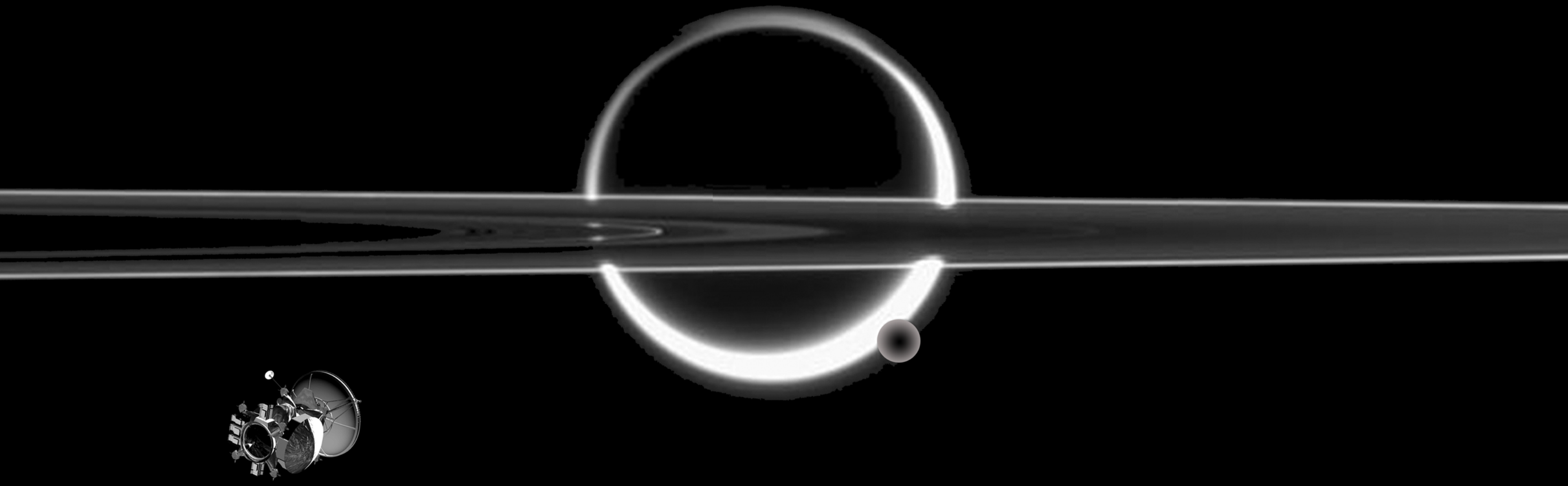
TSSM

Titan Saturn System Mission



NASA/ESA Joint Summary Report

January 16, 2009

Titan Saturn System Mission

A Joint Endeavour by ESA and NASA

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Foreword

In February 2008, ESA and NASA initiated joint studies of two alternatives for a highly capable scientific mission to the outer planets: the Titan Saturn System Mission and the Europa Jupiter System Mission. Joint Science Definition Teams (JSDTs) were formed with U.S. and European membership to guide study activities that were conducted collaboratively by engineering teams working on both sides of the Atlantic. The ESA contribution to this joint endeavor would be implemented as the Cosmic Vision Large-class (L1) mission and the NASA contribution as the Outer Planet Flagship Mission with a launch date in 2020. An ESA Assessment Report and a NASA Final Report have now been completed, focusing on the contribution of each agency to each mission. These will be reviewed by each agency between November 2008 and January 2009 and the agencies plan on reaching a joint decision on the destination for the mission to be announced in February 2009. The Joint Summary Report (JSR) is intended to provide, for each of the destinations, a high level description of the science rationale and goals; the mission concept; the NASA and ESA responsibilities and interdependencies; the role of other space agencies; and the costs, schedule and management approach. It also describes the membership and roles of the JSDT and the engineering study teams that supported them and a guide to the extensive documentation that has been developed for each mission concept. The TSSM and EJSM study teams have worked together to develop a common format for the JSR that enables comparative evaluation of the missions while, at the same time, permitting their individual characteristics to be effectively portrayed.

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Part of the research described in this report was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Research described in this report was also carried out at the European Space Agency.

TSSM

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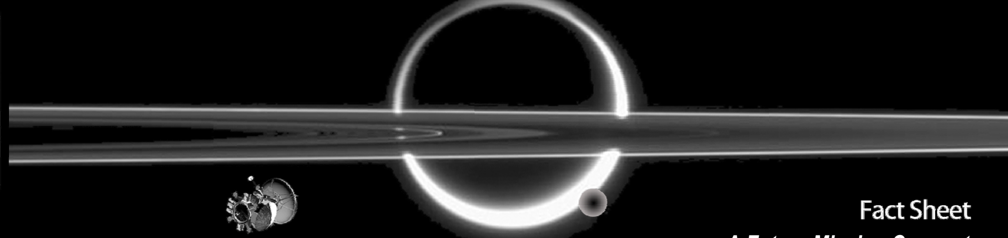


Fact Sheet

A Future Mission Concept

Why TSSM?

Rugged shorelines, laced with canyons, leading to ethane/methane seas glimpsed through an organic haze, vast fields of dunes shaped by alien siroccos…

An icy moon festooned with plumes of water-ice and organics, whose warm watery source might be glimpsed through surface cracks that glow in the infrared…

The revelations by Cassini-Huygens about Saturn's crown jewels, Titan and Enceladus, have rocked the public with glimpses of new worlds unimagined a decade before. The time is at hand to capitalize on those discoveries with a broad mission of exploration that combines the widest range of planetary science disciplines—Geology, Geophysics, Atmospheres, Astrobiology, Chemistry, Magnetospheres—in a single NASA/ESA collaboration.

The Titan Saturn System Mission will explore these exciting new environments, flying through Enceladus' plumes and plunging deep into Titan's atmosphere with instruments tuned to find what Cassini could only hint at. Exploring Titan with an international fleet of vehicles; from orbit, from the surface of a great polar sea, and from the air with the first hot air balloon to ride an extraterrestrial breeze, TSSM will turn our snapshot gaze of these worlds into an epic film.

TSSM Science Goals & Objectives

Goal A: Explore Titan, an Earth-like System

How does Titan function as a system? How are the similarities and differences with Earth, and other solar system bodies, a result of the interplay of the geology, hydrology, meteorology, and aeronomy present in the Titan system?

Goal B: Examine Titan's Organic Inventory – A Path to Prebiological Molecules

What is the complexity of Titan's organic chemistry in the atmosphere, within its lakes, on its surface, and in its putative subsurface water ocean? How does this inventory differ from known abiotic organic material in meteorites and contribute to our understanding of the origin of life in the Solar System?

Goal C: Explore Enceladus and Saturn's Magnetosphere – Clues to Titan's Origin and Evolution

What is the exchange of energy and material between the Saturn magnetosphere, solar wind and Titan? What is the source of geysers on Enceladus? Does complex chemistry occur in the geyser source?

Planning Payload

Orbiter

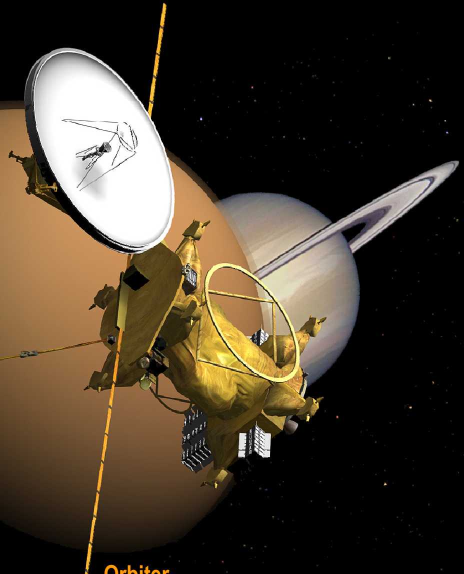
	Orbiter Planning Payload	Instrument Capabilities
HiRIS	High-Resolution Imager and Spectrometer (near IR)	1–6 µm global mapping at 50 m/pixel in three colors. Adjustable spectral editing for surface/atmosphere studies.
TiPRA	Titan Penetrating Radar and Altimeter	>20 MHz global mapping of subsurface reflectors with 10 m altitude resolution in altimetry mode & >10 m depth resolution. Lower data rate sounding mode with ~100 m depth resolution. ~1 km x 10 km spatial resolution.
PMS	Polymer Mass Spectrometer	TOF MS with M /ΔM ~10,000 for masses up to 10,000 Da. From 600 km to upper atmospheric *in situ* analysis of gases and aerosol precursors.
SMS	Sub-Millimeter Spectrometer	Heterodyne spectrometer with scanning mirror. Direct winds from Doppler and temperature mapping from ~200-1000 km altitude; carbon dioxide and nitrile profiles.
TIRS	Thermal Infrared Spectrometer	Passively cooled Fourier spectrometer, 7–333 µm. Organic gas abundance, aerosol opacity and temperature mapping 30–500 km.
MAPP	Magnetometer	Tri-axial fluxgate sensors. Noise level ~11pT$_{rms.}$ Interaction of field with ionosphere: internal and induced field.
	Energetic Particle Spectrometer	TOF Analyzer w/ss detectors to measure magnetospheric particle fluxes, ~10 keV to >MeV with 150° x 15° FOV.
	Langmuir Probe	Swept voltage/current probe. *In situ* electron density and temperature, ion speed constraint, including during aerosampling.
	Plasma Spectrometer	Electrostatic analyzer with Linear electric field TOF MS. Measures ion and electron fluxes at ~5 eV to ~5 keV. M/ΔM~10.
RSA	Radio Science and Accelerometer	All components part of spacecraft telecom system. Lower stratosphere and troposphere T profile. Gravity field.

Montgolfière

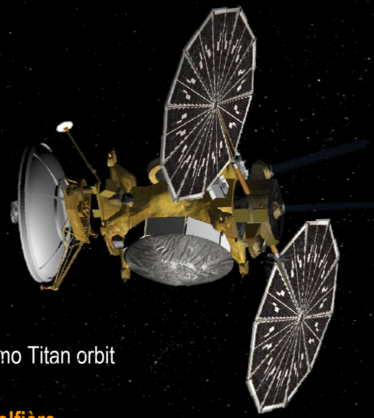
Montgolfière Planning Payload (10 km altitude in equatorial region)	
BIS	Balloon Imaging Spectrometer (1–5.6 µm)
VISTA-B	Visual Imaging System for Titan Balloon
ASI/MET	Atmospheric Structure Instrument/ Meteorological Package
TEEP-B	Titan Electric Environment Package
TRS	Titan Radar Sounder (>150 MHz)
TMCA	Titan Montgolfière Chemical Analyzer (1–600 Da Mass Spectrometer)
MAG	Magnetometer
MRST	Radio Science using spacecraft / montgolfière telecom system

Lander

Lake Lander Planning Payload	
TLCA	Titan Lander Chemical Analyzer (GCMS)
TiPI	Titan Probe Imager + Lamp
ASI/MET-TEEP	Atmospheric Structure Instrument/ Meteorological Package + Titan Electric Environment Package
SPP	Surface Properties Package + Acoustic Sensor Package with Magnetometer
LRST	Radio Science using spacecraft/lander telecom system



Mission & Spacecraft Overview

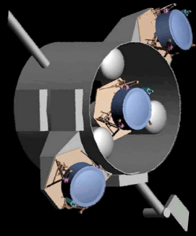


NASA Orbiter with ESA *in situ* elements

- Orbiter + Solar Electric Propulsion (SEP)
- Lake Lander and Montgolfière Balloon
- NASA provided launch vehicle and Radioisotope Power System

Mission Design

- 2020 gravity assist SEP trajectory
- 9 years to Saturn arrival
- SEP stage released ~5 yr after launch
- Montgolfière released on 1st Titan flyby, Lander on 2nd Titan flyby
- ~4 year prime mission: 2 yr Saturn tour, 2 mo Titan aerosampling, 20 mo Titan orbit



Orbiter

- 3-axis stabilized spacecraft
- 4 m High Gain Antenna with 35 W Ka-band amplifier gives high data downlink
- 5 Advanced Stirling Radioisotope Generators (4 baselined, 1 spare) provide 540 W at end of mission (Design also compatible with MMRTG RPS)
- 165 kg instrument payload allocation
- Orbiter dry mass 1613 kg (includes 35% system margin)
- Provides accommodation for two *in situ* elements (833 kg total allocation)
- SEP stage included for inner solar system thrusting
  - 3 NEXT ion thrusters
  - Two 7.5 kW Orion CEV-derived Ultraflex solar arrays
- Total launch mass 6203 kg on Atlas V 551

Montgolfière

- Buoyancy provided by US-supplied Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) (~1700 W thermal)
- 10.5 m diameter envelope
- 10 km nominal cruise altitude
- 6 mo nominal mission length
- Up to 600 kg launch mass including aeroshell
- Telecom relay through orbiter via 0.5 m HGA

Lander

- Lander targeted for northern mare
- Battery operated
- 9 hour nominal mission duration
- 190 kg launch mass including aeroshell
- Telecom relay through orbiter via X-band omni antenna

Science Team

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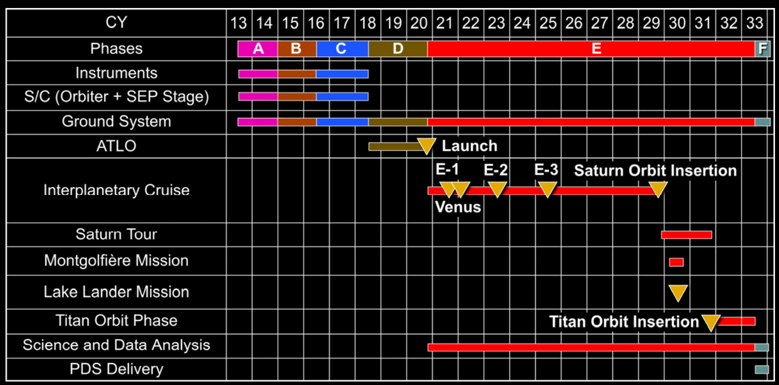
Elizabeth Turtle (JHU/APL)
Hunter Waite (SwRI)

Cost & Schedule

TSSM offers a low-risk mission, employing flight-proven designs for spacecraft, instruments, and ground system.

Mission safety is enhanced for TSSM through the implementation of a fully funded risk management and mission assurance program, and through the application of lessons learned from Cassini-Huygens and other recent deep space missions. Ample reserves for all systems reduce cost, schedule risk and help ensure mission success.

Total mission costs of TSSM are estimated to be respectively \$3.7B (RY) or \$2.5B (FY07) for NASA and up to €650 M (FY07) for provision of the *in situ* elements. The mission will benefit from substantial investments from CNES for the development and provision of the montgolfière. European instrumentation will be provided through national funding.



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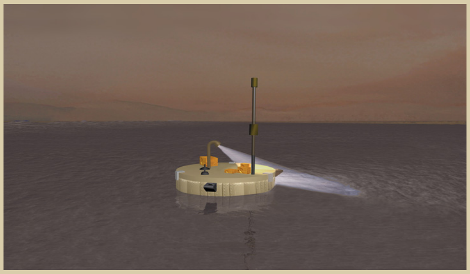
APPENDIX

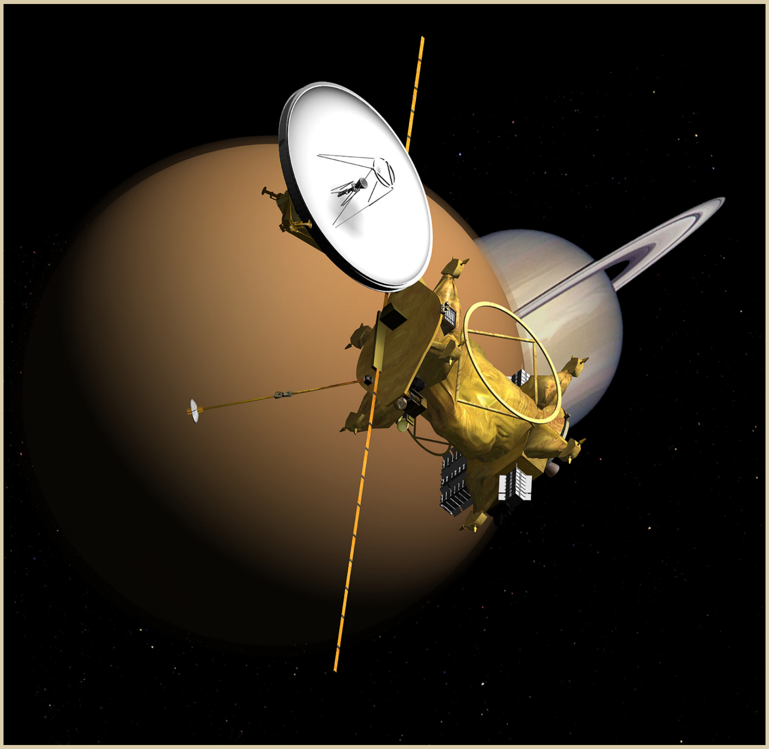
1.0 OVERVIEW



A parachute descent—like that of the Huygens probe in 2005—is happening again, but this time in the Saturn-cast twilight of winter in Titan's northern reaches. With a pop, the parachute is released. A few hours later, a muffled splash signals the beginning of the first floating exploration of an extraterrestrial sea—this one not of water but of liquid hydrocarbons.

Thousands of kilometers away, a hot air balloon (a montgolfière) cruises 10 kilometers above sunnier terrain, imaging vistas of dunes, river channels, mountains and valleys carved in water ice, and probing the subsurface for vast quantities of "missing" methane and ethane that might be hidden within a porous icy crust. The data are relayed to a Titan orbiter equipped to unveil Titan's mysteries with instruments for imaging, radar profiling, and atmospheric sampling, much more powerful and more complete than done by Cassini.

This spacecraft, preparing to enter a circular orbit around Saturn's cloud-shrouded giant moon, has just completed a series of flybys of Enceladus, a tiny but active world with plumes composed of water and organics being blown outward from its interior into space. As it flew by Enceladus, the Titan orbiter analyzed these plumes directly. Titan and Enceladus could hardly seem more different, and yet they are linked by their origin in the Saturn system, by a magnetosphere that sweeps up mass and delivers energy, and by the possibility that one or both worlds harbor life.



It is the goal of the NASA/ESA Titan Saturn System Mission (TSSM) to explore these exotic yet inviting worlds, to understand their natures, and assess their potential habitability.

The combination of orbiting, landing, and ballooning is a new and exciting approach to exploring Titan. The TSSM mission architecture provides the optimal balance between science, risk, and cost using three guiding principles:

Achieve science far beyond the high bar set by Cassini-Huygens.

Cassini will complete its final mission well over a decade before TSSM arrives at Saturn. The goals for this new focused mission build on the momentum of Cassini-Huygens and will extend our understanding of the seasonal variations by arriving earlier in the annual cycle. The orbiter, lake lander and montgolfière will view, smell and taste Enceladus and Titan at global, regional and local scales with instruments that will achieve fundamentally new science not achievable by the Cassini-Huygens survey.

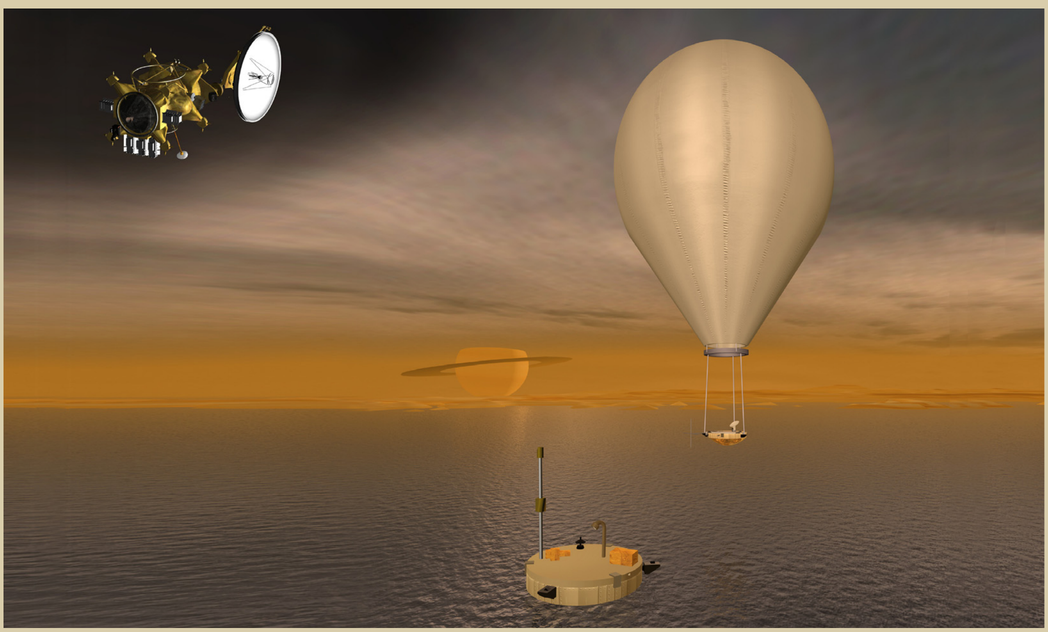
Build upon lessons learned from successful design and operational experience.

With Huygens, ESA demonstrated that it can design and land probes on Titan, and with Cassini, NASA has demonstrated that it can accurately deliver *in situ* spacecraft and implement long-lived orbiters at Saturn. Long-life design rules and extensive operational experience in the Saturn system have been applied to form the TSSM concept. Lessons learned from Galileo, Cassini-Huygens, New Horizons, and Mars Reconnaissance Orbiter have been applied to reduce risk and lower cost. Development of the montgolfière by ESA and CNES combines prior experience with Earth and planetary balloon systems to enable innovative science and unprecedented mobility for exploring Titan's lower atmosphere, surface, and subsurface.

Leverage international collaboration.

TSSM is a collaborative effort between NASA and ESA that has been designed to provide the best mission possible at an attractive cost to NASA and to ESA. This project organization and plan are based on the Cassini-Huygens model and lessons learned. The approach applies international resources to maximize science return, reduce risk, and ensure technical readiness.

TSSM will cover the full range of planetary science disciplines and revolutionize our understanding of the Titan and Enceladus systems. TSSM will be NASA's and ESA's opportunity to open a new phase of planetary exploration by projecting robotic presence on the land, on the sea, and in the air of an active, organic-rich world.



2.0 SCIENCE GOALS AND OBJECTIVES

2.1 Relevance and Motivation

Saturn's largest moon Titan has been an enigma at every stage of its exploration. For three decades after the hazy atmosphere was discovered from the ground in the 1940s, debate ensued over whether it was a thin layer of methane or a dense shield of methane and nitrogen. Voyager 1 settled the matter in favor of the latter in 1980, but the details of the thick atmosphere discovered raised an even more intriguing question about the nature of the hidden surface, and the sources of resupply of methane to the atmosphere. The simplest possibility, that an ocean of methane and its major photochemical product ethane might cover the globe, was cast in doubt by Earth-based radar studies then eliminated by Hubble Space Telescope and adaptive optics imaging in the near-infrared from large ground-based telescopes in the 1990s. These data, however, did not reveal the complexity of the surface that Cassini-Huygens would uncover beginning in 2004. A hydrological cycle appears to exist in which methane (in concert with ethane in some processes) plays the role on Titan that water plays on Earth (**Figure 2.1-1**). Channels likely carved by liquid methane and/or ethane, lakes and seas of these materials—some rivaling or exceeding North America's Great Lakes in size—vast equatorial dune fields of complex organics made high in the atmosphere and shaped by wind, and intriguing hints of geologic activity suggest a world with a balance of geologic and atmospheric processes that is the solar system's best analogue to Earth. Deep underneath Titan's dense atmosphere and active, diverse surface is an interior ocean discovered by Cassini and thought to be largely composed of liquid water.

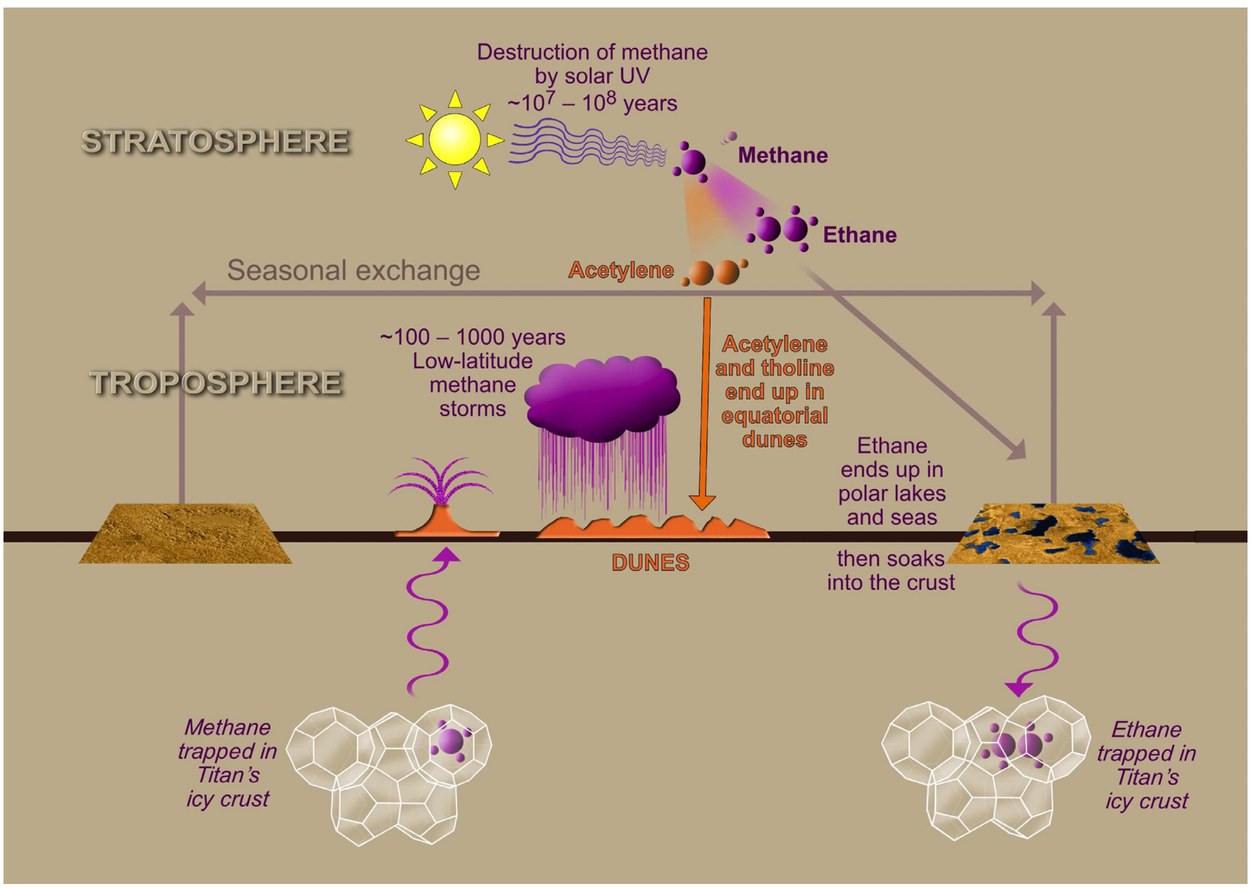


Figure 2.1-1. *A schematic view of the methane cycle on Titan shown with rough timescales for the various processes.*

Cassini-Huygens leaves us with many questions that require a future mission to answer. These include whether methane is out-gassing from the interior or ice crust today, whether the lakes are fed primarily by rain or underground methane-ethane aquifers (more properly, "alkanofers"), how often heavy methane rains come to the equatorial region, whether Titan's surface supported vaster seas of methane in the past, and whether complex self-organizing chemical systems have come and gone in the water volcanism, or even exist in exotic form today in the high latitude lakes. The composition of the surface and the geographic distribution of various organic constituents remain poorly known. Key questions remain about the ages of surface features, specifically whether cryovolcanism and tectonism are actively ongoing or are relics of a more active past. Ammonia, circumstantially suggested to be present by a variety of different kinds of Cassini-Huygens data, has yet to be seen. The presence of a magnetic field has yet to be established. The chemistry that drives complex ion formation in the upper atmosphere was unforeseen and is poorly understood. A large altitude range in the atmosphere, from 400–900 km in altitude, will remain poorly explored after Cassini. Much remains to be understood about seasonal changes of the atmosphere at all levels, and the long-term escape of constituents to space.

The NASA Astrobiology Institute (NAI) Executive Council, in a letter on September 22, 2008, "reaffirms Titan to be in the list of highest priority astrobiological targets in the solar system." Examining the TSSM mission, the NAI Executive Council states that *"the mission design provides an excellent match for and even exceeds the measurement objectives identified for targets of high astrobiological potential."* It concludes that "*a mission to Titan and the Saturn System [is]...in its highest priority mission category*."

No single target in the outer solar system encompasses such a breadth of disciplines within the planetary sciences as does Titan. It is a complete world in the sense that the Earth is, with the substitution of abiotic or prebiotic organic chemistry for life. Together Titan and Enceladus trump any other pairing beyond the asteroid belt for their promise of a wealth of new discoveries, and for their environments suitable for exploration in truly novel ways.

2.2 Science Goals and Objectives

The key scientific questions for the Titan Saturn System Mission divide into three goals.

2.2.1 Goal A—Titan: An Earthlike System.

Titan is a complex world more like the Earth than any other: it has a dense mostly nitrogen atmosphere, the only other place besides Earth to have one, it has an active climate and meteorological cycle where the working fluid—methane—behaves under Titan conditions the way that water does on Earth (**Figure 2.2-1**). And its geology—from lakes and seas to broad river valleys and mountains—while carved in ice is, in its balance of processes, again most like Earth. Beneath this panoply of Earth-like processes an ice crust floats atop what appears to be a liquid water ocean. *Goal A seeks to understand Titan as a system, in the same way that one would ask this question about Venus, Mars, and the Earth.* How are the distinctions between Titan and other worlds in the solar systems understandable in the context of the complex interplay of geology, hydrology, meteorology, and aeronomy? Is Titan an analogue for some aspect of the Earth's history, past or future? Why is Titan endowed with an atmosphere when Ganymede—Jupiter's moon virtually identical in size and mass—is not?

2.2.2 Goal B—Titan's Organic Inventory: A Path to Prebiotic Molecules

Titan is also rich in organic molecules—more so in its surface and atmosphere than anyplace in the solar system, including Earth (excluding our vast carbonate sediments) (**Figure 2.2-2**). These molecules were formed in the atmosphere, deposited on the surface and, in coming into contact with liquid water may undergo an aqueous chemistry that could replicate aspects of life's origins. *Goal B is to understand the chemical cycles that generate and destroy organics and assess the likelihood that they can tell us something of life's origins.*

2.2.3 Goal C—Enceladus and Saturn Magnetosphere

For Goal C, two aspects of the Saturnian system must be studied. These are Enceladus, whose interior is exposed to analysis through

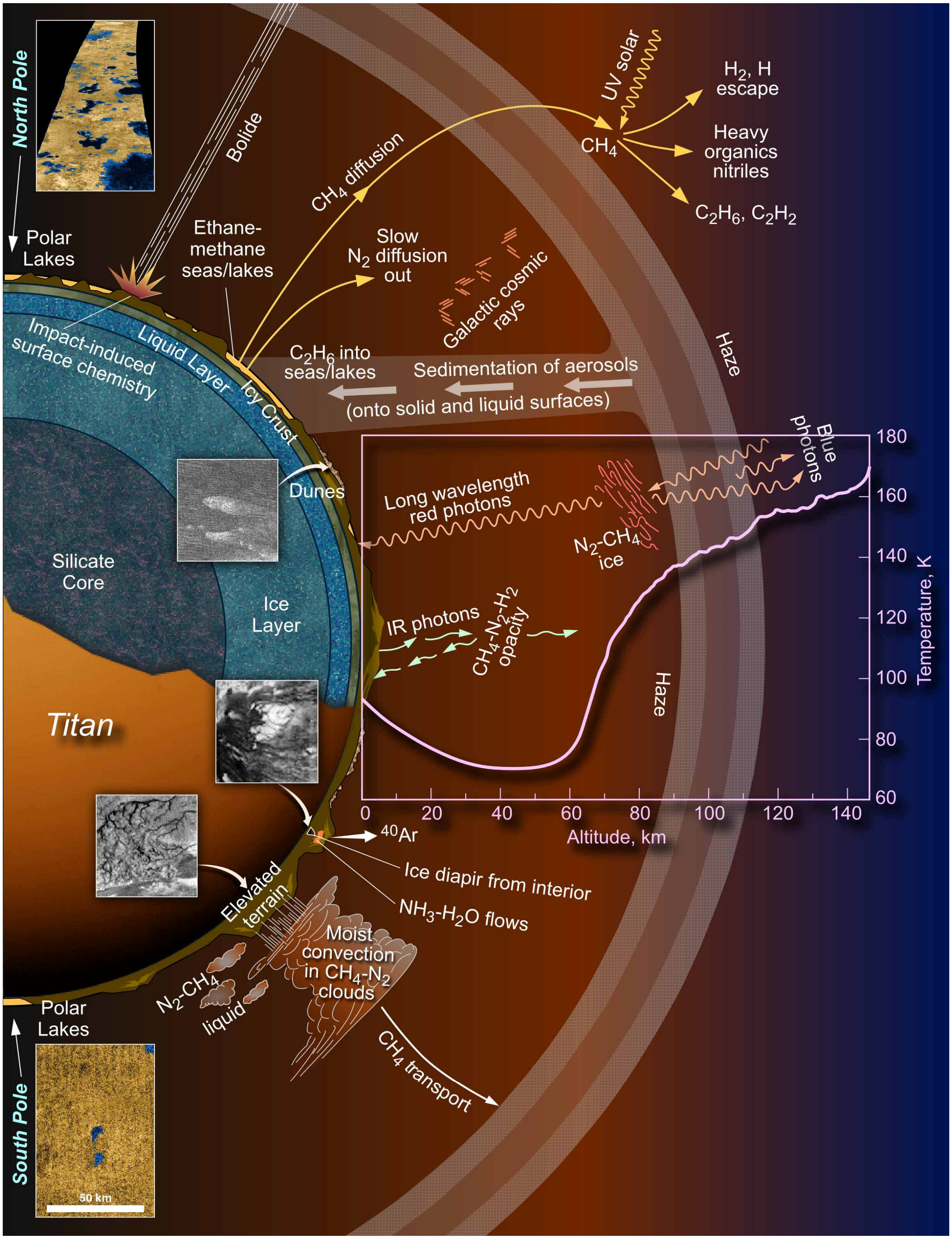


Figure 2.2-1. *Schematic illustration of the connections among Titan's interior, surface, atmosphere, and cosmic environment. Processes illustrated are confirmed or strongly implicated to be occurring on the surface. Images show lakes at north and south.*

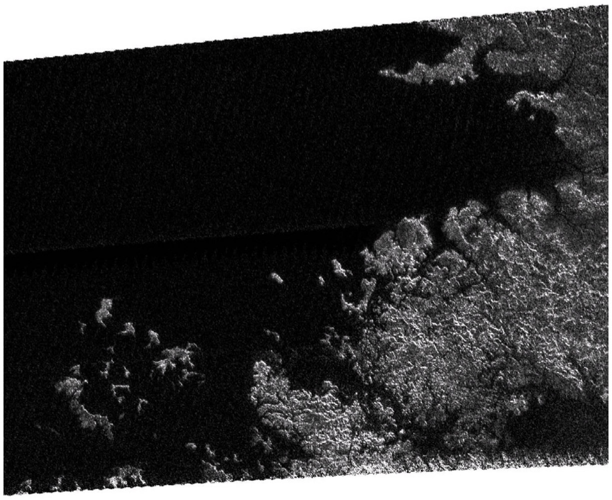


Figure 2.2-2. *A wealth of organic molecules are expected to be dissolved in the hydrocarbon seas of Titan. In this 160 km by 270 km view a northern sea floods coast lines with what is presumed to be mostly liquid methane and ethane.*

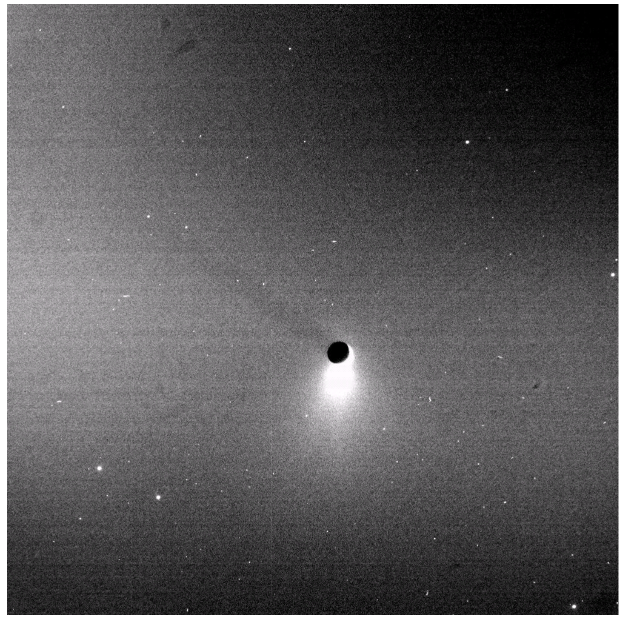


Figure 2.2-3. *Looking like a comet, Enceladus shows its plume in scattered sunlight as this moon casts a shadow some 500 km across on the rings of Saturn. Cassini ISS image. NASA/JPL/Space Science Institute.*

an active plume-geyser system, and the Saturnian magnetosphere which is a medium of exchange of matter and energy with Titan. Here the objectives divide into exploring those aspects of the Saturnian magnetosphere directly related to Titan, and exploring the composition of the Enceladus plumes and whether the source region is liquid water (with implications for the sources of heating). Exploring Enceladus, if liquid water exists in its interior, adds a second target of astrobiological importance to the mission: a "two for one" in the search for life and its origins in the solar system (**Figure 2.2-3**). *How Titan interacts with its Saturnian environment and what role Enceladus plays in both supplying material and being a separate source of information for the interior composition of Titan are the subjects of Goal C.*

2.3 Science Implementation

An orbiter, lake lander, and montgolfière constitute the Baseline mission. The nature of the Titan environment calls for direct sampling of the surface and mobility in the near-surface environment, in addition to the capability to map Titan on a global scale from orbit and visit other targets in the Saturn system. The instrument payloads on the various elements are the result of a deliberative process, involving heritage from the previous Science Definition Team study, three public workshops, the ESA TandEM mission proposal, and multiple meetings of the TSSM Joint Science Definition Team (JSDT) to achieve consensus. The payloads are described in §3.3. A brief discussion of the major mission elements and their science potential follows.

2.3.1 Orbiter

The orbiter carries six capable instruments plus radio science through the Saturnian system, including seven flybys of Enceladus, then on to an Aerobraking Phase in which it analyzes the atmosphere directly by plunging hundreds of kilometers deeper than the closest Cassini flyby, finally settling in to a circular mapping orbit of Titan with a suite of remote sensors more focused and yet more powerful than Cassini's. During the Saturn Tour Phase, the orbiter delivers the *in situ* elements to Titan and collects and relays their data to Earth. Following Titan orbit insertion, it captures a complete set of global high resolution data.

2.3.2 Montgolfière

The montgolfière will be delivered to ~20°N and will float around the equatorial region at a 10 km nominal altitude (Baseline design). An estimate for wind fields at this latitude and season indicate that at least one circumnavigation around Titan will be achieved during the montgolfière's 6 month prime mission (goal of 12 months). Modifications to the Baseline to add near surface operation capability (extended mission) will be evaluated in a future phase.

The montgolfière brings meter-scale imaging, surface composition mapping, and radar sounding of the subsurface close enough to the ground that high resolution and sensitivity, even greater than that of the orbiter, will be achieved. Traveling over 10,000 km in linear distance, the montgolfière will image and map diverse landscapes at close range, in Jules Verne style. Precision tracking of the montgolfière will allow winds to be measured, and sampling of aerosols in the air around the montgolfière will provide a linkage between the surface chemistry measured by the lander and the upper atmospheric chemistry measured by the orbiter. The possibility of instrumenting the montgolfière's discarded heat shield, which will float slowly through the thick atmosphere to a soft landing, is being studied. This would allow the tidal flexing of Titan's crust to be measured by radio tracking and/or seismometry; a magnetometer would be included in place of, or in addition to, that on the montgolfière for coupled measurements of induced and/or permanent magnetic fields.

2.3.3 Lake Lander

The short-lived lander will be designed for wet landing in Kraken Mare (Baseline) at ~72°N latitude. However, as with Huygens, the lander will be capable of landing either on a liquid or solid surface.

The lander's principal function is to sample and analyze organics on the surface; only two areas on Titan known to have organics are large enough to ensure targeting: the dunes and the largest lakes. Sampling on the dunes was deemed very complex, and it was recognized that the lakes are repositories, through dissolution of airborne solids, of organics scattered globally on Titan, as well as noble gases, which are a key clue to Titan's origin and evolution. Floating and sampling on a lake are straightforward, hence the decision to target the lander to one of the two big northern hemisphere lakes. An integrated chemical/isotopic analysis system, with a two-dimensional gas chromatograph will provide a very high level of diagnostic power; a camera will monitor an illuminated patch of lake for evidence of floating material and wind-driven small-scale waves.

During the descent under parachute, expected to last between 5–6 hours, the payload will be fully operational. It will also be operational for ~3–4 hours after landing, limited by the available battery power.

2.4 Science Synergies

Recent discoveries of the complex interactions of Titan's atmosphere with the surface, interior, and space environment demand focused and enduring observation over a range of temporal and spatial scales. The TSSM 2 year orbital mission at Titan will sample the diverse and dynamic conditions in the ionosphere where complex organic chemistry begins, observe seasonal changes in the atmosphere, and make global near-infrared and radar altimetric maps of the surface. This study of Titan from orbit with better instruments has the potential of achieving *orders-of-magnitude* increase in performance (e.g., sensitivity, resolution, dynamic range, etc).

Chemical processes begin in Titan's upper atmosphere and can be extensively analyzed by an orbiting spacecraft alone. However, there is substantial benefit in extending the measurements to Titan's lower atmosphere and the surface. Titan's surface may replicate key steps toward the synthesis of prebiotic molecules that may have been present on the early Earth as precursors to life. *In situ* chemical analysis, both in the atmosphere and on the surface, will enable the assessment of the kinds of chemical species that are present on the surface and of how far such putative reactions have advanced. Indeed, the lake lander's chemical analyzer will be sophisticated enough to detect evidence for biologically-mediated organic chemical processes in material sampled from the lake. The top-down space-to-lake analysis of the organic chemistry from the orbiter, montgolfière and lander presents an unparalleled opportunity to quan-

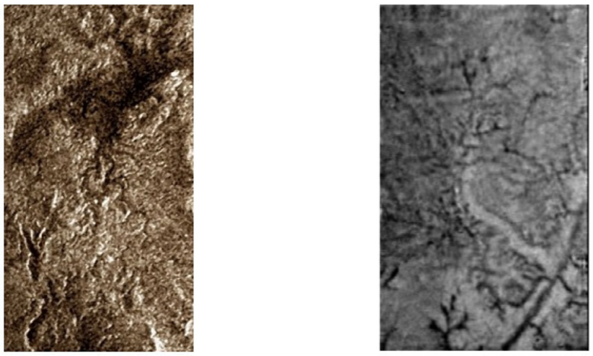


Figure 2.4-1. *Cassini coverage at large scales at 350–500 m resolutions shows areas of fluvial erosion but not the details of its style (left). The Huygens probe has revealed, at 10–20 m resolution, both dendritic-type fluvial erosion and what appears to be sapping of "ground-methane" (right).*

tify the full story of organic chemical evolution on Titan. *In situ* elements also enable powerful techniques such as high resolution subsurface sounding to be applied to exploring Titan's interior structure.

Detailed investigations of various terrain types at different locations are required to understand the forces that shape Titan's diverse landscape, a demanding requirement anywhere else, but one that is uniquely straightforward at Titan using a montgolfière hot air balloon. TSSM's montgolfière will circumnavigate Titan carried by winds, exploring with high resolution imaging and subsurface sounding. It will be able to image over hundreds of thousands of square kilometers at 10 m or better resolution, while the orbiter provides 50 m global context imaging (**Figure 2.4-1**). Likewise spectrometry by the orbiter and montgolfière will determine composition in a nested fashion with high resolution on the montgolfière supported by global orbital context.

Knowledge of the subsurface and interior structure is necessary to understand Titan's global evolution and its methane cycle. In addition to topography, the radars on the orbiter and the montgolfière will provide knowledge of the tectonics and sedimentary stratigraphy of the crust with different and complementary resolution. The gravity measurements on the orbiter and the electric and magnetic measurements on the montgolfière will allow us to determine the depth to the ocean and thus the thickness of the ice shell. Magnetometry aboard the montgolfière and lake lander will allow for sensitive field measurements beneath Titan's screening ionosphere, while orbiter magnetometry allows one to separate the inducing from the induced fields. Observations from the orbiter made over a period of months will allow resolving the multiple and varying frequencies in the signal. This is critical in defining both the background inducing magnetic field as well as the resulting induction signature, and then enabling possible resolution of any remaining intrinsic magnetic field.

Orbiter magnetometry also plays a role in studying Saturn's magnetosphere and the plasma interaction with Titan. In particular the interaction between Titan's ionosphere and the Saturnian magnetosphere causes the former to carry an imprint of the Saturnian field while in the magnetosphere, only to have this swept away by periodic excursions into the solar wind.

The combination of orbiting and *in situ* elements is a powerful opportunity for synergistic investigations—synthesis of data from these carefully selected instrumentation suites is the path to understanding this profoundly complex body.

2.5 Responses to Decadal Survey and Cosmic Vision Themes

TSSM heritage includes ESA's studies that led to a Cosmic Vision Program proposal for a Titan and Enceladus Mission (TandEM), accepted as fully responsive to the Cosmic Vision Goals. TSSM embraces all of the essential elements of that mission. The TSSM JSDT also examined the relevant documents of the US National Academy of Sciences, especially the Decadal Survey of 2003, whose large satellites panel ranked Titan and Europa as the highest priority targets (activity on Enceladus was unknown at the time). The JSDT, in a plenary session, cross-checked individual ranking of the mission against the questions provided by the Decadal Survey's Large Satellite Panel for Titan, obtaining a score of 4.4

Table 3.1-1. Ground Rules for TSSM study.

RPS options	Radioisotope Power System (MMRTG or ASRG)—to be provided by NASA, solar
Planetary Protection	Category II, ≤10^{-4} probability of contaminating a liquid water body
Launch Vehicle (LV)	Delta IV-H, Ares and Atlas family—costs given including launch services and nuclear processing
Technology Philosophy	NASA: Conservative approach ESA: TRL>5 by the start of B2 (1st Qtr, 2013)
Launch Dates	Nominally 2020 but investigate 2018–2022
DSN Capability	NASA: Ka-band downlink available, current 34 m available, current 70 m equivalent capability for emergency use only, DSN ground system throughput of up to 100 Mb/s ESA: ESA ground system
Architecture	NASA non-aerocapture Titan orbiter ESA *in situ* elements

out of 5. This reflects the very high science capability of the mission.

3.0 MISSION CONCEPT

3.1 Mission Architecture Overview and Design

The architecture selection process for TSSM was driven by the NASA and ESA study Ground Rules as summarized in **Table 3.1-1**.

As a result of the study efforts, a robust architecture has been developed that enables NASA/ESA Baseline and NASA-only mission options which respond fully, while to a different degree, to the science requirements.

The Baseline for TSSM was chosen from a comprehensive assessment of alternative concepts and was found to be the optimal balance between science, cost, and risk. Results shown in **Figure 3.1-1** indicate that a joint NASA/ESA mission with a combination of orbiter, solar electric propulsion (SEP), lander, and montgolfière provides the highest science value per unit of currency invested.

The Baseline architecture integrates an orbiter and *in situ* elements into a single flight system. Key Baseline mission parameters are shown in **Table 3.1-2** and further discussed in §3.2. **Figure 3.1-2** shows an overview of the Baseline mission events. The flight system begins its journey on an Atlas V 551 launch vehicle, followed by thrusting with a highly efficient SEP stage enabling significantly shorter trip time and an additional 300 kg of

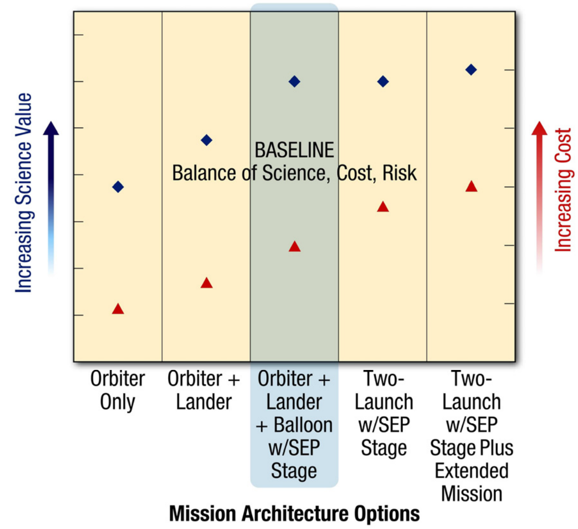


Figure 3.1-1. TSSM's Baseline architecture maximizes science return to investment ratio within NASA and ESA resources, at risk comparable to Cassini-Huygens.

Table 3.1-2. TSSM uses Earth and Venus gravity assists with SEP to deliver orbiting and in situ exploration assets to Titan

Parameter	Value
Launch Date	Sep 10–30, 2020
Start SEP Thrusting	Dec 1, 2020
End SEP Thrusting	Oct 14, 2025
SOI	Oct 28, 2029
Flight time to Saturn	9 years
TOI	Sep 29, 2031
SEP ΔV	~2.7 km/s
SEP Propellant	451 kg
Chemical Propellant	2528 kg
Chemical ΔV	~2.4 km/s
Orbiter Current Best Estimate Dry Launch Mass	1081 kg
Orbiter Dry Mass Margin	532 kg
SEP Stage Current Best Estimate Dry Launch Mass	502 kg
SEP Stage Dry Mass Margin	276 kg
In Situ Elements Current Best Estimate Launch Mass	579 kg
In Situ Element Airborne Support Equipment	43 kg
In Situ Elements Launch Mass Margin	211 kg

mass margin. There are multiple Earth-to-Saturn transfer options available as prime and backup trajectories from 2018 through 2022. The Baseline mission design uses an EVEEGA-SEP trajectory launching in

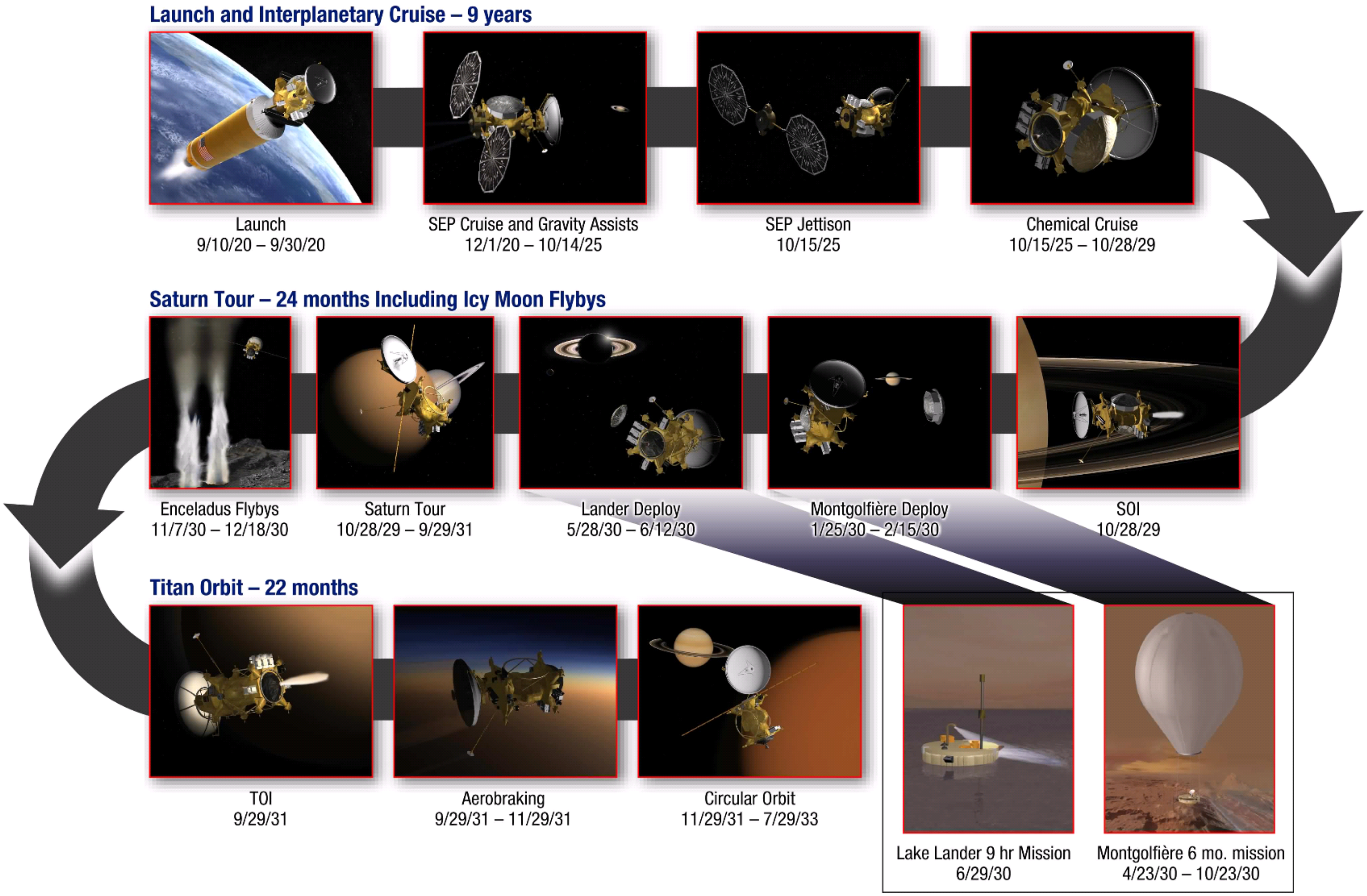


Figure 3.1-2. *Pictorial timeline for the Baseline Titan Saturn System Mission.*

September 2020 and arriving at Saturn in October 2029, delivering up to 6265 kg to Saturn approach, and an EVEEGA-SEP backup trajectory launching in 2021 for a 2031 arrival. Transfer times to Saturn are longer than for the Cassini-Huygens mission because in the 2018–2022 launch period Jupiter gravity assists to Saturn are not available.

During SEP thrusting, the flight system makes use of an inner planet gravity assist trajectory that delivers it to Saturn approximately 9 years after launch. When the SEP stage is no longer viable due to increasing distance from the sun, about five years after launch, the SEP stage is jettisoned using the highly reliable fault tolerant Superzip interface which routinely releases payloads from launch vehicles. Upon Saturn arrival the orbiter's chemical propulsion system places the flight system into orbit around Saturn, followed by approximately two years of Saturn tour science.

The Saturn Tour Phase is characterized by deployment of the *in situ* elements, a minimum of seven close Enceladus flybys and 16 Titan flybys. During this period repeated satellite gravity assists and maneuvers reduce the energy needed to insert into orbit around Titan. The montgolfière will be released on approach to the first Titan flyby for ballistic entry into Titan. The nominal lifetime of the montgolfière is six Earth months. At its deployment latitude of about 20°N, analysis based on Cassini-Huygens results indicates that the montgolfière should circumnavigate Titan at least once during its nominal lifetime. The Baseline approach is to have the orbiter release the lake lander on the second Titan flyby, targeted to a northern polar lake (Kraken Mare is the Baseline) at about 72°N. This delivery approach is even more robust than that used for Huygens and results in robust communications links for both *in situ* elements during their critical events and prime missions. A comparison of TSSM *in situ* entry parameters with Huygens values indicates similar or more benign conditions.

Titan orbit insertion (TOI) is accomplished at the end of the Saturn Tour Phase using the main engine. Capture into a 720 by 15,000 km elliptical orbit will be followed by a two-month aerobraking and aerosampling phase.

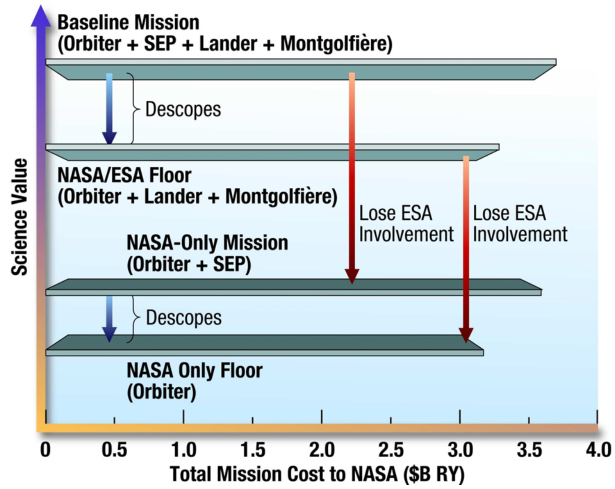


Figure 3.1-3. *NASA/ESA and NASA-only mission architectures include robust descopes while remaining above the science floor.*

The aerobraking sequence is designed using an atmospheric model developed for the study by a broad team of experts on Titan's atmosphere using Cassini and Huygens data. Titan's atmospheric variability is more than a factor of 10 less than Mars' and, therefore, Titan aerobraking is well understood and easier than that at Mars. Following aerobraking, a small periapsis maneuver will place the orbiter into a circular 1500 km, 85° inclination polar orbit for the 20 month orbital science phase. At this altitude the orbiter circles Titan approximately five times per Earth day.

The telecom subsystem is sized to provide a minimum science data downlink from Titan orbit of approximately 5.4 Gb per Earth day, assuming two 8 hr DSN passes per day at maximum range (~10.1 AU). Science operations are structured to address the science objectives, with three observational campaigns optimized for available power and downlink.

The TSSM Baseline mission architecture provides descope options for both NASA and ESA to a scientifically attractive NASA/ESA Floor mission (as shown in **Figure 3.1-3**) yielding a very robust project implementation plan. The floor for this NASA/ESA Baseline would not include the SEP stage, in addition to other identified descopes, and would result in a 1.5 year longer interplanetary trajectory.

In the event of an ESA decision not to participate, a NASA-only mission could proceed.

Transition to a viable NASA-only mission can occur at any time and at any point in any descope sequence from the Baseline mission to the NASA/ESA Floor mission. An important characteristic of this structure is that if an ESA decision not to participate occurred, even up to launch, there are clear transition pathways from the NASA/ESA mission to a viable NASA-only mission. If an ESA decision not to participate is made early (during or prior to the Project Phase A), NASA would have the option to implement a US provided *in situ* element or pursue other international contributions. Investigating non-ESA provided *in situ* elements was beyond the scope of this study and therefore the orbiter-only option was assessed. An orbiter-only mission with the instrument complement described here provides a much larger data set that probes Titan more deeply than did Cassini-Huygens, and will fundamentally revolutionize our understanding of Titan. It will do likewise for Enceladus. The orbiter-only mission has been judged by the JSDT to be well worth the price of a Flagship-class mission and compares favorably with any orbiter mission due to the breadth of disciplines addressed.

Galileo, Cassini-Huygens and Mars missions provide sufficient operational experience applicable to TSSM. Launch and transfer to the outer solar system follow in the footsteps of Galileo and Cassini. Saturn orbit insertion (SOI) and the Saturn system tour are very Cassini-like. Delivery of the *in situ* elements to Titan is very similar to and benefits from the delivery of the Huygens probe by the Cassini orbiter. Communicating with the Titan lander compares with relay of Huygens data to Cassini. Communication between the orbiter and the Titan montgolfière, while new, is straightforward with many downlink opportunities. Operational strategy and communication schedules maximize data return from the montgolfière and lander and do not interfere with Saturn tour science data that is taken during Enceladus and Titan flybys. This strategy allows for many repeat opportunities to compensate for potential loss of communication sessions. Finally, the Titan Orbit Phase is reminiscent of recent Mars high-resolution mapping missions, including aerobraking and operating a gimbaled HGA. All elements of this mission meet Planetary Protection requirements. Aside from balloon inflation (discussed in §3.2.1.2), the TSSM concept presents no unprecedented operational issues to the mission.

3.2 Mission Elements

The TSSM mission system is composed of the flight system, Launch Services, the Ground System, and the Payload System. This section includes a brief description of the first three mission elements. The Payload System elements (Planning Payload Model Instruments) are discussed in §3.3.

3.2.1 Flight System

The TSSM Baseline flight system is composed of three elements; the orbiter (**Figure 3.2-1**), augmented by a solar electric propulsion stage, an MMRTG-powered montgolfière, and a battery-powered lake lander.

3.2.1.1 Titan Orbiter

The TSSM orbiter (**Figure 3.2-2**) is a three-axis stabilized spacecraft powered by Radioisotope Power Systems (RPSs) that has strong similarity to the Cassini orbiter. The TSSM orbiter includes an articulated 4 m high gain antenna (HGA) using Ka-band for high rate science data downlink. A planning payload of six instruments plus radio science is accommodated with the model instruments located on a payload deck, as well as other locations on the spacecraft dictated by their observational requirements. Accommodation for the two *in situ* elements is provided at attachment points along the body of the orbiter. Five Advanced Stirling Radioisotope Generators (ASRGs) will power the spacecraft, with four providing 540 W of electrical power at end of mission (about 13 years after launch) and the fifth unit carried as a spare. The TSSM architecture is also compatible with use of MMRTGs if directed by NASA. Redundant 25 A-hr Lithium-ion (Li-ion) batteries provide for power demands that exceed the RPS capability during the science mapping orbit and at other times during the mission. The launch mass of the flight system is 6203 kg. This is within the currently Atlas V 551 capability of 6265 kg to the required launch energy. The flight system design includes ample mass and power margins in excess of what is typically required at this stage of maturity. Use of SEP

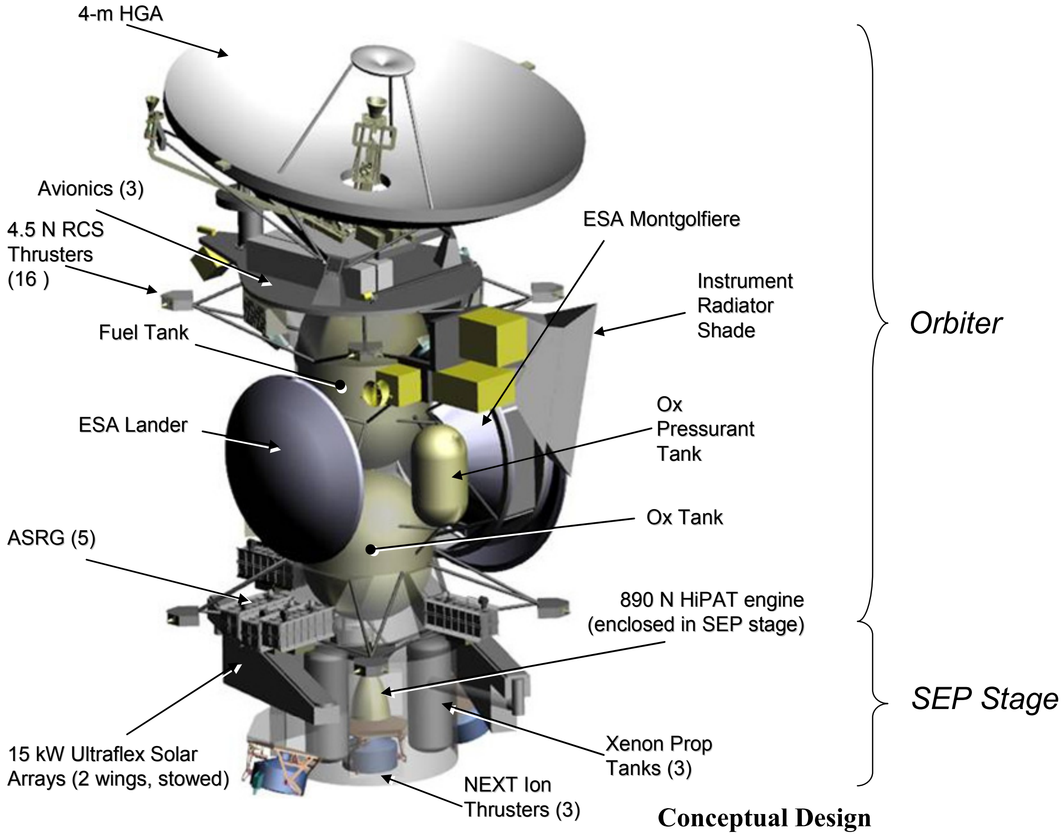


Figure 3.2-1. *Flying a chemically propelled mission to Titan results in a flight system that has many similarities to Cassini-Huygens, however the more capable instrumentation and focused operational plan for TSSM enable a giant leap in understanding beyond Cassini-Huygens.*

allows for significant mass growth of up to 300 kg beyond the current margins with a minimal impact of up to 1.5 years longer flight time.

The TSSM flight system also incorporates a SEP stage for efficient ΔV augmentation during the first half of the cruise trajectory. The SEP stage for TSSM was developed as a simple, bolt-on augmentation built around and incorporating the function of a Launch Vehicle Adapter (LVA). The basic LVA structure is used to support two Orion-derived 7.5 kW Ultraflex solar array wings, as well as three NEXT ion thrusters, power processing units (PPUs), xenon tanks, and electronics necessary for the control and operation of this self-contained stage. Interfaces with the launch vehicle and orbiter have been kept simple to allow the flexibility to operate with or without the SEP stage without significant changes to orbiter configuration.

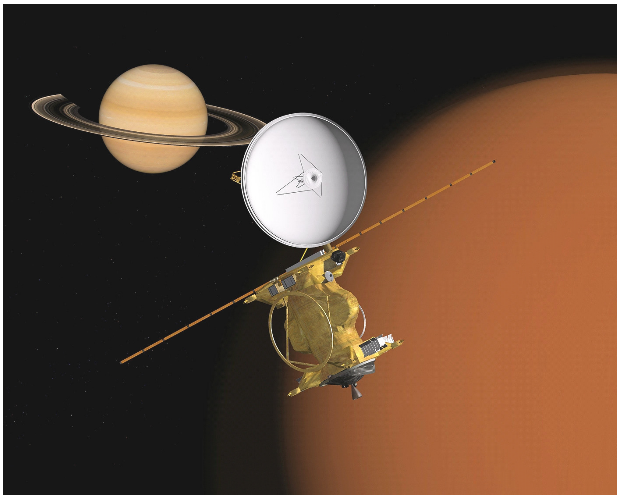


Figure 3.2-2. *TSSM orbiter concept in its deployed science configuration.*

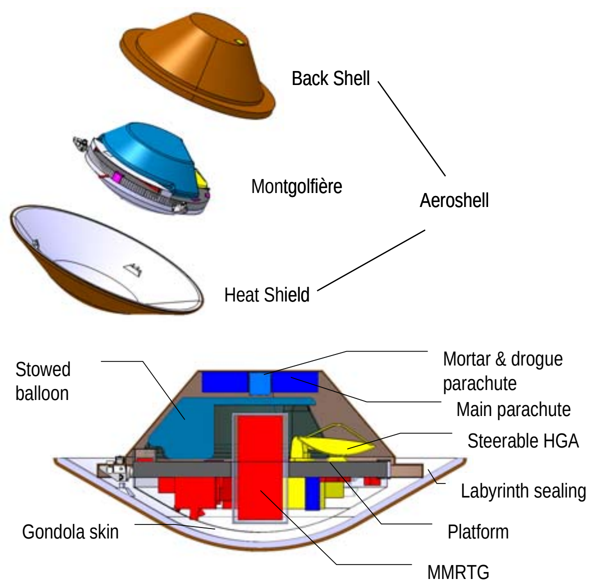


Figure 3.2-3. Conceptual design of the montgolfière integrates Huygens heritage with balloon element. An exploded view of entry system aeroshell is shown.

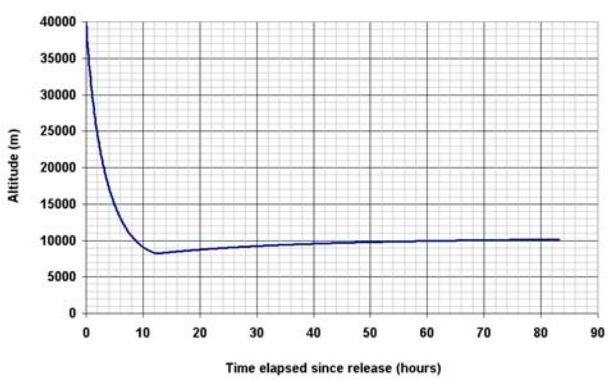


Figure 3.2-4. System modeling of the montgolfière descent profile indicates establishment of safe and stable float altitude of 10 km following balloon deployment at 40 km.

3.2.1.2 Montgolfière

The montgolfière *in situ* element is a hot air balloon. A Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) provides both electrical power (~100 W) to the gondola and heat (~1.7 kW) for buoyancy. The balloon envelope, nearly 11 m in diameter, uses double-wall construction for improved thermal insulation. An aeroshell, a heat shield plus a back shell, protects the montgolfière from the thermal load of entry (**Figure 3.2-3**).

Figure 3.2-5. Artist's rendering of the Montgolfière floating over the equatorial region of Titan.

The orbiter carries the montgolfière through SOI to the subsequent apoapsis, releasing it on a direct ballistic trajectory for entry at the first Titan flyby. After entry a pilot chute pulls off the back shell, deploying the main parachute that extracts the montgolfière from its heat shield. When the system has descended to ~40 km altitude the balloon envelope deploys and fills with ambient air, aided by the ram effect of the continuing descent. Heat from the MMRTG suspended within the envelope warms the air to positive buoyancy at ~8 km altitude (as shown in **Figure 3.2-4**). Once at buoyant equilibrium the montgolfière drifts passively with the winds at 1-2 m/s, actively maintaining its nominal 10 km altitude via barometric measurements and a vent valve at the balloon's zenith. **Figure 3.2-5** depicts the montgolfière in stable flight. The 10 km altitude was chosen to meet all science requirements while avoiding the risk from methane

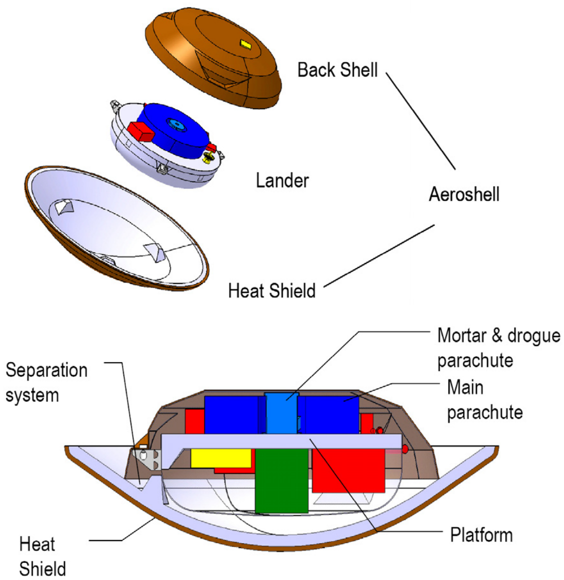


Figure 3.2-6. *Conceptual design of the lake lander in the stowed configuration. An exploded view of the Huygens heritage entry aeroshell is shown.*

and the potential risks associated with near surface operations.

The total estimated mass of the montgolfière element and its aeroshell is 571 kg including contingency. Its 144 kg gondola includes a 25 kg payload allocation for atmospheric measurements, imaging, spectrometry, subsurface radar profiling, and electric and magnetic field measurements (see §3.3). Data are transmitted to the orbiter via a steerable 50 cm HGA, for relay to Earth.

Plans for future studies include the possibility of instrumenting the montgolfière's heat shield for geophysical measurements. Spare volume between the heat shield and the gondola might accommodate, for example, a micro-accelerometer, a radio science instrument, an acoustic package, and a magnetometer. These should be investigated as opportunity instruments to enhance the geophysical science return.

3.2.1.3 Lake Lander

The orbiter spacecraft also carries the lake lander in its aeroshell to the Saturn system and releases it during the second Titan flyby. After releasing the lander, the orbiter will be in continuous contact with it, allowing the orbiter

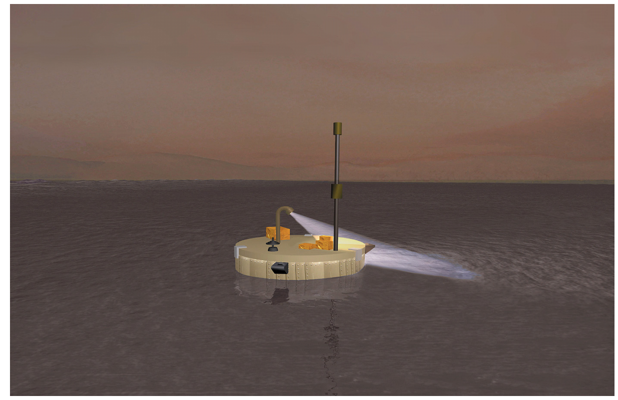


Figure 3.2-7. *Artist's rendering of the Lander in deployed configuration as it would be floating on Kraken Mare.*

to monitor the lander's trajectory and to collect and relay to Earth all telemetry data.

Entry and descent will largely build on heritage from Huygens, and the early phases will be similar to those described for the montgolfière above. Unlike Huygens, in the current Baseline the lander will descend on a single main parachute, thus spending more time in descent (about 5 hours) while performing atmospheric analysis of high northern latitudes. The floating lander design provides enough energy to perform scientific measurements for 3–4 hours after landing in the lake.

Figure 3.2-6 shows a conceptual design of the lander and an exploded view of the stowed configuration. Accommodating instrumentation and system support equipment inside the lander aids optimizing thermal balance. Environmental sensors and an omni-directional antenna are mounted on the upper side (**Figure 3.2-7**). The lander's total launch mass is 190 kg, including 32 kg of science instrumentation (see §3.3).

3.2.2 Launch Services

The TSSM Baseline mission makes use of a single NASA-provided Atlas V 551 launch vehicle. Final installation of NASA-provided RPS units and integration of the flight system with the launch vehicle will occur at Kennedy Space Center. Launch is from Cape Canaveral Air Force Station.

3.2.3 Ground System

Both NASA and ESA ground assets will be used for TSSM. **Figure 3.2-8** shows the three major elements of the integrated NASA and ESA ground system: Multi-Mission core capa-

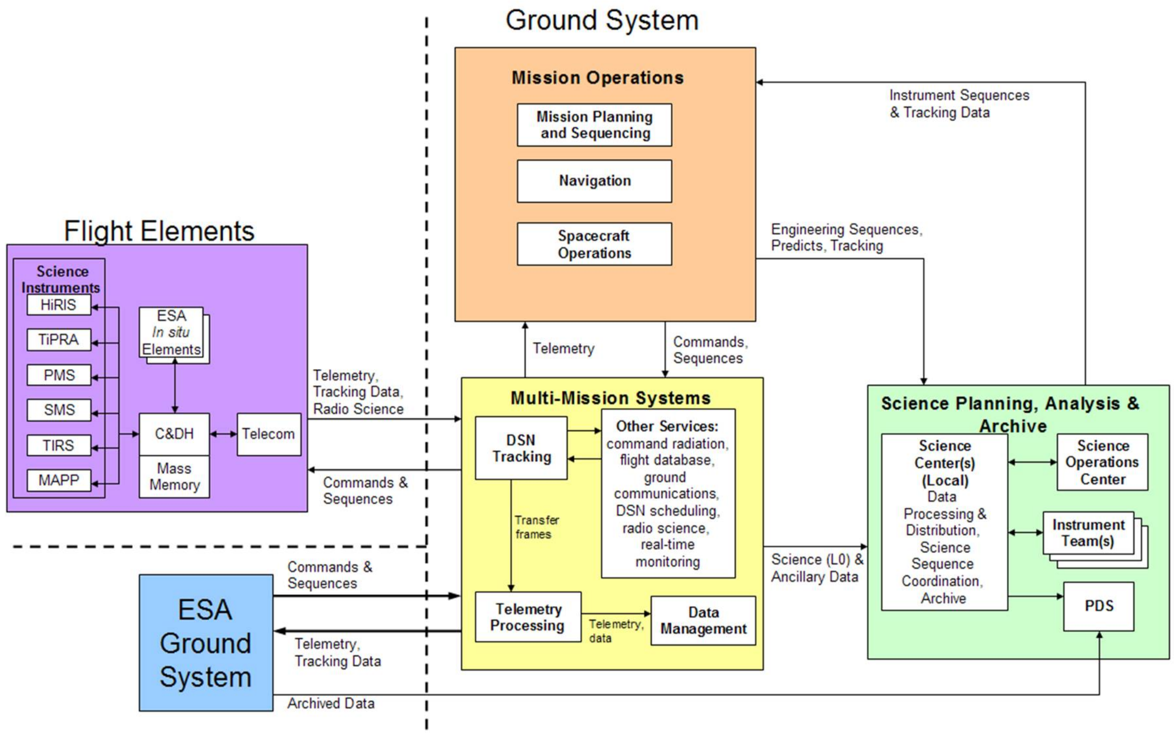


Figure 3.2-8. Proven NASA and ESA Ground Systems ensure maximum science data return.

bilities; TSSM specific Mission Operations System with its underlying ground data system; and the science support elements. As can be seen in the figure, the ESA ground system will interface directly with the multi-mission portion of the NASA ground system. As was done on Cassini-Huygens, this will enable telemetry from the *in situ* elements to be transferred from the JPL ground system to ESA's ground system and enable ESA to send commands to the *in situ* elements through JPL's ground system.

NASA's Deep Space Network (DSN) will perform all tracking for this mission, starting shortly after launch. During critical events, coverage will be provided by the appropriate station to ensure that the entire critical event is viewable in real time. Emergency support will also be available through the NASA DSN 70 m stations.

In addition to instrument based science observations, radio science will be performed by the orbiter and *in situ* elements using the radio science capabilities of the flight elements and the DSN. Radio science will use coherent, two-way (uplink and downlink) Ka- and X-band Doppler data.

3.3 Planning Payload Model Instruments

The Joint Science Definition Team (JSDT) identified the TSSM planning payload model instruments to respond directly to the science objectives outlined in §2.0. This planning payload, while notional, is used to bound the engineering aspects of the mission design, flight system and operational scenarios associated with obtaining the data to meet the science objectives.

The model instrument descriptions show proof of concept and are not intended to be either final selections or final implementations. Alternative instrument concepts and techniques that meet the mission objectives will be selected through a NASA/ESA coordinated Announcement of Opportunity process to meet the mission objectives. **Table 3.3-1** presents the orbiter planning payload, and instrument descriptions. **Table 3.3-2** and **Table 3.3-3** present the montgolfière and lake lander payload respectively.

Synergistic and complementary instruments carried by the separate mission elements

Table 3.3-1. *Orbiter model science instruments and science contributions.*

Inst.	Description	Science Contributions
HiRIS	High-Resolution Imager [in three colors (~2.0, 2.7, and 5–6 µm)] and Spectrometer (near IR). Two spectral mapping bands 0.85 to 2.4 µm (5 nm spectral resolution) and 4.8 to 5.8 µm (10 nm spectral resolution)	Global surface mapping at 50 m/pixel in three colors. Spectral mapping at 250 m/pixel. Surface composition and atmospheric studies.
TiPRA	>20 MHz Titan Penetrating Radar and Altimeter. Two dipole antennas (1st one used for Enceladus and then ejected; 2nd for Titan orbit phase)	Global mapping of subsurface reflectors with 10 m height resolution in altimetry mode and better than 10 m in depth resolution. Lower data rate depth sounding mode with ~100 m depth resolution. Approximately 1 km x 10 km spatial resolution.
PMS	Polymer Mass Spectrometer with M/ΔM ~10,000 for masses up to 10,000 Da	Upper atmospheric *in situ* analysis of gases and aerosol precursor aerosampling down to 600 km. Detection limit is better than 10^4 particles/cm^3.
SMS	Sub-Millimeter Heterodyne spectrometer with scanning mirror. 300 kHz spectral resolution, 12 km spatial resolution.	Measure winds directly from Doppler. Temperature mapping from ~200–1000 km altitude; Obtain CO, H_2O, nitrile and hydrocarbon profiles.
TIRS	Thermal Infrared Spectrometer Passively cooled Fourier Spectrometer 7–333 microns. Spectral resolution 0.125–15 cm^{-1}.	Organic gas abundance, aerosol opacity and temperature mapping 30–500 km.
MAPP	Magnetometer. Tri-axial fluxgate sensors 0–64 Hz. Noise levels of the order 11 pTrms	Measure interaction of field with ionosphere: internal and induced field.
	Energetic Particle Spectrometer. TOF analyzer with solid state detectors	Measures ions in the energy range of 2 keV/nucleon to 5 MeV/nucleon and electrons in the range from 20 to 1000 keV with 150° x 15° FOV.
	Langmuir Probe—Swept voltage/current probe.	Measure thermal plasmas in Titan's ionosphere over a range of densities from 10 to 10^6 cm^{-3} and temperatures from 0.01 to 10 eV.
	Plasma Spectrometer—Electrostatic analyzer system, with a linear electric field time-of-flight mass spectrometer.	Measures ion and electron fluxes at ~5 eV to a ~5 keV. M/ΔM~10.
RSA	Radio Science and Accelerometer. Components are part of the spacecraft bus: USO, transponder, and accelerometers.	Lower stratosphere and troposphere temperature profile. Gravity field.

Table 3.3-2. *Model instruments for the montgolfière.*

Inst.	Description	Science Contributions
BIS	Balloon Imaging Spectrometer (1–5.6 µm).	Mapping for troposphere and surface composition at 2.5 m resolution
VISTA-B	Visual Imaging System with two wide angle stereo cameras & one narrow angle camera.	Detailed geomorphology at 1 m resolution
ASI/MET	Atmospheric Structure Instrument and Meteorological Package.	Record atmosphere characteristics & determine wind velocities in the equatorial troposphere
TEEP-B	Titan Electric Environment Package	Measure electric field in the troposphere (0–10 kHz) and determine connection with weather.
TRS	> 150 MHz radar sounder	Detection of shallow reservoirs of hydrocarbons, depth of icy crust and better than 10 m resolution stratigraphic of geological features.
TMCA	1-600 Da Mass spectrometer	Analysis of aerosols and determination of noble gases concentration and ethane/methane ratios in the troposphere
MAG	Magnetometer	Separate internal and external sources of the field and determine whether Titan has an intrinsic and/or induced magnetic field.
MRST	Radio Science using spacecraft telecom system	Precision tracking of the montgolfière

Table 3.3-3. *Model instruments for the lake lander.*

Inst.	Description	Science Contributions
TLCA	Titan Lander Chemical Analyzer with 2-dimensional gas chromatographic columns and TOF mass spectrometer. Dedicated isotope mass spectrometer.	Perform isotopic measurements, determination of the amount of noble gases and analysis of complex organic molecules up to 10,000 Da.
TiPI	Titan Probe Imager using Saturn shine and a lamp	Provide context images and views of the lake surface.
ASI/MET -TEEP	Atmospheric Structure Instrument and Meteorological Package including electric measurements	Characterize the atmosphere during the descent and at the surface of the lake and to reconstruct the trajectory of the lander during the descent.
SPP	Surface properties package	Characterize the physical properties of the liquid, depth of the lake and the magnetic signal at the landing site.
LRST	Radio Science using spacecraft telecom system	Precision tracking of lander

maximize the overall scientific capability while maintaining a strong science return value for each independent element. With the goal to explore Titan as a system, the payloads provide instrumentation for remote sensing and *in situ* investigations. On the orbiter, remote sensing instruments provide a complete picture of the Titan system from space through the atmosphere to the surface and deep interior. These are complemented by detailed investigations performed on the *in situ* platforms: the montgolfière, circumnavigating Titan's equatorial region, and the lake lander, which samples the methane/ethane lakes and the chemicals dissolved therein. The combined capability of the three mission elements will provide science return which exceeds that of each standing alone.

3.4 Operational Scenarios

3.4.1 Saturn Tour Phase

The prime mission for the *in situ* elements falls within the Saturn Tour Phase. The montgolfière and lake lander will be released during the first two Saturn orbits. Montgolfière flight operations are autonomous and science operations are pre-planned on the ground. Windows for montgolfière telemetry relay to the orbiter will be planned well in advance with adjustments as needed for the montgolfière's position. The lander will execute only a pre-planned 9 hour sequence. All critical events and science data will be relayed to the orbiter in one continuous pass.

During the 24 month Saturn Tour Phase the orbiter will perform 16 Titan and seven Enceladus flybys with extensive remote sensing observations. Eight of the 16 Titan passes are low (720–1240 km) and the remaining eight will be higher. During these flybys, the instruments will generate 26 Gb of remote sensing and fields and particles data. Data collection will be optimized for analysis by mass spectrometry and direct sampling of fields and particles when the spacecraft samples Titan's atmosphere and optimized for imaging and other remote sensing when above the atmosphere.

During the seven Enceladus flybys the time near closest approach will be dedicated to direct sampling of the south polar plumes and to radar sounding. Each flyby will also provide excellent opportunities for high resolution imaging and IR spectrometry. The gimbaled high gain communication antenna will allow concurrent imaging of Enceladus and real-time downlink for radio science. Approximately 15 Gb of data will collected in the four hours around each closest approach (**Figure 3.4-1**).

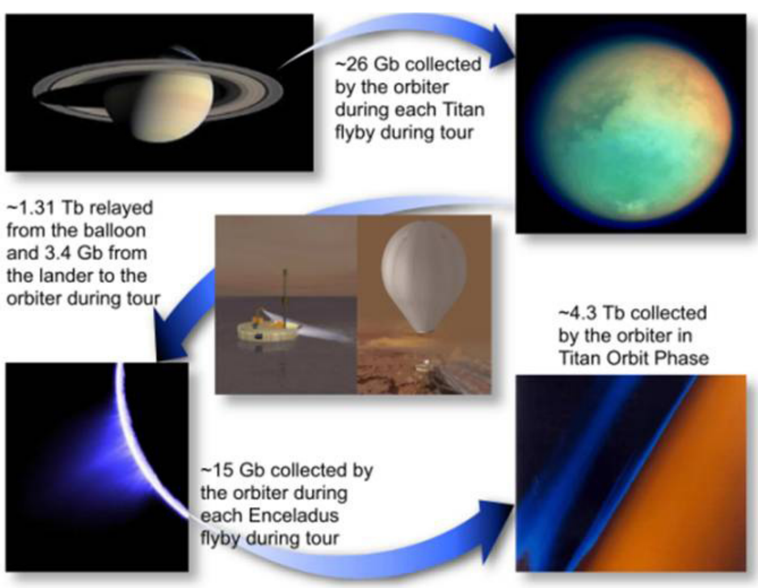


Figure 3.4-1. *The bulk of science data acquisition will occur during the Saturn tour, aerobraking at Titan, and Titan circular orbit. The montgolfière and lake lander data will be relayed by the orbiter to Earth during its Saturn tour.*

3.4.2 Aerobraking Phase

Titan orbit insertion begins the two month, ~200 orbit, aerobraking period. The periapsis altitude after TOI will be ~720 km with subsequent periapsis passes as low as 600 km that will enable complete coverage of the southern hemisphere below 1000 km altitude. *In situ* mass spectrometry data will be gathered at these low altitudes. With the telecom system operational during exo-atmospheric portions of the aerobraking orbits, Radio Science will obtain gravity and occultation data at various latitudes. The higher altitude portions of these orbits yield prime opportunities for global imaging, cloud mapping, limb sounding, and IR spectrometry. Up to 11 Gb will be collected on each aerobraking orbit.

3.4.3 Circular Orbit Phase

The Circular Orbit Phase executes three types of science campaigns, i.e., using defined instrument combinations, to ensure the science goals are achieved while managing power and data flow. Sixteen day pre-planned campaign durations were chosen to match Titan's rotation and orbit periods. There are two 8 hr downlinks scheduled each day for this phase, and every downlink will generate Radio Science data.

Once circular orbit is achieved, Campaign 1 (Atmosphere and Ionosphere) will begin and the MAPP and PMS instruments will operate continuously for the 16 day duration. A total of 43 Gb of data will be collected and downlinked during this campaign.

Campaign 2 (Surface Map) will execute for the next 16 days. MAPP instruments are still continuously operational, but now HiRIS and TiPRA will both be operational for 40% of each orbit—TiPRA on the night side, HiRIS on the day side. A total of 220 Gb of data will be collected, compressed, and returned to Earth.

Campaign 3 (Atmospheric Dynamics and Composition) executes for the next 16 days. For this set of 80 orbits, TIRS and SMS will operate continuously. Approximately 33 Gb of data will be collected, compressed and downlinked during this period.

To achieve the stated science objectives, Campaigns 2 and 3 alternate for the remainder of the first five months of the Circular Orbit Phase. At the end of five months, some or all of this cycle can be repeated, depending on the progress of science goal accomplishment. TSSM's operational scenario ensures that the instruments perform the required measurements while maintaining an efficient operational team and staying within the project budgets.

3.4.4 Extended Mission

Flight element designs and Titan's environment allow for an extended mission, possibly for years, if desired by NASA and ESA.

3.4.5 Decommissioning and Disposal Phase

The Decommissioning and Disposal Phase will put the orbiter on a trajectory spiraling slowly downward through the Titan atmosphere. This phase is expected to last six months; the decaying orbit will provide opportunities for unique atmospheric, magnetospheric and surface measurements.

3.4.6 Total Data Return

The potential cumulative data return from the Titan orbiter instruments exceeds 4.9 Tb. Up to 3.4 Gb of lander data and 1.3 Tb of montgolfière data can be returned.

3.5 Planetary Protection

Planetary protection (PP) requirements for Titan are in a period of revision, following the significant insight into the detailed working of the moon from the Cassini-Huygens mission. The final fate of the TSSM orbiter, impacting on the surface, means that the mission would likely be classified as Category II under current COSPAR and NASA policy (COSPAR 2002, NASA 2005), with comparatively few requirements. However, the study team recognizes that the NASA Planetary Protection Officer has received advice from the Planetary Protection Subcommittee of the NAC to protect Titan at a higher level (equivalent to COSPAR Category III for the orbiter and Category IV for the *in situ* elements). In addition, it is anticipated that COSPAR will review planetary protection status for icy moons in the near future, potentially before the end of Phase A.

Consequently, the TSSM study team's approach for the orbiter consists of managing planetary protection compliance to the COSPAR Category III level (accepting that the scientific case justifies it and that the NASA PPO will likely require it) by:

- Showing by analysis that the probability of an unintentional impact with Enceladus and Titan during the Saturn system tour will be below 1 x 10^{-3} as done by Cassini.
- Managing the descent to the surface, using resources such as propellant retained for the purpose, such that the probability that the spacecraft will contaminate any liquid water body on Titan does not exceed 1 x 10^{-4}.
- Ensuring that contaminated spacecraft hardware is not co-located with a perennial heat source capable of creating liquid water on the surface or in the shallow sub-surface. The viability of this approach is based on previous data for Mars. Confirmatory analysis will be performed in Phase A.

The NASA Planetary Protection Officer has indicated support for this approach, given that specific requirements and constraints for Titan and the broader Saturnian system are met.

Implications arising from planetary protection requirements were discussed by the Jovian and Saturnian Planetary Protection Working Group. In summary, planetary protection measures appear straightforward, and will not involve sterilization or other measures of similar complexity.

3.6 Technology Needs

While the TSSM orbiter and SEP Stage designs do not require new technology to achieve the Level 1 Science requirements, NASA's Evolutionary Xenon Thruster (NEXT) and the Advanced Stirling Radioisotope Generator (ASRG) are two enhancing technologies in advanced stages of engineering development that were adopted to add robustness to the mission architecture. In the case of each of these, there is a "fallback" to flight-qualified alternatives. The Titan Saturn System Mission could be accomplished with or without these new developments, but the mission will be more robust and more capable with them.

The montgolfière makes use of Huygens heritage (e.g., entry, aeroshell, avionics, etc.) but its balloon subsystem needs additional assessment with respect to material properties, rigidity, storage, and deployment. A substantial amount of planetary balloon development and testing has already been done by JPL and CNES. Balloon technology for Titan is well understood given the long terrestrial experience and Titan-specific advances over the last decade. Examples include: development of materials for cryogenic environments, testing and long term storage of materials; autonomous flight tests; balloon aerial deployment and inflation; gondola and MMRTG structural mockups and aerial deployment testing; montgolfière computational fluid dynamics analysis; steady state and dynamical performance simulations; and dynamic telecommunication tracking demonstrations. Further analysis and validation testing is planned. To address this, CNES has developed a Technical Development Plan (TDP) that includes analysis, test and verification of the balloon, and balloon material as well as demonstration flights. In addition, CNES has committed to substantial investment in a thorough Phase A effort, which will further mitigate potential montgolfière balloon implementation issues. ESA's development plans include system verification tests, drop tests and system test flights, as well as test and verification of MMRTG and balloon deployment.

ESA's lake lander follows directly from Huygens heritage and requires no new technology.

3.7 Other Risk Areas and Their Mitigation

TSSM has identified its risk areas and has mitigated them in the project plan and cost estimate.

3.7.1 Orbiter and SEP Stage Risks

Top risks for the orbiter are associated with selection of instruments and their development status, development of the SEP ion propulsion subsystem and availability of RPS.

Since the instruments will not be selected until July 2014, there is clearly uncertainty in what the contracted costs and development status will be. To address this, the estimated instrument costs are based on high heritage instrument systems and these costs include a 50% cost reserve. Additionally, plans for TSSM include the early development and testing of prototype instruments to reduce risk.

The primary approach for the SEP stage relies on the NASA GRC-developed NEXT ion thruster which remains to be flight qualified. Two back up flight proven thrusters and related components have been identified as fallback options. The cost estimate for the

NEXT development includes 50% cost reserve.

TSSM is compatible with use of either type of RPS (MMRTG or ASRG or both) however, a timely decision is needed as the design of the flight system progresses to avoid costly changes and delays. The timing of the RPS selection decision is not under the control of the TSSM project. To mitigate this risk, the project will work closely with the Program Executive at NASA Headquarters during the RPS Development Program, to ensure that requirements are known and a final decision on RPS is made prior to the completion of Phase A.

3.7.2 *In Situ* Element Risks

Development risk for the *in situ* elements is minimized through direct heritage from Huygens. The lander in particular is an evolution of the Huygens probe. Risks unique to the montgolfière are addressed by previous development activities and plans described in §3.6. In addition, both elements might be required to meet Planetary Protection Category IV requirements, which can be accommodated within the proposed designs. The cost estimate includes efforts to mitigate these risks.

4.0 NASA AND ESA IMPLEMENTATION RESPONSIBILITIES

4.1 Mission Elements

NASA responsibilities include the Titan orbiter with SEP stage, accommodation of *in situ* elements, launch vehicle, RPS for orbiter and montgolfière, ground system and orbiter system performance. ESA responsibilities include the *in situ* elements and their delivery to the launch site as well as provisions for ground system interfaces, and *in situ* system performance. Both NASA and ESA assume total mission performance responsibility. The proposed implementation approach has simple, clearly defined, programmatic and technical interfaces that enable NASA and ESA to jointly implement their responsibilities.

4.2 Science Instruments

The integrated JSDT has defined a planning payload for the purposes of conducting this study. It is anticipated that NASA and ESA would issue coordinated announcements of opportunity (AO) for the actual flight instrumentation for the orbiter and for the *in situ* elements. It is also anticipated that instruments related to each of the flight elements will be open for competition throughout the international community as was the case for Cassini-Huygens. European instruments will be provided through national agencies and institutes while US instruments will be from NASA Centers, universities or other science organizations. No pre-determined assignment for instrument delivery is anticipated (e.g., facility instrument).

4.3 Science Teams

The instruments on all mission elements will be solicited as a part of the coordinated Announcements of Opportunity by NASA and ESA for PI-led investigations. European scientists will be funded through their national agencies. All selected investigation leads will be part of the Project Science Steering Group (PSSG) that will be co-chaired by the NASA and the ESA Project Scientists. It is anticipated that a second solicitation for additional investigators would be planned as the flight system approaches Saturn (for TSSM) to engage scientists who would not have been established in their field at the time of the initial AO release.

4.4 Flight Operations

NASA and ESA will jointly execute the mission operations. ESA will be responsible for operating the *in situ* elements while NASA will be responsible for operating the orbiter. Pre-planned orbital scenarios will minimize the need for team-wide deliberations.

4.5 Management Approach

TSSM management efforts would build upon the relationships developed during the current study phase and involve close coordination between NASA, ESA and other major contributors. ITAR required Technical Assistance Agreements authorizing Caltech/JPL and Johns Hopkins University/APL to undertake cooperatives studies and implementation activities with ESA, CNES, and other entities and individual European scientists have now been approved by the U.S. State Department and will facilitate close working relationship on the studies and the project when it begins.

Management of the TSSM project would be modeled after the Cassini-Huygens project (and lessons learned) which included the NASA-provided Cassini orbiter and the ESA-provided Huygens probe. The Cassini orbiter delivered the battery powered Huygens probe to Titan and served as its communications relay as it descended through the atmosphere and landed on the surface. A very similar relationship exists for the TSSM orbiter and lake lander. Aspects unique to TSSM include integration of a NASA-provided radioisotope power system into the montgolfière during launch operations and longer communications relay function between the orbiter and montgolfière during the Saturn Tour Phase. TSSM management approach will be similar to that of Cassini-Huygens with two additions: provisions for providing and installing an RPS unit into the montgolfière (as was done for Ulysses) and extended montgolfière telecom relay operations (as is routinely done in the Mars program). Interfaces between NASA and ESA-provide elements, including mechanical, electrical, thermal, and communications, will be managed through interface control documents. Early exchange of representative hardware and software models will allow for high fidelity interface verifications.

5.0 NASA/ESA INTERDEPENDENCIES

5.1 Launch Capabilities

TSSM is implemented as a single launch on a NASA provided Atlas V 551 rocket in September of 2020. Delivery of the ESA *in situ* elements to Titan is dependent upon the NASA launch vehicle and orbiter accommodation.

5.2 Telecommunications

After separation from the orbiter, the *in situ* elements primarily depend upon the orbiter's RF communication subsystem to communicate with Earth in a way that is very similar to and benefits from Cassini-Huygens experience. The Universal Space Transponder (UST) used in the orbiter telecom subsystem has the flexibility to simultaneously communicate in multiple channels in X-band, allowing dedicated and redundant channels for *in situ* relay communications. During the primary mission of the *in situ* elements, their data will, in general, be transmitted from the orbiter to Earth at the highest priority. This communication scheme will continue during the Saturn Tour Phase, interrupted only by critical orbiter events.

5.3 Radioisotope Power Systems

The MMRTG provided for the ESA montgolfière will be supplied, controlled, handled, and installed by NASA and its contractors. This will necessitate a close collaboration between NASA and ESA to ensure smooth processing in the critical weeks of launch preparations. Full-scale models will be provided to ESA for early fit-checks and environmental testing, as well as an electrical simulator unit for the development and test phase of the montgolfière. The montgolfière design will allow for late integration of the MMRTG. The MMRTG will be mated to the montgolfière, as with the orbiter, for a fit-check and functional checkout at the Kennedy Space Center prior to final installation in the payload hazardous servicing facility (PHSF).

6.0 COST AND SCHEDULE

Both NASA and ESA have estimated the costs for their deliverable portions of TSSM including engineering development models, flight spares and all associated support equipment. The estimation methods used by each agency are specific to the mission concept development process within the agency. NASA has extensively studied missions to Titan and the Saturn system for several years and is able to provide a reasonably high fidelity cost estimate with element costs provided by the implementing organizations and reviewed by independent cost review boards.

6.1 NASA Costs

The cost to NASA for the Baseline TSSM mission concept is estimated at $3.7B RY ($2.5B FY07). This estimate includes cost reserves that were developed through a detailed bottoms-up analysis of risks: 10% Phase A, 35% Phase B–D and 15% Phase E–F. This cost estimate includes the TSSM orbiter, SEP stage, *in situ* element accommodation, science and instruments, Atlas V 551 launch vehicle, RPS, ground system and operations. The Project cost assumes it will be categorized as a Class A via NPR 8705.4, "Risk Classification for NASA Payloads," and as a Category 1 Project per NPR 7120.5D "NASA Space Flight Program and Project Requirements." The estimates represent the full life cycle cost for the mission through data analysis, archiving, and decommissioning. This cost does not

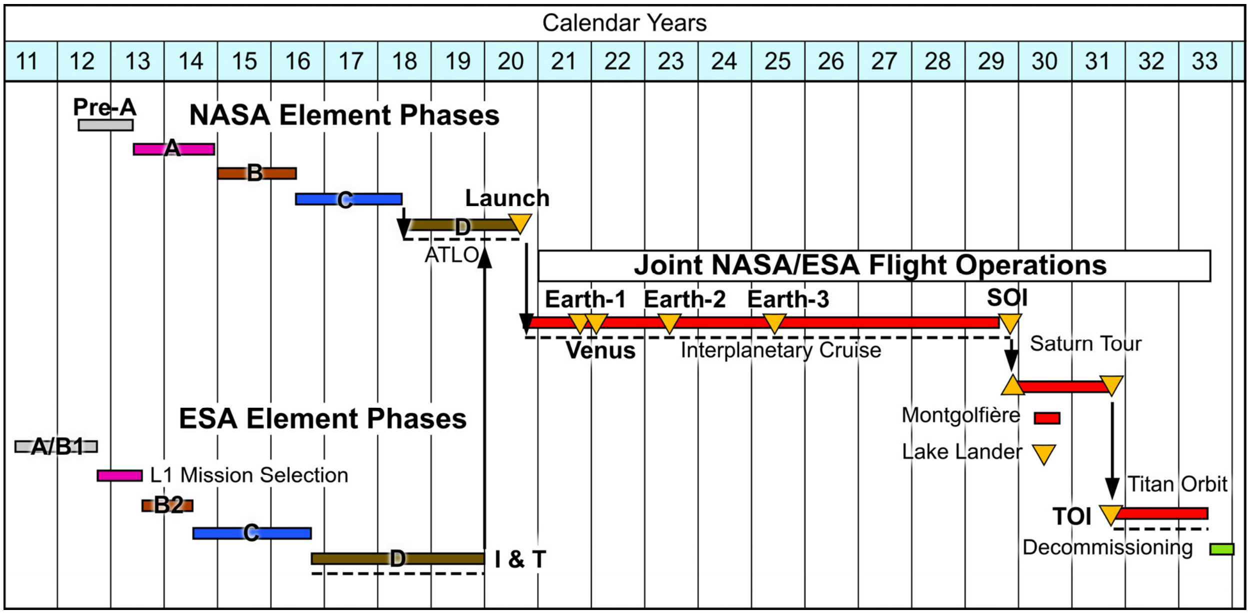


Figure 6.3-1. TSSM Baseline schedule uses parallel NASA and ESA developments leading to jointly conducted mission operations.

include ESA contributed *in situ* elements or other foreign contributions such as instruments or hardware.

6.2 ESA Costs

Preliminary cost was calculated using the CDF cost model, by comparison to Huygens and more recent developments, and suggests that the ESA costs are commensurate with the budget envelope for an L-class mission of the Cosmic Vision 2015–2025 Programme (650 M€ FY07 Cost-at-Completion). These ESA costs do not include the development and delivery of the balloon, which will be provided by CNES. The provision of science instruments is expected from European national funding, and thus is not included in ESA's costs.

6.3 High-Level Schedule

The development schedule for TSSM is based on proven development approaches used by NASA and ESA as well as previous experience implementing long duration deep space missions. The schedule, shown in **Figure 6.3-1**, was developed in accordance with NPR7120.5D and includes reserves in excess of study requirements and what is required by JPL and ESA practices. The Baseline launch date is 2020. There are no technical obstacles to supporting launch dates as early as 2018.

7.0 STUDY TEAM MEMBERS AND ROLES

An international science and technical team was formed by NASA and ESA with the goal to develop a focused cost-effective Titan Saturn System Mission (**Figure 7-1**). This team was led by JPL and ESA and was comprised of a NASA/ESA-appointed Joint Science Definition Team (JSDT) and an engineering team with members from NASA, JPL, JHU/APL, ESA and CNES. The JSDT and engineering team worked as a seamless integrated unit to define a mission that fully responds to the Statement of Work and Ground Rules for this study while at the same time assuring that the optimal balance between science cost and risk was achieved.

7.1 Joint SDT Function and Membership

NASA and ESA formed a Joint Science Definition Team (JSDT) with 16 US and 15 European members that was led by a NASA-appointed co-chair and study lead scientist and an ESA-appointed co-chair and study lead scientist. The JSDT included scientists from European countries as shown in (Appendix A, **Table A-1**). The role of the JSDT was to establish science goals and

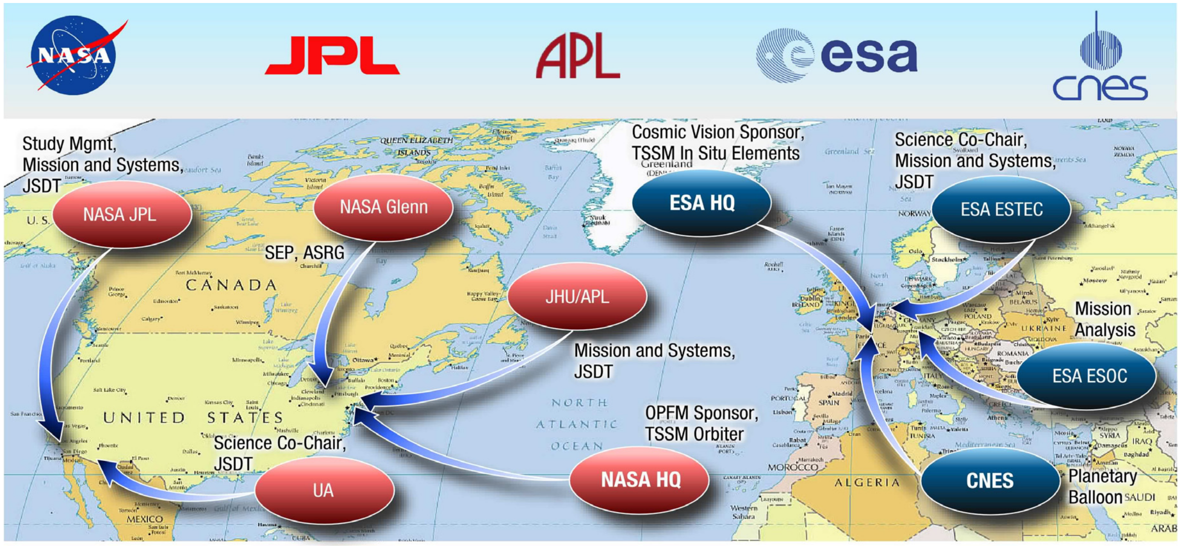


Figure 7-1. NASA/ESA geographically diverse team operates as a seamless integrated unit.

objectives that derive directly from guiding documents and to trace these through to define a planning payload and technical requirements on the mission. The JSDT was also a key participant in the design of the mission. The JSDT held seven face-to-face meetings and one teleconference. During the course of the study, the JSDT meetings included restricted working sessions as well as public forums to seek broad input from the international science community on the science objectives, potential remote sensing and *in situ* investigational methods, and measurement requirements. An instrument workshop for the science/instrument community was held in order to provide a better understanding of the mission constraints. Instrument sub-groups were formed within the JSDT to define measurement capabilities that respond directly to measurement requirements and to verify, through analysis, instrument performance with respect to achieving the science objectives. Members from mission architecture and design, system engineering, operations analysis and spacecraft design participated in each of the JSDT meetings to jointly resolve trades and develop operational strategies and scenarios to form a mission responsive to the science requirements.

7.2 NASA Study Team

The NASA engineering team included members from Jet Propulsion Laboratory (JPL), Johns Hopkins University/Applied Physics Laboratory (JHU/APL), NASA Glenn Research Center (GRC), NASA Goddard Space Flight Center (GSFC), University of Arizona and Observatoire de Paris-Meudon, France as shown in Appendix A, **Table A-2**. JPL provided study leadership, task management, requirements definition, system engineering, mission system design (flight and ground) and cost estimation. APL participated in mission system engineering, requirements analysis, project risk assessment, payload system engineering, model instrument definition and costing, *in situ* accommodation interface definition, project system integration and test and Phase E lessons learned.

NASA GRC supported the evaluation of Solar Electric Propulsion (SEP) options during the mission architectural assessment phase and provided input for SEP stage design and costing. GRC personnel also provided additional technical information for integration of ASRGs into the orbiter conceptual design.

7.3 ESA Study Team

Following the selection of the TandEM proposal to the Cosmic Vision 2015–2025 programme an internal assessment team was set-up. The ESA core team included a study scientist, a study manager and a payload study manager. During the main part of the work the ESA Concurrent Design Facility (CDF) was used for preliminary design with the primary goal of investigating the feasibility of the proposed mission concept.

An engineering team from CNES was integrated into the assessment study team. The main contribution was the provision of technical support for issues related to the design and interface of the balloon envelope.

The study team members are listed in Appendix A, **Table A-3**.

8.0 GUIDE TO STUDY DOCUMENTATION

The international NASA and ESA team has been building upon previous studies to configure an integrated mission concept which balances cost, risk and scientific value while responding to the science objectives of the Decadal Survey and Cosmic Vision Themes. There are several key NASA and ESA documents that led to initiation of the 2008 joint NASA/ESA study and the current study reports that were produced. These documents include the 2007 NASA Titan and Enceladus mission study reports, ESA Cosmic Vision 2015–2025 TandEM proposal, NASA Requirements and Ground Rules and Statement of Work. During the course of this study, a number of working groups were established, including Atmospheric, Surface, Mission Analysis, and Planetary Protection to perform analyses of specific scientific and technical issues in support of the study team. Results from the working groups can be found in separate working group reports. The purpose of this section is to provide a brief description of the key study documents and their relationship to one another. A diagram depicting the interrelationship between study documents is shown in **Figure 8-1**.

8.1 NASA Study Documentation

8.1.1 2007 Mission Studies

In FY07, NASA initiated Phase I studies of potential Outer Planet Flagship Missions to four icy satellite targets including missions to Titan and Enceladus. JHU/APL led the Titan Explorer study (29 August 2007) in collaboration with JPL while GSFC led the Enceladus Flagship mission concept study (29 August 2007) which was conceived as an entirely separate mission from Titan Explorer. Neither of these studies included international participation and in fact both were conducted in parallel to ESA's 2007 Cosmic Vision proposal cycle.

The Titan Explorer concept included an orbiter, dune lander and montgolfière balloon in a single launch configuration in which the orbiter was packaged in an aeroshell configuration allowing it to achieve orbit around Titan using the aerocapture method instead of chemical propulsion. The orbiter, lander, and balloon were designed to provide synergistic science at multiple, complementary scales.

The Enceladus study produced three concepts for further study: an Enceladus orbiter with a soft lander an Enceladus orbiter by itself, and a Saturn orbiter with a soft lander. These three cases were purposely selected to enable evaluation of different points in the architecture trade space and to expedite developing an understanding of basic system sizing, performance, and cost over the broad range of potential implementations.

Science, technical, and cost results from these studies were used as a stepping off point and resource for the joint NASA/ESA 2008 TSSM OPFM Study.

8.1.2 2008 Study Ground Rules and Statement of Work

Upon completion of NASA's 2007 OPFM studies and their independent review, NASA Headquarters elected to continue studying missions to two of those targets: Titan and the Saturn System (hence TSSM) and Europa and the Jupiter System (hence EJSM). In the same time frame, NASA and ESA agreed that the 2008 studies would be done as a collaborative effort thereby integrating results from the 2007 NASA studies and ESA's Cosmic Vision Programme selection. As a result, Ground Rules and Statement of Work documents were developed and provided by NASA (as highlighted in **Table 3.1-1**) to further focus the Titan Saturn System Mission. The Ground Rules describe parameters and tasks constraining the OPFM studies; the Statement of Work provides additional guidance on tasks and constraints unique to the Titan Saturn System Mission.

8.1.3 2008 TSSM Final Report

The NASA 2008 TSSM Final Report documents the results of the collaborative NASA/ESA mission concept study. This report addresses the entire mission science aspect but restricts treatment of the flight elements to the

NASA provided Titan orbiter, SEP stage and accommodation of ESA *in situ* elements. The ESA *in situ* elements are described separately in the ESA Assessment Report (§8.2.3), which is also included in the appendix of the TSSM Final Report.

8.2 ESA Study Documentation

8.2.1 TandEM Proposal for Cosmic Vision 2015–2025

In response to ESA's call for mission proposals for the Cosmic Vision 2015–2025 Programme, which was issued in March 2007, the TandEM proposal was put forth by the scientific team. Following that submission, the TandEM mission was selected for further study, in collaboration with NASA, and the share of responsibilities was agreed upon as documented in the Ground Rules and Statement of Work as presented in this report.

The baseline TandEM mission concept included two moderately sized spacecraft to be launched in ~2021 on one or two launch vehicles. They would provide both *in situ* and remote science measurements of both Titan and Enceladus. The two spacecraft were defined as follows: a Titan-Enceladus Orbiter (also carrying the Enceladus landers), and a Carrier for the Titan *in situ* investigation elements (the Titan balloon and up to three mini-probes).

8.2.2 ESA CDF Report

The ESA internal assessment of the *in situ* element feasibility was carried out in June and July 2008 with the assistance of ESA/ESTEC Concurrent Design Facility and support of an ESA/ESOC team for mission analysis and operations. The CDF consists of a temporary team of about 20 engineers of all involved disciplines that studied possible design options, including high level trade-offs and ultimately converged on a preliminary optimized design. This process allowed identification of critical elements, and also highlighted technology needs. A preliminary budget of the studied elements was provided.

The CDF team with the participation of CNES engineers performed a bottom up design of the montgolfière, a long lived lander (not included the baseline), and a small short lived lander, which was used as the basic building block for the current baseline lander to be targeted at a northern lake.

8.2.3 ESA Assessment Report

The results and conclusions of the CDF Report were taken as input to the ESA Assessment Report. The baseline *in situ* elements and their developments are described in this report.

8.2.4 Science Requirement Document for the *In Situ* Elements (Sci-RD)

In preparations for the internal ESA assessment study the Joint Science Definition Team (JSDT) summarized and compiled the scientific requirements. This was used to guide the assessment study and to assist in decisions that needed to be taken to arrive at a optimized design.

8.2.5 Reference Payload Definition Document (PDD)

The JSDT assigned a group of instrument experts who in collaboration with the JSDT defined high level instrument properties that satisfied the science requirements. This model payload as defined in this document was used to verify that the system could fulfill all requirements.

8.2.6 Mission Requirements Document (MRD)

The MRD describes the high level mission requirements as derived from the science requirements. These requirements were flowed down to the subsystem level. This document was used to focus the work of the CDF study and will, in an updated version, serve as an applicable document for the industrial study in the next phase.

8.3 Study Results Review Process

Elements of the TSSM concept study reports have been reviewed extensively:

1. Review and concurrence from NASA PPO for the orbiter planetary protection approach concept.
2. The Science Goals and Objectives were subjected to review by independent planetary scientists at all of the relevant science meetings in 2008.
3. The Science Goals and Objectives and the mission concept were presented at the Outer Planets Assessment Group (OPAG) meeting in April 2008.

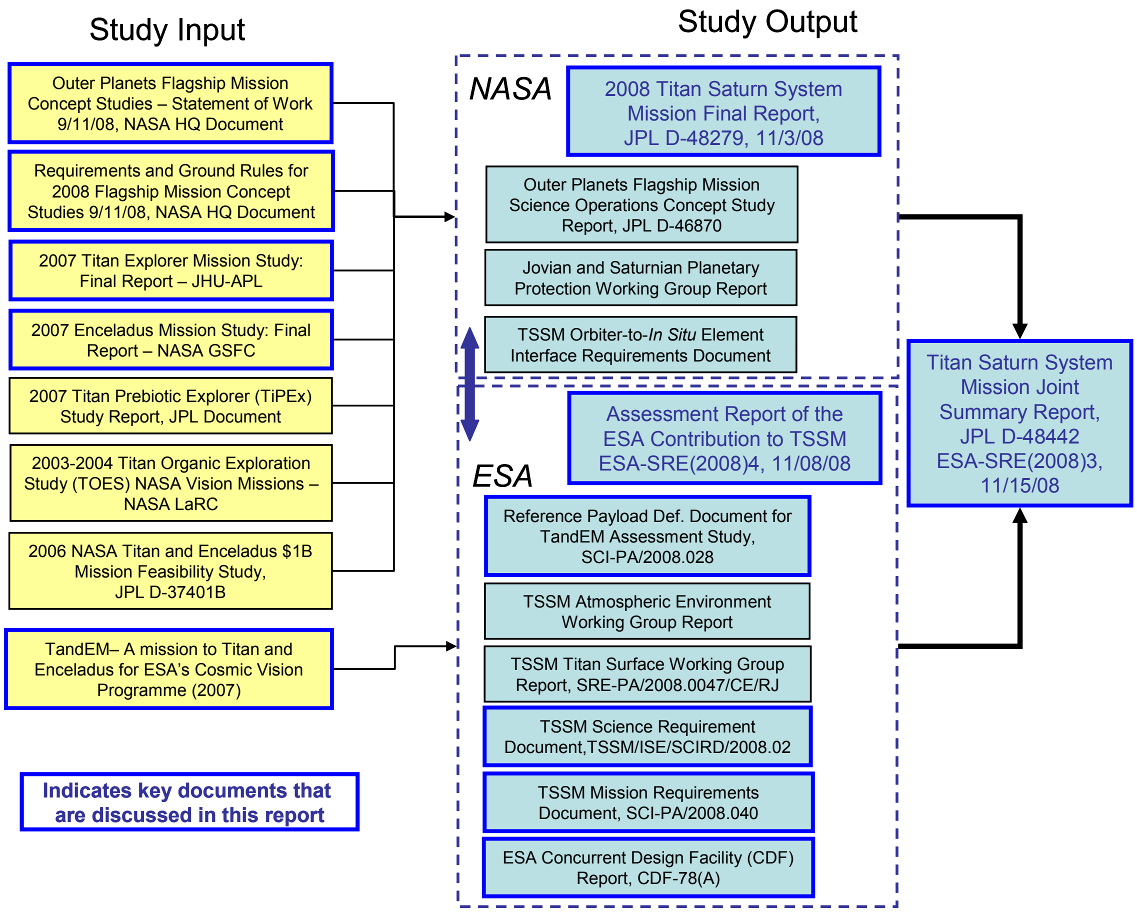


Figure 8-1. *Interrelationship of the 2008 TSSM study documentation.*

4. The mission concept and approach was subjected to two NASA HQ interim reviews in April and June of 2008.
5. Orbiter and SEP stage subsystems were subjected to focused internal reviews by JPL and APL personnel for technical validity including detailed comparison and contrasting with other flight proven subsystems.
6. The mission concept, measurement requirements, planning payload, science operational scenario, and overall approach was presented to the broad science and technical community through the conduct of an Instrument Workshop in June of 2008 and various conferences, symposiums, and workshops to communicate results and solicit external feedback.
7. The NASA portion of the mission implementation has been reviewed by technical, management, and cost review boards and line management organizations internal to JPL and APL. This resulted in a very thorough assessment of study results that produced 460 review item discrepancies (RIDs), all of which have been resolved in finalizing the TSSM study report.
8. The NASA TSSM study report was reviewed by both JPL and APL management and the ESA co-chair and lead scientist prior to submission to NASA for independent review.
9. The ESA Assessment Report was reviewed by ESA technical staff prior to submission to ESA for review.
10. This Joint Summary Report was reviewed by management from NASA, ESA, JPL, and APL prior to submission.

9.0 SUMMARY AND CONCLUSIONS

For over a decade NASA, most recently joined by ESA, has been studying mission concepts and developing technologies and instruments to explore Titan and Enceladus that have led to the current study. In 2007, NASA performed mission concept studies focused on four icy moon targets: Titan, Enceladus, Europa and Ganymede. Also in that year, ESA put forth its Cosmic Vision 2015–2025 call for mission concepts which resulted in selection of the *TandEM* concept focused on Titan and Enceladus. NASA and ESA study teams began working jointly in 2008 to merge their concepts and align their scientific goals through an integrated Joint Science Definition Team (JSDT). The resulting Titan Saturn System Mission (TSSM) Baseline is a joint cooperative venture between NASA and ESA to explore, in ways not previously possible, two worlds of intense astrobiological interest, Titan and Enceladus.

In the 50 years since space exploration began, TSSM will be the first *in situ* exploration of active organic chemistry and climate on the land, on the sea, and in the air of another world. The Baseline mission includes a full complement of NASA and ESA exploration elements. Orbiter, lander and montgolfière flight elements deploy highly capable complementary instruments in orbit, in atmospheric flight and on a large sea, and investigate the plumes of Enceladus in ways that Cassini cannot. The same instruments that provide orbital global coverage of Titan will be used to gain exceptional insights into the chemistry and internal evolution of Enceladus during seven targeted close flybys that promise to answer many of the most intriguing questions raised by Cassini. Furthermore, TSSM will make measurements that shed light on how Saturn's magnetosphere exchanges mass and energy with Titan and in particular feeds ions from other moons, such as Enceladus, into Titan's atmosphere.

TSSM provides comprehensive, yet focused, exploration of Titan and Enceladus:

- TSSM will explore two worlds of intense astrobiological interest (Titan and Enceladus) in a single NASA/ESA collaboration.
- TSSM engages the full range of planetary science disciplines and emerging young scientists.
- Cassini-Huygens discovered the scientific mother-lode. TSSM will mine the high value science through global coverage, *in situ* exploration and significant increases in instrument sensitivity, dynamic range and resolution.
- The stunning results will electrify the younger generation and engage the public in science and exploration.

While the NASA/ESA Baseline mission is the focus of this report, several variations were identified that still maintain Level 1 science requirements all the way down to a NASA-only science floor, defined as the orbiter alone. This Floor mission lacks the *in situ* investigations, but would retain the full set of orbital science investigations at Titan, as well as high resolution *in situ* atmospheric analysis throughout all mission phases, detailed Enceladus science through at least seven close flybys, and Saturn system science. Thus, there are a set of robust options for implementing TSSM.

The TSSM implementation plan leverages experience, reduces risk and ensures technical readiness. This plan builds upon the long-standing NASA/ESA Cassini-Huygens partnership. The capabilities (people, processes, and tools) to design and operate probes and Saturn-based orbiters at Titan are directly inherited. TSSM carries ample programmatic and technical margins. Its mission architecture and frequent launch opportunities ensure programmatic flexibility. This mission has waited until now, not because of technical challenges but, because Cassini-Huygens results were needed to plan a focused mission to Titan and Enceladus.

To touch, smell, and taste the organic soup of Titan and the organic-laden plumes of Enceladus opens the door to a bold new paradigm of solar system exploration. Scientifically and technically mature, TSSM is ready to do so now.

APPENDIX A. LISTING OF STUDY TEAM MEMBERS

Table A-1. *The Titan Saturn System Joint Science Definition Team draws from over ten different countries and multiple continents. Members are listed in alphabetical with JSDT co-chairs and study lead scientists listed first.*

Member	Affiliation	Expertise
Jean-Pierre Lebreton—Co-chair	ESA	Planetary Science
Jonathan Lunine—Co-chair	University of Arizona	Planetary Science
Athena Coustenis— European Lead Scientist	Observatoire de Paris-Meudon, France	Atmospheres
Dennis Matson— NASA Study Scientist	JPL	Planetary Science
Candice Hansen— NASA Deputy Study Scientist	JPL	Planetary Science
Lorenzo Bruzzone	University of Trento	Interiors, Gravity
Maria-Teresa Capria	Instituto di Astrofisica Spaziale, Rome	Enceladus, Origins
Julie Castillo-Rogez	JPL	Satellite Interiors
Andrew Coates	Mullard Space Science Laboratory, Dorking	Upper Atmospheres, Enceladus
Michele Dougherty	Imperial College London	Plasma Interactions
Andy Ingersoll	Caltech	Atmospheres
Ralf Jaumann	DLR Institute of Planetary Research, Berlin	Surfaces
William Kurth	University of Iowa	Particles and Fields
Luisa Lara	Instituto de Astrofísica de Andalucía, Granada	Atmospheres, Exospheres, Exoplanets
Rosaly Lopes	JPL	Geology
Ralph Lorenz	JHU/APL	Surfaces, Planetary Science
Chris McKay	Ames Research Center	Evolution of Solar System, Origins
Ingo Muller-Wodarg	Imperial College London	Plasma Interactions
Olga Prieto-Ballesteros	Laboratorio de Geologia Planetaria, Madrid	Astrobiology
François Raulin	LISA Universités Paris 12 & Paris 7	Exobiology, Planetary Protection
Amy Simon-Miller	GSFC	Atmospheres
Ed Sittler	GSFC	Plasma Physics, Ion Mass Spectrometry
Jason Soderblom	University of Arizona	Planetary Surfaces
Frank Sohl	DLR Institute of Planetary Research, Berlin	Interior Modeling, Geophysics
Christophe Sotin	JPL	Geology, Geodynamics
Dave Stevenson	Caltech	Geophysics, Satellite Interiors
Ellen Stofan	Proxemy Research	Geology
Gabriel Tobie	Université de Nantes	Interiors
Tetsuya Tokano	Universität zu Köln	Atmosphere Dynamics
Paolo Tortora	Università di Bologna	Interiors, Gravity
Elizabeth Turtle	JHU/APL	Impact Cratering, Remote Sensing
Hunter Waite	Southwest Research Institute	Mass Spectrometry, Aeronomy

Table A-2. *The integrated NASA technical team draws from organizations with deep space missions experience and a wealth of experience in long duration reliable mission system design. Members are listed in alphabetical order with study lead listed first.*

Member	Affiliation	Role
Kim Reh—Study Lead	JPL	Project Management and Systems Engineering
Mark Allen	JPL	SMS Model Instrument Support
Sami Asmar	JPL	RSA Model Instrument Engineer
Sarah Bairstow	JPL	Systems Engineering
Chuck Baker	JPL	Visualization
Pat Beauchamp	JPL	Science, Meas. Capability, Instrument Workshop
Matthew Bennett	JPL	Software
Scott Benson	NASA GRC	Solar Electric Propulsion

Member	Affiliation	Role
Alexis Benz	JPL	Systems Engineering
Tibor Balint	JPL	TandEM Liason, visualization
John Brasunas	GSFC	TIRS Model Instrument Support
John Brophy	JPL	Solar Electric Propulsion
Kate Coburn	JPL	Enterprise Support, Secretary
John Elliott	JPL	Flight Systems Lead, Systems Engineering
Michael Flaser	GSFC	TIRS Model Instrument Support
Marc Foote	JPL	TIRS Model Instrument Engineer
Troy Goodson	JPL	Navigation/Flight Path Control
Rob Green	JPL	HiRIS Model Instrument Engineer
Sam Gulkis	JPL	SMS Model Instrument Support
Jose Guzman	JHU/APL	Titan Orbit
Dave Hansen	JPL	Telecommunication
Ted Hartka	JHU/APL	Mechanical/Structure/Mechanisms
Ken Hibbard	JHU/APL	Systems Engineering
Mark Holdridge	JHU/APL	Operations and Lessons Learned
Denise Hollert	JPL	Mechanical/Structure/Mechanisms
Sarah Hornbeck	JPL	Systems Engineering
Melissa Jones	JPL	Systems Engineering
Insoo Jun	JPL	Radiation Environment and Performance
Ken Klaasen	JPL	Instrument Engineering, Measurement Capability
Milana Kozulina	JPL	Cost Lead
Tibor Kremic	NASA GRC	Solar Electric Propulsion
Try Lam	JPL	SEP Trajectory
Damon Landau	JPL	SEP Trajectory / Chemical Trajectory
James Leary	JHU/APL	Systems Engineering
Emmanuel Lellouch	Observatoire de Paris-Meudon, France	SMS Model Instrument support
Joe Lewis	JPL	Propulsion Tanks
Rob Lock	JPL	Mission Planning, Concept of Ops, Scenarios
Daniel Lyons	JPL	Aerobraking
Tom Magner	JHU/APL	Project Management and Systems Engineering
Carolina Maldonado	JPL	Command and Data Handling
Tim McElrath	JPL	Navigation/Orbit Determination
Peter Meakin	JPL	Attitude Control and Articulations
Imran Mehdi	JPL	SMS Model Instrument Engineer
Ricardo Mendoza	JPL	Telecommunications
Anthony Mittskus	JPL	Telecommunications
Bob Miyake	JPL	Thermal
David Mohr	JPL	Mission Planning, Concept of Ops, Scenarios
Margaret Morris	JHU/APL	Technical Editing
Barry Nakazono	JPL	Propulsion
Pablo Narvaez	JPL	EMI/EMC
Bill Nesmith	JPL	RPS
Don Nieraeth	JPL	Solar Electric Propulsion PPU Costing
Brian Okerlund	JPL	Mechanical Configuration, CAD
Joon Park	JPL	Artist
Michael Paul	JHU/APL	Systems Engineering, Risk Assessment
Fred Pelletier	JPL	Navigation/Orbit Determination
Mark Perry	JHU/APL	Payload System Engineering Lead
Anastassios Petropoulos	JPL	SEP Trajectory

Member	Affiliation	Role
Christina Poon	JPL	Technical Editing
Tom Randolph	JPL	BPT-4000 Hall Thruster
Ali Safaeinili	JPL	TiPRA Model Instrument Engineer
Carl Sauer	JPL	SEP Trajectory
Paul Schmitz	NASA GRC	ASRG/RPS
Richard Shaltens	NASA GRC	ASRG/RPS
Joseph Smith	JPL	Ground Systems Engineering
Bill Smythe	JPL	HiRIS, Measurement Capability, Sci. Ops.
Steve Snyder	JPL	NEXT Thruster
Tom Spilker	JPL	Mission Architect, Science Accommodation
Andy Spry	JPL	Planetary Protection
Nathan Strange	JPL	Mission Architecture and Design
Steve Thibault	JHU/APL	Project Systems Integration and Test Lead
Paul Timmerman	JPL	Power
Violet Tissot	JPL	Schedules
Tracy Van Houten	JPL	Systems Engineering
Steve Vernon	JHU/APL	RPS Integration
Chen-Wan Yen	JPL	Chemical Trajectory
Corby Waste	JPL	Artist
Dave Weir	JHU/APL	Payload Layout
Greg Welz	JPL	Msn Operations and Ground Data Systems Lead
Lee Wigglesworth	JPL	MAPP Model Instrument Engineer
Roger Yelle	University of Arizona	Titan Atmospheric Modeling

Table A-3. *The ESA technical team utilized its broad experience base and Concurrent Design Facility to rapidly integrate the science, payload and mission requirements into at a balanced conceptual design for TSSM which meets the science goals. Members are listed in alphabetical order with study manager listed first.*

Member	Affiliation	Expertise
Christian Erd—Study Manager	ESA	Project Management and Systems Engineering
Jens Romstedt—Study Payload Manager	ESA	Payload Systems Engineering
Peter Falkner	ESA	Project Management and Systems Engineering
Anamarija Stankov	ESA	Project Management and Systems Engineering
Stefano Santandrea	ESA	CDF Study Team Lead
Andrea Santovincenzo	ESA	CDF Study Team Lead
Mark Baldesarra	ESA	Systems
Torsten Bieler	ESA	Cost
Arnaud Boutonnet	ESA	Mission Analysis
Otto Brunner	ESA	Programmatics
Andrew Caldwell	ESA	Systems
Jean-Marc Charbonnier	Centre National d'Études Spatiales (CNES)	Balloon Design
Pierre Costes	ESA	Mechanisms
Jos Cremers	ESA	Structures
Antonio de Luca	ESA	Power
Luca Ferracina	ESA	Aerothermodynamics
Domenico Giunta	ESA	Communications
Peter Holsters	ESA	Communications
Robert Klotz	ESA	Configuration
Charles Lahorgue	ESA	Risk
Aitor Viana Sanchez	ESA	Data Handling

Member	Affiliation	Expertise
David Schwaller	ESA	Thermal
Keith Stephenson	ESA	Power
Rainer Timm	ESA	Ground System and Operations
Thomas Voirin	ESA	Guidance, Navigation and Control

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