, GHz | 7.15 |
| Telecommand data rate, kbps | >1 |
| Receiving antenna type(s) and gain(s), dBi | Same as D/L |

# Planetary Protection

The simplicity of the proposed mission's operations at Saturn provide for significant flexibility in addressing planetary protection issues. NASA's Planetary Protection Officer has not yet categorized Saturn, but compares it to Jupiter. The planetary protection requirement for Titan and Enceladus, which are within the Saturn system, is that no mission should exceed a probability of $10^4$ of introducing one or more viable organisms from Earth into liquid water at either location.

This mission concept's nominal plan for spacecraft disposal does not involve any categorized location. Disposal of the Saturn atmospheric entry probe would be, of course, in Saturn's atmosphere, where the extremely high temperatures at depth would vaporize even the refractory materials in the probe. Disposal of the carrier-relay spacecraft would be to a solar system escape trajectory, which would occur naturally after the carrier-relay spacecraft's Saturn flyby. Since Jupiter was the ultimate disposal site for the Galileo spacecraft and its probe, and Saturn has been accepted as the disposal site for the Cassini spacecraft, disposal of the Saturn probe in Saturn's atmosphere should also be acceptable.

Titan and Enceladus enter into only off-nominal scenarios, in which for some reason the ability to control the spacecraft's trajectory might be lost. Rigorous analyses of planetary protection probabilities have not been conducted yet for this proposed mission, but simple mathematics (area ratios with equally distributed trajectory probabilities) show that the probability of accidentally colliding with Titan is less than $10^{-5}$, and for Enceladus less than $10^{-7}$. More detailed analyses could show that by using actual trajectory probability distributions, those collision probability estimates would decrease by orders of magnitude, with no adjustments made to the trajectory. Then, by adjusting the Saturn arrival date by a few days, those probabilities could be further reduced with no significant impact on the science mission.

# Risk List

In the study, four medium (yellow) risks and three low (green) risks were identified, including both mission risks and implementation risks. The definitions used to score the risks are given in Table 3-14. Table 3-15 shows the seven risks identified for the proposed mission. In addition to these mission-specific risks, there is a programmatic risk of not having sufficient plutonium to fuel the ASRGs.

***Table 3-14. Definition of Risk Levels***

| Levels | Mission Risk | | Implementation Risk | |
|---|---|---|---|---|
| | **Impact** | **Likelihood of Occurrence** | **Impact** | **Likelihood of Occurrence** |
| 5 | Mission failure | Very high, >25% | Consequence or occurrence is not repairable without engineering (would require >100% of margin) | Very high, ~70% |
| 4 | Significant reduction in mission return (~25% of mission return still available) | High, ~25% | All engineering resources would be consumed (100% of margin consumed) | High, ~50% |
| 3 | Moderate reduction in mission return (~50% of mission return still available) | Moderate, ~10% | Significant consumption of engineering resources (~50% of margin consumed) | Moderate, ~30% |
| 2 | Small reduction in mission return (~80% of mission return still available) | Low, ~5% | Small consumption of engineering resources (~10% of margin consumed) | Low, ~10% |
| 1 | Minimal (or no) impact to mission (~95% of mission return still available) | Very low, ~1% | Minimal consumption of engineering resources (~1% of margin consumed) | Very low, ~1% |

## *Table 3-15. Risk List for the Proposed Mission*

| Risk | Level | Description | Impact | Likelihood | Mitigation |
|---|---|---|---|---|---|
| **All Options** | | | | | |
| Critical relay link between probe and carrier-relay spacecraft | M | Failure of relay link. | 5 | 1 | Redundant telecom relay system in carrier-relay spacecraft |
| Availability of TPS materials for probe | M | Programmatic risk that carbon-phenolic production ceases. Currently there are multiple vendors with a large production rate, and adequate testing facilities. | 5 | 1 | Consider multiple potential vendors |
| Probe deployment is a critical event | M | Probe fails to deploy | 5 | 1 | Redundant deployment mechanisms |
| Failure of an ASRG | M | Failure of an entire ASRG would result in mission failure. Design would be robust to failure of half an ASRG. | 5 | 1 | Include a spare ASRG in design |
| Mission duration | L | Reliability is more difficult to achieve for longer missions. | 5 | 3 | Standard long-life mission design principles |
| Entry site not characterized | L | No images, spectra, or thermal measurements are planned for entry site. Lack of context might make it difficult to interpret data. | 2 | 2 | Ground-based imaging of entry site |
| Descent into anomalous area | L | Probe might descend in region that is not representative of the average Saturnian atmosphere. This could compromise compositional goals, but unlikely to affect measurement of isotopic ratios (based on Galileo experience the probability is 1). | 1 | 3 | Science investigations exclude affected measurements |

# 4. Development Schedule and Schedule Constraints

## High-Level Mission Schedule

This proposed Saturn probe mission concept uses a 64-month development project (see “Development Schedule and Constraints”), 81 months of postlaunch flight operations, and 6 months of data analysis after termination of flight operations. Figure 4-1 shows a feasible high-level schedule for the proposed mission. Table 4-1 provides predicted durations of key phases in such a schedule. Phase A of a development project using the particular trajectory selected would begin in mid-2022, leading to launch on August 30, 2027, with commissioning at the end of Phase D one month later. On February 12, 2029, a DSM would set up the Earth-gravity-assist flyby of July 16, 2030 that would send the spacecraft to a Saturn arrival on June 22, 2034. About 8 months before arrival, preparations for probe release and entry would begin. Probe release would occur one month before arrival, and the carrier-relay spacecraft divert maneuver would follow immediately after release.

Spacecraft disposal would require no expenditure of resources. Since the proposed probe descent mission naturally would result in the destruction of the probe minutes after its prime mission would be over, and there would be no science instruments on the proposed carrier-relay spacecraft, there would be no useful option for an extended mission. Carrier-relay spacecraft disposal would be by means of a solar system escape trajectory, which would be the carrier-relay spacecraft’s natural trajectory after the Saturn flyby.

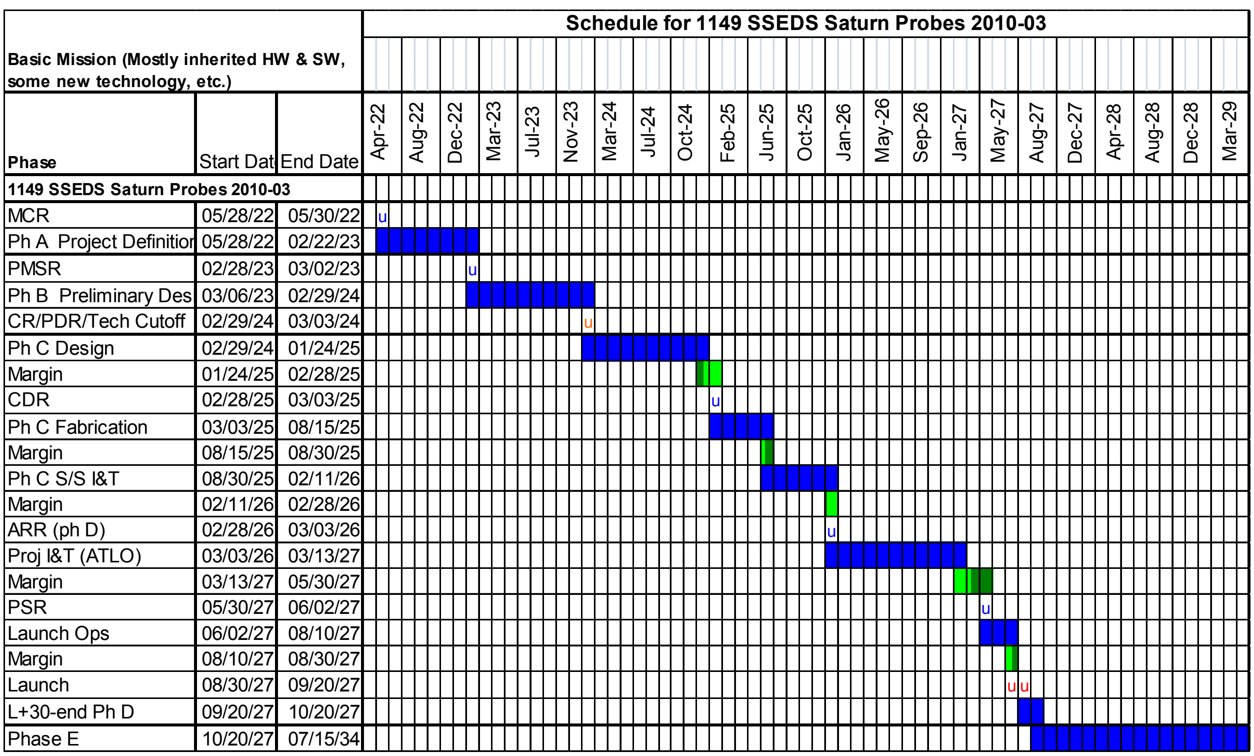


***Figure 4-1. Mission Schedule***

*Table 4-1. Key Phase Durations for Feasible Mission Schedule*

| Project Phase | Duration (Months) |
|---|---|
| Phase A—Conceptual Design | 9 |
| Phase B—Preliminary Design | 12 |
| Phase C—Detailed Design | 24 |
| Phase D—Integration & Test | 19 (carrier-relay spacecraft)<br>6 (probe, delivered to System I&T) |
| Phase E—Primary Mission Operations | 81 |
| Phase F—Data Analysis | 6 |
| Start of Phase B to PDR | 12 |
| Start of Phase B to CDR | 24 |
| Start of Phase B to delivery of instruments to probe | 36 |
| Start of Phase B to delivery of carrier-relay spacecraft | 36 |
| Start of Phase B to delivery of probe | 36 |
| System-level Integration & Test | 15 |
| Project total funded schedule reserve | 5.5 |
| Total development time phases B–D | 55 |

# Technology Development Plan

This proposed mission would require no new technology development. Development of the ASRG is assumed to be completed by a separate NASA development program.

# Development Schedule and Constraints

This proposed mission concept involves two elements—a carrier-relay spacecraft and an instrumented atmospheric probe. The mission complexity would be similar to that of a Discovery mission, except that the mission would go to the outer solar system. The reference schedules used in this report are derived from the JPL mission schedule database, which goes back to Voyager.

The schedule would be based on a typical AO-driven mission. The assumption for this schedule is that there would be no new technology development for the mission. Though some heritage could be claimed from the Galileo mission, a probe has not previously been designed for Saturn atmosphere, so there could potentially be additional complexity and new engineering beyond a basic, fully inherited mission. At this level of detail, development time and expected delivery dates for instruments are not determined: The assumption is that the instruments would be delivered to probe integration and test (I&T). The probe would then be delivered to project system I&T for integration onto the carrier-relay spacecraft.

The instruments would be integrated into the probe; then the probe would be integrated onto the carrier-relay spacecraft. Probe–carrier-relay spacecraft integration would happen fairly late in the project system I&T process, so much of the I&T efforts could be performed in parallel.

The proposed mission would have a robust launch window duration. There would be a similar launch opportunity in 2026. A launch slip past 2027 would most likely require a different type of trajectory, with unknown effects on the project schedule.

# 5. Mission Life-Cycle Cost

## Costing Methodology and Basis of Estimate

JPL's Team X generates a most likely cost for the JPL standard work breakdown structure (WBS) that may be tailored to meet the specific needs of the mission being evaluated. These estimates are done at WBS levels 2 and 3 and are based on various cost-estimating techniques. These estimating methods, not exclusive to each other and often combined, consist of grassroots techniques, parametric models, and analogies. The models for each station at Team X (a total of about 33 models) have been built and validated, and each model is owned by the responsible line organization. The models are under configuration-management control and are used in an integrated and concurrent environment, so the design and cost parameters are linked. These models are customized and calibrated using actual experience from completed JPL planetary missions. When these models have been applied, the resultant total estimated Team X mission costs have been consistent with mission actual costs.

The cost-estimation process begins with the customer providing the base information for the cost-estimating models and defining the mission characteristics, such as

- Mission architecture
- Payload description
- Master equipment list (MEL) with heritage assumptions
- Functional block diagrams
- Spacecraft/payload resources (mass [kg], power [W], etc.)
- Phase A–F schedule
- Programmatic requirements
- Model-specific inputs

Most of the above inputs are provided by the customer through a Technical Data Package.

For Decadal Survey missions, the following specific guidelines were also followed:

- Reserves were set at 50% for phases A–D
- Reserves were set at 25% for Phase E.
- Costs for the ASRGs were provided by the customer.

The cost for the launch vehicle was taken from the Decadal Survey ground rules.

## Cost Estimates

Tables 5-1 and 5-2 show costs and workforce by phase for all science activities for the proposed mission. The Total Mission Cost Funding Profile is shown in Table 5-3.

***Table 5-1. Costs by Phase***

| | **A $k** | **B $k** | **C $k** | **D $k** | **E $k** | **F $k** | **Total $k** |
|---|---|---|---|---|---|---|---|
| Science | 200.1 | 1175.3 | 4933.6 | 2286.7 | 7125.1 | 3240.0 | **18960.9** |
| Science Management | 95.3 | 703.6 | 1361.7 | 1078.0 | 2254.2 | 1184.1 | 6677.0 |
| Science Office | 95.3 | 703.6 | 1361.7 | 1078.0 | 2254.2 | 1184.1 | 6677.0 |
| Science Implementation | 104.8 | 471.7 | 3571.9 | 1208.7 | 4870.9 | 2055.9 | 12283.9 |
| Participating Scientists | 36.2 | 48.2 | 310.8 | 273.4 | 594.3 | 735.3 | 1998.1 |
| Teams Summary | 68.6 | 423.5 | 3261.1 | 935.3 | 4276.5 | 1320.7 | 10285.7 |

***Table 5-2. Workforce by Phase***

| | **A W-M** | **B W-M** | **C W-M** | **D W-M** | **E W-M** | **F W-M** | **Total W-M** | **Total W-Y** |
|---|---|---|---|---|---|---|---|---|
| Science | **5.0** | **31.2** | **175.1** | **70.5** | **216.9** | **115.8** | **614.4** | **51.2** |
| Science Management | 2.0 | 13.7 | 29.3 | 23.2 | 17.1 | 32.7 | 118.0 | 9.8 |
| Science Office | 2.0 | 13.7 | 29.3 | 23.2 | 17.1 | 32.7 | 118.0 | 9.8 |
| Science Implementation | 3.0 | 17.4 | 145.8 | 47.3 | 199.8 | 83.1 | 496.4 | 41.4 |
| Participating Scientists | 1.4 | 1.8 | 11.9 | 10.5 | 23.7 | 29.4 | 78.6 | 6.6 |
| Teams Summary | 1.6 | 15.6 | 134.0 | 36.8 | 176.1 | 53.6 | 417.8 | 34.8 |

# Potential Cost-Saving Options

Many cost-saving avenues were explored for this proposed mission concept, so few additional ones remain unused, but some of them could be significant. Examples of remaining avenues include the following:

- If the Falcon 9 Heavy were to become available in this time frame, cost savings might be achieved by use of that launch vehicle.
- Cost savings might be realized by having an industry build of the carrier-relay spacecraft.

## *Table 5-3. Total Mission Cost Funding Profile*

(FY costs[1] in Real Year Dollars, Totals in Real Year and 2015 Dollars)

| Item | FY2022 | FY2023 | FY2024 | FY2025 | FY2026 | FY2027 | FY2028 | FY2029 | FY2030 | FY2031 | FY2032 | FY2033 | FY2034 | Total (Real Yr.) | Total (FY 2015) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Cost | | | | | | | | | | | | | | | |
| Phase A Concept Study (included below) | 4.2 | 5.3 | | | | | | | | | | | | 9.5 | 7.7 |
| Technology Development (w/ Reserves) | | | | | | | | | | | | | | 0.0 | 0.0 |
| | Phase A-D | | | | | | | | | | | | | | |
| Mission PM/SE/MA | 0.4 | 5.9 | 19.3 | 26.8 | 27.6 | 28.1 | | | | | | | | 108.2 | 81.9 |
| Pre-launch Science | 0.0 | 0.6 | 2.0 | 2.8 | 2.9 | 3.0 | | | | | | | | 11.4 | 8.6 |
| Instrument PM/SE | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | | | | | | | | 0.0 | 0.0 |
| Probe Payload | 0.2 | 2.3 | 7.6 | 10.5 | 10.8 | 11.0 | | | | | | | | 42.4 | 32.1 |
| Flight PM/SE | 0.2 | 3.2 | 10.4 | 14.5 | 14.9 | 15.2 | | | | | | | | 58.6 | 44.3 |
| CRSC | 1.1 | 14.6 | 47.5 | 66.1 | 67.9 | 69.3 | | | | | | | | 266.4 | 201.7 |
| Probe | 0.2 | 2.4 | 8.0 | 11.1 | 11.4 | 11.6 | | | | | | | | 44.7 | 33.8 |
| Aeroshell | 0.3 | 4.4 | 14.2 | 19.8 | 20.3 | 20.7 | | | | | | | | 79.8 | 60.4 |
| MSI&T | 0.2 | 2.8 | 9.2 | 12.7 | 13.1 | 13.4 | | | | | | | | 51.4 | 38.9 |
| Ground Data System Dev | 0.1 | 1.3 | 4.1 | 5.7 | 5.8 | 6.0 | | | | | | | | 22.9 | 17.4 |
| Navigation & Mission Design | 0.0 | 0.6 | 2.0 | 2.8 | 2.9 | 2.9 | | | | | | | | 11.3 | 8.5 |
| Total Dev. w/o Reserves | 2.9 | 38.2 | 124.3 | 172.9 | 177.6 | 181.2 | | | | | | | | 697.0 | 527.6 |
| Development Reserves | 1.3 | 17.6 | 57.3 | 79.8 | 81.9 | 83.6 | | | | | | | | 321.6 | 243.4 |
| **Total A-D Development Cost** | 4.2 | 55.8 | 181.6 | 252.7 | 259.5 | 264.9 | | | | | | | | 1018.7 | 771.0 |
| Launch services | | | 40.4 | 70.3 | 72.2 | 73.7 | | | | | | | | 256.6 | 193.0 |
| | | | | | | | Phase E | | | | | | | | |
| Phase E Science | | | | | | | 2.1 | 2.2 | 2.3 | 2.3 | 2.4 | 2.5 | 2.1 | 15.9 | 10.4 |
| Other Phase E Cost | | | | | | | 12.3 | 12.6 | 13.0 | 13.3 | 13.7 | 14.1 | 11.9 | 90.9 | 59.4 |
| Phase E Reserves | | | | | | | 3.5 | 3.6 | 3.7 | 3.8 | 3.9 | 4.0 | 3.4 | 25.7 | 16.8 |
| **Total Phase E Cost** | | | | | | | 17.9 | 18.4 | 18.9 | 19.4 | 19.9 | 20.5 | 17.4 | 132.4 | 86.5 |
| Program Cost | 4.2 | 55.8 | 222.1 | 323.0 | 331.7 | 338.6 | 17.9 | 18.4 | 18.9 | 19.4 | 19.9 | 20.5 | 17.4 | 1407.7 | 1050.5 |
| Education/Outreach | | 0.1 | 0.4 | 0.5 | 0.5 | 0.5 | 0.9 | 1.0 | 1.0 | 1.0 | 1.0 | 1.1 | 0.9 | 8.8 | 6.0 |
| Other | | | | | | | | | | | | | | 0.0 | 0.0 |
| **Total NASA Cost** | **$4.2** | **$55.9** | **$222.4** | **$323.5** | **$332.2** | **$339.1** | **$18.8** | **$19.4** | **$19.9** | **$20.4** | **$21.0** | **$21.5** | **$18.3** | **$1,416.5** | **$1,056.5** |
| | | | | | | | | | | | | **Total Mission Cost (FY2015)** | | | **$1,056.5** |

[1] Costs include all costs including any fee

[2] MSI&T—Mission System Integration and Test <u>and</u> preparation for operations

# Appendix A. Acronyms

| | |
|---|---|
| ABSL | ABSL Power Solutions (company name) |
| ACS | attitude-control subsystem |
| ASI | atmospheric structure instrument |
| ASRG | Advanced Stirling Radioisotope Generator |
| ATLO | assembly, test, and launch operations |
| BOL | beginning of life |
| BRE | Broad Reach Engineering |
| BTE | bench test equipment |
| BWG | beam waveguide |
| C&DH | command and data handling |
| CBE | current best estimate |
| CDR | Critical Design Review |
| CML | concept maturity level |
| CPU | central processing unit |
| CRSC | carrier-relay spacecraft |
| D/L | downlink |
| DB | database |
| DSN | Deep Space Network |
| DSM | deep-space maneuver |
| DTE | direct to Earth |
| EEIS | end-to-end information system |
| EM | engineering model |
| EOL | end of life |
| ETR | Eastern Test Range |
| F/G | gap between F ring and G ring |
| FER | frame error rate |
| FPGA | field-programmable gate array |
| FSW | flight software |
| FTE | full-time equivalent |
| FY | fiscal year |
| GDS | ground data system |
| GFE | Government-furnished equipment |
| GNC (G&NC) | guidance and navigation control |
| GSE | ground-support equipment |
| H/W | hardware |
| HGA | high-gain antenna |
| I&T | integration and test |
| IMU | inertial measurement unit |
| JPL | Jet Propulsion Laboratory |
| LEOP | launch and early operations phase |
| LGA | low-gain antenna |
| LILT | low-intensity, low-temperature |
| LV | launch vehicle |
| MEL | master equipment list |
| MEL | mass element list |
| MEV | maximum expected value |
| MGA | medium-gain antenna |
| MLI | multilayer insulation |
| MOS | mission operations system |
| MS | mass spectrometer |
| MSA | mission support area |
| NDA | nondisclosure agreement |
| NICM | NASA Instrument Cost Model |
| NRC | National Research Council |
| NRE | nonrecurring engineering |
| PSDS Survey | Planetary Sciences Decadal |
| RCS | reaction-control subsystem |
| RHU | radioisotope heater unit |
| ROM | rough order of magnitude |
| RPS | radioisotope power source |
| SCIP | solar composition icy planetesimal |
| SDST | small deep-space transponder |
| SSR | solid-state recorder |
| SW | software |
| TCM | trajectory-correction maneuver |

| | |
|---|---|
| TRL | technology readiness level |
| TTC&M | tracking, telemetry, command, and monitoring |
| TTC | telemetry tracking and command |
| TWTA | traveling-wave tube amplifier |
| U/L | uplink |
| V&V | verification and validation |
| WBS | work breakdown structure |

# Appendix B. References

[1] Jet Propulsion Laboratory, "Saturn Atmospheric Entry Probe Trade Study Report," May 2010.

[2] Atkinson, D.H., et al., "Entry Probe Missions to the Giant Planets," Decadal White Papers. Filename Atkinson_Giant_Planets_Entry_Probe.pds, 2009. Available online: http://www.mrc.uidaho.edu/~atkinson/Papers/Publ/OutrPlanPrbsWhiteppr_Final.pdf.

[3] Guillot, T., and R. Hueso, "The composition of Jupiter: sign of a (relatively) late formation in a chemically evolved protosolar disc," Monthly Notices of the Royal Astronomical Society: Letters, Volume 367, Issue 1, pp. L47–L51, 2006.

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[5] Fletcher, L.N., G. Orton, N. Teanby, and P. Irwin, "Phosphine on Jupiter and Saturn from Cassini/CIRS," *Icarus* 202 (2), 543–564, 2009.

[6] Grevesse, N., M. Asplund, and A. Sauval, "The Solar Chemical Composition," *Space Sci. Rev.* 130 (1), 105–114, 2007.

[7] Jet Propulsion Laboratory Advanced Projects Design Team (Team X) Study 976, "Saturn Probe Follow-On," delivered to Johnny Kwok, Jet Propulsion Laboratory, April 4, 2008.

# Appendix C. Mass Summaries and Master Equipment Lists

The following mass summaries and MELs are included in this appendix:

- Probe
- Carrier-relay spacecraft

## *Probe Mass Summary*

| | Mass Fraction | Mass (kg) | Subsys Cont. % | CBE+ Cont. (kg) |
|---|---|---|---|---|
| **Payload on Probe** | | | | |
| Instruments | 6% | 9.2 | 15% | 10.5 |
| **Payload Total** | 6% | **9.2** | 15% | **10.5** |
| **Additional Elements Carried by Probe** | | | | |
| Descent Module Main Parachute | 3% | 5.0 | 30% | 6.5 |
| Mortar + cover + pilot (drogue) | 1% | 2.0 | 30% | 2.6 |
| Heat Shield Structure + Heat Shield TPS | 47% | 71.0 | 30% | 92.3 |
| Backshell Structure | 3% | 5.0 | 30% | 6.5 |
| Backshell TPS | 5% | 7.0 | 30% | 9.1 |
| Heat Shield Seperation Hardware | 2% | 3.0 | 30% | 3.9 |
| **Carried Elements Total** | 61% | **93.0** | 30% | **120.9** |
| **Descent Module** | | | | |
| Attitude Control | 0% | 0.0 | 0% | 0.0 |
| Command & Data | 3% | 5.2 | 14% | 5.9 |
| Power | 9% | 13.9 | 30% | 18.1 |
| Propulsion Hardware | 0% | 0.0 | 0% | 0.0 |
| Structures & Mechanisms | 12% | 18.0 | 30% | 23.4 |
| Cabling | 3% | 4.3 | 30% | 5.5 |
| Telecom | 2% | 2.9 | 10% | 3.2 |
| Thermal | 3% | 4.9 | 24% | 6.1 |
| **Descent Module Total** | | 49.2 | 27% | 62.2 |
| **Probe Total** | | 151.3 | 28% | 193.6 |
| Subsystem Heritage Contingency | | 42.3 | | |
| System Contingency | | 22.7 | | |
| **Probe with Contingency** | | **216** | | |

## *Probe MEL*

| | CBE Mass Per Unit | # of Units | Current Basic Est. | %-Unc. (% of CBE) | Predicted Basic Est. |
|---|---|---|---|---|---|
| **Launch Mass** | | | **151.3 kg** | **43%** | **216.4 kg** |
| **Launch Vehicle PLA** | | | **0.0 kg** | **30%** | **0.0 kg** |
| **Stack (w/ Wet Element)** | | | **151.3 kg** | **43%** | **216.4 kg** |
| **Useable Propellant** | | | **0.0 kg** | **0%** | **0.0 kg** |
| **Stack (w/ Dry Element)** | | | **151.3 kg** | **43%** | **216.4 kg** |
| **Carried Elements** | | | **93.0 kg** | **30%** | **120.9 kg** |
| Descent Module Main Parachute | | | 5.0 kg | 30% | 6.5 kg |
| Mortar + cover + pilot (drogue) | | | 2.0 kg | 30% | 2.6 kg |
| Heat Shield Structure + Heat Shield TPS | | | 71.0 kg | 30% | 92.3 kg |
| Backshell Structure | | | 5.0 kg | 30% | 6.5 kg |
| Backshell TPS | | | 7.0 kg | 30% | 9.1 kg |
| Heat Shield Seperation Hardware | | | 3.0 kg | 30% | 3.9 kg |
| **Dry Element** | | | **58.3 kg** | **64%** | **95.5 kg** |
| | | | | | |
| **Wet Element** | | | **58.3 kg** | **64%** | **95.5 kg** |
| **Dry Element** | | | **58.3 kg** | **64%** | **95.5 kg** |
| **System Contingency** | | | **22.7 kg** | **39%** | |
| **Subsystem Heritage Contingency on Descent Module** | | | **14.4 kg** | **25%** | |
| **Payload** | | | **9.2 kg** | **15%** | **10.5 kg** |
| **Instruments** | | **2** | **9.2 kg** | **15%** | **10.5 kg** |
| Mass Spectrometer | 8.0 kg | 1 | 8.0 kg | 15% | 9.2 kg |
| ASI | 1.2 kg | 1 | 1.2 kg | 15% | 1.3 kg |
| **Bus** | | | **49.2 kg** | **27%** | **62.2 kg** |
| **Attitude Control** | | **1** | **0.0 kg** | **0%** | **0.0 kg** |
| Shielding: | 0.0 kg | 1.0 | 0.0 kg | 0% | 0.0 kg |
| **Command & Data** | | **6** | **5.2 kg** | **14%** | **5.9 kg** |
| Processor: RAD750-Box Component | 0.6 kg | 1 | 0.6 kg | 5% | 0.6 kg |
| Memory: MOAB-Box component | 0.3 kg | 1 | 0.3 kg | 17% | 0.4 kg |
| Telecom_I_F: CAPI-Box component | 0.3 kg | 1 | 0.3 kg | 17% | 0.4 kg |
| Backplane: BRE Backplane/PCU-Box component | 0.3 kg | 1 | 0.3 kg | 17% | 0.4 kg |
| Chassis: BRE Chassis-Box component | 2.9 kg | 1 | 2.9 kg | 17% | 3.4 kg |
| Analog_I_F: MREU | 0.8 kg | 1 | 0.8 kg | 6% | 0.9 kg |
| **Power** | | **13** | **13.9 kg** | **30%** | **18.1 kg** |
| Li-SOCl2 (Primary Battery) | 1.3 kg | 3 | 3.9 kg | 30% | 5.0 kg |
| Thermal Battery (Thermal Battery) | 1.1 kg | 1 | 1.1 kg | 30% | 1.5 kg |
| Chassis | 2.3 kg | 1 | 2.3 kg | 30% | 3.0 kg |
| Load Switches Boards | 0.8 kg | 1 | 0.8 kg | 30% | 1.0 kg |
| Pyro Switches* Boards | 0.8 kg | 1 | 0.8 kg | 30% | 1.0 kg |
| Houskeeping DC-DC Converters* Boards | 1.0 kg | 1 | 1.0 kg | 30% | 1.3 kg |
| Power/Shunt Control* Boards | 1.0 kg | 1 | 1.0 kg | 30% | 1.3 kg |
| Battery Control Boards | 0.8 kg | 3 | 2.4 kg | 30% | 3.1 kg |
| Shielding | 0.6 kg | 1 | 0.6 kg | 30% | 0.8 kg |
| **Propulsion** | | **0** | **0.0 kg** | **0%** | **0.0 kg** |
| **Mechanical** | | **5** | **22.2 kg** | **30%** | **28.9 kg** |
| Struc. & Mech. | | 4 | 18.0 kg | 30% | 23.4 kg |
| Primary Structure | 5.6 kg | 1 | 5.6 kg | 30% | 7.3 kg |
| Secondary Structure | 1.0 kg | 1 | 1.0 kg | 30% | 1.3 kg |
| Probe Shell (0.5 m Dia Sphere, 5 mm Wall, Ti) | 11.0 kg | 1 | 11.0 kg | 30% | 14.3 kg |
| Integration Hardware | 0.4 kg | 1 | 0.4 kg | 30% | 0.5 kg |
| Cabling Harness | 4.3 kg | 1 | 4.3 kg | 30% | 5.5 kg |

| | CBE Mass Per Unit | # of Units | Current Basic Est. | %-Unc. (% of CBE) | Predicted Basic Est. |
|---|---|---|---|---|---|
| **Telecom** | | **3** | **2.9 kg** | **10%** | **3.2 kg** |
| UHF Patch | 0.2 kg | 1 | 0.2 kg | 20% | 0.2 kg |
| Electra-Lite | 2.7 kg | 1 | 2.7 kg | 10% | 2.9 kg |
| Coax Cable, flex (120) | 0.1 kg | 1 | 0.1 kg | 0% | 0.1 kg |
| **Thermal** | | **148** | **4.9 kg** | **24%** | **6.1 kg** |
| Multilayer Insulation (MLI) | 0.5 kg | 6 | 3.0 kg | 30% | 3.9 kg |
| Thermal Surfaces | | 6 | 0.1 kg | 0% | 0.1 kg |
| General | 0.0 kg | 6 | 0.1 kg | 0% | 0.1 kg |
| Thermal Conduction Control | | 101 | 0.2 kg | 22% | 0.3 kg |
| General | 0.1 kg | 1 | 0.1 kg | 0% | 0.1 kg |
| Isolation (G-10) | 0.0 kg | 100 | 0.2 kg | 30% | 0.2 kg |
| Temperature Sensors | | 25 | 0.5 kg | 15% | 0.6 kg |
| Thermistors | 0.0 kg | 25 | 0.5 kg | 15% | 0.6 kg |
| RHU's | 0.1 kg | 10 | 1.0 kg | 15% | 1.2 kg |

## *Carrier-Relay Spacecraft Mass Summary*

| | Mass Fraction | Mass (kg) | Subsys Cont. % | CBE+ Cont. (kg) |
|---|---|---|---|---|
| *Power Mode Duration (hours)* | | | | |
| **Payload on this Element** | | | | |
| Instruments | 2% | 9.2 | 15% | 10.5 |
| **Payload Total** | 2% | **9.2** | 15% | **10.5** |
| **Additional Elements Carried by this Element** | | | | |
| Probe (Without Instruments) | 30% | 142.2 | 45% | 205.9 |
| **Carried Elements Total** | 30% | **142.2** | 45% | **205.9** |
| **Spacecraft Bus** | | | | |
| Attitude Control | 2% | 9.9 | 10% | 10.9 |
| Command & Data | 2% | 10.3 | 14% | 11.8 |
| Power | 18% | 86.8 | 30% | 112.8 |
| Mono-Propellant Hardware | 9% | 43.4 | 7% | 46.3 |
| Structures & Mechanisms | 18% | 87.3 | 30% | 113.5 |
| S/C-Side Adapter | 2% | 9.8 | 30% | 12.8 |
| Cabling | 4% | 19.4 | 30% | 25.2 |
| Telecom | 6% | 28.3 | 14% | 32.2 |
| Thermal | 7% | 32.6 | 27% | 41.4 |
| **Bus Total** | | 327.9 | 24% | 406.9 |
| **Spacecraft Total (Dry)** | | 479.2 | 30% | 623.3 |
| Subsystem Heritage Contingency | | 144.1 | | |
| System Contingency | | 64.5 | | |
| **Spacecraft with Contingency** | | **688** | | |
| Mono-Propellant | 28% | 269.3 | | |
| **Spacecraft Total (Wet)** | | **957** | | |
| | | | | |
| **Launch Mass** | | **957** | | |
| | | | | |
| **Launch Vehicle Capability** | | **1135** | Atlas V 401 | |
| | | | | |
| **Launch Vehicle Margin** | | **177.8** | 16% | |
| **JPL Design Principles Margin** | | **49%** | | |

## *Carrier-Relay Spacecraft MEL*

| | CBE Mass Per Unit | # of Units | Current Basic Est. | %-Unc. (% of CBE) | Predicted Basic Est. |
|---|---|---|---|---|---|
| **Launch Mass** | | | **748.6 kg** | **28%** | **957.5 kg** |
| **Launch Vehicle PLA** | | | **0.0 kg** | **30%** | **0.0 kg** |
| **Stack (w/ Wet Element)** | | | **748.6 kg** | **28%** | **957.5 kg** |
| **Useable Propellant** | | | **268.7 kg** | **0%** | **268.7 kg** |
| **Stack (w/ Dry Element)** | | | **479.8 kg** | **44%** | **688.7 kg** |
| **Carried Elements** | | | **142.2 kg** | **45%** | **205.9 kg** |
| Probe (Without Instruments) | | | 142.2 kg | 45% | 205.9 kg |
| **Dry Element** | | | **337.7 kg** | **43%** | **482.9 kg** |
| | | | | | |
| **Wet Element** | | | **606.4 kg** | **24%** | **751.6 kg** |
| **Useable Propellant** | | | **268.7 kg** | **0%** | **268.7 kg** |
| **System 1: Monoprop** | | | **268.7 kg** | **0%** | **268.7 kg** |
| **Dry Element** | | | **337.7 kg** | **43%** | **482.9 kg** |
| **System Contingency** | | | **64.8 kg** | **19%** | |
| **Subsystem Heritage Contingency** | | | **80.4 kg** | **24%** | |
| **Payload** | | | **9.2 kg** | **15%** | **10.5 kg** |
| **Instruments** | | **2** | **9.2 kg** | **15%** | **10.5 kg** |
| Mass Spectrometer | 8.0 kg | 1 | 8.0 kg | 15% | 9.2 kg |
| ASI | 1.2 kg | 1 | 1.2 kg | 15% | 1.3 kg |
| **Bus** | | | **328.5 kg** | **24%** | **407.5 kg** |
| **Attitude Control** | | **22** | **9.9 kg** | **10%** | **10.9 kg** |
| Sun Sensor 1 | 0.1 kg | 16.0 | 0.9 kg | 10% | 1.0 kg |
| Star Tracker 1 | 3.4 kg | 2.0 | 6.8 kg | 10% | 7.5 kg |
| IMU 1 | 0.8 kg | 3.0 | 2.3 kg | 10% | 2.5 kg |
| Shielding: | 0.0 kg | 1.0 | 0.0 kg | 0% | 0.0 kg |
| **Command & Data** | | **12** | **10.3 kg** | **14%** | **11.8 kg** |
| Processor: RAD750-Box Component | 0.6 kg | 2 | 1.1 kg | 5% | 1.2 kg |
| Memory: MOAB-Box component | 0.3 kg | 2 | 0.6 kg | 17% | 0.7 kg |
| Telecom_I_F: CAPI-Box component | 0.3 kg | 2 | 0.6 kg | 17% | 0.7 kg |
| Backplane: BRE Backplane/PCU-Box component | 0.3 kg | 2 | 0.6 kg | 17% | 0.7 kg |
| Chassis: BRE Chassis-Box component | 2.9 kg | 2 | 5.8 kg | 17% | 6.8 kg |
| Analog_I_F: MREU | 0.8 kg | 2 | 1.6 kg | 6% | 1.7 kg |
| **Power** | | **20** | **86.8 kg** | **30%** | **112.8 kg** |
| No Solar Panels | 0.0 kg | 0 | 0.0 kg | 30% | 0.0 kg |
| Li-SOCl2 (Primary Battery) | 0.0 kg | 0 | 0.0 kg | 30% | 0.0 kg |
| Li-ION (Secondary Battery) | 4.8 kg | 3 | 14.4 kg | 30% | 18.8 kg |
| Thermal Battery (Thermal Battery) | 0.0 kg | 0 | 0.0 kg | 30% | 0.0 kg |
| Advanced Stirling (ASRG-850C) | 24.0 kg | 2 | 48.0 kg | 30% | 62.4 kg |
| Chassis | 12.0 kg | 1 | 12.0 kg | 30% | 15.6 kg |
| Array Segment Switches* Boards | 0.8 kg | 0 | 0.0 kg | 30% | 0.0 kg |
| Load Switches Boards | 0.8 kg | 2 | 1.6 kg | 30% | 2.1 kg |
| Thruster Drivers* Boards | 0.8 kg | 2 | 1.6 kg | 30% | 2.1 kg |
| Pyro Switches* Boards | 0.8 kg | 4 | 3.2 kg | 30% | 4.2 kg |
| Houskeeping DC-DC Converters* Boards | 1.0 kg | 2 | 2.0 kg | 30% | 2.6 kg |
| Power/Shunt Control* Boards | 1.0 kg | 2 | 2.0 kg | 30% | 2.6 kg |
| High Voltage Down Converter* Boards | 20.0 kg | 0 | 0.0 kg | 30% | 0.0 kg |
| Battery Control Boards | 0.8 kg | 0 | 0.0 kg | 30% | 0.0 kg |
| ARPS (Stirling) Controller* Boards | 0.8 kg | 0 | 0.0 kg | 30% | 0.0 kg |
| Diodes* Boards | 0.8 kg | 1 | 0.8 kg | 30% | 1.0 kg |
| Shielding | 1.2 kg | 1 | 1.2 kg | 30% | 1.5 kg |

| | CBE Mass Per Unit | # of Units | Current Basic Est. | %-Unc. (% of CBE) | Predicted Basic Est. |
|---|---|---|---|---|---|
| **Propulsion** | | **32** | **44.0 kg** | **7%** | **46.9 kg** |
| System 1: Monoprop | | 32 | 44.0 kg | 7% | 46.9 kg |
| Hardware | | 32 | 43.4 kg | 7% | 46.3 kg |
| Gas Service Valve | 0.2 kg | 1 | 0.2 kg | 2% | 0.2 kg |
| Temp. Sensor | 0.0 kg | 1 | 0.0 kg | 5% | 0.0 kg |
| Liq. Service Valve | 0.3 kg | 1 | 0.3 kg | 2% | 0.3 kg |
| LP Transducer | 0.3 kg | 2 | 0.5 kg | 2% | 0.6 kg |
| Liq. Filter | 0.5 kg | 1 | 0.5 kg | 2% | 0.5 kg |
| LP Latch Valve | 0.4 kg | 2 | 0.7 kg | 2% | 0.7 kg |
| Temp. Sensor | 0.0 kg | 10 | 0.1 kg | 5% | 0.1 kg |
| Lines, Fittings, Misc. | 1.8 kg | 1 | 1.8 kg | 50% | 2.7 kg |
| Monoprop Main Engine | 0.5 kg | 4 | 2.1 kg | 5% | 2.2 kg |
| Monoprop Thrusters 1 | 0.3 kg | 8 | 2.6 kg | 5% | 2.8 kg |
| Fuel Tanks | 34.6 kg | 1 | 34.6 kg | 5% | 36.3 kg |
| **Mechanical** | | **7** | **116.5 kg** | **30%** | **151.5 kg** |
| Struc. & Mech. | | 5 | 87.3 kg | 30% | 113.5 kg |
| Primary Structure | 63.0 kg | 1 | 63.0 kg | 30% | 81.9 kg |
| Secondary Structure | 6.5 kg | 1 | 6.5 kg | 30% | 8.5 kg |
| Probe Separation Hardware | 9.3 kg | 1 | 9.3 kg | 30% | 12.1 kg |
| Probe Spin Table | 4.1 kg | 1 | 4.1 kg | 30% | 5.4 kg |
| Integration Hardware | 4.4 kg | 1 | 4.4 kg | 30% | 5.7 kg |
| Adapter, Spacecraft side | 9.8 kg | 1 | 9.8 kg | 30% | 12.8 kg |
| Cabling Harness | 19.4 kg | 1 | 19.4 kg | 30% | 25.2 kg |
| **Telecom** | | **37** | **28.3 kg** | **14%** | **32.2 kg** |
| X/X-HGA 1.5m diam Parabolic | 3.1 kg | 1 | 3.1 kg | 20% | 3.7 kg |
| X-MGA (19dB) MER | 0.6 kg | 1 | 0.6 kg | 10% | 0.7 kg |
| X-LGA | 0.5 kg | 2 | 0.9 kg | 10% | 1.0 kg |
| UHF-MGA Patch Array | 1.3 kg | 1 | 1.3 kg | 20% | 1.5 kg |
| SDST X-up/X down | 2.7 kg | 2 | 5.4 kg | 10% | 5.9 kg |
| Electra-Lite | 2.7 kg | 1 | 2.7 kg | 10% | 2.9 kg |
| X-band TWTA, RF=25W | 3.0 kg | 2 | 6.0 kg | 20% | 7.2 kg |
| Hybrid Coupler | 0.0 kg | 1 | 0.0 kg | 10% | 0.0 kg |
| Filter, low power | 0.2 kg | 1 | 0.2 kg | 10% | 0.2 kg |
| X-band Diplexer, high isolation | 0.8 kg | 2 | 1.6 kg | 10% | 1.8 kg |
| Waveguide Transfer Switch (WGTS) | 0.4 kg | 3 | 1.1 kg | 10% | 1.3 kg |
| Coax Transfer Switch (CXS) | 0.1 kg | 1 | 0.1 kg | 10% | 0.1 kg |
| Coax Cable, flex (190) | 0.2 kg | 8 | 1.3 kg | 10% | 1.4 kg |
| WR-112 WG, rigid (Al) | 0.4 kg | 9 | 3.9 kg | 10% | 4.3 kg |
| Coax Cable, flex (120) | 0.1 kg | 2 | 0.2 kg | 10% | 0.2 kg |
| Shielding | | 0 | 0.0 kg | 0% | 0.0 kg |
| **Thermal** | | **208** | **32.6 kg** | **27%** | **41.4 kg** |
| Multilayer Insulation (MLI) | 0.5 kg | 29 | 14.5 kg | 30% | 18.9 kg |
| Thermal Surfaces | | 17 | 1.3 kg | 30% | 1.7 kg |
| General | 0.1 kg | 17 | 1.3 kg | 30% | 1.7 kg |
| Thermal Conduction Control | | 1 | 0.2 kg | 30% | 0.3 kg |
| General | 0.2 kg | 1 | 0.2 kg | 30% | 0.3 kg |
| Heaters | | 10 | 0.9 kg | 30% | 1.2 kg |
| Custom | 0.1 kg | 2 | 0.1 kg | 30% | 0.1 kg |
| Propulsion Tank Heaters | 0.1 kg | 2 | 0.2 kg | 30% | 0.3 kg |
| Propulsion Line Heaters | 0.1 kg | 6 | 0.6 kg | 30% | 0.8 kg |
| Temperature Sensors | | 100 | 1.0 kg | 15% | 1.2 kg |
| Thermistors | 0.0 kg | 100 | 1.0 kg | 15% | 1.2 kg |

| | CBE Mass Per Unit | # of Units | Current Basic Est. | %-Unc. (% of CBE) | Predicted Basic Est. |
|---|---|---|---|---|---|
| Thermostats | | 4 | 0.1 kg | 15% | 0.1 kg |
| Mechanical | 0.0 kg | 4 | 0.1 kg | 15% | 0.1 kg |
| Thermal Louvers | 1.0 kg | 2 | 2.0 kg | 30% | 2.5 kg |
| Heat Pipes | | 8 | 1.2 kg | 0% | 1.2 kg |
| Loop HP | 0.2 kg | 8 | 1.2 kg | 0% | 1.2 kg |
| RHU's | 0.1 kg | 30 | 3.0 kg | 15% | 3.5 kg |
| Instrument Thermal Control | 0.0 kg | 0 | 0.0 kg | 0% | 0.0 kg |
| Other Components | | 7 | 6.5 kg | 30% | 8.5 kg |
| Shunt Radiator | 6.5 kg | 1 | 6.5 kg | 30% | 8.5 kg |
| Prop Module MLI | 0.0 kg | 6 | 0.0 kg | 30% | 0.0 kg |