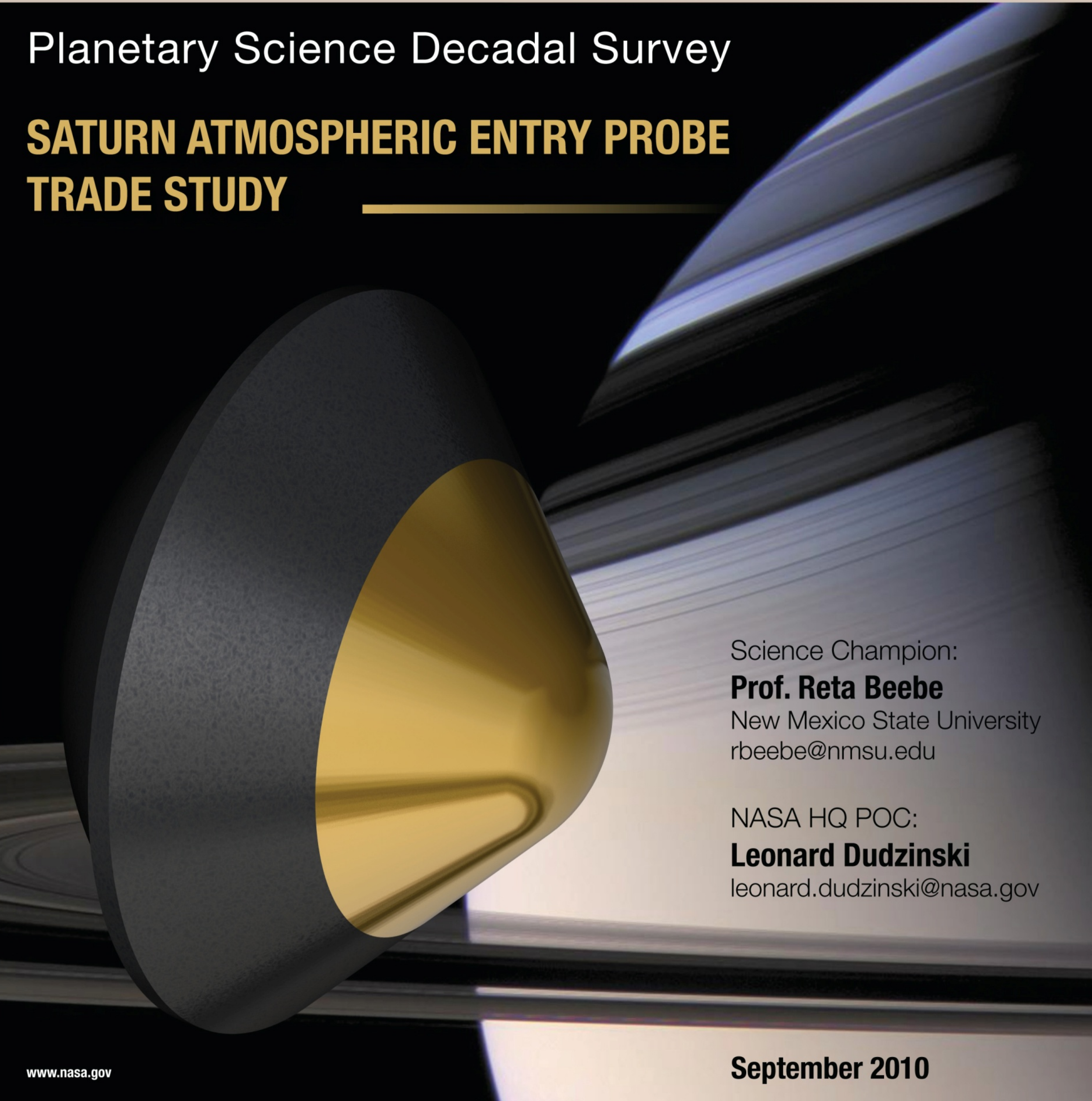
National Aeronautics and Space Administration

Mission Concept Study



Planetary Science Decadal Survey

SATURN ATMOSPHERIC ENTRY PROBE TRADE STUDY

Science Champion:
Prof. Reta Beebe
New Mexico State University
rbeebe@nmsu.edu

NASA HQ POC:
Leonard Dudzinski
leonard.dudzinski@nasa.gov

www.nasa.gov

September 2010

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

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

Planetary Science Decadal Survey

Mission Concept Study Final Report

Figures

Tables

Appendices

Study Participants

Role	Participant	Affiliation
Study Lead and Primary Author	Dr. Thomas R. Spilker	Jet Propulsion Laboratory
Giant Planets Panel Contributing Authors		
Science Champion	Prof. Reta Beebe	New Mexico State University
Science	Dr. Heidi Hammel	Space Science Institute
Science	Dr. Amy Simon-Miller	NASA Goddard Space Flight Center
Science	R. Wayne Richie	NASA Langley Research Center (ret.)
Science	Dr. Kuniyo M. Sayanagi	California Institute of Technology
Saturn Probe Trade Study Team		
Systems Engineer	Cate Heneghan	Jet Propulsion Laboratory
Mission Design	George Carlisle	Jet Propulsion Laboratory
Mission Design	Jeff Parker	Jet Propulsion Laboratory
Power	Paul Stella	Jet Propulsion Laboratory
Propulsion	Frank Picha	Jet Propulsion Laboratory
Systems Engineer	Omair Khan	Jet Propulsion Laboratory
Telecom Systems	Dave Morabito	Jet Propulsion Laboratory
Consultant	Tibor Balint	Jet Propulsion Laboratory
JPL SS 2012 PSDS Trades Lead	Chet Borden	Jet Propulsion Laboratory
JPL SS 2012 PSDS Lead	Kim Reh	Jet Propulsion Laboratory
NASA HQ POC	Leonard Dudzinski	NASA

The study team would like to thank the following for their valuable contributions:

- Prof. David Atkinson
- Prof. Sushil Atreya
- Dr. Anthony Colaprete
- Dr. Paul Mahaffey
- Dr. Ethiraj Venkatapathy

Acknowledgments

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Executive Summary

This study found it might be possible to implement a Saturn probe mission in which a flyby carrier-relay spacecraft (CRSC) would deliver a single probe within the resource constraints of NASA's New Frontiers Program. Achievement of this goal would require a small and focused set of science objectives.

The mission's science objectives, specified by the study science team, are divided into two groups: "Tier 1," essentially the science floor objectives that must be addressed to make the mission worthwhile, and "Tier 2," the next highest priority level, with objectives that prospective PIs could reasonably add, given sufficient resources. By request from the science team, this study used as requirements only the Tier 1 objectives:

- Determine the noble gas abundances and isotopic ratios of H, C, N, and O (and Ar?) in Saturn's atmosphere
- Determine the atmospheric structure at the probe descent location(s)

The primary objective of this study was to determine whether any probe mission capable of accomplishing these science objectives could fit within the New Frontiers constraints. A secondary objective was to determine if a single mission delivering two such entry probes to different locations at Saturn might fit within New Frontiers constraints. This secondary objective was judged unlikely early in the study and was removed from further consideration.

The Saturn probe mission concept is fairly straightforward from engineering and mission design perspectives, resembling a simplified version of the Galileo Probe mission to Jupiter in many ways, as detailed in Appendix C. The mission would consist of three main phases: launch and transfer (cruise) to Saturn; approach and targeting; and the science mission. The launch/transfer phase could use any of several different types of Earth-to-Saturn transfer trajectories. This study uses a propulsion-intensive ΔV-EGA trajectory (in which a single Earth gravity assist follows a deep space maneuver) as a stressing case. Other trajectory options exist that could significantly reduce that trajectory's delta-V requirement at the expense of additional cruise duration. These should be investigated in subsequent studies as a potential cost-saving approach. The approach and targeting phase would closely resemble that of the Galileo Probe mission. The only significant difference is that the Saturn probe's CRSC would have fewer constraints on its trajectory, so that trajectory could be better optimized for probe data relay.

The science mission phase would have many similarities to that of the Galileo Probe mission, as well as some distinct differences, many described in Appendix C. Instead of the "bent pipe" relay mode used by Galileo, requiring simultaneous pointing at Earth with its high-gain antenna (HGA) and at the probe entry site with its relay receiving antenna, this study's CRSC would collect and store probe data onboard for later forwarding to Earth. Penetration to the 5-bar level satisfies the science objectives, requiring a descent of some 55 minutes from the beginning of transmissions. Since the descent module, designed for the 10-bar level to account for atmospheric uncertainties, would most likely survive longer than required, the CRSC would continue to point at the entry site, receiving and storing data for ~15 minutes after the nominal end of mission. The CRSC would continue its flyby trajectory, departing the Saturn system on a solar system escape trajectory for spacecraft disposal.

Downlink of the data from the CRSC would be performed a short time after the data relay is complete. Since the entire probe data set is only ~2 Mb, 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 would be downlinked in the DSN pass immediately after the probe descent. The ~2 Mb data volume is not a hard limit, though it is deemed more than adequate for the Tier 1 science objectives. If the need arises, there are multiple areas of flexibility in the telecom system and trajectory designs that could yield a larger data volume.

This mission would not need any new technology developments. The conceptual design relies on carbon phenolic heat shield technology, but does not need the exquisite performance of the Galileo Probe's heat shield, likely allowing the use of readily available carbon phenolic materials currently applied to solid rocket motor nozzles. Notably, testing of heat shield materials under the conditions an entering Saturn probe would experience could be done with existing facilities. Power options assessed for the CRSC included advanced Stirling radioisotope generators (ASRGs) as well as advanced low intensity, low temperature (LILT) solar arrays. The ASRG is currently under development by NASA and Department of Energy (DoE), and should be flight ready in the time frame of interest to this Decadal Survey. If solar power were to be implemented, current-technology solar cells could be used; however, the mission might benefit from development of solar cell fabrication technologies that could produce a substantially higher yield of LILT-tolerant cells from each production batch, thus resulting in cost savings.

This is a relatively low-risk mission concept, with much flexibility in its implementation. Most of its primary risks are programmatic, not technical. The main implementation risks involve availability of appropriate carbon phenolic materials and ASRGs. The main mission risk would be a critical deployment (probe release) after more than six years in space. Because the science objectives do not require measuring the deep absolute abundances of oxygen and nitrogen, the risk of entering a non-representative region is significantly decreased from that of the Galileo mission. Abundant flexibility in trajectories, schedule, and flight system design (none of the subsystems are at the limits of their performance) provides multiple avenues for reducing remaining risks or addressing problems that arise during implementation.

Study Purpose, Objectives, and Approach

Study Purpose and Objectives

The purposes of this study are to determine whether a Saturn probe mission that achieves the science objectives detailed in Section 1, "Scientific Objectives" might be feasible within the NASA New Frontiers Program cost cap. This assessment will allow the Planetary Science Decadal Survey (PSDS) Giant Planets Panel to decide whether to recommend a more detailed study. The trade study's primary objective is to understand if there are particular power, propulsion, or telecommunications technologies that would enable implementing such a mission under the New Frontiers Program.

A secondary study objective is to clarify the costs associated with possible variations or additions to the primary mission.

Ultimately, the study seeks to scope the range of missions, within the New Frontiers cost cap, that could obtain fundamental in-situ measurements to constrain theories of giant planet and solar system formation, as well as to complement Cassini's atmospheric remote-sensing data.

Study Approach

This study differs from other studies supporting the 2012 Planetary Science Decadal Survey in that the objective was to evaluate a trade space of alternatives to determine whether there were feasible mission concept options, within a designated mission architecture (atmospheric entry probes), that satisfy science and cost objectives, rather than to assess a specific mission point design.

In assessing these trade space options, the study approach was to determine feasibility at a system level, rather than the more detailed subsystem level of a Team X mission study. Selected subsystems that were judged to be design drivers were evaluated to a sufficient level of detail to verify (at a system level) suitability for follow-on study (e.g., power system alternatives include solar arrays and Stirling RPS). Cost estimates were also performed at a system level (estimated parametrically) and are at a lower level of fidelity than Team X cost estimates.

Guidelines provided by the science team in the Study Questionnaire [1] called for the study to focus on New Frontiers and "sub-flagship" missions (i.e., below $1.2 billion, $FY15, and assuming 50% reserve on Phase A–D costs (excluding launch vehicle and RPS) and 25% on Phase E), ideally with a launch in the NF-4 time slot. Further, it was to be assumed that there should be no substantial new technology development. The only exception is the possible inclusion of Stirling RPS power using the ASRG already in an advanced stage of development and expected to be flight ready for the time frame of interest for this study.

The science team requested that the study investigate alternative Saturn probe science scenarios. In particular, there was interest in understanding how the cost estimate would be affected by limiting the instrument suite to a mass spectrometer and T-P sensors vs. adding a nephelometer and/or a Tunable Laser Spectrometer. The science team also wanted to know whether a flyby spacecraft concept for delivery and communication would allow delivery of:

1. Two shallow probes (and if so, the latitudinal limits on the entries);
2. A secondary deep probe (i.e., staged probes with the second reaching deeper than 20 bars) to measure water in the well-mixed region below the cloud deck; or
3. Two flybys, staggered in time to allow for longer communication with a single descending probe (so the probe can get deeper).

In conducting this study, the study team used the following task sequence:

- Identify the primary design drivers for a Saturn Atmospheric Entry Probe mission
- Assemble a team of discipline experts to address the design drivers and perform trades at the subsystem level
- Use mass and power tables from previous design studies as candidate “reference” design points; determine the most appropriate to use as this study’s reference
- Use cost modeling results (from the study that generated the reference design) as a cost estimation baseline; extrapolate those costs to the reference fiscal year specified by the NASA Study Ground Rules (FY2015) [2].
- Modify the mass, power, and cost tables using the results of the trade studies to generate “deltas” to the reference
- Apply the deltas and modify reserves to conform to the reserves policies specified by the NASA Study Ground Rules to generate a rough cost estimate for the mission concept
- Report results via teleconference to the Study Science Champion (Prof. Reta Beebe) and the Study Science Team
- If the Giant Planets Panel decides to recommend a follow-on Team X study (which it did), communicate this study’s results to Team X
- Generate a Final Report document and transmit it to NASA and the NRC

1. Scientific Objectives

Science Questions and Objectives

See Atkinson, D.H., et al., "Entry Probe Missions to the Giant Planets" [3].

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 could 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 (atomic mass >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, helium, and entrained 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 [4] 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 [5]

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	2.1×10^{-4}	0.59 ±0.0	?	20–30 (?)	30–50 (?)
Ar	1.7×10^{-6}	5.34 ±1.1	?	20–30 (?)	30–50 (?)
Kr	2.1×10^{-9}	2.0 ±0.4	?	20–30 (?)	30–50 (?)
Xe	2.1×10^{-10}	2.1 ±0.4	?	20–30 (?)	30–50 (?)
C	2.8×10^{-4}	3.8 ±0.7	9.3 ±1.8	20–30	30–50
N	6.8×10^{-5}	4.9 ±1.9	2.7–5.0	20–30 (?)	30–50 (?)
O	5.1×10^{-4}	0.5 ±0.2 (a)	?	20–30 (?)	30–50 (?)
S	1.6×10^{-5}	2.9 ±0.7	?	20–30 (?)	30–50 (?)
P	2.6×10^{-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
$^3He/^4He$	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) [6], relative to solar composition of [7]

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 greater depths. 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 "Proximal Orbits" in the end-of-mission 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 Proximal Orbits 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% Helium/solar (±2%) Ne, Ar, Kr, Xe, S, N ±20% Isotopes ±10% O profile above clouds	Mass spectrometer (MS)	Descent to 5 bar 70-minute relay Sample interval ≤7 km
Determine the atmospheric structure at the probe descent location	Acceleration Temperature Pressure	Atmospheric structure instrument (ASI)	Descent to 5 bar 70-minute relay 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	—
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 elements such as S, N, and O found in simple atmospheric constituents	—	MS	—

This matrix describes the linkages between science objectives and how they are achieved. Note that functional requirements are requirements placed by science on the mission concept (e.g., requirements on the spacecraft, trajectory, mission architecture, etc.).

2. High-Level Mission Concept

Mission Overview

The Saturn probe mission concept is fairly straightforward from engineering and mission design perspectives since it resembles a simpler and easier version of the Galileo Probe mission to Jupiter in many ways. Appendix C discusses in detail the differences between the two missions and their destinations. While there are a few relative difficulties and complications compared to Galileo, they are minor compared to the major advantages.

Science objectives requiring measurements of isotopic ratios of key atmospheric constituents drive the need to penetrate Saturn's deep 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, motivated designing to the 10-bar level. Releasing the main parachute at some point (approximately the 1-bar level) 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. Section 3, "Technical Overview" covers instrumentation to make the required science measurements.

There would be three main mission phases: launch and transfer (cruise) to Saturn; approach and targeting; and the science mission. The launch/transfer phase would deliver the CRSC and probe to Saturn approach. In the approach and targeting phase, the CRSC would deliver the probe to its proper Saturn entry trajectory, then divert to the proper flyby trajectory for data relay. The brief science mission phase would have the probe enter Saturn's atmosphere and perform the science measurements, relaying the data to the CRSC overhead for storage and subsequent forwarding to Earth.

Jupiter gravity assists are usually advantageous for transfer to the Saturn system. However, for the decade of interest to this Decadal Survey, 2013–2022, there are no programmatically viable launch windows that include JGA windows, so another trajectory type would have to be used. Fortunately, there are many different trajectory types that could satisfy the mission requirements, so the launch/transfer phase would not impose challenging constraints upon the mission concept.

Similarly, the approach and targeting phase would not involve significant challenges. The Galileo Probe mission demonstrated every major function required during this phase. These include approach navigation (by the CRSC) to the probe's proper entry trajectory, spin-up and release of the probe, and retargeting of the CRSC to the proper trajectory and timing for probe data relay.

Although there are some differences, the Saturn probe's science mission would be very similar to that of the Galileo Probe. The Saturn entry probe would enter at an atmosphere-relative velocity of ~27 km/s, significantly less than the Galileo probe's 47.4 km/s (see Appendix C). After the entry heating and deceleration phase, a deployed drogue parachute 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 CRSC would begin. Descent to the required 5-bar level would take some 55 minutes, assuming the main parachute is released near the 1-bar level. Since the descent module would be designed to reach the 10-bar level and most likely would survive longer than required, the CRSC would continue to point at the entry site and receive the probe signal for ~15 minutes after the nominal end of mission, continuing to store data in onboard memory for relay to Earth.

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 reference downlink rate of 1.6 kbps it 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 CRSC would be on a flyby trajectory so it would need no orbit insertion maneuver, continuing on a solar system escape trajectory for spacecraft disposal.

Concept Maturity Level

Table 2-1 summarizes the NASA definitions for concept maturity levels (CMLs). The objective of this trade study was to investigate, at an architectural level, whether there are feasible mission concepts for dropping a small entry probe with a scientifically focused instrument suite into Saturn's atmosphere within the New Frontiers cost cap. If this trade study were successful in identifying feasible candidate mission concepts, there would be a follow-on mission design study at CML 4 using the full Team X capability.

This trade study precursor to a full Team X mission study focused on those disciplines that were considered drivers in the ability to identify feasible alternatives. The primary technologies evaluated were power (ASRG and LILT solar technologies), propulsion, and probe-to-CRSC telecom (as a function of distance and available geometries). Each of these technologies was evaluated to a CML 3 to provide confidence that feasible options existed to proceed to a CML 4 study. Other technologies included in this study are sufficiently well understood, and models are of sufficient fidelity, that they are already at CML 3. Establishing cost to be within the New Frontiers cost cap is at a CML 3 level.

The results of this study provide valuable information to subsequent point design studies.

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

Per request from the science team, this study minimized use of new technologies. In the electric power area there are two potential technologies needing further development—Stirling RPS and LILT solar arrays for use at Saturn—but they would not both be used on a single mission. The ASRG, while in an advanced stage of development, will require completion of the current, NASA funded, development program. The use of solar arrays for this mission is based on current cell technology, but could benefit from additional technology development to lower costs as discussed in the power trades section below.

Entry into Saturn's atmosphere from hyperbolic approach to the Saturn system involves intense heating, but that heating is still nearly an order of magnitude less intense than a similar entry into Jupiter's atmosphere. The aerothermal environment requires carbon phenolic for the heat shield's Thermal Protection System (TPS), but under conditions well within the carbon phenolic performance envelope; it would not require the enhanced performance needed for the Galileo Probe, where entry conditions were at the upper edge of that envelope. Notably, at entry speeds (relative to the atmosphere) of 30 km/s or less, TPS and heat shield performance could be tested using existing facilities (E. Venkatapathy, private communication). The ~27 km/s entry speed of a Saturn probe falls within this limit, so use of the Galileo Probe's heritage carbon phenolic is *not* required. Carbon phenolic currently being manufactured for use in solid rocket motor nozzles might be used instead.

For probe-to-CRSC communications, it was determined that existing Electra-Lite ultra-high frequency (UHF) equipment on the probe could transmit to an Electra-Lite receiver on the CRSC. All equipment is already space qualified except for the antennas: a patch on the probe, and a 2 x 2 patch array on the CRSC. The tracking loop on the Electra-Lite receiver would need modification to accommodate the lower-than-standard data rate. Those are engineering developments, since design of such antennas and tracking loops is well understood.

The mass spectrometer instrument concept used for this study would need to be developed, but it is only slightly different from the Galileo Probe mass spectrometer and requires no new technology.

Key Trades

The primary task of this study was to perform trades among a Saturn probe mission's propulsion, power, and telecommunications subsystems, including the significant influence of trajectories. As discussed in the Study Approach section, this study's resources were insufficient to conduct a full flight system design study, so results from a relevant previous study were used as a starting point. The trade analyses were treated as "deltas" to that study's flight system design and operations concept.

Power

This study investigated the use of solar vs. radioisotope power for the CRSC. While all deep space missions thus far flown to the distance of Jupiter and beyond have used RPSs for primary power, NASA is currently preparing to launch its first outer planet science mission powered by solar arrays, Juno, in 2011. The recent development of newer types and chemistries of solar cells, with higher efficiencies and better performance under low-intensity, low-temperature (LILT) conditions, potentially moves the limits of solar power capability farther from the sun. Current-technology triple-junction cells appear to demonstrate sufficiently high performance to meet the requirements of a low-power Saturn mission with a solar array area from two to five times that of Juno. The team felt it would be valuable to assess the potential for applicability of this technology for the mission concept under study.

Major issues entering into the trade and feasibility study include the spacecraft's power needs, both electrical and thermal; the mass, packaging, and cost of solar cells and the mass and size of large array structures to support them; and the mass and cost of ASRGs. The PSDS Ground Rules [2] specify the ASRG's mass, cost, and power profile. The costs of solar cells and support structures are relatively well known, but there is considerable uncertainty in the array area needed. For this study, the uncertainty arises partly from uncertainty in solar cell performance under LILT conditions, and partly from uncertainty in the CRSC's power needs.

A Saturn probe CRSC represents the low end of the scale of required spacecraft power for an independent, full-functional spacecraft, The probe itself would be powered entirely by primary batteries and would produce only ~2 Mb of science data in its entire mission. The CRSC would have no science instruments of its own. It would be used only to deliver the probe to Saturn and relay to Earth the probe's modest volume of science data. Based on similar previous studies, such a spacecraft could be expected to operate on significantly less than 300 W.

But a Saturn probe mission would operate at nearly twice the heliocentric distance of Juno at Jupiter. LILT effects increase the uncertainty in the performance of individual solar cells, increasing the need for current studies to carry larger power margins. In terms of solar cell device physics, the mechanisms causing the observed LILT behavior are not yet fully understood. Research performed by the study's power subsystem engineer found that even within a single production batch of cells, some cells showed little or moderate LILT degradation of performance, while some showed serious degradation. Testing at "normal" temperatures and intensities, and even at somewhat reduced temperatures and intensities, proved to be poor predictors of performance under severe LILT conditions. Two approaches could address this uncertainty: 1) research into the device physics, leading to development of production processes that eliminate or greatly reduce the fraction of poorly performing cells; or 2) a significant program of testing and selection to populate the arrays with cells of proven performance. The first approach would be a technology development; without that technology development, the latter approach would be required. That testing and selection approach would be lengthy and relatively expensive, because it would require testing every cell under conditions very similar to those at Saturn, and possibly it would involve overproduction of cells to yield the required quantity of LILT-tolerant cells. These costs would have to be factored into total mission costs. For this study's sizing and cost estimates, LILT performance uncertainties appeared in multiple parameters such as effective average cell efficiency and required power margin.

As mentioned above, this study's estimates of the solar option's array size were subject to uncertainties in CRSC power needs as well as cell performance. Most of this stems from uncertainty in the power needed for thermal control. This study's resource limits did not allow performing a thermal analysis and design, but instead the study adapted results from analyses in the 2008 study [8]. But the 2008 study used a transfer trajectory with a much smaller delta-V budget, so the current study's much larger propellant tanks would likely need far more thermal control power, possibly as much as 300 W more, from electrical heaters or RHUs (which might or might not be available). That figure is something of a worst case, since there are many options for trajectories with small delta-V budgets that could use small propellant tanks, but it points out the magnitude of the uncertainty: thermal power requirements could be a small fraction of the total CRSC power requirement, or they could be more than half the total. This study assumed an optimistic thermal case similar to that of the 2008 study and estimated the required array area at ~90 m^2, about double the area of the Juno array. Lack of a custom thermal design limited the fidelity achieved in the solar power system sizing estimates, and thus its cost estimates.

Estimating mass and cost for the ASRG option was a much more straightforward task. Two ASRGs would provide the necessary electrical power for the CRSC, and their waste heat would provide sufficient thermal control for most locations, via a capillary-pumped loop heat pipe system. This system would carry the added benefit of simpler operations, since ASRGs have no sun-pointing requirement.

Within the limits of the study, the power trade did not yield a clear choice based on cost or feasibility. It is recommended that this trade be studied further in a dedicated point design study.

Telecom

Transferring the relatively small volume of data from a Saturn probe flight system to Earth would seem a straightforward, non-controversial task; however, over the past seven to eight years, considerable discussion has been devoted to the advantages and disadvantages of various telemetry methods for a future Saturn probe, especially concerning relay vs. direct-to-Earth (DTE) transfer. It is not a simple, single-discipline problem, since trajectories and power are inseparably involved—delivering the probe to a location that maintains a useful line of sight to Earth throughout the science mission would require either a significantly extended transfer to Saturn or a huge deep-space maneuver, and a probe using DTE must transmit sufficient power through a low-gain antenna (LGA) to be received from a distance of 8 AU or more. It appears that a significant part of evaluations of the cost effectiveness of the two approaches hinges on what ground assets are assumed available (notably, the size of receiving apertures), and this in itself is a topic of considerable discussion and uncertainty. This study did not revisit the relay vs. DTE trade but assumed only current assets would be available at the time the probe enters Saturn's atmosphere. This essentially rules out DTE because there are no existing facilities with sufficient aperture to receive telemetered data without requiring an inordinate amount of transmit power on the probe; thus, relay communications are assumed.

Using relay communications to send the data to Earth, the primary issues for the telecom system would be ensuring the communications geometry would allow the links involved, having frequencies available that the probe and CRSC could use cost-effectively, having sufficient transmitted power, and having antennas with gain appropriate to the transmitted power and that could be pointed to the required accuracy. This study found that this is not a particularly challenging problem.

The Saturn probe flight system's telecom subsystem would involve two separate links: the "relay link," the one-way link from the probe descent module to the CRSC, and the two-way up/downlink from the CRSC to a DSN ground station at Earth. The two-way link to Earth is straightforward, with low data rate requirements and few critical contact periods. The primary objective of the CRSC-to-Earth link's trades was to determine the least costly implementation approach, such as X-band vs. Ka-band, smaller high-gain antenna (HGA) with higher radiated power vs. larger HGA with lower radiated power, etc. The primary objective of the probe-to-CRSC relay link's trades was to provide a plan for robust data relay at the required minimum data rate or higher, over the span of time needed for the probe descent. An accompanying objective was to minimize the cost of that subsystem. Some of the relay link trades involve the science mission trajectory, and some are essentially independent of trajectory. The trajectory-dependent trades deal with the communications geometry: over what distances the relay link must operate, how far off the probe's nominal zenith is the ray path to the CRSC, etc. Trajectory-independent trades involve such aspects as how far from the probe's zenith the transmitting antenna axis can deviate (due to, for example, turbulence-induced swinging), what the radio absorption properties of Saturn's atmosphere are, and how they influence choices of radio frequency (RF) power and frequency, whether the relay link should share the two-way link's HGA or have a dedicated relay link antenna, etc.

Standard JPL mission design techniques yield good communications geometries. The study's science mission trajectory designer found a set of trajectories, adaptable to the great majority of Saturn approach conditions (and thus most years of arrival at Saturn) that would provide excellent geometries for relaying the data from the probe to the CRSC. They would keep the probe-to-CRSC direction <40 degrees away from zenith (for low atmospheric attenuation), would keep the probe-to-CRSC range at <75,000 km and as little as ~50,000 km, and provide this combination for at least the 70 minutes required for the probe to reach the 10-bar level. Options exist to increase the minimum range to get even longer communications windows. Low zenith angles have two major benefits: 1) the transmitting antenna beamwidth can be smaller, yielding higher gain, thus improving the power/data rate trade space; and 2) near the end of the science mission, when the probe transmits through the greatest overhead RF absorption, the path length through the atmosphere is minimized, improving the power/data rate trade space by reducing the maximum signal attenuation the system must overcome. These trajectories would also provide low probe entry speeds, well below the limit of heat shield testability. The CRSC trajectories would provide good geometries for downlink to Earth after the probe science mission has ended, with trajectories in most years having no Saturn eclipse soon after that. In years where the straightforward CRSC trajectory solutions would involve Saturn eclipses, options exist in most cases to change the CRSC approach aim point, increasing the trajectory's inclination and eliminating the eclipse, at the cost of using increased minimum range to maintain the 70-minute communications window. The study found significant flexibility in the trajectory options, so communications geometry is, for most years, simply not a problem.

With the availability of proper geometries established, availability of appropriate frequencies and cost-effective hardware was addressed. Characteristics of Saturn's atmosphere drove the frequency choice for the relay link, and thus the hardware to implement the system. Notably, as discussed in Appendix C, Saturn's lack of significant synchrotron radiation, and relatively benign entry conditions, meant that for most components, standard, off-the-shelf, relatively inexpensive spacecraft-to-spacecraft UHF equipment ("Electra-Lite") would be well matched to the mission needs. The custom-build L-band system required by the Galileo Probe to avoid the worst of Jupiter's synchrotron radiation band, and the resultant higher transmitter power to overcome the increased atmospheric absorption at that frequency, would not be necessary. The Electra-Lite hardware would need only a few minor modifications: removal of the cards associated with the transmitting function for the CRSC receiving system and those associated with the receiving function for the probe transmitting system; and modification of the CRSC receiver's tracking loop bandwidth to accommodate the lower-than-usual data rates involved. The only custom-designed hardware would be the patch transmit antenna on the probe and the 2 x 2 patch array receive antenna on the CRSC. Design rules for these devices are well understood. The study found that for the CRSC, rather than using the same antenna for both the relay and two-way links, separate relay and two-way link antennas are preferable. Use of UHF is consistent with a CRSC receive antenna of reasonable size and with the appropriate combination of antenna gain and beamwidth. At a transmitted power of only ~8.5 W (about 1/3 that of the Galileo Probe), this system easily delivers 500 bps relay link performance (about three times that of the Galileo Probe), even at communication distances larger than those typical of the science mission trajectories examined in the study.

The CRSC-to-Earth link, both uplink and downlink, would be best described as standard, with required data rates actually significantly lower than previous missions to the Saturn system. Downlink rates as low as 1 kbps would suffice at any of the DSN-supported frequencies. The trades quickly converged to X-band as the least expensive option, with power needs that would not drive a solar power system to impractical array sizes. For such low data rates, standard, commonly-available, and relatively inexpensive hardware could provide data rates of 1.5 to 2 kbps: X-band telecom system electronics packages, standard X-band LGAs and HGA, waveguides and waveguide switches, etc. It would be possible to increase the downlink data rate using Ka-band equipment, but at significantly increased cost. It would also be possible to implement the same data rate as the X-band system with Ka-band hardware, either by decreasing HGA size or reducing RF power output, but still at *increased* cost over the X-band system.

Trajectories

Trajectory trades for the Saturn probe mission concept separate easily into the three mission phases: launch and transfer to the vicinity of Saturn; Saturn approach and targeting; and the science mission. Launch and transfer to Saturn could use any of a large number of different trajectory types and launch dates, with a range of different characteristics such as cruise duration and Saturn arrival characteristics: arrival date, magnitude and direction of the approach V-infinity vector, etc. The approach and targeting phase is straightforward and essentially the same as for the Galileo Probe mission, with minor modifications to accommodate differences in Saturn arrival characteristics and the details of the science mission trajectories. For the science mission phase, the primary roles of trajectory design are to deliver the probe to a location on Saturn that is scientifically acceptable and provides acceptable entry circumstances (i.e., entry speed and flight path angle) and to optimize the geometry for the probe-to-CRSC data relay.

This study did not attempt to define a "best trajectory" for the transfer to Saturn. The uncertainty in launch date does not allow such a decision now. The "Mission Design: Earth to Saturn" subsection of Section 3, "Technical Overview", details the range of potential launch dates, trajectory options available, and the particular trajectory selected for use for this study. The selected trajectory is propulsion-intensive and thus stresses the CRSC propulsion system, but there were many other options that would have been less stressing. Future studies, conducted when there is less uncertainty in launch dates, should revisit the transfer trajectory trade as a potential avenue for cost savings.

As discussed in Appendix C and in the Telecom subsection above, various fundamental characteristics of the Saturn system and the Saturn probe mission objectives combine to yield great flexibility in choosing the trajectory for the science mission phase. This allowed a design for the science mission trajectories (both probe and CRSC) that yields excellent data relay performance from a relatively low-cost telecom system, probe entry at a site acceptable to the study science team, and entry circumstances well within the performance envelope of current entry systems technologies. The "Mission Design: Science Mission" subsection of Section 3, "Technical Overview," details the trajectory design selected for this study and summarizes how the trajectories would change for different Saturn approach characteristics.

Propulsion

Propulsion turned out to be the most straightforward element of the trades. The only trade aspect greatly affecting propulsion is the Earth-to-Saturn transfer trajectory. For this study the propulsion-intensive ΔV-EGA trajectory was assumed, driving the need for a large and relatively expensive hybrid propulsion subsystem. Hybrid systems have two or more engine systems, at least one a bipropellant system, and at least one a monopropellant system. Depending on the year of arrival at Saturn, there are many other trajectory types, and even other ΔV-EGA trajectories, with significantly smaller mission delta-Vs, which could be flown with simpler and less expensive (by tens of $M) monopropellant systems. But even the hybrid system needed for the study trajectory is not a technology item: the 2.7 km/s mission delta-V is not significantly greater than the Cassini spacecraft's mission delta-V, and is considered "in family."

One propulsion trade involving the Earth-to-Saturn transfer is the trade between chemical-only and SEP. The study found that where an Atlas V 551 would be needed for the study trajectory and chemical propulsion, use of SEP might reduce the launch C3 to the point that an Atlas V 401 would suffice. Bottom-line results of this trade depend on the cost difference between the two launch vehicles and the cost of the SEP system, including the power, thermal, and structures costs. It is possible that for a solar-powered option, the large solar array needed at Saturn might produce sufficient power in the inner solar system to power a SEP system, but there are additional issues with this approach. The light intensity and temperatures in the inner solar system are such that the output characteristics of an individual cell (such as cell voltage) are different from those under LILT conditions. A solar array to handle both power scenarios would need to be reconfigurable, with varying numbers of cells in each "string" to match the lighting levels, temperatures, and string output to the power needs. This could increase the complexity and thus the cost of the array. This trade should be revisited in a subsequent, more detailed point-design study, that could propagate all these sensitivities over all the CRSC subsystems, for a higher-fidelity assessment of the impacts on the entire flight system and project.

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 simplified version of (i.e., would measure fewer chemical species than) the mass spectrometer flown on the Galileo Probe mission, and would have strong heritage from that design. 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 two sets of sensors for measuring temperature and pressure, and a 3-axis accelerometer. Data from these sensors would also be used to properly contextualize other instrument measurements. The data streams from all 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 combined data rate allocated for the two 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 wish 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. Based upon information provided to the study science team about these instruments by NASA instrument experts, this study used slightly higher power dissipation figures than used by the 2008 study. The high level of heritage for these instruments prompts a lower contingency posture as shown in the table.

Table 3-1. Strawman 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. Strawman Atmospheric Structure Instrument

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. Strawman Payload Mass and Power

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont. (Carried at System Level)	MEV (W)
MS	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

This study did not perform a full parametric flight system design. Instead, it used the parametric flight system design from a 2008 design study [8] as a starting point, and made changes as needed to the subsystems specifically targeted in this study's trades: power, telecom, and propulsion. Trajectory trades do not enter directly into the flight system, but manifest indirectly in the affected subsystems. High-level characteristics of the carrier-relay spacecraft (CRSC) and probe concepts are summarized in Tables 3-4 and 3-5, respectively.

The proposed flight system concept is composed of two major flight elements: the CRSC and the atmospheric probe. The CRSC would serve two primary functions: 1) transfer and support of the probe from launch to a specified impact trajectory at Saturn; and 2) probe data relay, consisting of reception and onboard storage of the probe's data until it loses the radio link with the probe, followed by many-times redundant downlink of those data to Earth. Aside from its science function the probe must survive atmospheric entry, so its aeroshell must protect its descent module from the extreme entry environment and deploy to allow the descent module to collect and relay the science data. Performance characteristics of both CRSC and probe are such that high heritage hardware could be used to reduce cost (and cost uncertainty) and reduce mission and implementation risk.

Design of the Saturn entry probe is largely modeled on the Galileo Probe to Jupiter, with modifications for the more benign entry conditions at Saturn and a smaller science payload. Accommodation of the science instruments would be similar to that of the Galileo Probe, but is simpler because the smaller number of instruments would simplify integration and test.

Reflecting its relatively simple function, the CRSC design is straightforward, emphasizing low cost but accommodating a long-duration mission to Saturn. Its subsystems would be redundant only in the most critical components, consistent with a NASA New Frontiers Program mission. The mass capability of the launch vehicle would provide a large mass margin, so no effort (or cost) would need to be expended on light-weighting. Assuming NASA completes its planned flight qualification of the ASRG, no CRSC subsystem, whether ASRG powered or solar-powered, would need space qualification. The following subsystem summaries give more detailed descriptions of the CRSC's subsystems. The first three listed, Power, Telecom, and Propulsion, were customized for this study, while the rest describe the subsystem designs from the 2008 design study [8].

Power

The electrical power subsystem would use dual string power electronics with the second string 'cold,' i.e., not powered, unless there is a fault in the primary string. This study used power modes and their power demand estimates from the 2008 study. Those estimates are considered representative (with some conservatism) at the system level for a Saturn probe mission.

Power generation for the RPS option would be provided by two ASRGs providing a total of 262 W_E seven years after launch, with two 16 A-hr (each) Li-ion batteries for load leveling and a third battery to meet single fault tolerance requirements. The ASRGs would power the flight system during cruise and keep the batteries charged. During probe data relay and data downlink the ASRGs and batteries together would power the CRSC. One side of an ASRG could fail and power would still be sufficient to recharge batteries in quiet cruise. Per the PSDS Ground Rules, the ASRGs are assumed to be flight qualified by the launch date. The remainder of the power subsystem would consist of high heritage components.

The solar-powered option would use a LILT-tolerant solar array. A solar array sized to provide power equivalent to the EOM ASRG output was estimated to be ~90 m^2, about twice the area of the Juno arrays. This area estimate includes additional margin to account for uncertainties in individual cell performance under LILT conditions, but does not include the potentially much greater impact that might result from additional thermal control requirements in the absence of ASRG waste heat. These would require additional electrical heater power, RHUs, or a combination in the solar implementation. Further assessment in a focused point-design study will be required to better determine an optimum solar array area. A solar powered implementation, like the RPS-based implementation, would use secondary and possibly primary batteries for operations during the science mission.

The probe's descent module would be powered by battery alone. Primary batteries would power the instruments and avionics from wake-up to end of mission. A thermal battery would power the pyros for jettison of the heat shield and parachute deployments.

Telecom

The CRSC would have two separate telecom systems. One is the relay link system for receiving data transmitted by the probe, and the other is the two-way, DTE system for downlinking data to Earth and for receiving uplinked data, commands and command sequences, etc. The two-way system would satisfy the low data rates (1.6 kbps down, 1 kbps up) using standard, redundant X-band design and hardware for deep space missions, reducing cost as compared to a Ka-band system. The UHF relay link system would use a 2×2 patch array MGA and an Electra-Lite proximity radio, with the unneeded transmit cards removed and the tracking loop bandwidth adjusted for the lower-than-standard data rates. The patch array MGA would require a straightforward engineering development, while the rest of the telecom design is high heritage.

The probe telecom system would transmit to the CRSC via a transmit-only Electra-Lite UHF radio, transmitting ~8.5 W RF (about 1/3 of the Galileo Probe transmitter's RF power) through a single patch antenna on the upper face of the descent module. The relay link supports data rates of 500 bps.

Propulsion

The propulsion subsystem would be a hybrid system, with a large bipropellant main engine for large maneuvers, 8 monopropellant thrust vector control engines, 4 spin control thrusters to spin the entire flight system for probe release, and 12 coupled monopropellant thrusters for attitude control and small maneuvers. The propulsion subsystem hardware design has high heritage, with no need for development or delta qualification. The large delta-V requirement for this system, ~2.7 km/s, is a result of the Earth-to-Saturn transfer trajectory chosen for the study. Other trajectory types might decrease the delta-V budget by nearly two orders of magnitude, allowing use of a much simpler and less costly monopropellant-only system.

ACS

The 3-axis stabilized CRSC would use high-heritage hardware and algorithms. Redundant star trackers and IMUs would perform precision inertial attitude determination, with sun sensors for safing. The propulsion system's coupled monopropellant thrusters would provide attitude control. The entire flight system would spin up for probe release, providing spin attitude control for the probe during its post-release cruise. A system of three accelerometers, part of the ASI science instrument package, would provide descent module attitude sensing during entry and descent.

Mechanical

The CRSC would consist of a hexagonal, modular (bays), carbon-fiber composite frame that would house the central bipropellant fuel and pressurant tanks and avionics. The only mechanisms are the solar array deployment mechanisms (in the case of the solar powered option) and the probe release mechanism. The mechanical design has high flight heritage.

The entry probe would consist of the descent module structure that would carry the instruments, avionics, main parachute, and an aeroshell. The aeroshell structure would support the carbon phenolic thermal protection system, a drogue parachute, and mechanical mounting points for the descent module and for mounting the probe on the CRSC. The probe design relies heavily on Galileo heritage.

Thermal

The CRSC thermal control subsystem would consist of a combination of active and passive thermal control elements. For either ASRG-powered or solar-powered options, both the CRSC and the probe would rely on RHUs for passive heat sources. Use of RHUs on the CRSC for the solar-powered option would considerably reduce the electric power that would be needed otherwise (for electric heaters), reducing size, mass, and cost of the solar arrays. The RPS option would use waste heat from its ASRGs for bus and propellant tank heating through a capillary-pumped loop heat pipe system. For both options, the primary thermal design would be supplemented by active elements such as louvers and additional electric heaters, and by passive elements such as MLI blankets and bus structural components used as thermal radiators. Aside from the ASRGs, the thermal design would use high flight heritage components.

The probe thermal control subsystem would consist of high-heritage passive components such as MLI blankets and RHUs. Since the design penetration depth in Saturn's atmosphere is only the 10-bar level, where temperatures are a relatively mild 10 to 20°C, no phase change material would be needed.

CDS & Flight Software

The CRSC's CDS subsystem would consist of high flight heritage components and is a fairly simple design, based on JPL's Multimission System Architecture Platform (MSAP) technology and the BAE RAD750 processor. This system, designed as part of the 2008 study, might be oversized for the current study's mission, since the 2008 study included an IR imaging instrument on its CRSC, greatly increasing the volume of science data to be handled. The CRSC system would be dual redundant with a cold backup.

Table 3-4. Conceptual CRSC Characteristics

Carrier Parameters	Value/ Summary, units
General	
Design life, months	72
Structure	
Structures material	Aluminum/titanium/ composite
Number of articulated structures	0
Number of deployed structures	1 (RPS option), 2 (solar option)
Thermal Control	
Type of thermal control used	RHUs/electrical heaters (solar option) Capillary pumped loop heat pipe using ASRG waste heat (RPS option)
Propulsion	
Estimated delta-V budget, m/s	2700
Propulsion type and associated propellant	Hybrid bi-propellant and mono-propellant

Carrier Parameters	Value/ Summary, units
Number of thrusters and tanks	One 890 N bi-propellant engine Four 22 N engines Twelve 0.9N ACS engines Two propellant tanks, one pressurant tank
Specific impulse of each propulsion mode, seconds	329, bipropellant; 230, mono-propellant
Attitude Control	
Control method	3-axis
Control reference	Inertial
Attitude control capability, degrees	0.25
Attitude knowledge limit, degrees	0.125
Agility requirements	<1°/min
Articulation/#–axes	N/A
Sensor and actuator information	Star-tracker, IMU, Sun Sensors, 0.9N thrusters
Command & Data Handling	
Flight element housekeeping data rate, kbps	0.0005
Data storage capacity, Mbits	2000
Maximum storage record rate, kbps	2
Maximum storage playback rate, kbps	2
Power	
Type of power source	RPS or solar
Science mission average power consumption, watts	265
Battery type	Li-ion
Battery storage capacity, amp-hours	32

Table 3-5. Conceptual Probe Characteristics

Probe Parameters	Value/ Summary, units
General	
Design Life, months	72 (< 1 month active, 71 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	
Flight Element housekeeping data rate, kbps	0.0005
Data storage capacity, Mbits	2000
Maximum storage record rate, kbps	2
Maximum storage playback rate, kbps	2

Probe Parameters	Value/ Summary, units
Power	
Type of power source	Primary Batteries
Number of active power sources	3
Number of on-orbit spare power sources	2
Expected power generation at Beginning of Life (BOL) and End of Life (EOL), watts	BOL = >212
On-orbit average power consumption, watts	212
Battery type	Li-SOCl2; Thermal
Battery storage capacity, amp-hours	20

Technology Description

Power

Both RPS and solar power were considered as possible alternatives for powering the CRSC. The RPS used for the study was the ASRG currently under development by NASA, the DoE, and industrial partners. Performance, mass, and cost figures used in the study were specified in the PSDS Ground Rules document [2]. If that development adheres to its current schedule, the ASRG would be flight qualified in time for missions flying under this PSDS; thus, for those missions, the ASRG would not be a technology development. The solar cell technology used for the solar option was triple-junction GaAs cells without concentrators, on standard (but lightweight) rigid structures. To populate the large arrays with solar cells of acceptable LILT performance, the study assumed a cell selection program that involves testing *every single cell* under Saturn-like conditions. This would allow fabrication of the arrays without developing any new technology. Avoiding such an expensive program would require some form of technology development, whether it is research that yields better production processes, or entirely new cell types or chemistries, or some other approach.

Telecom

The study found that using relay communications to send the data from the probe to the CRSC and then to Earth would not be a particularly challenging problem. No technology developments would be needed. The probe-to-CRSC link could use off-the-shelf Electra-Lite UHF equipment with few modifications, all minor. Standard X-band equipment would be cost-effective for the CRSC-to-Earth link.

Carbon Phenolic

A probe entering Saturn's atmosphere directly from approach on a typical Earth-to-Saturn trajectory would enter at a speed, relative to Saturn's atmosphere, of ~26 km/s or higher. The trajectory used in this study has the probe enter at ~27 km/s. The extremely harsh environment generated by this hypersonic flow would require high-performance thermal protection system (TPS) materials to allow the descent module to survive entry.

Atmospheric entry at Saturn is more benign than atmospheric entry at Jupiter, where entry speeds start at ~47.3 km/s for ideal equatorial entry, and can increase from there; however, despite the factor of 10 decrease in peak heating rate, the heating environment is still sufficiently harsh that only the highest-performance ablative TPS material currently available, carbon phenolic, would suffice. Although this is the same material used on the Galileo Probe, for a Saturn probe the material does not need to be of such exquisite quality as the Galileo Probe's. That probe's entry conditions were at the very edge of the carbon phenolic performance envelope, while Saturn entry conditions are well within its "comfort zone." A narrowly defined, tightly controlled manufacturing process was needed for the Galileo Probe carbon phenolic, including a specific type of rayon cloth feedstock that is no longer manufactured. Without expensive restart of a rayon production line, available feedstock is limited to quantities in storage. The less challenging environment of a Saturn entry allows considering alternate sources of carbon phenolic, such as that being used, in fairly large quantities, in the manufacture of solid rocket motor nozzles.

Another aspect of carbon phenolic heat shields is testing and qualification. This is now a problem for Jupiter entry, since the Giant Planet Facility used for testing the Galileo Probe heat shield materials is no longer operational; however, other currently existing facilities can test materials under conditions appropriate for Saturn entries up to 30 km/s (Ethiraj Venkatapthy, private communication). This is important because it allows testing and qualification of the alternate-source carbon phenolic.

Propulsion

The fundamental concept of a Saturn entry probe is not propulsion-intensive. Targeting and deployment of the probe on an accurate entry trajectory, and retargeting of the CRSC by the divert maneuver, could all be done with significantly less than 100 m/s of delta-V. It is the Earth-to-Saturn transfer trajectory that could, in some cases, drive up delta-V requirements until they become a challenge. This is the case with the trajectory used for this study, with a total delta-V requirement of some 2.7 km/s, slightly more than that of the Cassini/Huygens mission. This appears to be among the most demanding of the "2-year ΔV-EGA" trajectories to Saturn with opportunities essentially every year, so it is something of a stressing case: if the mission could fly on this trajectory, the propulsion system for any other trajectory should be less challenging and less expensive. Use of a less demanding trajectory is one avenue for cost savings in subsequent studies.

A delta-V of 2.7 km/s is not a technology driver. This delta-V is in family with the Cassini spacecraft capability; however, it does require a large and fairly expensive bipropellant propulsion subsystem (relative to an all-monopropellant subsystem). Since it involves multiple large maneuvers with periods of many months between, it would require positive isolation of the oxidizer and fuel pressurization lines, either by valve ladders or by separate pressurant tanks, both of which are considered standard practice techniques. The actual propulsion system would probably be a hybrid system, using the bipropellant engine(s) for the small number of large, high-delta-V maneuvers, and other monopropellant engines for smaller maneuvers and attitude control.

Concept of Operations and Mission Design

Concept of Operations

The three high-level Saturn probe mission concept phases—launch/transfer, approach and targeting, and science mission—all have been demonstrated in previous missions and thus involve no new operations challenges. Multiple options exist for all phases, especially the launch/transfer phase.

In all cases, the flight mission would begin with launch, most likely from one of the launch complexes at Cape Canaveral, Florida. The study identified the Atlas V as the most likely launch vehicle, with generous launch margin indicated on the Atlas V 551 for the reference ΔV-EGA trajectory.

The "Mission Design" section below details the many trajectory options for the launch/transfer phase. None of these trajectory types would require new operations procedures. This study selected as its reference trajectory a 2-year ΔV-EGA trajectory for its combination of launch capability, flexibility, and short transfer duration, 6.3 years from launch to Saturn arrival. This particular trajectory includes three sizeable propulsive maneuvers of >800 m/s each: a deep space maneuver (DSM) required of a ΔV-EGA trajectory, a powered flyby maneuver immediately after perigee of the Earth flyby, and a deep space "broken plane" maneuver ~8 months after the Earth flyby.

With one exception, operations during the transfer phase should not deviate significantly from processes already demonstrated in multiple predecessor missions. Procedures for such operations as aim-point biasing for Earth flybys (used when nuclear payloads are involved), TCMs, DSMs, and navigation are well understood. The exception is the powered Earth flyby, which to date has not been used for a NASA science mission. It would combine an Earth flyby with a critical maneuver, which requires continuous communications coverage. Many other candidate trajectories do not involve a powered Earth flyby, so this complication would not apply to them. Periods of quiescent operations between events might have

DSN contacts once every two weeks. Preparations for events such as DSM, TCMs, etc., and monitoring afterward, would increase the contact frequency. The transfer phase would deliver the combined probe and CRSC to Saturn approach, ready to begin the approach/targeting phase.

The approach/targeting phase would begin upon handoff from the transfer phase, three to four months before probe release, which could be one to five months before arrival. This phase has many similarities to the equivalent phase of the Galileo Probe mission. Initial tasks include increased navigation activities, TCMs, probe and CRSC systems checks, and operations readiness tests (ORTs) for the operations team. The TCMs would place the combined spacecraft on the probe's approach and entry trajectory, for spin-up and release at the proper time. Once released, the probe would continue on a ballistic trajectory, without intervention from the CRSC or the ground. All post-release events on the probe would be pre-programmed and driven by an event timer and g-switches. Upon probe release there would be post-release navigation checks on the CRSC, a divert maneuver to place the CRSC on the proper trajectory to perform its data relay function, and TCMs as needed to maintain that trajectory.

A few (two to four) hours before probe entry, the approach/targeting phase would end and the science mission phase would begin. The CRSC would power up its relay radio receiver and turn to point its probe relay antenna to the entry site. After the probe's 5-minute entry heating and deceleration period, near the 0.1-bar pressure level, the probe would deploy a drogue parachute that would help to jettison the aeroshell and open the main parachute, beginning primary data acquisition and radio relay to the CRSC. The CRSC would store multiple copies of the data in onboard memory. The descent module would reach the nominal end of mission at the 5-bar level, some 55 minutes later and 250 km deeper than the beginning of transmissions. Since the descent module would be designed for the 10-bar level and most likely would survive well past the required 5-bar level, the CRSC would continue to point at the entry site and receive the probe signal for ~15 minutes after the nominal end of mission, continuing to store data in onboard memory for relay to Earth.

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, it could be transferred to the ground in slightly more than 20 minutes. Multiple copies would be downlinked in the DSN pass immediately after the probe descent. If one of the RF antennas, either the HGA for downlink or the probe relay antenna, were to be equipped with a one-axis gimbal, it might be possible to perform bent-pipe relay of the data to Earth in real time, in addition to later playbacks. This study did not use that option, preferring instead the less expensive store-and-forward architecture alone. Although not generally the case, for some trajectories there might be a sun eclipse and Earth occultation by Saturn soon after the probe's mission ends, with attendant increased operational complexity. This would require continued downlink of data copies after the eclipse period ends, and might require engineering attention to surviving the eclipse's thermal effects and, for the solar powered option, loss of solar power. This study did not address eclipse effects because most acceptable trajectories can avoid eclipses altogether without significant impact on mission performance (see "Mission Design: Science Mission").

At EOM, there would be no stressing operations requirements. The CRSC would be on a flyby trajectory, so unlike the Galileo spacecraft it would perform no orbit insertion maneuver, continuing on a solar system escape trajectory for spacecraft disposal.

Mission Design: Earth to Saturn

The study's NASA Point of Contact, Len Dudzinski, suggested that NASA expects two New Frontiers Program AOs in the decade of interest, released every five years after the current cycle's 2009 AO release. This places nominal project starts for those cycles in 2016 and 2021, approximately, with launches as early as 2020 or as late as 2029. There are no advantageous JGA opportunities for transfer to Saturn in that time period, so this study examined other options.

Even without considering JGAs, there are many different types of Earth-to-Saturn transfer trajectories, with a large range of launch C3s, typically 9–50 km^2/s^2. Launch on a direct trajectory from Earth to Saturn has a C3 greater than 100 km^2/s^2. These were not considered in this study. Other trajectory types, with various advantages and disadvantages, include multiple inner solar system gravity assists (ISSGAs; usually using Venus and Earth) and ΔV-EGA trajectories that would use a single Earth gravity assist after a fairly large DSM of ~400 to 1000 m/s delta-V. Those using multiple ISSGAs, especially ones launching to Venus for the first gravity assist, would have the lowest launch C3s (9 to 20 km^2/s^2) and thus have high launch mass capability for a given launch vehicle. However, they generally have longer transfer times, which, coupled with multiple gravity assists, drives up operations costs, and the opportunities are somewhat sporadic in time. Some, but not all, could accommodate Saturn being significantly out of the ecliptic plane. For most of these opportunities, the long transfer durations, sporadic launch window occurrences, and C3 variability from one opportunity to the next make them unattractive options, but a few might be considered under some circumstances. ΔV-EGA trajectories would feature shorter transfer times, typically simpler operations, and launch opportunities essentially every year. However, they would have larger launch C3s that would reduce launch mass capability. Also, their Earth flyby approach vector, in the ecliptic plane with relatively large V-infinity, yields less capability for accommodating large out-of-ecliptic excursions, a deficiency that sometimes must be mitigated by significant additional propulsion. Those with the shortest transfer times, as little as 6 years, are the 2-year ΔV-EGA trajectories, so named because the Earth gravity assist occurs ~2 years after launch, with C3 ~25 km^2/s^2. At the high end of the C3 range are 3-year ΔV-EGA trajectories with C3 ~50 km^2/s^2 and transfer times typically about 1 year longer than for the 2-year ΔV-EGAs. These have the least capability for accommodating out-of-ecliptic excursions.

This study chose a 2-year ΔV-EGA reference trajectory. Preliminary estimates of the spacecraft mass suggest it would not be large, ~1 metric ton (dry) including the entry probe, so low-C3 trajectories are not critical. This trajectory is something of a “stressing” case because it has a large total delta-V budget. In addition to the usual DSM, there are two more maneuvers of almost the same delta-V magnitude as the DSM: a “powered flyby” maneuver that could occur just after perigee of the Earth flyby, and a “broken-plane” maneuver that would accommodate Saturn’s out-of-ecliptic position at arrival. Total delta-V for this trajectory would be almost 2.6 km/s. Delta-V for the Saturn approach and targeting phase raise that to nearly 2.7 km/s, requiring a fairly large bipropellant propulsion system that potentially could offset the savings from the short six-year transfer. Figure 3-1 illustrates this trajectory and gives dates for the major events, plus delta-Vs and Saturn arrival conditions. Launch on May 21, 2020, would be to a C3 of 27 km^2/s^2, which would yield the two-year Earth return trajectory. The 885 m/s DSM on May 16, 2021, would reduce the perihelion, thus raising the approach V-infinity for the Earth flyby on March 21, 2022. Perigee for that flyby would be at an altitude of 300 km, demonstrated by the Galileo mission and easily achievable using the Cassini/Huygens mission’s phased targeting approach for nuclear safety. Immediately after perigee the 843 m/s powered flyby maneuver would provide the additional departure V-infinity needed to reach Saturn. The final large maneuver, the 835 m/s broken-plane maneuver on November 16, 2022, would rotate the transfer orbit plane from the ecliptic plane to Saturn’s heliocentric orbit plane. Arrival at the Saturn B-plane would occur on May 20, 2026, with an approach V-infinity vector of magnitude 7.377 km/s, and direction 15.9 degrees south of Saturn’s equatorial plane. Assisted by the CRSC’s large propulsion system, an Atlas V 551 could deliver 1700 kg to Saturn approach with this trajectory, yielding a substantial launch mass margin. The Saturn approach V-infinity, while larger than that of many other trajectories, would still not be so large that it would have a significant impact on the probe entry speed, the propellant needed for targeting and divert maneuvers, or the CRSC flyby trajectory. This approach trajectory would tie into the approach/targeting phase of the mission.

A fully comprehensive transfer trajectory search was beyond the schedule scope of this study. Also, circumstances for a given programmatic opportunity might make aspects of multiple ISSGA trajectories attractive and thus a better option than the ΔV-EGA trajectories. Future studies, especially ones focusing on particular programmatic and launch opportunities, should perform a more detailed examination of trajectory space.

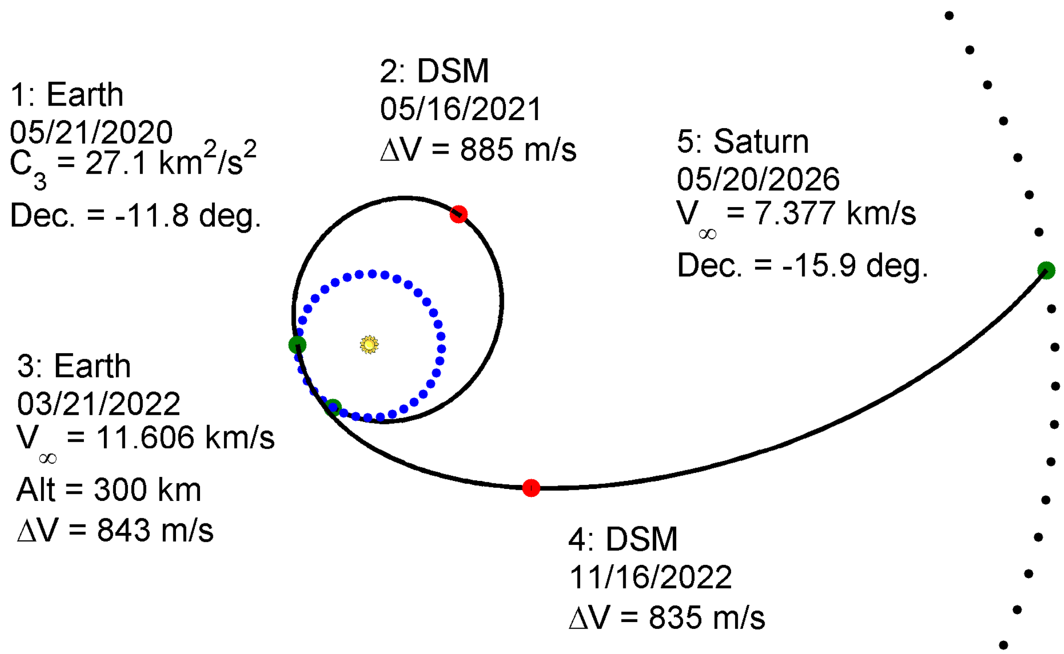


Figure 3-1. Reference Mission Transfer Trajectory

Mission Design: Science Mission

This section treats two phases of the Saturn probe mission concept: the approach/targeting phase and the formal science mission phase. The approach/targeting phase would deliver the two flight elements to the locations needed to perform the science mission. An important result of this study's analyses is that for most arrival dates there is significant flexibility in choosing trajectories for the probe and CRSC science missions. The lack of any competing requirements, such as accommodating an orbit insertion maneuver or a satellite flyby, allows optimization for the probe mission only, a significant simplification from the Galileo Probe mission.

The approach/targeting phase would begin four to nine months before arrival at Saturn. It would include probe release, which could be one to approximately five months before arrival, navigation and targeting activities that would begin three to four months before probe release, and the CRSC's divert maneuver one to two weeks after probe release. Initial radiometric navigation activities (using the DSN) would establish the approach trajectory, and one or two TCMs would then correct the trajectory to that needed for proper probe entry into Saturn's atmosphere. The delta-V for these TCMs would be part of the mission's statistical delta-V budget. Further navigation activity would verify the proper trajectory, leading to probe release. After probe release, a deterministic CRSC deflection maneuver would retarget the CRSC to its desired flyby trajectory, adjusting both the path and the timing of the flyby for its data relay task. For probe release one month before arrival, the baseline for this study, the delta-V for the divert maneuver would be ~55 m/s, with additional statistical delta-V for a TCM afterward. Earlier release would decrease the divert maneuver's deterministic delta-V at the cost of poorer probe delivery accuracy, but the delivery accuracy would be sufficient for releases up to several months before arrival. For comparison, the Galileo Probe release occurred five months before arrival at Jupiter.

The probe's trajectory after release would be ballistic, with no further adjustments, and there would be no communication between the probe and the CRSC until the probe entered Saturn's atmosphere. The CRSC would establish the probe's entry attitude and spin the probe, either via a spin-release mechanism or by spinning the entire combined spacecraft for release. This study did not revisit that trade but used the 2008 design study choice of spinning the entire spacecraft. Before release, the CRSC would set an event timer on the probe to initiate the science mission activities.

A few hours before probe entry the approach/targeting phase would end and the science mission phase would begin. The probe's event timer would initiate warm-up activities, first for the primary batteries that power the entire science mission, then for the descent module subsystems, timed so they are ready upon reaching the entry interface. Meanwhile, the CRSC would turn from Earth-point to pointing the relay reception antenna toward the probe entry site. The beamwidth of this reception antenna is such that the probe's entry footprint, which would include all navigation, tip-off, and timing errors associated with probe delivery, is wholly contained within its usable beam. Figure 3-2 illustrates the probe and CRSC trajectory geometries, with communication paths shown for four times spanning the 70-minute communication window. Figure 3-3 shows the variation in range and zenith angle, two parameters critical to the relay link's performance, during the window. Note that the CRSC trajectory's periapse radius would be well inside the outer edge of Saturn's main rings at ~141,000 km, and of course the probe trajectory traverses the main rings' entire radial span. Both vehicles avoid the ring collision hazard by having non-zero inclinations and, on the inbound legs, crossing the ring plane in the clear zone between the F and G rings, a region successfully traversed by Voyager and Cassini. Since the probe would enter Saturn's atmosphere it has no outbound leg, but the CRSC does. It would cross the ring plane again well outside of the hazardous parts of the rings and avoid an eclipse of the sun by Saturn. This trajectory would also avoid all of Saturn's known moons, Titan and Enceladus in particular due to their planetary protection ramifications, and continue without intervention to a solar system escape trajectory for spacecraft disposal (see the Planetary Protection section below). The probe approach geometry for this trajectory would allow probe entries at latitudes between 20 and 25 degrees south of Saturn's equator, a range the science team deemed acceptable. Table 3-6 provides parameter values for key elements of the reference mission design. Masses are representative of an RPS implementation for the CRSC; mission operations and ground data systems parameter values are taken directly from the 2008 Saturn probes report [8].

The study found that for most arrival years it would be a fairly simple task to find combinations of probe and CRSC trajectories that yield relay link windows of 70 minutes or more with communications ranges less than 75,000 km and as little as 50,000 km. The trajectories selected for this study serve as a good example. For those Saturn arrival geometries whose approach asymptotes have very low declinations, it might be difficult to find trajectories that retain these advantageous communications geometries while still avoiding ring and moon hazards, Saturn eclipses, etc. Subsequent studies, especially those targeting particular arrival time windows, should examine the Earth-to-Saturn trade space carefully, including the Saturn arrival geometries.

This study concludes that for most Saturn arrival dates there would be significant trajectory design flexibility for mission architectures using relay communications. Long probe-to-CRSC communications windows, 70 minutes or more in duration, would not be difficult to achieve with relatively low communications ranges and low probe-to-CRSC off-zenith angles, yielding relatively high data rates with low-power telecom systems. In addition to flexibility in selecting the minimum range and minimum zenith angle, some adjustments are possible in the relative timing of those events for better optimization of mission performance.

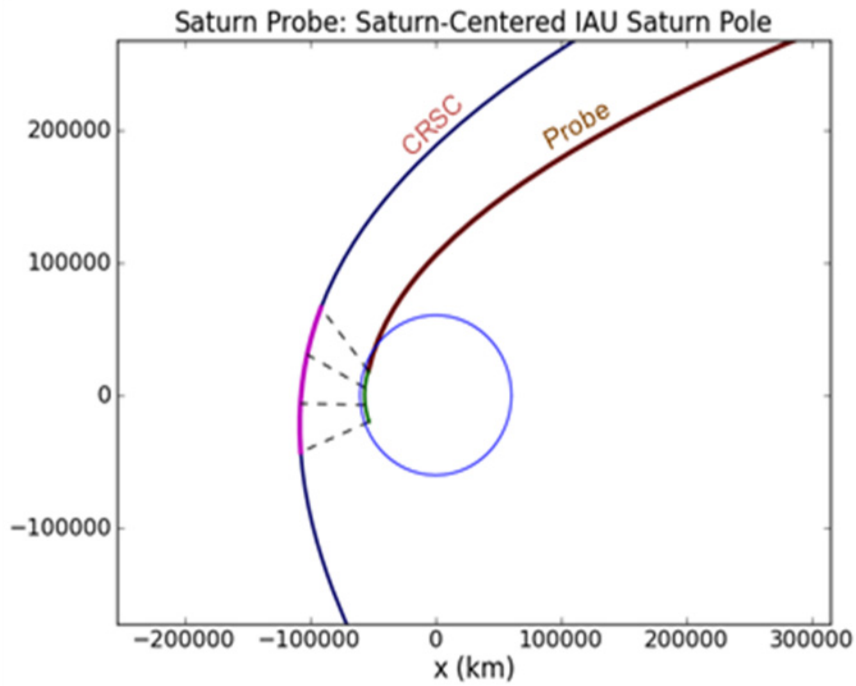


Figure 3-2. Reference Probe Entry and Saturn Flyby Trajectories

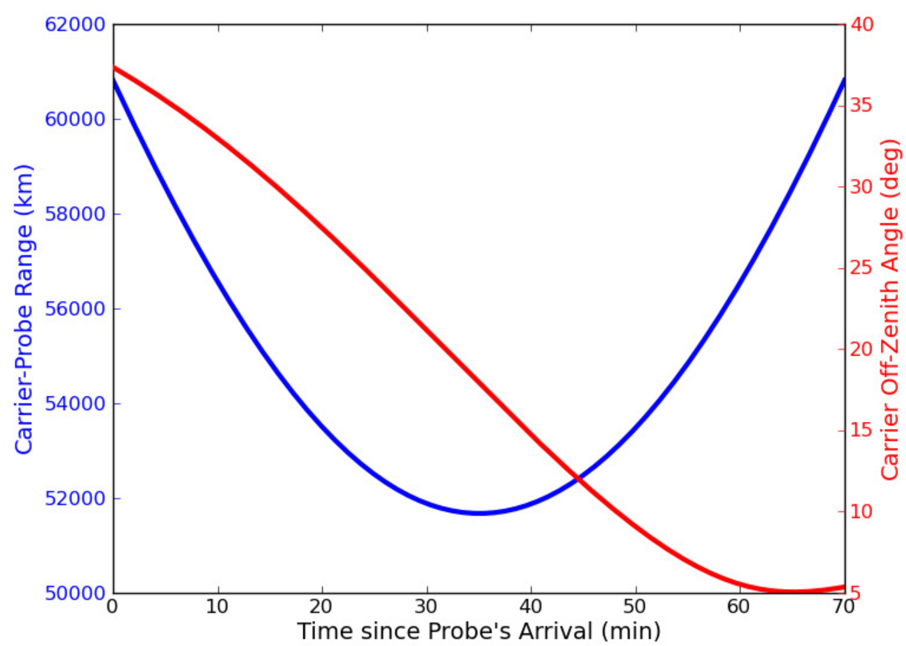


Figure 3-3. Variation in Range and Zenith Angle During Communication Window

Table 3-6. Study Reference Mission Design

Parameter	Value	Units
Orbit Parameters (apogee, perigee, inclination, etc.)	—	—
Mission Lifetime	72	months
Maximum Eclipse Period	0	min
Launch Site	KSC	—
Total Flight Element #1 (CRSC) Mass **with** contingency (includes probe and instruments)	1060	kg
Total Flight Element #2 (Probe) Mass **with** contingency (includes instruments)	230	kg
Propellant Mass **without** contingency	2071	kg
Propellant contingency	7	%
Propellant Mass **with** contingency	2216	kg
Launch Adapter Mass **with** contingency	(Included in Dry Mass)	kg
Total Launch Mass	3276	kg
Launch Vehicle (use the Options specified in the NASA Ground Rules)	Option 5	Type
Launch C3	27	km^2/s^2
Launch Vehicle Lift Capability	3885	kg
Launch Vehicle Mass Margin	609	kg
Launch Vehicle Mass Margin (%)	16	%

Planetary Protection

The simplicity of the proposed mission's operations at Saturn provides for significant flexibility in addressing planetary protection issues. This flexibility means meeting expected planetary protection requirements is likely a matter of analysis rather than spacecraft implementation. This study assumed that meeting planetary protection requirements would incur no significant cost impacts. NASA's Planetary Protection Officer has not yet categorized Saturn, but compares it with 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 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 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.

Procedures for aim-point biasing for Earth flybys (used when nuclear payloads are involved) are well understood and within risk targets.

Risk List

The Saturn probes trade study identified high level mission and programmatic risks that could be considered design drivers for subsequent, more detailed mission point design studies. The study did not perform a quantitative risk assessment. This is in part due to the study guidelines provided by the science team that called for no substantial new technology development in order to minimize risk.

The study team identified the following risks. Follow-on studies should consider these risks as a part of their study.

1. Programmatic risk of not having sufficient plutonium to fuel ASRGs. Mitigation might include the use of LILT solar array technology, but further evaluation would be required to ensure feasibility.
2. Risk (potentially either implementation or programmatic) of not being able to use rocket nozzle carbon phenolic materials for the TPS. If unable to use that material, heritage carbon phenolic based on the Galileo probe could be used; however, if the Saturn probe heat shield is not identical to the Galileo Probe heat shield, re-qualification might be needed. The impact would be additional cost due to re-qualification and possibly a new (or modified) test facility.
3. Implementation risk of very low yield LILT solar cell production. This is a cost risk due to potential cost overrun of a lengthy testing and selection process and, potentially, the need for over-production to provide a sufficient number of LILT-tolerant solar cells.
4. Mission risk for probe entering a weather-induced, non-representative region of Saturn's atmosphere (i.e., the Galileo Probe problem). This is considered to be a low probability/low impact event because the science measurements needed for this type of mission are not influenced by weather as the Galileo Probe's science observations were.
5. Mission risk for failure of the probe-to-CRSC relay link. The link would be single-string, creating a potential single point of failure. Risk is judged to be low due to the Saturn probe relay link ranges being smaller than the Galileo probe, the Saturn radiation environment being orders of magnitude less intense than at Jupiter, and previous experience using similar technology.
6. Mission risk for failure of a critical deployment (probe release) after more than six years in space.

4. Development Schedule and Schedule Constraints

High-Level Mission Schedule

Because this was a limited-scope trade study instead of a comprehensive point design study, no custom project schedule was generated. The study assumed a standard New Frontiers Program development schedule: 9 months Phase A, 12 months Phase B, and 43 months Phase C/D, including one month after launch for check-out and commissioning. Table 4-1 shows a feasible set of durations of key phases associated with the New Frontiers development schedule. The flight operations schedule assumed the trajectory and associated events described in the Concept of Operations and Mission Design section. Significant events in the reference Earth-to-Saturn transfer trajectory include: launch in May of 2020, a large DSM for the ΔV-EGA trajectory one year later, an Earth flyby and powered flyby maneuver in March of 2022, a broken plane maneuver in November of 2022, and arrival at Saturn in May of 2026. Probe release could occur one to five months before Saturn arrival; the study assumed one month. Pre-release navigation activities and TCMs for probe targeting could occur in the three to four months before release.

An extended mission is not possible with the reference mission concept because the probe's mission naturally results in its destruction, and there are no instruments on the CRSC. Phase F consists only of a brief period of science data reduction. Enhancements to the reference mission concept that would add instruments to the CRSC could potentially allow an extended mission.

Table 4-1. Key Phase Duration

Project Phase	Duration (Months)
Phase A – Conceptual Design	9
Phase B – Preliminary Design	12
Phase C – Detailed Design	24
Phase D – Integration & Test	19
Phase E – Primary Mission Operations	71
Phase F – Extended Mission Operations	0
Total development time Phase B–D	55

Technology Development Plan

This proposed mission concept 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

Since the estimated schedules are based upon analogies to previous missions for this study, it is not possible to present detailed development schedules. Such specifics are out of scope for a low-CML trade space study and would be generated upon selection of a particular mission architecture for further study as a point design.

Schedule constraints did arise from programmatic factors included in the ground rules of the Decadal Survey. The mission concept was nominally sized for launch in the 2020 timeframe.

5. Mission Life-Cycle Cost

This is a low maturity level concept (CML 3) study. CML 3 cost estimates are at a system level (estimated parametrically or by analogy) and are at a lower level of fidelity than Team X cost estimates.

The cost estimation methodology inherited cost modeling results from the FY08 study [8] that generated the baseline design as a cost estimation baseline and extrapolated those costs to the referenced fiscal year in the NASA Study Ground Rules (FY2015). As needed, mass, power, and cost tables were modified using the results of the trade studies to generate “deltas” to the FY08 baseline. These deltas were applied and reserves modified to conform to the reserves policies specified by the NASA Study Ground Rules to generate a rough cost estimate for the mission concept.

Total mission costs for both the ASRG and solar implementations were estimated to be ~$990M FY15. Phase A-D development costs (~$850M FY15) include the payload system costs ($40M FY15, including probe instruments and payload management); flight system costs ($350M FY15, including descent module, TPS, probe, and CRSC hardware and management); and other costs for project management, operations preparations, ATLO, launch approval for a nuclear payload, reserves, etc. NEPA costs were added using analogies to similar missions. Phase E operations costs were driven by the operations team and DSN tracking costs. The cost of the launch vehicle was not included, consistent with the ground rules for the previous New Frontiers call for proposals. At the level of resolution possible in this study, the cost of the RPS and solar-powered options were found to be roughly equivalent, though uncertainties in implementation will require more detailed point-design studies to determine whether this is a valid result.

The high-level costing provided by this study (consistent with a CML 3 level of fidelity) indicates that the costs for a scientifically viable single-probe mission are consistent with it being a potential New Frontiers Program candidate. The least expensive option would be a shallow probe (to 5 bars, designed to 10 bars). Significant conservatism was exercised during the trade study. More detailed study is justified via a point design study. This would enable better definition of resource requirements, which could open the concept to enhancements such as additional probe payload or multiple probes.

Study cost results reflect architecture options that could address the Tier 1 science objectives. Per the science team’s request, the instrument suite was limited to a mass spectrometer and an atmospheric structure instrument package. A quick cost analysis was conducted to determine whether the addition of a nephelometer and/or a tunable laser spectrometer might be able to address some of the Tier 2 objectives and still fit into the New Frontiers cost cap. The indication from this quick cost assessment was that it was likely to drive mission costs above the cap, so the two additional instruments were dropped from further consideration.

Potential Cost-Saving Options

A number of potential opportunities for cost savings were identified during the study that would benefit from higher fidelity mission concept assessments. Candidate options for more detailed study include:

- The 2008 study from which design and costs were derived was originally a solar-powered mission carrying two probes. Optimizing CRSC design for one probe might result in structures mass savings. Also, optimizing CRSC structures for the ASRG option, rather than inheriting the CRSC structures mass based on LILT solar arrays, might reduce mass and cost.
- Another type of transfer trajectory. The “2-year ΔV-EGA” trajectory to Saturn used in this study is propulsion-intensive, with two additional large maneuvers, so it is something of a stressing case. There are abundant opportunities for other types of transfer trajectories, allowing mission designers flexibility in trading among delivered mass, delta-V, cruise duration, operational complexity, launch window timing, and other transfer trajectory attributes. Future studies, especially those targeting specific time windows, should perform more comprehensive searches for Earth-to-Saturn transfers in the time frame of interest. This should be fertile ground for finding cost saving options.

- Saving delta-V by reducing accuracy of probe targeting and earlier release, thus saving propulsion system cost.

6. Integrated Assessment and Conclusions

The Saturn probe trade study yielded results that indicate further study is warranted. First and foremost, it appears that a single-probe mission designed to penetrate to a depth of 10 bars might be a viable NASA New Frontiers Program candidate. Although there might be some engineering developments needed, no new technology developments would be required to fly this mission.

More detailed implementation studies might confirm this as a New Frontiers candidate and determine the level of resources available for adding Tier 2 science objectives. Also, there are implementation trades that should be analyzed at higher fidelity than possible in this limited-scope study.

A Saturn probe mission, as described in this study, would be simpler and easier to implement and execute than the Galileo Probe to Jupiter in many ways. This can be summarized by three high-level observations: (1) Saturn is an easier destination for probes than Jupiter, (2) the kind of dedicated Saturn probe mission concept studied has fewer science and operations constraints and requirements than the Galileo probe mission, and (3) the studied mission concept has many fewer science instruments than the Galileo Probe mission. Appendix C discusses many of the details supporting these observations.

There could be substantial flexibility in mission design space for this mission. This lends confidence that despite other constraints that might come later, there should be enough mission design space available to accommodate those constraints. The flexibility also helps with management resource flexibility, launch timing, etc. Although the Earth-to-Saturn transfer trajectory assumed for this study is propulsion-intensive, this is not an inherent feature of trajectories to Saturn. There are abundant opportunities for other types of transfer trajectories, allowing mission designers flexibility in trading among delivered mass, delta-V, cruise duration, operational complexity, launch window timing, and other transfer trajectory attributes. Future studies, especially those targeting specific time windows, should perform more comprehensive searches for Earth-to-Saturn transfers in the time frame of interest. This should be fertile ground for finding cost-saving options.

The study found that implementing a telecom system for a Saturn probe mission using relay communication through a CRSC would not be a difficult problem and requires no new technology. Standard spacecraft-to-spacecraft UHF hardware would be sufficient for the probe-to-CRSC link, easily providing data rates of ~500 bps, about 4 times that of the Galileo Probe. Downlink from the CRSC to Earth could use data rates as low as ~1 kbps, but standard, relatively inexpensive X-band hardware could provide 1.5 to 2 kbps. Standard Ka-band hardware could provide higher data rates, but at increased cost. The flexibility in science mission trajectories lends confidence that a wide range of telecom issues could be addressed without significantly impacting the science return.

The use of solar and radioisotope (ASRG) sources was evaluated as a trade in the study. Results of the trade confirmed that the ASRG implementation would be less massive than a solar implementation, but the difference in estimated total mission cost for the two approaches was smaller than the cost resolution possible with this low-CML study. The solar option does appear to be feasible, if augmented by primary or secondary batteries, but the uncertainty in individual solar cell behavior at these extreme LILT conditions compels large design margins and thus large, heavy arrays. However, if ASRGs are unavailable, LILT solar arrays could provide an alternative power system capability to perform such a Saturn probe mission. Assuming NASA and DoE complete the development of the ASRG, neither power source option would require new technology development.

It is likely that Galileo-heritage carbon phenolic TPS material would not be required for a Saturn probe mission. The much lower heating rates resulting from the lower entry speeds would allow considering alternate sources of carbon phenolic, such as that currently manufactured for use in solid rocket motor nozzles. Existing facilities could test such materials under conditions appropriate to Saturn atmospheric entries at speeds up to 30 km/s, covering the range of sufficient speeds with some margin.

This study did not estimate the cost impact of addressing one or more of the Tier 2 science objectives. This impact would vary considerably with the specific objectives being considered. For objectives that might be addressed using the instruments for the Tier 1 objectives, or slight modifications of those instruments, the impact could be quite small, possibly as small as adding one or more science team members. Others would require additional instruments, with potentially significant impact. It might be possible to enhance the mission's science by extending the altitude range of some Tier 1 objectives without altering the flight system. If resource constraints would allow, it might be possible to place one or more instruments on the CRSC for enhanced prime mission science return. This could allow an extended mission in which Mission of Opportunity proposals could be considered.

As discussed previously, two major areas in which continued trade study would be very useful are further evaluation of Earth-to-Saturn transfer trajectories and electric power sources. Depending on the circumstances surrounding different opportunities to fly a Saturn probe mission, different attributes of the different trajectories could vary in importance, so analyses of a wide range of different trajectory types would be useful. For a given programmatic opportunity, comprehensive examination of the trajectories within the programmatic launch window could lead to significant cost savings. More detailed examination of the power source trade is recommended, especially considering the effects of other subsystems back on the power system once a choice is made. For instance, a decision to use solar power might result in the thermal subsystem needing many electric heaters, which could potentially as much as double the spacecraft's total electrical power requirement.

The PSDS white paper, "Entry Probe Missions to the Giant Planets" [3] discusses the significant science return from conducting entry probe missions at the ice giants Uranus and Neptune as well as at Saturn. This suggests the possibility of a campaign to complete entry probe missions at all the giant planets. Entry probes for Uranus and Neptune would be very similar to a Saturn entry probe. Science and measurement objectives also would be similar. Regarding implementation, although the ice giants' masses are significantly less than Saturn's, the combination of their higher densities and slower rotation rates, along with the higher approach speeds necessitated by their larger heliocentric distances, make atmosphere-relative entry speeds there similar to those at Saturn. Their compositions are similar to Saturn's altitudes relevant to hypersonic deceleration. Previous low-CML studies indicate that due to constraints arising from orbital dynamics, ice giant entry probes would be best delivered and supported either by flyby missions, or by large flagship missions with large post-orbit-insertion delta-V capability.

Appendix A. Acronyms

AO	announcement of opportunity
ASI	atmospheric structure instrument
ASRG	advanced Stirling radioisotope generator
BOL	beginning of life
CBE	current best estimate
C&DH	command and data handling
CDS	command and data subsystem
CML	concept maturity level
CRSC	carrier-relay spacecraft
DoE	Department of Energy
DSM	deep space maneuver
DSN	Deep Space Network
DTE	direct-to-Earth
EOL	end of life
EOM	end of mission
FY	fiscal year
HGA	high-gain antenna
IMU	inertial measurement unit
IR	infrared
ISSGA	inner solar system gravity assist
JGA	Jupiter gravity assist
JPL	Jet Propulsion Laboratory
LGA	low-gain antenna
LILT	low-intensity, low-temperature
MEL	master equipment list
MEV	maximum expected value
MLI	multi-layer insulation
MGA	medium-gain antenna
MS	mass spectrometer
MSAP	Multi-mission System Architecture Platform
NASA	National Aeronautics and Space Administration
NEPA	National Environmental Policy Act
NF	New Frontiers
NRC	National Research Council
ORT	operations readiness tests
PI	Principal Investigator
PSDS	Planetary Science Decadal Survey
RF	radio frequency
RHU	radioisotope heater unit
RPS	radioisotope power source
RTG	radioisotope thermoelectric generators
SCIP	solar composition icy planetesimal
SEP	solar electric propulsion
TCM	trajectory correction maneuver
T-P	temperature - pressure
TPS	thermal protection system
TRL	technology readiness level
UHF	ultra-high frequency
∆V-EGA	Delta-V Earth gravity assist

Appendix B. References

[1] Planetary Science Decadal Survey: Questionnaire for Low Concept Maturity Level Mission Study, Science Champion: Dr. Reta Beebe, November, 2009.

[2] "NASA Ground Rules for 2012 PSDS Studies," NASA Headquarters instructions, Revision 2, November 10, 2009.

[3] 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://www8.nationalacademies.org/ssbsurvey/publicview.aspx or http://www.mrc.uidaho.edu/~atkinson/Papers/Publ/OutrPlanPrbsWhiteppr_Final.pdf.

[4] 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.

[5] Atreya, S.K., "Saturn Probes: Why, Where, How?" Proceedings of the 4th International Planetary Probe Workshop, NASA Jet Propulsion Laboratory Document, 2007.

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

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

[8] 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. Comparison of Saturn Probes to Galileo Probe

Certain fundamental characteristics of the Saturn system as compared to the Jupiter system, along with the Saturn probe's mission objectives as compared to the Galileo Probe's (and Orbiter's) mission objectives, contribute to the relative ease and simplicity of the kind of Saturn probe mission examined in this study. This ease and simplicity would have ramifications for the total mission cost, supporting the suggestion that a simple Saturn probe mission would be less costly than the Galileo Probe mission and might fit the New Frontiers Program's resource envelope. The Saturn system characteristics are: 1) Saturn's mass is much less than Jupiter's, 2) Saturn is farther from the sun than Jupiter, and 3) Saturn has a substantial ring system with far more total ring mass than Jupiter's rings. Differences in mission objectives include 1) the Saturn probe science objectives do not involve any other part of the Saturn system except Saturn's atmosphere, so there would be no satellite flybys or other objectives to compete with the probe's mission; 2) the Saturn probe mission would not require orbiting Saturn, so the CRSC would not need an orbit insertion maneuver; and 3) the Saturn probe science objectives require penetration only to the 5-bar level (10-bar level for science margin). Figure C-1 is a flow-down chart showing how the ramifications of these characteristics lead to concrete implementation or operations comparisons between the Saturn probe mission concept and the Galileo mission. The remaining text of this Appendix expands upon the flow-down paths illustrated in Figure C-1. In the text, numbers in curly brackets refer to the numbered boxes in that figure.

Saturn's mass is ~1/3 that of Jupiter but Saturn's lower density results in a radius at the tropopause that is nearly 85% of Jupiter's. This makes Saturn's gravity well much shallower than Jupiter's and makes its gravitational acceleration in the upper troposphere about a third that of Jupiter. The shallower gravity well results in reduced entry speeds {1}, as low as 26 km/s compared to the minimum of ~47 km/s at Jupiter, and this yields significantly smaller entry heating rates {9} and inertial loads {10}. The lower gravitational acceleration produces larger atmospheric scale heights at Saturn, also contributing to less intense entry heating and inertial loads. The larger scale heights come with two disadvantages: the heat pulse duration is longer, requiring more thermal insulation between the descent module and the ablating surface {11}; and, coupled with the lower gravitational accelerations, it makes for longer descent durations {12}.

Saturn is farther from the sun than Jupiter, averaging 9.54 AU to Jupiter's 5.2 AU, decreasing the intensity of sunlight to 30% of that at Jupiter. The added distance means that missions to Saturn require more energetic transfer trajectories to climb farther out of the sun's gravity well, and take longer to get there {13}. But the decreased sunlight intensity means Saturn's troposphere is colder at a given pressure level than Jupiter's, so the lower saturation vapor pressures push the volatile constituents deeper into the atmosphere. Some of those volatiles (in particular, ammonia and water) are the primary radio-absorbing species in giant planet atmospheres. Limiting via condensation the abundance of these absorbers reduces the overhead radio opacity at Saturn at levels above (roughly) the equilibrium base of the water cloud, at about the 15- to 20-bar level {2}, reducing radio communications power requirements and thus contributing to a more favorable communications trade space {17}.

Saturn has its substantial ring system, far more extensive and massive than Jupiter's relatively tenuous rings. Although this places some constraints on trajectories in the Saturn system, avoiding ring collision hazards {14} and data relay geometries that would have signals pass through the main rings {15}, there is a major benefit: the rings damp down the energetic charged particle environment. Abundant trapped ions and electrons at Jupiter have their energies pumped up to tens of MeV. With insufficient ring mass to absorb them, Jupiter accumulates one of the harshest radiation environments in the solar system. Even spacecraft making one-time passes through the Jovian system at distances less than ~15 R_J must design to elevated radiation dose levels, driving up costs. At Saturn, the rings absorb most of those energetic particles, yielding a radiation environment that is orders of magnitude less intense than at Jupiter {3, 6}. This reduced radiation environment allows reducing CRSC costs by using standard parts instead of radiation-hard parts {19}. The lack of radiation "keep-out" zones {5} provides more trajectory optimization flexibility {7}, allowing much smaller data relay link ranges than those of the Galileo link (50,000 to 75,000 km, compared to Galileo's 215,000 to 240,000 km) {8}, longer over-flight periods {18}, and adjustment of other parameters such as the profile of probe-to-CRSC off-zenith angles. Together these provide a less costly trade space among elements of the communications trade space: data rates, required RF power, and cost {17}. This flexibility also mitigates the trajectory constraints mentioned above (green lines from {7} to {14} and {15}). The longer over-flight period mitigates the disadvantage of longer descent durations, shown by the green line from {18} to {12}.

There is another advantage to the reduced radiation environment, indirect but nonetheless substantial. At Jupiter, the energetic charged particles gyrating in Jupiter's magnetic field produce synchrotron radiation at radio frequencies, from above 1 GHz down to a few MHz and lower. The peak of the spectrum is near 300 MHz, where the intensity matches that of a blackbody at ~100,000 K! This RF radiation is noise to a radio receiver and effectively prevents communications at frequencies anywhere near the peak. The Galileo Probe could not use UHF equipment, partly because UHF frequencies are too near the synchrotron radiation peak. It had to use higher frequencies, farther from the peak, near 1.4 GHz (L-band). However, this involves another communications problem previously mentioned: atmospheric absorption of radio signals. At tropospheric pressures and typical spacecraft-to-spacecraft communications frequencies, the RF absorptivities of water and ammonia vary roughly as frequency squared. At the 10-bar level in Jupiter's atmosphere, the RF attenuation at L-band due to the atmosphere overhead is about a factor of 10 larger than that at the typical UHF frequency of 401 MHz. Galileo's choice of L-band was a compromise between decreasing synchrotron noise and increasing atmospheric attenuation with increasing frequency. A Saturn probe mission would encounter insignificant synchrotron radiation {4}, so it would be free to use UHF frequencies {16} where the atmospheric attenuation is much lower, contributing to the favorable data rate/RF power/cost trade space {17}. Standard UHF equipment is readily available and is less costly than L-band equipment.

The Saturn probe science and mission objectives are simpler than those of the Galileo Probe, contributing to reduced mission costs. Tier-1 Saturn probe science objectives would require only two instruments, where the Galileo Probe carried six {22}. Since the Saturn probe mission would be dedicated to the probe, it would not be necessary to place its CRSC in Saturn orbit, so no orbit insertion maneuver would be needed. There are no secondary science objectives outside of the probe's objectives, so there are no influences on the trajectory design for such things as satellite flybys or ring observations. These characteristics contribute to making the Saturn probe baseline trajectory design much more flexible than that for the Galileo Probe mission {7}, in which the orbiter had to perform probe data relay, an orbit insertion maneuver, and an Io flyby, all during the same periapse pass. Another advantage of the lack of an orbit insertion maneuver is that the CRSC would continue on a hyperbolic trajectory similar to a high-delta-V gravity assist trajectory. The CRSC would then depart the Saturn system on a solar system escape trajectory, providing a no-cost spacecraft disposal strategy that would meet planetary protection requirements {20}. Finally, the Saturn probe mission design would have the probe's descent module operate only to the 10-bar level (after adding margin) in Saturn's atmosphere, where temperatures are a mild 280 to 290 K, so the descent module instruments and electronics would not need to withstand high temperatures or other extreme conditions {21}.

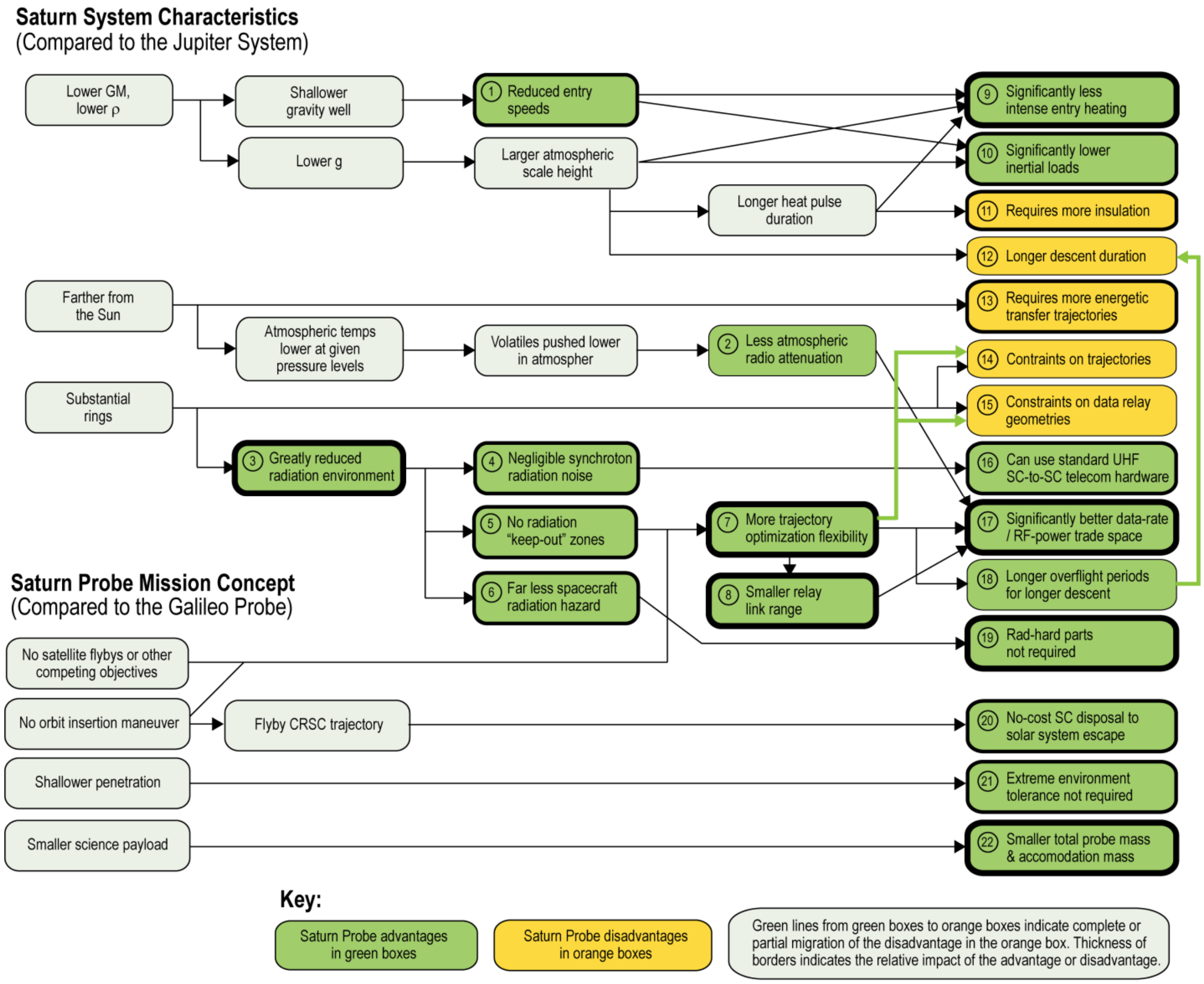


Figure C-1. Comparison of the Saturn Probe Mission Concept with the Galileo Probe Mission