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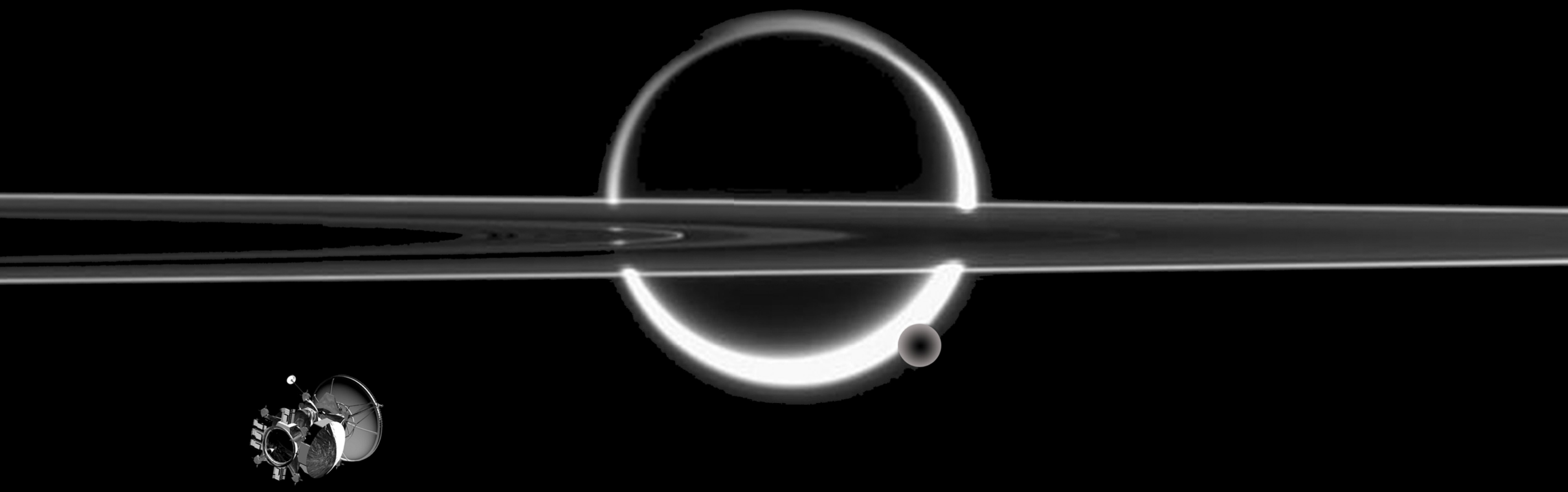

Mission Concept Study

Planetary Science Decadal Survey
Titan Saturn System Mission

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March 2010

Data Release, Distribution, and Cost Interpretation Statements

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

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

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

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

Planetary Science Decadal Survey

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Acknowledgments

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

Executive Summary

(Taken directly from Titan Saturn System Mission Study 2008: Final Report [1], Section 1.)

Overview

Titan is a high priority for exploration, as recommended by NASA's 2006 Solar System Exploration (SSE) Roadmap (NASA 2006), NASA's 2003 National Research Council (NRC) Decadal Survey (NRC Space Studies Board 2003) and ESA's Cosmic Vision Program Themes. Recent revolutionary Cassini-Huygens discoveries have dramatically escalated interest in Titan as the next scientific target in the outer Solar System. This study demonstrates that an exciting Titan Saturn System Mission (TSSM) that explores two worlds of intense astrobiological interest can be initiated now as a single NASA/ESA collaboration.

The Cassini-Huygens mission has revealed the Earth-like world of Saturn's moon Titan and showed the potential habitability of another moon, Enceladus. As anticipated by the 2003 Decadal Survey, recent Cassini-Huygens discoveries have revolutionized our understanding of the Titan system and its potential for harboring the "ingredients" necessary for life. These discoveries reveal that Titan is very rich in organics, possibly contains a vast subsurface ocean, and has energy sources to drive chemical evolution. The complex interaction between the atmosphere and surface produces lakes, dunes, and seasonal changes that are features that Titan shares with Earth. Cassini's discovery of active geysers on Enceladus revealed a second icy moon in the Saturn system that is synergistic with Titan in understanding planetary evolution and in adding another potential abode in the Saturn system for life as we know it. These discoveries have dramatically escalated the interest in Titan as the next scientific target for an outer Solar System mission.

Although the scope of science possible at Titan covers the entire range of planetary science disciplines, the TSSM team has developed a mission architecture that focuses NASA and ESA resources on the highest priority science questions. Results of this study confirm that a flagship-class mission to Titan (including the Saturn system and Enceladus) could be done at acceptable risk within the specified budgetary constraints and can proceed now.

Background

NASA and ESA are completing Pre-Phase A concept studies in support of a joint selection process for the next Outer Planet Flagship Mission (OPFM).

The Titan Saturn System Mission (TSSM) study was directed to redesign the 2007 Titan Explorer mission concept to meet new constraints specified under the revised Requirements and Ground Rules document (2008) and Statement of Work (2008), key elements of which are listed below.

- Respond to the 2007 Study independent review board findings.
- Produce a mission concept that optimally balances science, cost, and risk.
- Define a NASA/ESA Baseline and Floor mission that includes a NASA-provided Titan orbiter that would not utilize aerocapture. The orbiter shall have the capability of delivering and providing relay communications for multiple Titan in situ elements that would be provided by ESA as part of a collaborative program.
- Define a NASA-only mission and Floor mission that could be implemented by NASA in the event ESA does not participate.
- Include Saturn system and Enceladus as Level 1 science requirements to the extent they inform us about Titan.
- Include minimum of 33% reserves/margins in all areas.

- Use a launch date of 2020 for schedule and cost purposes. Alternative launch dates from 2018 through 2022 should be identified.

This study and its predecessors are intended to support a joint NASA-ESA down-select to a single OPFM expected in February 2009.

Study Approach

TSSM builds upon the results of more than a decade of previous studies as well as thorough science assessment, rigorous systems engineering, and experience gained from the Cassini-Huygens mission to develop a high fidelity concept in support of the NASA/ESA OPFM down-selection process.

An international science and technical team was formed with the goal to develop a focused, cost-effective TSSM (Figure ES-1). NASA and ESA formed a Joint Science Definition Team (JSDT) with 16 US and 15 European members. It was led by a NASA-appointed co-chair (from the University of Arizona, UA) and an ESA-appointed co-chair (from ESA/ESTEC) that established science objectives and participated in the design of the mission. JPL and ESA jointly formed the technical team with members from JPL, APL, NASA Glenn, ESA/ESTEC, ESA/ESOC, and CNES. It designed the mission and its elements. The JSDT and technical team worked as an integrated unit to define a mission that fully responds to the Statement of Work and Ground Rules for this study. This was achieved by establishing science goals and objectives that derive directly from guiding documents and then tracing these forward to define a planning payload and technical requirements on the mission as described in §2.0 and §4.1.1. These provided the basis for the team to develop a concept that balances cost and risk and achieves the science goals established by the JSDT as described in §2.0.

The Baseline Mission concept developed by the study team includes a NASA orbiter with Solar Electric Propulsion (SEP) stage and ESA provided lander and montgolfière balloon. The floor for this NASA-ESA mission preserves all flight elements except the SEP stage with the impact of taking as much as 1.5 years longer to reach Saturn.

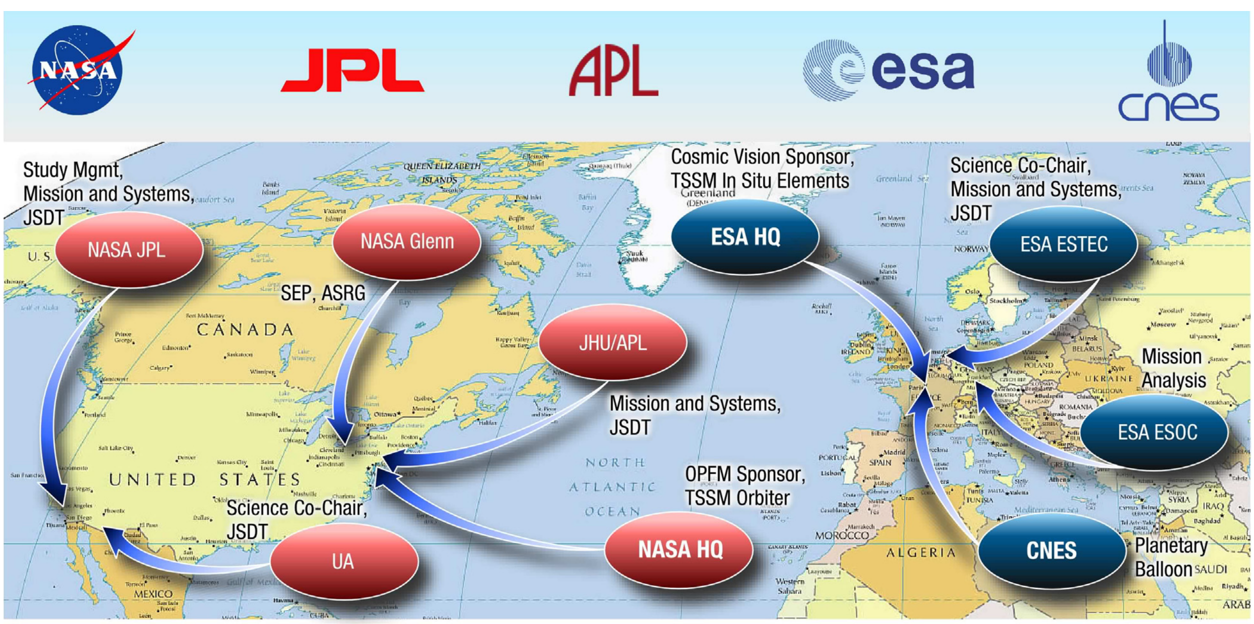

Figure ES-1. NASA/ESA geographically diverse team operates as a seamless integrated unit incorporating lessons learned from the Cassini-Huygens model.

Science Overview

Titan, a rich, diverse body offering the potential for extraordinary scientific return, is emerging as the compelling choice for the next Outer Planet Flagship Mission.

Titan, a complex, Earth-like moon with organics, shares features both with other large icy satellites and the terrestrial planets. It is subjected to tidal stresses, and its surface has been modified tectonically to form mountains. It is likely that cryovolcanism exists where liquid water, perhaps in concert with ammonia and carbon dioxide, makes its way to the surface from the interior. Cassini revealed that Titan has the largest accessible inventory of organic material in the solar system aside from Earth, and its active hydrological cycle is analogous to that of Earth, but with methane replacing water. Titan's clouds, rain, flash floods, and greenhouse and anti-greenhouse effects might provide important lessons for Earth's long-term climate evolution. Albeit with dramatically different chemistry, Titan's landscape appears remarkably Earth-like, featuring dunes, fluvial channels, and mountain ridges, as well as polar lakes filled with liquid hydrocarbons. Titan's dense atmosphere is mostly nitrogen—like Earth's—and varies seasonally in temperature, dynamical behavior, and composition, including a winter polar structure analogous to Earth's ozone hole. Finally, although Titan is similar to Earth in many ways, its atmosphere is unique in the solar system, experiencing strong dynamical forcing by gravitational tides (a trait Titan may share with many extrasolar planets). A mission launched in the 2018–2022 timeframe would provide a unique opportunity to measure a seasonal phase complementary to that observed by Voyager and by Cassini, including its extended missions.

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 two-year orbital mission at Titan would 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 a *2–3 order-of-magnitude* increase in Titan science return over that of the Cassini mission.

Chemical processes begin in Titan's upper atmosphere and could be extensively sampled by an orbiting spacecraft alone. However, there is substantial additional benefit of 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, would enable the assessment of the kinds of chemical species that are present on the surface and of how far such putative reactions have advanced. The rich inventory of complex organic molecules that are known or suspected to be present at the surface makes new astrobiological insights inevitable. *In situ* elements also enable powerful techniques such as subsurface sounding to be applied to exploring Titan's interior structure. Understanding the forces that shape Titan's diverse landscape benefits from detailed investigations of various terrain types at different locations, a demanding requirement anywhere else, but one that is uniquely straightforward at Titan using a montgolfière hot-air balloon. TSSM's montgolfière could circumnavigate Titan carried by winds, exploring with high resolution cameras and subsurface-probing radar. The combination of orbiting and *in situ* elements is a powerful and, for Titan, unprecedented opportunity for synergistic investigations—synthesis of data from these carefully selected instrumentation suites is the path to understanding this profoundly complex body.

En route to Titan, opportunities exist to significantly extend our understanding of Saturn's magnetosphere. Furthermore, the tour through the Saturn system would take the orbiter through the plumes of Enceladus (Figure ES-2). Using more capable instrumentation not available on the Cassini spacecraft, these investigations would not only inform us about these fascinating parts of the Saturn system, but would help us address important questions about Titan as well.

The TSSM Science Goals as shown in Table ES-1 respond directly to NASA's science objectives, ESA's Cosmic Vision themes, and science questions raised by the extraordinary discoveries by Cassini-Huygens. TSSM science would embrace geology, meteorology, chemistry, dynamics, geophysics, space physics, hydrology, and a host of other disciplines. Thus, it would engage a wider community than for

Table ES-1. TSSM science goals.

Goal	Summary
Goal A: Titan: an Earthlike System	How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?
Goal B: Titan's Organic Inventory	To what level of complexity has prebiotic chemistry evolved in the Titan system?
Goal C: Enceladus and Saturn's magnetosphere	What can be learned from Enceladus and from Saturn's magnetosphere about the origin and evolution of Titan?

Figure ES-2. The TSSM orbiter would have multiple opportunities to sample Enceladus' plumes.

virtually any other target in the outer Solar System. Clearly, Titan, a rich, diverse body offering the promise of extraordinary scientific return, is emerging as the compelling choice for the next NASA Flagship mission.

Mission Architecture Assessment

A robust architecture has been developed that would enable NASA/ESA or NASA-only mission options that respond comprehensively to the science requirements.

Many different mission architectures and trades were explored. Various combinations of orbiter and *in situ* elements, propulsion elements, single-launch versus multiple-launch scenarios and delivered mass versus trip time performance were assessed. Per the study ground rules, aerocapture concepts were not pursued as part of this study but can be found in the 2007 Titan Explorer study report.

The TSSM Baseline mission 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 ES-3 indicate that the combination of orbiter, solar electric propulsion, lander, and montgolfière would provide the highest science value per unit of currency invested.

This Baseline mission architecture provides descope options for both NASA and ESA to a scientifically attractive NASA/ESA Floor mission (as shown in Figure ES-4 and described in §3.3.1.2), yielding a very robust project implementation plan. The Baseline is comprised of a NASA orbiter with SEP stage and ESA-provided lander and montgolfière hot air balloon. The floor for this NASA/ESA mission would not include the SEP stage, in addition to other potential descopes (§4.11.7.8), and would result in a 1.5-year longer interplanetary trajectory. The impact to science is limited to later return of science data. The impact to the mission is reduced flexibility.

In the event of an ESA decision not to participate, a NASA-only mission could proceed. If this decision is made late in the process an exciting orbiter-only mission would be feasible that fully meets the Level 1 science requirements. However, if the decision occurred during or prior to Phase A there would be the possibility of a mission with US provided *in situ* elements (and/or possibly 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. The orbiter-only architecture described in this report preserves Titan, Saturn system, and Enceladus Level 1 science but gives up montgolfière and lander

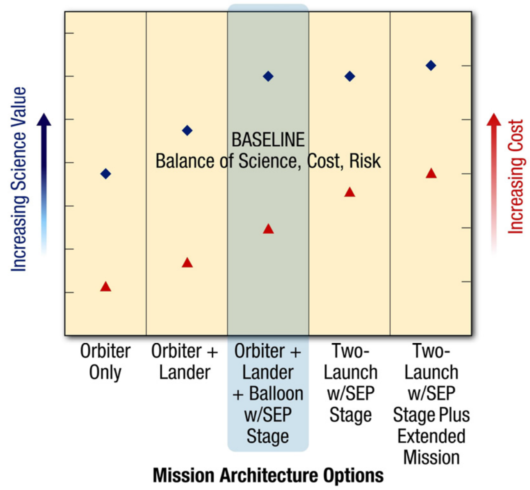

Figure ES-3. TSSM's Baseline architecture maximizes science return to investment ratio within NASA and ESA resources, at risk comparable to Cassini-Huygens.

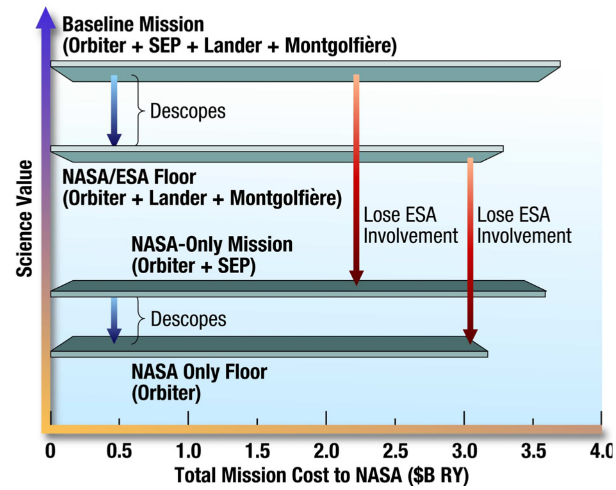

Figure ES-4. NASA/ESA and NASA-only mission architectures include robust descopes while remaining above the science floor.

measurements. The impact to science of the fully descoped NASA-only orbiter mission is limited to later return of science data. The impact to the mission is reduced flexibility.

An orbiter-only mission with the instrument complement described here provides a qualitatively different and quantitatively more powerful data set about Titan than did Cassini-Huygens, and would fundamentally revolutionize our understanding of Titan. It would 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.

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.

Mission Implementation

TSSM implementation options include orbiter and in situ elements that build upon and apply the design, operational experience and lessons learned from Cassini-Huygens, Galileo, Mars Orbiter, New Horizons, Dawn, MESSENGER, Beagle-2 and Exomars missions.

The flight elements shown in Figure ES-5 would be launched on an Atlas V 551 launch vehicle in 2020 using a gravity-assist SEP trajectory to achieve a trip time of 9 years to Saturn. Following Saturn orbit insertion, the orbiter would conduct a Saturn system tour, including 7 close Enceladus flybys and 16 Titan flybys. This phase would allow excellent opportunities to observe Saturn, multiple icy moons and the complex interaction between Titan and Saturn's magnetosphere. The montgolfière would be released on the first Titan flyby, after Saturn orbit insertion, and would use an X-band relay link with the orbiter for communications. The lander would be released on the second Titan flyby and communicate with the orbiter during the flyby only. This 24-month period would also mark the mission phase when all of the Titan *in situ* data is relayed back to Earth. Following its tour of the Saturn system, the orbiter would enter into a highly elliptical Titan orbit to conduct a two-month concurrent Aerosampling and Aerobraking Phase in Titan's atmosphere, sampling altitudes as low as 600 km. The orbiter would then execute a final periapsis raise burn to achieve a 1500-km circular, 85° polar-mapping orbit. This Circular Orbit Phase would last 20 months.

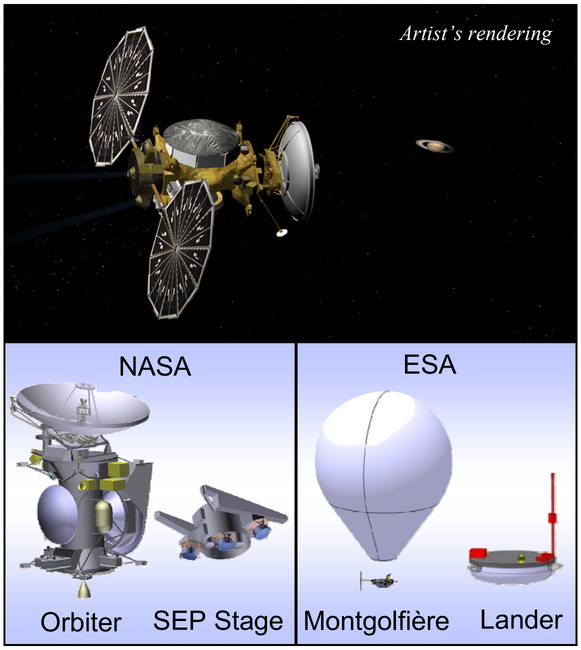

Figure ES-5. Baseline mission concept includes coordinated orbital observation and in situ elements.

On completion of the mission, a Decommissioning and Disposal Phase would be initiated by performing a moderate sized maneuver that begins the orbit decay. Small maneuvers during the decay would target the final impact site to ensure planetary protection requirements are met.

The orbiter concept has mass allocations of 165 kg for its remote sensing instruments and 830 kg for ESA-provided *in situ* elements. Payload and operational scenarios were developed with the JSDT to meet the prioritized science objectives. Flight and ground systems are sized to provide the data volumes necessary to return measurement data from the orbiter and *in situ* elements.

The integrated JSDT has defined a model/planning payload for the purposes of conducting this study. Instrumentation for the orbiter, lake lander, and montgolfière elements were configured in an optimal way to collaboratively achieve the mission science goals. It is anticipated that NASA and ESA would issue coordinated announcements of opportunity (AO) for the mission instrumentation, respectively for the orbiter and for the *in situ* elements. It is anticipated that instruments related to each of the mission elements would be open for competition throughout the international community as this was the case for Cassini-Huygens.

TSSM benefits from proven experience, proven Flight Systems, existing launch capabilities, lessons learned and well-understood trajectory options. The design relies on traditional chemical propulsion (similar to Cassini and Galileo), proven solar electric propulsion, a power source consisting of five Advanced Stirling Radioisotope Generators (ASRGs) and a robust data relay and downlink system. The concept is also fully compatible with Multimission Radioisotope Thermoelectric Generators (MMRTGs). Table ES-2 lists major characteristics of the Baseline mission. NASA will decide which RPS would be used.

The TSSM concept meets or exceeds reserves and margins prescribed in the study ground rules that exceed JPL's Flight Project Practices and Design Principles developed and used successfully over the past several decades. Design life of the flight system is based on design rules and techniques manifestly demonstrated by Voyager, Galileo, and Cassini during their long-life missions. Environmental risk factors are minimal and well-understood.

The same organizations that partnered on Cassini-Huygens have partnered to bring their experience to carry out TSSM:

- JPL has built and is currently operating the Cassini orbiter at Saturn.
- JPL is the only organization to have delivered probes to the outer planets.
- JPL and APL are the only organizations to have sent RPSs to the outer planets.
- ESA (through CNES) has an active terrestrial ballooning program and has previously worked on balloons for both Mars and Venus.
- ESA is the only organization to have landed a probe (Huygens) on Titan.

Table ES-2. Key mission characteristics of the TSSM Baseline mission concept.

Architecture	Orbiter with *in situ* elements
Launch vehicle	Atlas V 551
Launch date	9/2020
Trajectory	Earth-Venus-Earth-Earth gravity assist
Flight time to Saturn	9 years
Saturn System Tour Phase	24 months
Number of close Enceladus encounters during the Saturn Tour	7
Number of Titan encounters during the Saturn Tour	16
Titan Aerosampling Phase	2 months
Titan Orbital Phase	20 months
Radiation Design Point*	<15 krads
Science Instruments, mass allocation	
Orbiter	6 plus radio science; 165 kg
Montgolfiére	7 plus radio science; ~25 kg
Lake Lander	5 plus radio science; ~32 kg
Average data volume return from Titan orbit	5.4 Gb/Earth day (compressed)
Cumulative data volume	
Orbiter	>4.9 Tb
Montgolfiére	>300 Gb – 1.3 Tb
Lake Lander	>500 Mb – 3.4 Gb

*Behind 100 mils of Al, RDF of 1

Cost, Schedule, and Risk

The TSSM Baseline concept provides a comprehensive response to science objectives that leverages NASA and ESA resources and reduces risk to ensure technical readiness.

As shown in Figure ES-3, NASA/ESA and NASA-only options have been defined with associated descope paths.

The total cost to NASA (rounded up) is estimated to be $3.7B in real year dollars (RY) for the NASA/ESA Baseline mission and $3.3B (RY) for the NASA/ESA Floor mission. This cost to NASA does not include ESA's costs. The costs to ESA are commensurate with the budget envelope for an L-class mission of the Cosmic Vision 2015–2025 program (650M€ Cost-at-Completion). These ESA costs do not include the development and delivery of the balloon envelope, which would be provided by CNES. Furthermore the provision of science instruments is expected from European national funding, and is therefore also not included in ESA's costs. Clearly this collaborative partnership provides a very significant science-to-cost ratio benefit to both NASA and ESA. In the event that ESA makes the decision not to participate, the cost of a NASA-only mission is estimated to be $3.6B (RY) and the fully descoped NASA-only Floor mission is estimated to cost $3.2B (RY).

Budget reserves for these costs were established by comparing a top down architectural assessment of risk with a bottoms-up WBS assessment based upon perceived risk. Reserves estimates from each of these two methods were triangulated with the reserves floor of 33% as called out by the Ground Rules. The larger of the three values was used by the project. As determined from the process described above, the TSSM budget reserves are calculated as:

- Phase A = 10%
- Phase B through D = at 35% per Bottoms Up analysis. The Cost Risk Subfactors analysis yielded a 34% estimate. Further details are discussed in Appendix D.
- Phase E = 15%

The reserves base is the current best estimate cost including RPS but excludes DSN Aperture, Launch System, and EPO.

The TSSM project implementation schedule is based on experience from prior Flagship missions and the unique aspects of this mission. It includes milestones and funded schedule margins consistent with NASA directive NPR 7120.5D and JPL Flight Project Practices. This schedule is driven primarily by long lead procurements, an extensive Verification and Validation (V&V) program, and mission trajectory considerations. Coordination with ESA during development and integration of the *in situ* elements is planned. A timeline for the mission with phase durations, key decision points, and operational modes is shown in Figure ES-6. The current schedule is based on a 2020 launch as directed in the ground rules for this effort. If a 2018 launch opportunity is preferred, the schedule could be adjusted for the two year advance. Later dates are easily accommodated as well.

An ESA baseline schedule was derived during the assessment study of the ESA provided *in situ* elements and it is confirmed as being compatible with a 2020 launch. Earlier launch dates are also possible.

While the science resulting from TSSM is a giant leap beyond Cassini-Huygens, the development risk for the Baseline TSSM is comparable to that for Cassini-Huygens. Long-lead items such as radioisotope power systems (RPS), propulsion systems, and structure are planned to be initiated early in the development process to ensure on-time availability for integration. Because the NASA orbiter and ESA *in situ* elements build upon Cassini-Huygens, MRO, MESSENGER, Dawn, New Horizons, Beagle-2 and Exomars experience and lessons learned, the technical development, and cost risks are well understood.

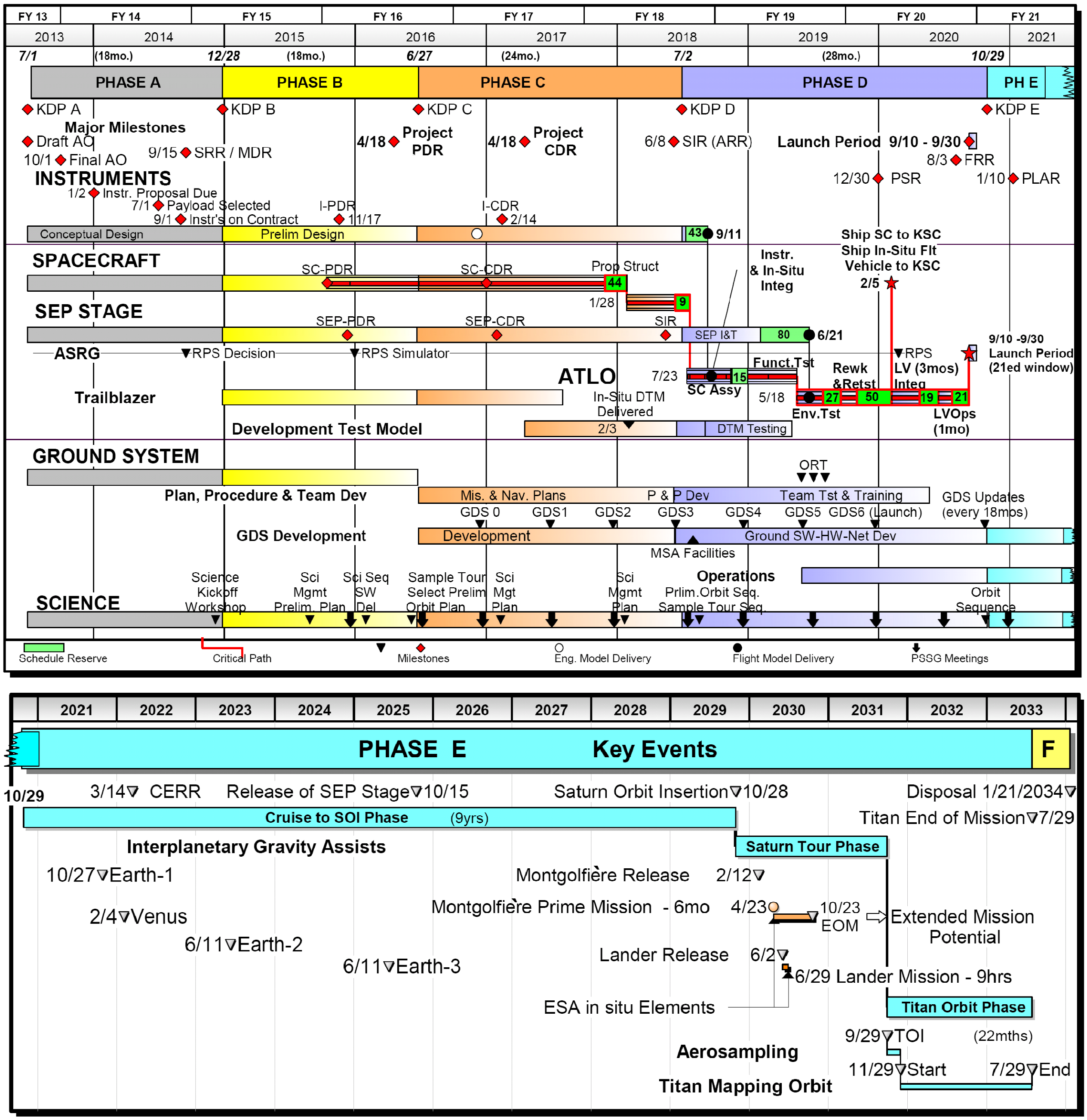

Figure ES-6. Top-level Baseline mission timeline.

Summary and Conclusions

Important science questions are now well established for Titan and the time is right to initiate a dedicated robust mission to answer them. TSSM would provide unequalled value by exploring two worlds of intense astrobiological interest (Titan AND Enceladus) as a single NASA/ESA collaboration. The excitement can continue!

A mission to study Titan in depth is a high priority for exploration, as stated by the 2003 NRC Decadal Survey large satellites panel.

> *Europa and Titan stand out as the highest-priority targets….It cannot now be predicted whether Europa or Titan will ultimately prove to be the most promising satellite for long-term exploration. However, Cassini-Huygens will surely revolutionize our understanding of Titan…*

Since the 2003 Decadal Survey, Cassini-Huygens discoveries have revolutionized our understanding of Titan and its potential for harboring the "ingredients" necessary for life. With these recent discoveries, the high priority of Titan is reinforced (NAI letter, Appendix M).

Remarkably, the picture that has emerged is one in which all the aspects of astrobiological interest are packaged in one body. Titan appears to have an ocean beneath its crust, almost certainly mostly of liquid water. Contact with rock during the early history of Titan, as the body differentiated, would have led to a salty ocean. The ocean would be suffused with organics from Titan's interior and from its surface (delivered by impacts), leaving Titan with a warm, salty, organic-laden ocean. Added to this is a dense atmosphere with active climate and organic chemistry, a surface of hydrocarbon seas and river channels, and a climate system that is more Earth-like in its operation than that of any other place in the solar system.

The Titan Saturn System Mission represents the logical next step in outer planets exploration with a host of features, ready to be implemented now.

- Unequalled exploration of two worlds of intense astrobiological interest (Titan AND Enceladus) in a single NASA/ESA collaboration.
- Major advance beyond Cassini-Huygens in accomplishing Decadal objectives.
- Science engagement over the full range of planetary science disciplines—Geology, Geophysics, Atmospheres, Astrobiology, Chemistry, Magnetospheres—through deployment of new instruments in orbit, in atmospheric flight, and on a large sea, and investigate the plumes of Enceladus in ways that Cassini could not do.
- Built upon a demonstrated capability to design, land, and operate probes on Titan (e.g., ESA Huygens), and Saturn-based orbiters (e.g., NASA Cassini).
- Baseline mission options provide feed forward SEP stage to enable other science missions.
- Leverages synergistic NASA/ESA resources, reduces risk, and ensures technical readiness.
- Ensures programmatic flexibility with frequent launch opportunities.
- Offers NASA-only options in the event ESA decides not to participate.

A unique mission for an extraordinary world, the Titan Saturn System Mission provides a kind of planetary exploration never before attempted by humans and ideally suited to the environment of Titan. This study confirms that the mission is ready to proceed.

1. Scientific Objectives

Science Questions and Objectives

See Titan Saturn System Mission Study 2008: Final Report [1], Section 2.

Science Traceability

Table 1-1. Science Traceability Matrix—Orbiter

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENT
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O1:** Determine how energy is deposited in the upper atmosphere to drive the chemistry and the escape rate of major atmospheric constituents.	**I1:** Quantify the deposition of radiation into Titan's atmosphere.	**M1:** Measure properties of thermal-magnetospheric charged particles that deposit energy into Titan's atmosphere such as fluxes, composition and spatial/temporal dependence of electrons and ions. Measure electrons from 0–1 MeV with 20° angular resolution and 30% energy resolution in the upward-looking and downward-looking hemispheres; ions from 0 to 1 MeV with 20° angular resolution and 30% energy resolution in the upward-looking downward-looking hemispheres and with the ability to stare in the ram and corotation directions at low energies (<30 keV). The plasma instrument must be able to separate methane group ions, ammonia group ions and water group ions.	**A1:** Low Energy Plasma and Particles Instrument includes plasma (ion and electron) spectrometers with energy range eV–30keV Energetic particle spectrometers cover the range 10 keV to 1 MeV. These form part of a combined package with dual head vector Magnetometer and Langmuir probe. Plasma instrument will require time resolution better than 60 s in order to resolve 1 atmospheric scale height or better.	MAPP	Periapses from 700 km upward during aerosampling and 950 km upwards during main mission. Complete range of local times and latitudes. Downward and upward going hemispheres visible.Knowledge of the orbiter attitude and a rigid boom to house the magnetometer sensors. If onboard plasma moments are required, the magnetic field measured on board (i.e., without on the ground correction due to spacecraft interference) must have sufficient accuracy to provide the required pitch angle accuracy, this puts constraints on the magnetic cleanliness requirements of the orbiter and the boom length.
			M2: Energy input from thermal-magnetospheric sources. Measure thermal electron density and temperature *in situ* and density profiles as a function of altitude from the ionospheric peak to the orbiter. Measure ionospheric ion density, winds and temperatures in top side ionosphere.	**A1:** Langmuir (swept voltage/current) probe as part of combined package with Low Energy Plasma and Particles Instrument, Energetic Particle Spectrometer and dual vector magnetometer. Time resolution better than 60 s to resolve atmospheric scale height.	MAPP	Periapses from 700 km upward during aerosampling and 950 km upwards during main mission. Complete range of local times and latitudes.
			M3: Energy input from EUV and UV as a function of altitude from the ionospheric peak to the orbiter.	**A1:** Modeled from swept voltage/current obtained by Langmuir probe.	MAPP	Periapses from 700 km upward during aerosampling and 950 km upwards during main mission.
		I2: Quantify the escape flux of elemental hydrogen, carbon, nitrogen.	**M1:** Vertical profiles of atmospheric constituents containing H, C, and N, including major isotopologues, from 800 to 2000 km altitude with precision of better than 5%.	**A1:** Direct sampling Mass spectrometry up to 10,000 Da with sensitivity of less than 10^4 cm^{-3} and dynamic range of 10^8.	PMS	Periapses varying from 700 km upward during aerosampling. Ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination. High Data Volume Data Rate: 48 kbits/s.
				A2: Submillimeter sounding at 540–640 GHz with resolution 300 khz and 5% precision in retrieved abundances.	SMS	Limb viewing from polar orbit, in-track and off-track orientation

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENT
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O1:** Determine how energy is deposited in the upper atmosphere to drive the chemistry and the escape rate of major atmospheric constituents.	**I2:** Quantify the escape flux of elemental hydrogen, carbon, nitrogen.	**M2:** Vertical profiles of atmospheric constituents containing H, C, and N, including major isotopologues, from 100 to 500 km altitude with precision of better than 1%.	**A1:** Passive Thermal-infrared Fourier Transform spectrometry, in the 30–1400 wavenumbers (7–333 μm) region; resolution 0.1–3.0 wavenumber.	TIRS	Limb and nadir viewing on polar orbit, in-track and off-track orientation
			M3: Magnetic field of Titan where escape mechanisms of C, N, H are operating. Measure vector magnetic field perturbations of order a few nT (with a resolution of order 0.04 nT) to quantify the escape flux of elemental hydrogen, carbon, and nitrogen	**A1:** Vector Magnetometry (part of a combined instrument).	MAPP	Continuous measurements, globally distributed at varying altitudes.
	O2: Characterize the relative importance of exogenic and endogenic oxygen sources.	**I1:** Quantify the flux of exospheric oxygen into the atmosphere.	**M1:** Vertical profiles atmospheric constituents containing oxygen including major isotopologues, from 100–1500 km altitude with precision better than 5%.	**A1:** Submillimeter sounding at 540–640 GHz with resolution 300 khz and 5% precision in retrieved abundances.	SMS	Limb viewing from polar orbit, in-track and off-track orientation
				A2: Direct sampling Mass spectrometry up to 10,000 Da at 1% peak height with mass resolution 3000–10,000 and high sensitivity (0.1 ppm at 850 km).	PMS	Periapses varying from 700 km upward and ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination. Low Data Volume Data Rate: 4 kbits/s
			M2: Vertical profiles of atmospheric constituents containing oxygen including major isotopologues, in lower atmosphere with precision of 1%.	**A1:** Passive Thermal-infrared Fourier Transform spectrometry, in the 30–1400 wavenumbers (7–333 μm) region (CO at 30–80 cm^{-1}, H_2O at 60–200 cm^{-1}, CO_2 at 670 cm^{-1}) resolution 0.1–3.0 wavenumber.	TIRS	Limb and nadir viewing on polar orbit, rotation in azimuth
		I2: Quantify the flux of endogenic oxygen from the surface and interior.	**M1:** Inventory of surface constituents containing oxygen including major isotopologues at 250 m resolution.	**A1:** Near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Prefer mapping phase orbit within ±3 hrs from local noon
	O3: Characterize the major processes controlling the global distribution of atmospheric chemical constituents.	**I1:** Characterize the major chemical cycles.	**M1:** Vertical, latitudinal and temporal dependence of condensed and gaseous species in the atmosphere from the surface to 1500 km with precision better than 10%.	**A1:** Passive Thermal-infrared Fourier Transform spectrometry, in the 30–1400 wavenumbers (7–333 μm) region; resolution 0.1–3.0 wavenumber.	TIRS	Limb and nadir viewing on polar orbit, rotation in azimuth
				A2: Submillimeter sounding at 540–640 GHz with resolution 300 khz and 10% precision in retrieved abundances.	SMS	Limb viewing on polar orbit, rotation in azimuth
				A3: Direct sampling Mass spectrometry up to 10,000 Da with mass resolution 3000–10,000 at 1% peak height, high sensitivity (0.1 ppm at 850 km) and a dynamic range of 10^8.	PMS	Periapses varying from 700 km upward and ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENT
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O3:** Characterize the major processes controlling the global distribution of atmospheric chemical constituents.	**I2:** Determine the relative importance of global transport.	**M1:** 4D transport with precision of better than 5%.	**A1:** Mid- to far-infrared spectra of the stratosphere in the 30–1400 wavenumbers (7–333 μm) region, spectral resolution of 3 to 15 wavenumbers, spatial resolution of <5 mrad IFOV.	TIRS	Limb and nadir viewing on polar orbit, rotation in azimuth
				A2: Submillimeter sounding at 540–640 GHz with resolution 300 khz and 10% precision in retrieved abundances and 5 m/s in winds.	SMS	Limb viewing from polar orbit, in-track and off-track orientation
				A3: Direct sampling Mass spectrometry up to 10,000 Da with mass resolution 3000–10,000 at 1% peak height, high sensitivity (0.1 ppm at 850 km) and a dynamic range of 10^8.	PMS	Periapses varying from 700 km upward and ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination.
	O4: Characterize the atmospheric circulation and flow of energy and its variability on short-timescales.	**I1:** Determine the atmospheric thermal and dynamical state.	**M1:** Temperature versus pressure for altitude, lat/long, and time. Stratospheric temperature to 1 K and tropospheric / mesospheric temperatures to 0.1 K; pressure to 10%. Vertical resolution < scale height thermosphere and stratosphere; 0.5 km troposphere.	**A1:** Mid- to far-infrared spectra of the stratosphere in the 30–1400 wavenumbers (7–333 μm) region, spectral resolution of 3 to 15 wavenumbers, spatial resolution of <5 mrad IFOV.	TIRS	Limb and nadir viewing on polar orbit, rotation in azimuth
				A2: Radio occultations over latitudes 85°N to 85°S using the USO. End to end radio link stability (Allan deviation) required to carry out the measurement is 10^{-13} at 10 s integration time.	RSA	Optimized occultation geometry
				A3: Submillimeter sounding at 540–640 GHz with resolution 300 khz and 1 K accuracy in retrieved atmospheric temperatures.	SMS	Limb viewing on polar orbit, rotation in azimuth
			M2: Winds with ~5 m/s or better accuracy. Zonal and meridional. Global 3D wind and temperature fields from 100 to 1500 km at vertical resolution of 10 km.	**A1:** Image clouds using a low spatial and spectral resolution mode of the near-IR spectrometer that provides images in multiple near-IR wavelengths, both in and out of the methane windows, 130 km wide with 1 km resolution during the circular mapping phase, and 1000 km wide with 2 km resolution during aerobraking.	HiRIS	Requires observations during Saturn orbit and aerosampling (elliptical orbit) phase
				A2: Mid- to far-infrared spectra of the stratosphere in the 30–1400 wavenumbers (7–333 μm) region, spectral resolution of 3 to 15 wavenumbers, spatial resolution of <5 mrad IFOV.	TIRS	Limb and nadir viewing on polar orbit, rotation in azimuth
				A3: Submillimeter at 540–640 GHz with resolution 300 khz down and 5 m/s accuracy in retrieved zonal and meridional winds.	SMS	Limb viewing from polar orbit, in-track and off-track orientation

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SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENT
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy and its variability on short-timescales.	**I2:** Determine the impact of haze and clouds.	**M1:** Cloud frequency with a spatial resolution of1 km and fields of view >hundreds of kilometers in extent.	**A1:** Image clouds using a low spatial and spectral resolution mode of the near-IR spectrometer that provides images in multiple near-IR wavelengths, both in and out of the methane windows, 130 km wide with 1 km resolution during the circular mapping phase, and 1000 km wide with 2 km resolution during aerobraking.	HiRIS	Requires observations during Saturn orbit and aerosampling (elliptical orbit) phase
			M2: Cloud top altitude and vertical extent, morphology, size of clouds and likelihood of precipitation. Resolve heights to 10% of a scale height; determine cloud bases through direct or indirect (e.g., methane vapor profile) approaches. Repeat observations of early summer hemisphere convective clouds at spatial resolution 1 km.	**A1:** Image clouds using a low spatial and spectral resolution mode of the near-IR spectrometer that provides images in multiple near-IR wavelengths, both in and out of the methane windows, 130 km wide with 1 km resolution during the circular mapping phase, and 1000 km wide with 2 km resolution during aerobraking.	HiRIS	Repeat passes over high southern latitudes during mapping phase.
		I3: Determine the effects of atmospheric composition.	**M1:** Vertical distributions of abundances of minor constituents as a function of latitude, time of day and season with better than 10% accuracy.	**A1:** Mid-infrared spectra of the stratosphere in the 30–1400 wavenumbers (7–333 µm) region, spectral resolution of 0.1–3 wavenumbers, spatial resolution of <5 mrad IFOV.	TIRS	Limb and nadir viewing on polar orbit, rotation in azimuth
				A2: Submillimeter sounding at 540–640 GHz with resolution 300 khz and 5% precision in retrieved abundances.	SMS	Limb viewing from polar orbit, in-track and off-track orientation
				A3: Direct sampling Mass spectrometry up to 10,000 Da at 1% peak height with mass resolution 3000–10,000 and a dynamic range of 10^8.	PMS	Periapses varying from 700 km upward during aerosampling. Ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination.
		I4: Determine the effects of surface processes on meteorology.	**M1:** Global topography with 10 m depth resolution in the region from 85°N to 85°S. Horizontal resolution required is 5–10 km cross track, 1 km lateral (along track) with 10 m vertical precision altimetry. Long temporal coverage of active regions.	**A1:** Altimetry measurements with single band (>20 MHz center) radar with capability of ~10 m height resolution and 1 km (along-track) and 5-10 km (cross-track) spatial resolution.	TiPRA	TiPRA can operate on the nightside.
			M2: Map extent of surface covered by liquid at 50 m resolution and 80% surface coverage.	**A1:** High-resolution near-IR imaging at 2.05 ± 0.08 µm, 2.73 ± 0.08 µm, and 5.35 ± 0.45 µm.	HiRIS	Prefer mapping phase orbit at ±4 hrs from local noon
			M3: Temperature gradients between liquid surface and surrounding terrains with 1 K precision.	**A1:** Mid- to far-infrared spectra of the stratosphere from 30–1400 wave numbers (7–333 µm), spectral resolution of 3 to 15 wave numbers, spatial resolution of <5 mrad IFOV.	TIRS	Nadir viewing

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SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENT
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy and its variability on short-timescales.	**I4:** Determine the effects of surface processes on meteorology.	**M4:** Identify active volcanism in the equatorial region with 50 m resolution from orbit and .2.5 m resolution from 10 km altitude	**A1:** High-resolution near-IR imaging at 2.05 ± 0.08 μm, 2.73 ± 0.08 μm, and 5.35 ± 0.45 μm.	HiRIS	Prefer mapping phase orbit at ±4 hrs from local noon
				A2: Mid- to far-infrared spectra of the stratosphere from 30–1400 wave numbers (7–333 μm), spectral resolution of 3 to 15 wave numbers, spatial resolution of <5 mrad IFOV.	TIRS	Limb and nadir viewing on polar orbit, rotation in azimuth
	O5: Characterize the amount of liquid on the Titan surface today.	**I1:** Quantify the total major-hydrocarbon (methane / ethane) inventory present in the lakes and seas.	**M1:** Lake and sea bathymetry. Lateral 10 km /10 m vertical precision.	**A1:** Single band (>20 MHz center) penetrating radar and altimetry with capability of sub-surface sounding to a depth of ~5 km with ~10 m depth resolution.	TiPRA	Measurement above the lake early and late in the mapping phase for seasonal progression
			M2: Map extent of surface covered by liquid at 50 m resolution and 80% surface coverage.	**A1:** High-resolution near-IR imaging at 2.05 ± 0.08 μm, 2.73 ± 0.08 μm, and 5.35 ± 0.45 μm.	HiRIS	Prefer mapping phase orbit at ±4 hrs from local noon. Measurement above the lake early and late in the mapping phase for seasonal progression
		I2: Determine the depth of the lake at the landing site.	**M1:** Lake and sea bathymetry. Lateral 10 km /10 m vertical precision.	**A1:** Single band (>20 MHz center) penetrating radar and altimetry with capability of sub-surface sounding to a depth of ~5 km with ~10 m depth resolution.	TiPRA	Coordinated effort with lander and orbiter.
	O6: Characterize the major processes transforming the surface throughout time.	**I1:** Determine the origin of major crustal features; correlate regional elevation changes with geomorph-ology and compositional variations.	**M1:** Surface topography with 10 m height resolution in the region from 85°N to 85°S. Horizontal resolution required is 5–10 km cross track, 1 km lateral (along track) with 10 m vertical precision altimetry. Long temporal coverage of active regions	**A1:** Altimetry measurements with single band (>20 MHz center) radar with capability of ~10 m height resolution and 1 km (along-track) and 5–10 km (cross-track) spatial resolution.	TiPRA	TiPRA can take data on the nightside.
			M2: Surface topography with 10 m height resolution and 0.5 km spatial resolution.	**A1:** High-resolution near-IR stereo imaging at 5.35 ± 0.45 μm.	HiRIS	Requires two global maps: one acquired near nadir and one acquired looking off nadir
			M3: Surface composition with 250 m resolution in region at all available latitudes	**A1:** Near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Prefer mapping phase orbit within ±3 hrs from local noon
			M4: Map surface features at 50 m resolution in multiple wavelengths and 80% surface coverage and correlate morphology and spectral characteristics of surface features with topography.	**A1:** High-resolution near-IR imaging at 2.05 ± 0.08 μm, 2.73 ± 0.08 μm, and 5.35 ± 0.45 μm.	HiRIS	Prefer mapping phase orbit at ±4 hrs from local noon

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SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENT
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O6:** Characterize the major processes transforming the surface throughout time.	**I2:** Characterize the origin of major surface features, including the effects of liquid flow, tectonic, volcanic, and impact events.	**M1:** Map surface features at 50 m resolution in multiple wavelengths and 80% surface coverage and correlate morphology and spectral characteristics of surface features with topography.	**A1:** High-resolution near-IR imaging at 2.05 ± 0.08 μm, 2.73 ± 0.08 μm, and 5.35 ± 0.45 μm.	HiRIS	Prefer mapping phase orbit at ±4 hrs from local noon
			M2: Search for surface changes, especially in lakes, channels, volcanic and aeolian features (tectonic changes and impacts are less likely).	**A1:** Repeated high-resolution near-IR imaging of selected regions on several timescales at 2.05 ± 0.08 μm, 2.73 ± 0.08 μm, and/or 5.35 ± 0.45 μm.	HiRIS	Repeated observations over variety of timescales, especially in regions where changes are likely (e.g., polar regions, sites of clouds/storms/precipitation), prefer mapping phase orbit at ±4 hrs from local noon
		I3: Determine the internal magnetic signal of Titan	**M1:** Magnetic map of the surface	**A1:** Dual sensor, vector magnetometer, with sensors located on a boom away from the magnetic signature of the Orbiter**.**	MAPP	Precise location of the orbiter, Orbiter attitude and rigid boom for the magnetometer sensor. Continuous magnetic field data, as much coverage of the surface as possible. Consideration of magnetic cleanliness requirements vs. boom length
		I4: Detect and measure the depth of shallow subsurface reservoirs of liquid (hydro-carbons).	**M1:** Sounding profiles of subsurface dielectric horizons, over the entire mappable surface, up to 5 km depth at 10 m vertical resolution, and long temporal coverage of active regions.	**A1:** Single band (>20 MHz center) penetrating radar with capability of sub-surface sounding to a depth of ~5 km with ~10 m depth resolution.	TiPRA	TiPRA can take data on the nightside.
	O7: Determine the existence of a subsurface liquid water ocean.	**I1:** Determine crustal/subcrustal structure; reflectance of subsurface stratification.	**M1:** Sounding profiles of subsurface dielectric horizons, over the entire mappable surface, up to 5 km depth at 10 m vertical resolution, and long temporal coverage of active regions.	**A1:** Single band (>20 MHz center) penetrating radar with capability of sub-surface sounding to a depth of ~5 km with ~10 m depth resolution.	TiPRA	TiPRA can take data on the nightside.
		I2: Determine if the crust is decoupled from the interior and the thickness and rigidity of the icy crust.	**M1:** Degree-two gravity coefficients (J_2, C_{22}, S_{22}) to yield k_2 and phase lag. Harmonic amplitudes down to 0.1 ppm Titan surface gravity (equivalent to 1.3×10^{-5} cm/s^2).	**A1:** Relative velocity between the spacecraft and ground station determined from Doppler tracking with an accuracy up to 50 μm/s with 60 s integration periods. (Ka-band link stability ~10^{-15} after all calibrations including accelerometer for non-gravitational forces).	RSA	Optimized gravity configuration near closest approach with minimized non-gravitational forces; repeat observations at the same C/A point but different true anomalies (e.g., apoapsis, periapsis)
			M2: Rotation parameters to 0.1 degree/yr and pole position shift to 0.1 degree/year.	**A1:** Repeated high-resolution near-IR imaging at 2.05 ± 0.08 μm, 2.73 ± 0.08 μm, and/or 5.35 ± 0.45 μm.	HiRIS	Repeated observations of fiducial points
			M3: The long-wavelength topography of Titan and topographic effects of large-scale geologic structures. Lateral 1–10 km/vertical 10 m; satisfied by global topographic measurements.	**A1:** Altimetry measurements with single band (>20 MHz center) radar with capability of ~10 m height resolution and 1 km (along-track) and 5–10 km (cross-track) spatial resolution.	TiPRA	TiPRA can take data on the nightside. Need to tune the frequency after first pass.

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SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENT
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O7:** Determine the existence of a subsurface liquid water ocean.	**I3:** Determine the induced magnetic field signatures in order to confirm subsurface liquid and place constraints on the conductivity and depth of the liquid	**M1:** Measure vector magnetic field perturbations of order a few nT (with a resolution of order 0.04 nT). Measurements of the inducing magnetic field allow separation of the inducing magnetic field (measured by the orbiter) from the induced fields (measured by the montgolfière/lander).	**A1:** Vector Magnetometry (part of a combined instrument).	MAPP	Requires a combination of orbiter and montgolfière magnetometer measurements to be able to unequivocally resolve the induced signatures.
	O8: Determine the state of internal differentiation, whether Titan has a metal core and an intrinsic magnetic field, and constrain the crustal expression of thermal evolution of Titan's interior.	**I1:** Map interior structure of Titan.	**M1:** Global gravity field to at least degree six. Doppler accurate to 50 μm/s with 60 s integration periods.	**A1:** Relative velocity between the spacecraft and ground station determined from Doppler tracking with an accuracy up to 50 μm/s with 60 s integration periods. (Ka-band link stability $\sim 10^{-15}$ after all calibrations including accelerometer for non-gravitational forces).	RSA	Prefer mapping phase orbit height of 1500 km
		I2: Determine whether Titan has a dynamo.	**M1:** Detect or set limits on the intrinsic magnetic field of Titan. Measure vector magnetic field perturbations of order a few nT (with a resolution of order 0.04 nT).Thermal and magnetospheric plasma measurements will provide supportive role with regard to external currents from magnetospheric measurements.	**A1:** Vector Magnetometry (part of a combined instrument).	MAPP	Continuous measurements, globally distributed at varying altitudes. Knowledge of orbiter attitude and location, and a rigid magnetometer boom. Consideration of magnetic cleanliness requirements vs. boom length.
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O1:** Determine the processes leading to formation of complex organics in the Titan atmosphere and their deposition on the surface.	**I1:** Assay the speciation and abundances of atmospheric trace molecular constituents.	**M1:** Abundances of monomer and polymer organic species and inorganic species with a detectability of <1 ppb and an accuracy of better than 3% over an altitude range from 30–1500 km.	**A1:** Passive Thermal-infrared Fourier Transform spectrometry, in the region from 30–1400 wavenumbers (7–333 μm); resolution 0.1–3.0 wavenumber.	TIRS	Limb and nadir viewing on polar orbit, rotation in
				A2: Submillimeter sounding at 540–640 GHz with resolution 300 khz and 10% precision in retrieved abundances.	SMS	Limb viewing from polar orbit, in-track and off-track orientation

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SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENT
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O1:** Determine the processes leading to formation of complex organics in the Titan atmosphere and their deposition on the surface.	**I1:** Assay the speciation and abundances of atmospheric trace molecular constituents.	**M1:** Abundances of monomer and polymer organic species and inorganic species with a detectability of <1 ppb and an accuracy of better than 3% over an altitude range from 30–1500 km.	**A3:** Direct sampling Mass spectrometry up to 10,000 Da with mass resolution 10,000 at 1% of the peak height, sensitivity of 1 ppb at 850 km and a dynamic range of 10^8.	PMS	Periapses varying from 700 km upward during aerosampling. Ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination.
			M2: Stable isotope ratios of nitrogen, carbon, oxygen and hydrogen in photochemical products of methane, nitrogen and carbon monoxide.	**A1:** Direct sampling Mass spectrometry up to 10,000 Da with mass resolution 10,000 at 1% of the peak height and a dynamic range of 10^8.	PMS	Periapses varying from 700 km upward during aerosampling. Ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination.
		I2: Assay the molecular complexity of the condensed phase.	**M1:** Abundances of organic species in the atmosphere with a detectability of <1 ppb and an accuracy of better than 3% over an altitude range of 30–500 km, at polar latitudes with <5 mradians spatial resolution and long temporal coverage.	**A1:** Passive Thermal-infrared Fourier Transform spectrometry, in the region 30–1400 wavenumbers (7–333 μm); resolution 0.1–3.0 wavenumbers.	TIRS	Limb and nadir viewing on polar orbit, rotation in azimuth
		I3: Quantify the sources of chemical energy for atmospheric chemistry.	**M1:** 3D ion-electron plasma measurements with FOV ~2π steradians, view flow in corotation and ram directions; view upward and downward looking hemispheres (unlikely to be simultaneous at all times). 3D plasma electron measurements must cover the energy range from 1 eV to 30 keV with angular resolution ~ 20°x20°, energy resolution ΔE/E ~18% and geometric factor GF ~ $1.0e^{-3}$ cm^2-ster-eV/eV. Electron measure-ments from 0.01 eV to 40 eV will be provided by LP. 3D plasma ion measurements must cover the energy range from 1 eV to 30 kV, angular resolution 20°x20°, energy resolution ΔE/E ~18%, mass range $1 \leq M/Q \leq$ 10,000 amu/charge, and geometric factor GF ~ $1.0e^{-3}$ cm^2-ster-eV/eV .The energetic particle measurements will be from 20 keV to 1 MeV for electrons and 10 MeV for ions with energy resolution ΔE/E ~30%, angular resolution ~30° and GF ~ 0.05 cm^2-ster or greater. The energetic ion measurements should have mass resolution M/ΔM ~10 or better.	**A1:** Low Energy Plasma and Particles Instrument (measures ion and electron fluxes from few ev^{-10} MeV. Plasma instrument (E/Q <30 kV) must separate water group, methane group and ammonium group ions with TOF mass resolution M/ΔM ~10 to 60 Energetic Particle Spectrometer (measures magnetospheric particle fluxes from 10 keV to >Mev) with M/ΔM ~10 as part of a combined package with dual head vector Magnetometer and Langmuir probe.	MAPP	Periapses from 700 km upward during aerosampling and 950 km upwards during main mission. Complete range of local times and latitudes. Downward going hemisphere visible.

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SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENT
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O1:** Determine the processes leading to formation of complex organics in the Titan atmosphere and their deposition on the surface.	**I3:** Quantify the sources of chemical energy for atmospheric chemistry.	**M2:** Thermal electron density and temperature from ionosphere peak upward.	**A1:** Langmuir (swept voltage/current) probe as part of combined package with Low Energy Plasma and Particles Instrument, Energetic Particle Spectrometer and dual vector magnetometer. (Note: to obtain implied vertical profile requires topside sounding using low frequency ionospheric sounder addition to TiPRA similar to MARSIS)	MAPP	Atmospheric sampling phase to get vertical profiles.
			M3: Flux of UV photons.	**A1: :** Modeled from swept voltage/current obtained by Langmuir probe (part of combined package)	MAPP	Continuous measurements, globally distributed at varying altitudes
		I4: Determine surface composition.	**M1:** Inventory organic and inorganic surface constituents at 250 m spatial resolution.	**A1:** Near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 µm and 4.8–5.8 µm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Prefer mapping phase orbit within ±3 hrs from local noon
	O2: Characterize the degree to which the Titan organic inventory is different from known abiotic organic material in meteorites.	**I1:** Assay the composition of organic deposits exposed at the surface, including dunes, lakes, seas.	**M1:** Inventory organic and inorganic surface constituents at 250 m spatial resolution.	**A1:** Near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 µm and 4.8–5.8 µm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Prefer mapping phase orbit within ±3 hrs from local noon
	O3: Characterize what chemical modification of organics occurs on the surface.	**I1:** Determine the roles of cratering and cryovolcanism in modification and hydrolysis of organics.	**M1:** Inventory organic species between +65 and -90 degrees latitude with 250 m spatial resolution and long temporal coverage.	**A1:** Repeated near-IR mapping spectroscopy within the 2- and 5-µm atmospheric-methane transmission windows (1.9–2.4 µm and 4.8–5.8 µm) with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Prefer mapping phase orbit within ±3 hrs from local noon
			M2: Sounding profiles of subsurface dielectric horizons with 10 m vertical resolution and extensive surface coverage. Horizontal resolution required is 5–10 km cross track, 1 km lateral (along track) with 10 m vertical precision altimetry.	**A1:** Single band (>20 MHz center) penetrating radar with capability of sub-surface sounding to a depth of ~5 km with ~10 m depth resolution.	TiPRA	

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SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENT
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O3:** Characterize what chemical modification of organics occurs on the surface.	**I2:** Determine the importance of surface inorganic compounds as surface catalysts or doping agents.	**M1:** Identify inorganic salts and compounds containing phosphorous and other potentially reactive inorganic agents, from latitude 85°N to 85°S with 250 m spatial resolution and long temporal coverage.	**A1:** Partially completed with repeated near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 µm and 4.8–5.8 µm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Prefer mapping phase orbit within ±3 hrs from local noon
		I3: Quantify the sources of energy for surface chemistry and identify the sites where it may have been present.	**M1:** Flux of cosmic rays.	**A1:** Use star tracker to determine flux.		
			M2: Distribution of impacts visible at the surface or buried as a result of erosional and depositional modification.	**A1:** High-resolution near-IR imaging at 2.05 ± 0.08 µm, 2.73 ± 0.08 µm, and 5.35 ± 0.45 µm.	HiRIS	Prefer mapping phase orbit at ±4 hrs from local noon
				A2: Single band (>20 MHz center) penetrating radar with capability of sub-surface sounding to a depth of ~5 km with ~10 m depth resolution.	TiPRA	TiPRA can take data on the nightside.
			M3: Map surface at 50 m resolution in multiple wavelengths and correlate morphology and spectral characteristics of surface features with topography.	**A1:** High-resolution near-IR imaging at 2.05 ± 0.08 µm, 2.73 ± 0.08 µm, and 5.35 ± 0.45 µm.	HiRIS	Prefer mapping phase orbit at ±4 hrs from local noon
			M4: Map compounds such as acetylene and polyacetylene that indicate sites of chemical energy from latitudes 85°N to 85°S with 250 m spatial resolution and long temporal coverage.	**A1:** Repeated near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 µm and 4.8–5.8 µm with spectral resolution >400 and spatial resolution = 250 m	HiRIS	Prefer mapping phase orbit within ±3 hrs from local noon
		I4: Quantify the amount of aerosols deposited on Titan's surface and their modification as they get buried.	**M1:** Sounding profiles of subsurface dielectric horizons with 10 m vertical resolution and extensive surface coverage. Horizontal resolution required is 5–10 km cross track, 1 km lateral (along track) with 10 m vertical precision altimetry.	**A1:** Single band (>20 MHz center) penetrating radar with capability of sub-surface sounding to a depth of ~5 km with ~10 m depth resolution.	TiPRA	TiPRA can take data on the nightside. Profiles coordinated with HiRIS data.
	O4: Characterize the complexity of species in the subsurface ocean.	**I1:** Determine whether evidence of sub-surface ocean species is present in cryovolcanic sites.	**M1:** Map compounds such as ammonia, sulfates, and more complex organics (e.g., CH_3COOH) at cryovolcanic sites with 250 m spatial resolution.	**A1:** Near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 µm and 4.8–5.8 µm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Prefer mapping phase orbit within ±3 hrs from local noon

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENT
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O5:** Characterize bulk composition, sources of nitrogen and methane, and exchange between the surface and the interior.	**I1:** Determine whether carbon dioxide is primarily internally derived or photo-chemically produced.	**M1:** Isotopic composition of surface carbon and oxygen species at 250 m resolution.	**A1:** Partially met with near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Prefer mapping phase orbit within ±3 hrs from local noon
			M2: Isotopic composition of atmospheric carbon and oxygen species from the surface to 1500 km.	**A1:** Mid-infrared spectra of the stratosphere with 30–1400 wave numbers (7–333 μm), spectral resolution of 0.1 to 3 wave numbers, spatial resolution of <5 mrad IFOV.	TIRS	Limb and nadir viewing on polar orbit, rotation in azimuth
				A2: Submillimeter sounding at 540–640 GHz with resolution 300 khz and 5% precision in retrieved abundances.	SMS	Limb viewing from polar orbit, in-track and off-track orientation
				A3: Direct sampling Mass spectrometry up to 10,000 Da with mass resolution 10,000 at 1% peak height and dynamic range of 10^8.	PMS	Periapses varying from 700 km upward during aerosampling. Ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination.
		I2: Determine whether methane is primordial or derived from carbon dioxide.	**M1:** Isotopic composition of atmospheric carbon with precision of 0.1 per mil at altitudes from 600 km upwards (particularly in well mixed region below 850 km).	**A1:** Direct sampling Mass spectrometry with sensitivity of 10 ppb at 850 km altitude. A dual inlet system with a reference gas is required for accurate isotope determination.	PMS	Periapses varying from 700 km upward during aerosampling. Ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination.
			M2: Isotopic composition of surface carbon species at 250 m spatial resolution.	**A1:** Near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Prefer mapping phase orbit within ±3 hrs from local noon
		I3: Determine whether molecular nitrogen is derived from ammonia.	**M1:** Isotopic composition of atmospheric nitrogen from 600 km upwards to a precision of 0.1 per mil.	**A1:** Direct sampling Mass spectrometry with sensitivity of 10 ppb at 850 km altitude. A dual inlet system with a reference gas is required for accurate isotope determination.	PMS	Periapses varying from 700 km upward during aerosampling. Ram direction pointing of the instrument during aerosampling. Sample inlet should be located far from the main thrusters to avoid contamination.
			M2: Inventory compounds such as ammonia and ammonium hydrate between +65 and -90 degrees latitude with 250 m spatial resolution.	**A1:** Near-IR mapping spectroscopy within the atmospheric transmission windows from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400 and spatial resolution = 250 m.	HiRIS	Prefer mapping phase orbit within ±3 hrs from local noon

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE				MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENT
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?		**O5:** Characterize bulk composition, sources of nitrogen and methane, and exchange between the surface and the interior.	**I4:** Determine whether pockets of partial melt are present at depth.	**M1:** Sounding profiles of subsurface dielectric horizons with 10 m vertical resolution and extensive surface coverage. Horizontal resolution required is 5–10 km cross track, 1 km lateral (along track) with 10 m vertical precision altimetry.	**A1:** Single band (>20 MHz center) penetrating radar with capability of sub-surface sounding to a depth of ~5 km with ~10 m depth resolution.	TiPRA	TiPRA can take data on the nightside. Profiles coordinated with HiRIS data.
			I5: Determine the isotopic ratios of noble gases'	**M1:** Quantify noble gas isotopic ratios (Ar, Kr, Xe)	**A1**: Direct sampling Mass spectrometry with sensitivity of 10 ppb at 850 km altitude. A dual inlet system with a reference gas is required for accurate isotope determination.	PMS	Periapses varying from 700 km upward during aerosampling. Ram direction pointing of the instrument during aerosampling.
Goal C: What can be learned from Enceladus and from Saturn's magnetos phere about the origin and evolution of Titan?	**Saturn Magnetosphere**	**O1:** Determine how Titan's atmosphere evolves by virtue of its coupling to the Saturn magneto-sphere and Titan's low gravity.	**I1:** Determine how energy is deposited in the upper atmosphere of Titan to drive the chemistry and the escape rate of major atmospheric constituents.	**M1:** 3D ion-electron plasma measurements with FOV $\sim 2\pi$ steradians, view flow in corotation and ram directions; view upward and downward looking hemispheres (not likely to be simultaneous at all times). The 3D plasma electron measurements must cover the energy range from 1 eV to 30 keV with angular resolution $\sim 20° \times 20°$, energy resolution $\Delta E/E \sim 18\%$ and geometric factor GF $\sim 1.0e^{-3}$ cm^2-ster-eV/eV. Electron measurements from 0.01 eV to 40 eV will be provided by LP. The 3D plasma ion measurements must cover the energy range from 0.1 V to 30 kV, angular resolution $20° \times 20°$, energy resolution $\Delta E/E \sim 18\%$, mass range $1 \leq M/Q \leq 10{,}000$ amu/charge, and geometric factor GF $\sim 1.0e^{-3}$ cm^2-ster-eV/eV (ability to attenuate GF desirable for ionospheric measurements. The hot plasma and energetic particle measurements will be from 20 keV to 1 MeV for electrons and 10 MeV for ions with energy resolution $\Delta E/E \sim 30\%$, angular resolution ~30° and GF ~ 0.05 cm^2-ster or greater. The energetic ion measurements should have mass resolution $M/\Delta M \sim 10$ or better.	**A1:** Measure ion and electron fluxes from few ev-10 MeV. Plasma instrument (E/Q <30 kV) must separate water group, methane group and ammonium group ions with TOF mass resolution $M/\Delta M \sim 10$ (ST) and 60 (LEF). Energetic Particle Spectrometer (measures magnetospheric particle fluxes from 10 keV to >Mev) with $M/\Delta M \sim 10$ as part of a combined package. The plasma instrument will need to measure the ion composition within Saturn's magnetosphere with water group ions indicating an Enceladus source and nitrogen ions and methane ions indicating a Titan source.	MAPP	Periapses from 700 km upward during aerosampling and 950 km upwards during main mission. Complete range of local times and latitudes. Downward and upward going hemispheres visible.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE				MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENT
Goal C: What can be learned from Enceladus and from Saturn's magnetosphere about the origin and evolution of Titan?	**Saturn Magnetosphere**	**O1:** Determine how Titan's atmosphere evolves by virtue of its coupling to the Saturn magneto-sphere and Titan's low gravity.	**I1:** Determine how energy is deposited in the upper atmosphere of Titan to drive the chemistry and the escape rate of major atmospheric constituents.	**M2:** Thermal electron density and temperature *in situ* and density profiles as a function of altitude from the ionospheric peak to the orbiter.	**A1:** Langmuir (swept voltage/current) probe as part of combined packager. (Note: to obtain implied vertical profile requires topside sounding using low frequency ionospheric sounder addition to TiPRA [similar to MARSIS])	MAPP	Periapses from 700 km upward during aerosampling and 950 km upwards during main mission. Complete range of local times and latitudes.
				M3: Abundances of upper atmospheric constituents with M up to 10,000 Da; mass resolution 10,000 at 1% of peak height at altitudes from 700 km through 1000 km; sensitivity including isotopes, detectability down to 0.01 ppb.	**A1:** Direct sampling Mass spectrometry up to 10,000 Da with mass resolution 10,000 at 1% peak height and dynamic range of 10^8.	PMS	Ram direction pointing of the instrument during flybys. Sample inlet should be located far from the main thrusters to avoid contamination.
			I2: Determine the escape rates and mechanisms of major atmospheric species on Titan.	**M1:** Vertical profiles of carbon, nitrogen and oxygen containing compounds as major and minor constituents near the exobase of Titan with accuracy better than 5%.	**A1:** Submillimeter sounding at 540–640 GHz with resolution 300 khz.	SMS	Limb viewing from polar orbit, in-track and off-track orientation
					A2: Mid-infrared spectra of the stratosphere over the region 30–1400 wave numbers (7–333 μm), spectral resolution of 0.1 to 3 wave numbers, spatial resolution of <5 mrad IFOV.	TIRS	Limb and nadir viewing on polar orbit, rotation in azimuth
	Enceladus	**O2:** Infer the crustal and deep internal structure of Enceladus, including the presence of gravity anomalies, and the moon's tidal history.	**I1:** Test for the presence of crustal or deeper structures associated with Enceladus' internal activity, including an interface between a solid crust and a liquid layer, as well as partial melt pockets	**M1:** Degree-two gravity coefficients (J_2, C_{22}, S_{22}). Harmonic amplitudes down to 0.1 ppm Enceladus surface gravity.	**A1:** Relative velocity between the spacecraft and ground station determined from Doppler tracking with an accuracy up to 50 μm/s with 60 s integration periods. (Ka-band link stability ~10^{-15} after all calibrations including accelerometer for non-gravitational forces).	RSA	Optimized gravity configuration near closest approach with minimized non-gravitational forces as well as Doppler tracking over long arcs.
				M2: Sounding profiles of subsurface dielectric horizons, in the active region, up to 50 km depth at 100 m vertical resolution and a spatial resolution better than 2 km.	**A1:** Single band (>20 MHz center) penetrating radar and altimetry with capability of sub-surface sounding to a depth of ~50 km with ~10 m depth resolution.	TiPRA	Observations at C/A for all flybys. Use long radar echo gate in order to receive echoes from greater penetration depths. Simultaneous observation with RSA to obtain both the subsurface structure and associated gravity signature.
			I2: Test for true polar wander on Enceladus.	**M1:** Obliquity and spin of Enceladus.	**A1:** Repeated high resolution near-IR imaging at 2.05 ± 0.08 μm, 2.73 ± 0.08 μm, and 5.35 ± 0.45 μm.	HiRIS	Acquired ~600 km from Enceladus. Repeated on multiple passes.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE				MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENT
Goal C: What can be learned from Enceladus and Saturn's magnetosphere about the origin and evolution of Titan?	**Enceladus**	**O3:** Characterize the chemistry of the Enceladus plumes.	**I1:** Determine the composition of the plume, including isotopic abundances.	**M1:** Abundances and time variability of organic and inorganic species in the plume, including heavy polymers at mass resolution 10,000 at 1% of peak height.	**A1:** Direct sampling Mass spectrometry up to 10,000 Da with mass resolution 10,000 at 1% peak height and dynamic range of 10^8.	PMS	Ram direction pointing of the instrument during flybys. Sample inlet should be located far from the main thrusters to avoid contamination. High Data Volume Data Rate: 48 kbits/s
					A2 Submillimeter sounding at 540–640 GHz with resolution 300 khz.	SMS	Map plumes
		O4: Understand the formation of the active region near the south pole, and whether liquid water exists beneath the area.	**I1:** Characterize the global and regional geo-morphology of Enceladus' surface.	**M1:** Map surface features at 0.5 km spatial resolution at the global scale.	**A1:** Whole-disk near-IR imaging at 2.05 ± 0.08 μm, 2.73 ± 0.08 μm, and 5.35 ± 0.45 μm.	HiRIS	Acquired ~15,000 km from Enceladus
				M2: Composition of surface at 1 km spatial resolution at the global scale.	**A1:** Near-IR mapping spectroscopy from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400.	HiRIS	Acquired ~6,000 km from Enceladus
				M3: Map surface features at 30 m spatial resolution of candidate locations on a regional scale.	**A1:** High-resolution Near-IR imaging at 2.05 ± 0.08 μm, 2.73 ± 0.08 μm, and 5.35 ± 0.45 μm.	HiRIS	Acquired ~1000 km from Enceladus
				M4: Surface topography at 10 m vertical resolution, a spatial resolution along-track up to 100 m, and cross-track up to 1 km of candidate locations on a regional scale.	**A1:** Single band (>20 MHz center) penetrating radar and altimetry with capability of sub-surface sounding to a depth of ~50 km with ~10 m depth resolution.	TiPRA	Observations at C/A for all flybys. Simultaneous observation with RSA to obtain both the subsurface structure and associated gravity signature.
				M5: Composition of surface geologic features at 300 m spatial resolution of candidates locations on a regional scale.	**A1:** Near-IR mapping spectroscopy from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400.	HiRIS	Acquired ~1,800 km from Enceladus
				M6: Sounding profiles of subsurface dielectric horizons, in the active region up to 50 km depth, at 10 m vertical resolution, a spatial resolution along-track up to 0.1 km and cross-track up to 1 km.	**A1:** Single band (>20 MHz center) penetrating radar and altimetry with capability of sub-surface sounding to a depth of ~50 km with ~10 m depth resolution.	TiPRA	Observations at C/A for all flybys. Use long radar echo gate in order to receive echoes from greater penetration depths Simultaneous observation with RSA to obtain both the subsurface structure and associated gravity signature.
			I2: Determine whether thermal anomalies exist underneath the surface.	**M1:** Surface temperature distribution with precision 1 K; spatial resolution 100 meters.	**A1:** Mid-infrared spectra of the surface in the 30–1400 wave numbers (7–333 μm) region, spectral resolution of 3 to 15 wave numbers, spatial resolution of <5 mrad IFOV.	TIRS	Nadir viewing of the surface, range less than 600 km
				M2: Sounding profiles of subsurface dielectric horizons, in the active region up to 50 km depth	**A1:** Single band (>20 MHz center) penetrating radar and altimetry with capability of sub-surface sounding to a depth of ~50 km with ~10 m depth resolution.	TiPRA	Observations at C/A for all flybys. Use long radar echo gate in order to receive echoes from greater penetration depths Simultaneous observation with RSA to obtain both the subsurface structure and associated gravity signature.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE				MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENT
Goal C: What can be learned from Enceladus and Saturn's magnetosphere about the origin and evolution of Titan?	**Enceladus**	**O4:** Understand the formation of the active region near the south pole, and whether liquid water exists beneath the area.	**I3:** Determine the origin of the surface organic materials and its connection with interior reservoirs.	**M1:** Gravity field amplitude down to 0.1 ppm Enceladus surface gravity.	**A1:** Relative velocity between the spacecraft and ground station determined from Doppler tracking with an accuracy up to 50 μm/s with 60 s integration periods. (Ka-band link stability ~10^{-15} after all calibrations including accelerometer for non-gravitational forces).	RSA	Optimized gravity configuration near closest approach with minimized non-gravitational forces
				M2: Composition of surface organics at 300 m spatial resolution.	**A1:** Near-IR mapping spectroscopy from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400.	HiRIS	Acquired ~1,800 km from Enceladus
		O5: Identify and characterize candidate sites on Enceladus for future *in situ* exploration.	**I1:** Determine whether extrusion of water ice or liquid water has occurred recently.	**M1:** Distribution of water ice and frost at 300 m spatial resolution.	**A1:** Near-IR mapping spectroscopy from 0.85–2.4 μm and 4.8–5.8 μm with spectral resolution >400.	HiRIS	Acquired ~1,800 km from Enceladus
				M2: Sounding profiles of subsurface dielectric horizons, in the active region, up to 50 km depth at 10 m vertical resolution, a spatial resolution along-track up to 0.1 km and cross-track up to 1 km.	**A1:** Single band (>20 MHz center) penetrating radar and altimetry with capability of sub-surface sounding to a depth of ~50 km with ~10 m depth resolution.	TiPRA	Observations at C/A for all flybys. Use long radar echo gate in order to receive echoes from greater penetration depths Simultaneous observation with RSA to obtain both the subsurface structure and associated gravity signature.
				M3: Surface temperature distribution with precision 1 K; spatial resolution 100 meters.	**A1:** Mid-infrared spectra of the stratosphere in the 30–1400 wave numbers (7–333 μm) region, spectral resolution of 3 to 15 wave numbers, spatial resolution of <5 mrad IFOV.	TIRS	Nadir viewing of the surface, range less than 600 km
			I2: Determine whether areas of extremely thin crust or exposed liquid within cracks exist.	**M1:** Variations in the tiger stripe regions as a function of true anomaly at 30 m spatial resolution.	**A1:** High-resolution near-IR imaging at 2.05 ± 0.08 μm, 2.73 ± 0.08 μm, and/or 5.35 ± 0.45 μm repeated at multiple true anomalies.	HiRIS	Acquired ~1000 km from Enceladus. Requires multiple flybys over the south polar region.
				M2: Gravity field amplitude down to 0.1 ppm Enceladus surface gravity at candidate locations. Repeat coverage for different true anomalies.	**A1:** Relative velocity between the spacecraft and ground station determined from Doppler tracking with an accuracy up to 50 μm/s with 60 s integration periods. (Ka-band link stability ~10^{-15} after all calibrations including accelerometer for non-gravitational forces).	RSA	Optimized gravity configuration near closest approach with minimized non-gravitational forces, as well as Doppler tracking over long arcs.
				M3: Sounding profiles of subsurface dielectric horizons, in the active region, up to 50 km depth at 10 m vertical resolution, a spatial resolution along-track up to 0.1 km and cross-track up to 1 km.	**A1:** Single band (>20 MHz center) penetrating radar and altimetry with capability of sub-surface sounding to a depth of ~50 km with ~10 m depth resolution.	TiPRA	Observations at C/A for all flybys. Use long radar echo gate in order to receive echoes from greater penetration depths Simultaneous observation with RSA to obtain both the subsurface structure and associated gravity signature.
				M4: Surface temperature distribution with precision 1 K; spatial resolution 100 meters.	**A1:** Mid-infrared spectra of the stratosphere in the 30–1400 wave numbers (7–333 μm) region, spectral resolution of 3 to 15 wave numbers, spatial resolution of <5 mrad IFOV.	TIRS	Nadir viewing of the surface, range less than 600 km

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

Table 1-2. Science Traceability Matrix—Montgolfière

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O2:** Characterize the relative importance of exogenic and endogenic oxygen sources.	**I1:** Quantify the flux of exospheric oxygen into the atmosphere.	**M3:** O content of the aerosols	**A1:** *In situ* analysis of the aerosols collected at the level of the montgolfière	TMCA	Collect aerosols that are falling from higher altitudes; 1 km and 5° attitude knowledge of montgolfière.
			M4: Amount of O bearing molecules in the troposphere	**A1:** Infrared spectra of the atmosphere, including CO and CO_2	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
		I2: Quantify the flux of endogenic oxygen from the surface and interior.	**M1:** Inventory of surface constituents containing oxygen, including major isotopologues at 250 m or better resolution	**A2:** Infrared spectral maps of the surface at wavelengths absorbed by the O bearing molecules (4.92 µm for CO_2) at 10% level within a pixel	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
	O3: Characterize the major processes controlling the global distribution of atmospheric chemical constituents.	**I1:** Characterize the major chemical cycles.	**M1:** Vertical, latitudinal, and temporal dependence of condensed and gaseous species in the atmosphere from 0 to 1500 km with precision better than 10%	**A5:** Pump the atmosphere into the chemical analyzer to analyze ethane mole fraction and other volatile species in troposphere (gas and condensed phase), with a precision of 5%	TMCA	Tracking of the montgolfière (lat, long, alt); 1 km and 5°attitude knowledge required.
		I2: Determine the relative importance of global transport.	**M3:** Ethane mole fraction in the troposphere (gas and condensed phases) at different longitudes (day/night variations); ethane/methane	**A1:** Pump the atmosphere into the chemical analyzer to analyze ethane mole fraction in troposphere (gas and condensed phase), with a precision of 5%	TMCA	Tracking of the montgolfière (lat, long, alt); 1 km and 5° attitude knowledge of montgolfière
	O4: Characterize the atmospheric circulation and flow of energy.	**I1:** Determine the atmospheric thermal and dynamical state.	**M5:** Track the drift of the montgolfière to infer strength and directions of winds.	**A1**: The location of the montgolfière relative to Titan by tri-axial accelerometers and gyroscopes (inertial platform) to infer wind field and gusts.	ASI/ MET	ASI should be placed as close as possible to the center of gravity of the gondola. 1 km and 5° attitude knowledge of montgolfière.
			M6: Measure deposition of sunlight as a function of altitude to infer the radiation balance in the troposphere.	**A1:** Solar light arriving at the altitude of the montgolfière during its journey in the tropical regions	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required. 1 km and 5° attitude knowledge of montgolfière.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy.	**I1:** Determine the atmospheric thermal and dynamical state.	**M7:** Vertical profile of temperature, pressure, and density (T and P accuracy to 0.1 K and 1 mPa and resolution to 0.02 K and 0.1% respectively). Determine the trajectory of the montgolfière during entry and descent and floating phase	**A1:** Measure T by a Pt wire resistance thermometer and P by Kiel probe and capacitive gauges. Pressure and temperature measurements during the descent. Monitor meteorological conditions during the montgolfière journey	ASI/ MET	ASI pressure inlet and thermometers should have access to the atmospheric unperturbed flow (outside the descent probe boundary layer). The trajectory of the probe (entry and descent module reconstructed from the engineering sensor data (e.g., IMU), the high sensitive scientific accelerometer (and/or IMU). Coordination with orbiter RSA data.
				A2: Three-axis *in situ* accelerometer measurements to a precision of 10^{-5} m/s^2 during entry and during the montgolfière journey	ASI/ MET	ASI-ACC should be placed as close as possible to the entry module CoG. ASI operating before nominal interface entry altitude (1270 km). Coordination with orbiter RSA data.
			M8: Pressure, temperature variations in space and time (T and P accuracy to 0.1 K and 1 mPa and resolution to 0.02 K and 0.1% respectively)	**A1:** Pressure, temperature, and accelerometry during the journey of the montgolfière	ASI/ MET	1 km and 5° attitude knowledge of montgolfière.
			M9: Determine large surface temperature	**A1:** Infrared spectra of the surface between 5 and 5.6 μm will enable us to see T variations larger than 50 K.	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
			M10: Timing (local time, orbital phase) of cloud occurrence, evolution, cloud base/top and appearance	**A1:** Continuous monitoring of cloud formation	VISTA -B	1 km and 5° attitude knowledge of montgolfière required.
				A2: Continuous monitoring of meteorological conditions	ASI/ MET	1 km and 5° attitude knowledge of montgolfière
		I2: Determine the impact of haze and clouds.	**M4:** Track the motion of clouds (and cryovolcanic vents, if any). Search for orographic clouds.	**A1:** Imaging from the gondola at 10 m resolution	VISTA -B	1 km and 5° attitude knowledge of montgolfière
				A2: Infrared spectral maps of the clouds and terrain	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy.	**I2:** Determine the impact of haze and clouds.	**M5:** Particle size distribution and optical properties of clouds and haze	**A1:** Infrared measurements of reflective light	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
			M6: Profile of methane mole fraction and its variations in the equatorial regions; fraction of methane in the condensed phase compared to the total atmospheric methane abundance	**A1:** Infrared spectral maps to measure the width of the methane absorption bands to determine the amount of methane	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
				A2: Pump the atmosphere into the chemical analyzer to analyze methane mole fraction in troposphere (gas and condensed phase), with a precision of 1%	TMCA	Tracking of the montgolfière (lat, long, alt); 1 km and 5° attitude knowledge required.
				A3: *In situ* monitoring of T and P conditions. Simultaneous measurements of pressure and T are necessary to assess the phase of the species (e.g., condensation) and to associate a certain pressure level in the atmosphere (or equivalent altitude level) to the mole fractions determined by TMCA.	ASI/ MET	1 km and 5° attitude knowledge of montgolfière
		I3: Determine the effects of atmospheric composition.	**M3:** Profile of ethane mole fraction and its variations in the equatorial regions; fraction of ethane in the condensed phase compared to the total atmospheric ethane abundance	**A1:** Infrared spectral maps to measure the width of the ethane absorption bands to determine the amount of ethane	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy.	**I3:** Determine the effects of atmospheric composition.	**M3:** Profile of ethane mole fraction and its variations in the equatorial regions; fraction of ethane in the condensed phase compared to the total atmospheric ethane abundance	**A2:** Pump the atmosphere into the chemical analyzer to analyze ethane mole fraction in troposphere (gas and condensed phase), with a precision of 1%	TMCA	Tracking of the montgolfière (lat, long, alt); 1 km and 5° attitude knowledge required.
				A3: *In situ* monitoring of T and P conditions Simultaneous measurements of pressure and T are necessary to assess the phase of the species (e.g., condensation) and to associate a certain pressure level in the atmosphere (or equivalent altitude level) to the mole fractions determined by TMCA.	ASI/ MET	1 km and 5° attitude knowledge of montgolfière.
			M4: Determine the topography and find correlation with clouds and turbulences.	**A1:** Topography and clouds are determined by the stereo imaging	VISTA -B	1 km and 5° attitude knowledge of montgolfière
				A2: Topography is determined by first echo of the radar sounder	TRS	Precise identification of the trajectory of the montgolfière increases the quality of the measurements; 1 km and 5° attitude knowledge required.
				A3: Infrared spectrometry to monitor the clouds	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context
				A4: *In situ* monitoring of meteorological conditions (T, P, and wind) to investigate thermal variations, turbulence and dynamics (e.g., gravity waves and tides)	ASI/ MET	1 km and 5° attitude knowledge of montgolfière.
		I4: Determine the effects of surface processes on meteorology.	**M4:** Identify active volcanism in the equatorial region with 50 m resolution from orbit and .2.5 m resolution from 10km altitude	**A1:** Infrared spectral maps	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context
				A2: Stereo and high-res imaging from the Gondola	VISTA -B	1 km and 5° attitude knowledge requirement of montgolfière

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy.	**I4:** Determine the effects of surface processes on meteorology.	**M6:** Search for possible surface methane sources (vents, etc.) in the equatorial regions.	**A1:** Stereo and high-res imaging from the Gondola	VISTA -B	1 km and 5° attitude knowledge of montgolfière
				A2: Monitor atmospheric methane concentration.	TMCA	Precise location of montgolfière to 1 km and 5° attitude knowledge.
				A3: *In situ* monitoring of meteorological conditions by direct T and P measurements (T and P accuracy to 0.1 K and 1 mPa and resolution to 0.02 K and 0.1% respectively) and gondola attitude	ASI/ MET	Precise location of montgolfière to 1 km and 5° attitude knowledge.
				A4: Infrared spectral maps to measure the width of the methane absorption bands to determine the amount of methane	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context
			M7: Global distribution of surface wind directions	**A1:** Direction of dunes/cloud movement	VISTA -B	Precise location of montgolfière to 1 km and 5° attitude knowledge .
				A2: Wind field inferred from T and P measurements (T and P accuracy to 0.1 K and 1 mPa and resolution to 0.02 K and 0.1% respectively) and monitoring the gondola attitude	AS/ MET	Wind field inferred from T and P measurements and monitoring the gondola attitude; 1 km and 5° attitude knowledge requirement of montgolfière
		I5: Determine the exchange of momentum, energy and matter between the surface and atmosphere and characterize the planetary boundary layer.	**M6:** Global distribution of surface roughness and topography	**A1:** Radar measurements	TRS	Precise location of montgolfière—1 km and 5° attitude knowledge required.
				A2: Stereo imaging (10 m/pix)	VISTA -B	Precise location of montgolfière—1 km and 5° attitude knowledge required.
				A3: Measure the shadows of reliefs within the infrared maps	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
			M7: Diurnal temperature variations and time-series meteorology	**A1:** Measure the temperature by a Pt wire resistance thermometer with $\Delta T = 0.1$ K	ASI/ MET	Same as ASI/MET above

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy.	**I5:** Determine the exchange of momentum, energy and matter between the surface and atmosphere and characterize the planetary boundary layer.	**M8:** Distribution of condensates at the surface	**A1:** Infrared identification of condensate species	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
				A2: High spatial resolution color images of the surface at equatorial latitudes; ground truth for orbiter measurement	VISTA-B	Precise location of montgolfière to 1 km and 5° attitude knowledge of montgolfière
			M9: Abundance of water ice at the surface	**A1:** Infrared mapping through the methane windows and compare windows where ice absorbs (e.g., 1.6 and 2.0 µm) and where it does not (1.05 µm).	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
		I6: Determine the connection between weather, ionosphere, and electricity.	**M2:** Global electric circuit and fair-weather electric field in the range from 0–10 kHz. With a height resolution of 1 km	**A1:** Measurement of electric field using dipole antennas; vertical and horizontal electric field in the frequency range from DC to VLF (~10 kHz)	TEEP-B	1 km and 5° attitude knowledge of montgolfière
			M3: Extra low and low frequency (ELF-VLF) magnetic components of the atmospheric electricity from 0–10 kHz	**A1:** Measurement of magnetic field using loop antenna; vertical and horizontal electric field in the frequency range from DC to VLF (~10 kHz nas or search coils)	TEEP-B	1 km and 5° attitude knowledge of montgolfière
			M4: Search for electric discharges.	**A1:** Long exposure nighttime imaging	VISTA-B	Precise location of montgolfière from Inertial Navigation System (INS); 1 km requirement
				A2: Electric field and optical sensors	TEEP-B	Coordinated with VISTA-B
			M5: Electrical conductivity and permittivity of the atmosphere (positive and negative ions + electrons) to 1 km resolution in the range 10^{-14} to 10^{-6} Sm^{-1} and electrons only, with a height resolution to 100 m in the range 10^{-11} to 10^{-6} Sm^{-1}	**A1:** Relaxation probe to measure the conductivity of all charged species	TEEP-B	Time series of conductivity (all charged species)
				A2: Mutual impedance probe which measures the conductivity of electronics only	TEEP-B	Amplitude and phase of electric signal

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O5:** Characterize the amount of liquid on the Titan surface today.	**I3:** Determine surface composition that might reveal the presence of liquids.	**M1:** Optical maps in the methane windows at 2.5 m resolution	**A1:** Use the infrared images at different incidence angles to determine the nature of the surface (liquid or solid)	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
			M2: Precipitation rate, solid or liquid nature of precipitation	**A1:** *In situ* monitoring of T and P conditions with reference to the altitude level	ASI/ MET	1 km and 5° attitude knowledge of montgolfière
				A3: *In situ* observations at all wavelengths.	VISTA -B	Precise location of montgolfière to 1 km and 5° attitude knowledge of montgolfière
		I4: Determine the nature of precipitation responsible for the formation of valley networks in the tropical regions.	**M1:** Lateral variations of surface compounds in the valley networks at 5 m resolution	**A1:** Map lateral variations of surface composition in the river networks and at their mouth	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
				A3: High spatial resolution color images of the surface at equatorial latitudes; ground truth for orbiter measurement	VISTA -B	Precise location of montgolfière to 1 km and 5° attitude knowledge.
	O6: Characterize the major processes transforming the surface throughout time.	**I1:** Determine the origin of major crustal features; correlate regional elevation changes with geomorph-ology and compositional variations.	**M5:** Measure regional topography	**A1:** Stereo images of the surface	VISTA -B	Precise location of montgolfière to 1 km and 5° attitude knowledge. .
				A2: Reflection of radar signal	TRS	Precise identification of the trajectory of the montgolfière increases the quality of the measurements
		I2: Characterize the origin of major surface features, including the effects of liquid flow, tectonic, volcanic, and impact events.	**M4:** Geological maps at 2.5 m resolution	**A1:** Infrared mapping through the methane windows	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
		I3: Determine the internal magnetic signal.	**M1:** Magnetic map, taken from a constant altitude	**A1:** Dual sensor magnetometer fixed to boom on gondola	MAG	Precise location of montgolfière to 1 km and 5° attitude knowledge 1 km continuous magnetic field data, as much coverage of the surface as possible. Consideration of magnetic cleanliness requirements vs. boom length. Complementarities with orbiter measurements during Titan flybys.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O6:** Characterize the major processes transforming the surface throughout time.	**I4:** Detect and measure the depth of shallow subsurface reservoirs of liquid (hydrocarbons).	**M2:** Subsurface sounding at frequency between 150 and 200 MHz in order to detect liquid reservoirs less than 1 km deep.	**A1:** High resolution subsurface profiles over few hundred meters (500 m) spot size and vertical resolution <6 m	TRS	Precise location of the montgolfière makes it possible an integrated multiscale analysis of the TRS profiles with the radar measurements acquired by the sounder on the orbiter. Precise location of montgolfière to 1 km and 5° attitude knowledge.
		I5: Determine the subsurface structures and constrain the stratigraphic history of dunes.	**M1:** Subsurface sounding along the montgolfière journey at a frequency between 150 and 200 MHz (vertical resolution of less than 10 meters and spatial resolution less than 200 meters)	**A1:** Radar sounding	TRS	Comparison between optical remote sensing images and radar profiles. Precise location of the montgolfière makes it possible an integrated multiscale analysis of the TRS profiles with the radar measurements acquired by the sounder on the orbiter. Precise location of montgolfière to 1 km and 5° attitude knowledge.
	O7: Determine the existence of a subsurface liquid water ocean.	**I2:** Determine if the crust is decoupled from the interior and the thickness and rigidity of the icy crust.	**M1:** Map of geological structures at different true anomalies	**A1:** High-resolution mapping of surface features with their precise location	VISTA-B	Precise location of montgolfière to 1 km and 5° attitude knowledge.
		I3: Determine the induced magnetic field signatures in order to confirm subsurface liquid and place constraints on the conductivity and depth of the liquid	**M3:** *In situ* vector magnetic field measurements	**A1:** Dual sensor magnetometer fixed to boom on gondola	MAG	Precise location of montgolfière to 1 km and 5° attitude knowledge. Continuous magnetic field data combined with magnetic field measurements from the orbiter and lander. Nightside data at 0600 Saturn Local Time highly desirable. Desirable (not required) to have some measurements with the lander, montgolfière, and orbiter in a line radiating from Saturn.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		MISSION REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O8:** Determine the state of internal differentiation, whether Titan has a metal core and an intrinsic magnetic field, and constrain the crustal expression of thermal evolution of Titan's interior.	**I2:** Determine whether Titan has a dynamo.	**M2:** *In situ* vector magnetic field measurements	**A1:** Dual sensor magnetometer fixed to boom on gondola	MAG	Precise location of montgolfière to 1 km and 5° attitude knowledge. Continuous magnetic field data combined with magnetic field measurements from the orbiter and lander. Nightside data at 0600 Saturn Local Time highly desirable. Desirable (not required) to have some measurements with the lander, montgolfière, and orbiter in a line radiating from Saturn.
		I3: Quantify exchange between interior and atmosphere.	**M3:** Measure noble gases and isotopes (esp., Ar, Kr, Xe) to ppb levels in gas phase and aerosols	**A1:** *In situ* measurement of aerosols and atmospheric gas phase, with a precision of 1%	TMCA	Good location to 1 km and 5° attitude knowledge of montgolfière
			M4: Subsurface layering	**A1:** High resolution subsurface profiles over few hundred meters (500 m) spot size and vertical resolution <6 m	TRS	Precise location of the montgolfière to integrate multiscale analysis of the TRS profiles with the radar measurements acquired by the sounder on the orbiter; 1 km and 5° attitude knowledge of montgolfière
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O1:** Determine the chemical pathways leading to formation of complex organics at all altitudes in the Titan atmosphere and their deposition on the surface.	**I1:** Assay the speciation and abundance of atmospheric trace molecular constituents.	**M4:** Concentration of molecular constituents in the troposphere with S/N ratio >100	**A1:** IR reflectance spectra with long integration times to enable spectral summing over homogeneous regions.	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
			M5: Latitudinal and vertical distribution of minor species and its temporal variation	**A1:** *In situ* analysis of minor species	TMCA	Same location of the montgolfière at different times; analysis of only low molecular mass species
			M6: Day-night variation of minor species to infer information about condensation	**A1:** *In situ* analysis of minor species gas and condensed phase	TMCA	Same location of the montgolfière during at least one full Titan day
			M7: Monitor T and P conditions to help determine species abundances and condensation.	**A1:** *In situ* measurements of T and P with reference to the altitude level. Simultaneous measurements of P and T are necessary to assess the phase of the species (e.g., condensation) and to associate a certain pressure level in the atmosphere (or equivalent altitude level) to the mole fractions determined by TMCA.	ASI/ MET	1 km and 5° attitude knowledge of montgolfière.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		MISSION REQUIREMENTS
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O1:** Determine the chemical pathways leading to formation of complex organics at all altitudes in the Titan atmosphere and their deposition on the surface.	**I2:** Assay the molecular complexity of the condensed phase.	**M2:** Chemical composition (elemental, molecular isotopic, and chiral) of aerosols	**A1:** Collect aerosols during their descent to the surface	TMCA	1 km and 5° attitude knowledge of montgolfière
			M3: Chemical abundance of gases in troposphere	**A1:** *In situ* analysis of major and minor species	TMCA	1 km and 5° attitude knowledge of montgolfière
			M4: Monitoring of T and P (T and P accuracy to 0.1 K and 1 mPa; and resolution to 0.02 K and 0.1% respectively) conditions to asses condensation status	**A1:** *In situ* measurements of T and P with reference to the altitude level	ASI/ MET	1 km and 5° attitude knowledge of montgolfière
		I3: Quantify the sources of chemical energy for atmospheric chemistry.	**M3:** Search for electric discharges	**A1:** Electric field and optical sensors	TEEP-B	Coordinated with VISTA-B
			M4: Infrared spectra of relevant complex organics	**A1:** Identify organic species in the 5–5.6 μm wavelength range	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
		I4: Determine surface composition.	**M3:** High spatial resolution (2.5 meters at 10 km) infrared spectra at wavelengths larger than 4.8 μm	**A1:** Identify organic species in the 5–5.6 μm wavelength range	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
			M4: *In situ* sampling of surface organic inventory	**A1:** MS analysis of collected surface material	TMCA	Surface composition measured when landing.
	O2: Characterize the degree to which the Titan organic inventory is different from known abiotic organic material in meteorites.	**I1:** Assay the composition of organic deposits exposed at the surface, including dunes, lakes, and seas.	**M5:** High-resolution images to detect organic materials	**A1:** Identify organic species in the 5–5.6 μm wavelength range	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
				A2: Stereo images	VISTA -B	Precise location of montgolfière to 1 km and 5° attitude knowledge.
		I3: Determine the location and the composition of complex organics in and around impact craters in the equatorial regions.	**M1:** High-spatial resolution mapping of organics in areas such as impact craters and cryovolcanoes.	**A1:** High spatial resolution (2.5 meters at 10 km) infrared spectra at wavelengths between 5 and 6 μm	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
				A2: High resolution color images	VISTA -B	Precise location of montgolfière tp 1 km and 5° attitude knowledge.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		MISSION REQUIREMENTS
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O3:** Characterize what chemical modification of organics occurs on the surface.	**I1:** Determine the roles of cratering and cryovolcanism in modification and hydrolysis of organics.	**M4:** Subsurface stratification of organics.	**A1:** Radar sounding of the subsurface at frequency between 150 and 200 MHz allowing a spatial resolution of a few hundred meters (500 m) and vertical resolution <6 m	TRS	Precise identification of the trajectory of the montgolfière to 1 km and 5° attitude knowledge required.
		I2: Determine the importance of surface inorganic compounds as surface catalysts or doping agents.	**M2:** Identify inorganic salts and compounds containing phosphorous and other potentially reactive inorganic agents in equatorial regions.	**A1:** Partially met with repeated near-IR mapping spectroscopy within the atmospheric transmission windows. High spatial resolution (2.5 m at 10 km) infrared mapping of the surface	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
	O4: Characterize the complexity of species in the subsurface ocean.	**I1:** Determine whether evidence of sub-surface ocean species is present in cryovolcanic sites.	**M2:** Map compounds such as ammonia, sulfates, and more complex organics (e.g., CH_3COOH) at cryovolcanic sites	**A1:** Near-IR mapping spectroscopy within the atmospheric transmission windows with 2.5 m spatial resolution.	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
	O5: Characterize bulk composition, sources of nitrogen and methane, and exchange between the surface and the interior.	**I1:** Determine whether carbon dioxide is primarily internally derived or photochemically produced.	**M3:** Profile of CO and CO2 in the troposphere	**A1:** Infrared spectroscopy within the methane windows.	BIS	Precise identification of the trajectory of the montgolfière to 1 km and 5° attitude knowledge required
		I2: Determine whether methane is primordial or derived from carbon dioxide.	**M5:** Map of surface CO_2 in the equatorial regions	**A1:** High spatial resolution (2.5 m at 10 km) infrared mapping of the surface.	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
		I3: Determine whether molecular nitrogen is derived from ammonia.	**M5:** Detect ammonia in surface material: down to 1% in local deposits	**A1:** High spatial resolution (2.5 m at 10 km) infrared mapping of the surface	BIS	Adapt the observation strategy to the motion of the montgolfière. Coordination with VISTA-B for context is required.
		I4: Determine whether pockets of partial melt are present at depth.	**M2:** Subsurface sounding at frequency between 150 and 200 MHz in order to detect liquid reservoirs less than 1 km deep.	**A1:** High resolution subsurface profiles over few hundred meters (500 m) spot size and vertical resolution <6 m	TRS	Precise location of the montgolfière makes it possible an integrated multiscale analysis of the TRS profiles with the radar measurements acquired by the sounder on the orbiter. Precise location of montgolfière to 1 km and 5° attitude knowledge.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

Table 1-3. Science Traceability Matrix—Lake Lander

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O1:** Determine how energy is deposited in the upper atmosphere to drive the chemistry and the escape rate of major atmospheric constituents.	**I1:** Quantify the deposition of radiation into Titan's atmosphere.	**M4:** Vertical profile of the magnetic field magnitude and direction to quantify the magnetic shielding effect of the ionosphere and extent of the penetration of Saturn's magnetic field.	**A1:** Measure dual sensor (gradiometer) vector magnetic field along the path of the probe during the entry and descent with a good knowledge of the location of the probe to reconstruct the descent.	SPP	Magnetometer on during descent, and some consideration of the magnetic cleanliness of the lander. A dual sensor magnetometer with the sensors mounted ideally on a boom or mast away from the probe body to allow characterization of the magnetic field coming from the probe to enable ground processing to remove this contaminating field and achieve a more accurate measurement of the ambient magnetic field (so-called gradiometer configuration). This could also be achieved (if a boom or mast is not feasible) by having an primary sensor at an extremity of the probe and several secondary sensors fitted along an axis of the probe to provide a gradiometer type measurement.
		I2: Quantify the escape flux of elemental hydrogen, carbon, nitrogen.	**M3:** Magnetic field of Titan during descent to correlate with orbiter data. Measure vector magnetic field perturbations of order a few nT (with a resolution of order 0.04 nT) to quantify the escape flux of elemental hydrogen, carbon and nitrogen.	**A1:** Vector magnetometry (part of a combined instrument, integrated with a low energy plasma and particles instrument, energetic particle spectrometer and Langmuir probe).	SPP	
	O2: Characterize the relative importance of exogenic and endogenic oxygen sources.	**I2:** Quantify the flux of endogenic oxygen from the surface and interior.	**M2:** Amount of O in the lake	**A1:** GC x GC separation followed by high resolution MS and MEMS sensor analysis.	TLCA	Liquid sampling from the lake.
			M3: Isotopic ratio $^{18}O/^{16}O$	**A1:** GC x GC separation followed by pyrolysis and isotopic mass spectrometry.	TLCA	Lake and atmosphere sampling
			M4: Nature and composition of O-bearing molecules	**A1:** GC x GC separation followed by high resolution MS and MEMS sensor analysis.	TLCA	Lake and atmosphere sampling
	O3: Characterize the major processes controlling the global distribution of atmospheric chemical constituents.	**I1:** Characterize the major chemical cycles.	**M1:** Methane and ethane mole fraction in the troposphere	**A4:** Direct gas inlet into MS	TLCA	Atmospheric sampling during the descent.
		I2: Determine the relative importance of global transport.	**M2:** Isotopic ratios of C and N in both the liquid phase and in the aerosols that may be present in the lake	**A1:** Collect the liquid phase and the compounds in suspension and analyze with isotopic mass spectrometry. Liquid separation by GC x GC / combustion furnace / isotope ratio mass spectrometer for C and N ratios. Sol analysis by pyrolysis of filtered solids.	TLCA	Lake sampling with solid and liquid separation.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy.	**I1:** Determine the atmospheric thermal and dynamical state.	**M3:** Vertical profile of temperature, pressure (T and P accuracy to 0.1 K and 1 mP and resolution to 0.02 K and 0.1% respectively) and density in the northern hemisphere above a lake.	**A1:** Measure T by a Pt wire resistance thermometer and P by Kiel probe and capacitive gauges during the descent, monitor meteorological conditions at the surface of the lake	ASI/ MET	ASI-ACC should be placed as close as possible to the entry module Center of Mass. ASI pressure inlet and thermometers should has access to the atmospheric unperturbed flow (outside the descent probe boundary layer) The trajectory of the probe (entry and descent module reconstructed from the engineering sensor data (e.g., IMU), the high sensitive scientific accelerometer (and/or IMU)
			M3: Vertical profile of temperature, pressure (T and P accuracy to 0.1 K and 1 mPa and resolution to 0.02 K and 0.1% respectively) and density in the northern hemisphere above a lake.	**A2:** Three-axis *in situ* accelerometer measurements during entry to a precision of 10^{-5} m/s^2 in order to reconstruct the location of the lander during its descent.	ASI/ MET	ASI-ACC should be placed as close as possible to the entry module Center of Mass. ASI operates before nominal interface entry altitude (1270 km).
			M4: Surface temperature of lakes to 0.1 K accuracy with a resolution of 0.02 K	**A1:** Measure the temperature at the surface of the lake with a Pt wire resistance thermometer	ASI/ MET	Continuous measurements for duration of lander lifetime.
		I2: Determine the effect of haze and clouds.	**M3:** Extent and lateral and vertical distribution of clouds above the lakes	**A1:** Acquire image in the VIS/NIR during the probe's descent from an altitude of ~50 km	TiPI	The amount of light is minimal and comes from Saturn shine and diffuse scattering in Titan's atmosphere.
		I3: Determine the effects of atmospheric composition.	**M2:** Mole fraction of methane, ethane, and other compounds in the troposphere.	**A1:** Direct gas inlet into MS	TLCA	Atmospheric sampling during the descent.
		I4: Determine the effects of surface processes on meteorology.	**M3:** Temperature gradients between liquid surface and surrounding terrains with 1 K precision. Pressure and temperature at the surface of the lake	**A2:** Measure T by a Pt wire resistance thermometer and P by Kiel probe and capacitive gauges	ASI/ MET	Continuous measurements for duration of lander lifetime.
			M5: Nature of the molecules evaporating from the lake	**A1:** Direct gas inlet into sorption bed followed by heated injection into GC x GC MS	TLCA	Collect atmospheric sample above the lake surface.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O4:** Characterize the atmospheric circulation and flow of energy.	**I5:** Determine the exchange of momentum, energy and matter between the surface and atmosphere and characterize the planetary boundary layer.	**M1:** Wind directions at the surface of the lake	**A1:** Measure T by a Pt wire resistance thermometer and P by Kiel probe and capacitive gauges	ASI/ MET	Continuous measurements for duration of lander lifetime.
			M2: Temperature of the atmosphere at the surface of the lake to 0.1 K	**A1:** T measurements with fast sampling to study the boundary layer	ASI/ MET	Continuous measurements for duration of lander lifetime.
			M3: Wave motion on lake	**A1:** Record motion of liquid lander through accelerometers	SPP	Continuous measurements for duration of lander lifetime.
			M4: Methane humidity as a function altitude and time	**A1:** Atmospheric sound speed	SPP	Continuous measurements for duration of lander lifetime.
			M5: Distribution of condensates at the surface	**A1:** Record images of the lake just before landing	TiPI	Huygens like measurement with LEDs turned on
		I6: Determine the connection between weather, ionosphere and electricity.	**M1:** Electrical conductivity and permittivity of the atmosphere (positive and negative ions + electrons) to 1 km resolution in the range 10^{-14} to 10^{-6} Sm^{-1} and electrons only, with a height resolution to 100 m in the range 10^{-11} to 10^{-6} Sm^{-1}	**A1:** Relaxation probe to measure the conductivity of all charged species	ASI/ MET	Measurements during descent.
				A2: Mutual impedance probe which measures the conductivity of electrons only	ASI/ MET	Measurements during descent
			M2: Global electric circuit and fair-weather electric field in the range from 0–10 kHz. With a height resolution of 1 km	**A1:** Measurement of electric field using dipole antennas	ASI/ MET	Vertical and horizontal electric field in the frequency range from DC to VLF (~10 kHz)
			M3: Extremely low frequency-very low frequency (ELF-VLF) magnetic components from 0–10 kHz	**A1:** Measurement of magnetic field using loop antennas or search coils	ASI/ MET	Measurements during descent
			M4: Search for electric discharges	**A1:** Electric field and optical sensors	ASI/ MET	Coordinated with TiPI
	O5: Characterize the amount of liquid on the Titan surface today.	**I1:** Quantify the total major hydrocarbon (methane / ethane) inventory present in the lakes and seas.	**M3:** Separate ethane, ethylene acetylene, and hydrogen cyanide in the liquid mixture	**A1:** GC x GC MS	TLCA	Lake sampling
			M4: Bulk properties such as sound speed, density, refractive index, thermal conductivity, permittivity	**A1:** Acoustic force transducers (1–10 MHz), archimedes float, refractometer, line heat source, capacitor stack	SPP	Sensors need to be exposed to liquid after landing. Acoustic sensors need to be facing each other with clear path between them.
			M5: Permittivity and electric conductivity) in the range 10^{-14} to 10^{-6} Sm^{-1} of the surface (liquid or solid substrate	**A1:** Mutual impedance probe which measures permittivity and the conductivity of electrons and relaxation probe which measures the conductivity of all charged species	ASI/ MET	Lake sampling
		I2: Determine the depth of the lake at the landing site.	**M1:** Acoustic sounding	**A1:** SONAR: 10–20 khz acoustic pulse every 1 to 10 s.	SPP	Sonar needs to be immersed into lake, facing vertically downward.
			M2: Monitor probe motion at and after splashdown	**A1:** Accelerometers	SPP	Location at center of mass of probe

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENTS
Goal A: How does Titan function as a system; to what extent are there similarities and differences with Earth and other solar system bodies?	**O6:** Characterize the major processes transforming the surface throughout time.	**I2:** Characterize the origin of major surface features, including the effects of liquid flow, tectonic, volcanic, and impact events.	**M3:** Map the distribution of different surface features around the landing site	**A1:** Record images before and after landing	TiPI	Use Saturn shine to map Titan's surface.
	O7: Determine the existence of a subsurface liquid water ocean.	**I3:** Determine the induced magnetic field signatures in order to confirm subsurface liquid and place constraints on the conductivity and depth of the liquid	**M3:** Vector magnetic field measurements on the Titan surface to quantify the induced magnetic field and hence constrain the presence of a sub-surface conducting layer (possibly liquid water ocean)	**A1:** Measure dual sensor (gradiometer) vector magnetic field on Titan's surface	SPP	Knowledge of probe attitude and location. Continuous magnetic field data (desirable, to combine data with magnetic field measurements from the montgolfière and orbiter). Also desirable (not required) to have some measurements with the lake lander, montgolfière, and orbiter in a line radiating from Saturn. Consideration of magnetic cleanliness requirement, and use of gradiometer configuration.
	O8: Determine the state of internal differentiation, whether Titan has a metal core and an intrinsic magnetic field, and constrain the crustal expression of thermal evolution of Titan's interior.	**I3:** Quantify exchange between interior and atmosphere.	**M1:** D/H in methane and ethane to 0.1 per mil in the atmosphere and the lake	**A1:** Isotope ratio mass spectrometry with GC separation of Hydrogen in atmosphere and pyrolytic reduction to measure D/H in methane and ethane.	TLCA	Lake sampling
			M2: Measure noble gases	**A1:** Direct inlet into noble gas concentrator / getter and then into an MS	TLCA	*In situ* analysis of noble gases during the descent and at the surface of the lake

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENTS
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O1:** Determine the chemical pathways leading to formation of complex organics at all altitudes in the Titan atmosphere and their deposition on the surface.	**I1:** Assay the speciation and abundance of atmospheric trace molecular constituents.	**M3:** Detailed molecular analysis of the lake and atmosphere above the lake	**A1:** GC x GC separation followed by high resolution MS.	TLCA	Liquid and atmosphere sampling
		I3: Quantify the sources of chemical energy for atmospheric chemistry.	**M4:** Search for electric discharges during descent	**A1:** Electric field	ASI/ MET	Altitude and attitude measured during the descent by accelerometers and gyros.
				A2: Acquire image in the VIS/NIR during the probe's descent	TiPI	Knowledge of position during descent.
		14: Determine surface composition.	**M2:** Map the distribution of different surface features	**A1:** Record images just after landing	TiPI	LEDs turned on
		I5: Determine the composition of organics in the lake and the isotopic ratios of major elements.	**M1:** Isotopic ratio of C, N, and O in the organic molecules to 0.1 per mil	**A1:** GC x GC separation followed by conversion and isotopic mass spectrometry. Combustion for C and N analysis and pyrolysis for O analysis.	TLCA	Lake sampling
	O2: Characterize the degree to which the Titan organic inventory is different from known abiotic material in meteorites.	**I1:** Assay the composition of organic deposits exposed at the surface, including dunes, lakes, and seas.	**M2:** Inventory organic content of the lakes, including potential solid species in suspension	**A1:** GC x GC-MS for liquids. Pyrolysis GC x GC – MS for solids	TLCA	Lake sampling with solid and liquid separation before analysis
			M3: Determine optical and electrical properties of the liquid (transparency, refraction)	**A1:** Measure refractive index, permittivity, and conductivity	SPP	2 kB @ 1 Hz
			M4: Determine optical properties of the lake materials to identify time dependent variations	**A1:** Measure surface albedo variations just before and after landing	TiPI	LEDs turned on
		I2: Determine the chirality of organic molecules.	**M1:** Chirality of complex organics	**A1:** GC x GC-MS with derivatization and chiral columns.	TLCA	Lake sampling
	O3: Characterize what chemical modification of organics occurs at the surface.	**I1:** Determine the roles of cratering and cryovolcanism in modification and hydrolysis of organics.	**M3:** Search for complex oxygenated organics dissolved or in suspension	**A1:** GC x GC-MS for liquids. Pyrolysis GC x GC – MS for solids	TLCA	Lake sampling with solid and liquid separation before analysis

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

SCIENCE OBJECTIVE			MEASUREMENT	INSTRUMENT		FUNCTIONAL REQUIREMENTS
Goal B: To what level of complexity has prebiotic chemistry evolved in the Titan system?	**O5:** Characterize bulk composition, sources of nitrogen and methane, and exchange between the surface and the interior.	**I1:** Determine whether carbon dioxide is primarily internally derived or photochemically produced.	**M2:** Isotopic composition of atmospheric carbon and oxygen species from the surface to 1500 km.	**A2:** GC x GC separation of lake samples followed by conversion and isotopic mass spectrometry. Combustion for C analysis and pyrolysis for O analysis.	TLCA	Lake sampling
		I2: Determine whether methane is primordial or derived from carbon dioxide.	**M3:** Isotopic composition in lake of carbon in methane to 0.1 per mil and compare with isotopic composition in the atmosphere	**A1:** Isotope ratio mass spectrometry with GC separation of methane in atmosphere or lake liquid and combustion to measure C isotopes	TLCA	Lake and atmosphere sampling
			M4: Isotopic ratio of C in other lake organics	**A1:** GC x GC separation followed by combustion and isotopic mass spectrometry.	TLCA	Lake sampling
		I3: Determine whether molecular nitrogen is derived from ammonia.	**M3:** Isotopic composition of atmospheric nitrogen and noble gas isotopic ratios (Ar, Kr, Xe) to a precision of 0.1 per mil	**A1:** Direct inlet into noble gas concentrator / getter and then into a MS	TLCA	Measurement made during descent and on the surface.
			M4: Analyze dissolved N_2 and ammonia in the lakes and determine their isotopic composition	**A1:** Membrane inlet with cold trapping of ammonia followed by pyrolysis and isotopic mass spectrometry.	TLCA	Lake sampling
		I5: Determine the isotopic ratios of noble gases	**M1:** Quantify noble gas isotopic ratios (Ar, Kr Xe)	**A2:** Direct inlet into noble gas concentrator / getter and then into a MS	TLCA	Measurement made during descent and on the surface.

KEY: O1…O4 = Objective 1…Objective 4; I1…I4 = Investigation 1 …Investigation 4; M1…M4 = Measurement 1…Measurement 4; A1…A4 = Approach 1…Approach 4

2. High-Level Mission Concept

Overview

See Titan Saturn System Mission Study 2008: Final Report [1], Section 4.

Concept Maturity Level

Table 2-1 summarizes the NASA definitions for concept maturity levels (CMLs).The Titan Saturn System Mission (TSSM) concept is between CMLs 5 and 6. Detailed science traceability, defined relationships, and dependencies are all completed for the planning payload. The basic implementation mode has been selected and major partnerships are established. Technologies and risks have been defined. Mitigation plans are in place and some early mitigation activities are being executed. The basic verification and validation (V&V) approach has been defined for the planetary protection and radioisotope power source (RPS) requirements and testbeds/software and integration and test (I&T) approaches are story-boarded. The development schedule has been developed through to the subsystem levels (in some cases below that) and integrated into a master schedule. This schedule was used to develop a quasi-grassroots cost estimate. The spacecraft, planetary protection, project integration and test, and mission design are a grassroots estimate, but other areas are model based. In two areas (mission assurance and education and public outreach) the costs are rules-of-thumb based.

Table 2-1. Concept Maturity Level Definitions

Concept Maturity Level	Definition	Attributes
CML 6	Final Implementation Concept	Requirements trace and schedule to subsystem level, grassroots cost, V&V approach for key areas
CML 5	Initial Implementation Concept	Detailed science traceability, defined relationships and dependencies: partnering, heritage, technology, key risks and mitigations, system make/buy
CML 4	Preferred Design Point	Point design to subsystem level mass, power, performance, cost, risk
CML 3	Trade Space	Architectures and objectives trade space evaluated for cost, risk, performance
CML 2	Initial Feasibility	Physics works, ballpark mass and cost
CML 1	Cocktail Napkin	Defined objectives and approaches, basic architecture concept

Technology Maturity

Mission / Orbiter Technology Maturity

See Titan Saturn System Mission Study 2008: Final Report [1], Section 4.9.

Montgolfière / Lake Lander Technology Maturity

See TSSM In Situ Elements 2008 Assessment Study Report [2], Section 11.

Key Trades

See Titan Saturn System Mission Study 2008: Final Report [1], Section 4.4.7.

- A single main engine was chosen over a dual engine concept. This trade will be revisited.
- Solar electric propulsion (SEP) was chosen over a chemical system with a large launch vehicle (Delta IV Heavy), or with a longer trip time, and a shorter science phase to keep within the 14-year nominal RPS lifetime. See Table 2-2 for the list of propulsion options.

Table 2-2. TSSM Propulsion Trade

Case	Launch Vehicle	Cruise Propulsion	Flight Time to Saturn (years)	In-Situ Element	($RY)	($FY07)
1	A541	Chemical	8	None	($377)	($273)
2	A551	Chemical	10.5	B+L	($205)	($145)
3	A551	SEP	9	B+L	—	—
4	A521	SEP	7.5	None	($223)	($160)
5	Delta IVH	Chemical	9	B+L	$244	$148
6	Delta IVH	SEP	6	B+L	$299	$215
7	Ares V	Chemical	3	B+L	$159	$136

Table 2-3. TSSM Completed Trade Studies

Trade Name	Trade Options*	Discussion
SEP	**Include SEP stage** vs. chemical only propulsion	Although approximately $100M more expensive, the inclusion of a SEP stage significantly reduces trip time and enhances mission flexibility by providing significant additional margin for mass growth traded against trip time.
SEP architecture	Integral vs. **separable SEP stage**	A separable SEP stage was chosen for the TSSM design as it allows for a significant mass jettison before Saturn Orbit Insertion (SOI), thus increasing delivered mass capability to Titan. Design of the SEP stage as a self-contained unit also results in a feed-forward flight element that would be available to future missions.
RPS system	MMRTG vs. **ASRG**	ASRGs were chosen based on their reduced mass, increased power output, and reduced cost. If a programmatic decision is made to use MMRTGs, TSSM is carrying extra mass margin (above the required 33%) and power margin to accommodate either RPS system.
Power requirements	Four vs. **five** vs. Six MMRTGs	Power requirements for science instruments and telecom dictated the use of the equivalent of five MMRTGs. With four MMRTGs, adequate power would not be available to operate instruments (the duty cycles would have to be unacceptably low). Six MMRTGs would make a more comfortable science scenario, but would cause the mission to exceed the study guidelines for available plutonium quantity when combined with the MMRTG on the Montgolfière and RHU demands. Unless NASA directs the use of MMRTGs, this trade is no longer applicable due to a change in study guidelines allowing the use

Trade Name	Trade Options*	Discussion
		of ASRGs. Subsequent analysis showed that four ASRGs accommodate the power requirements met by five MMRTGs (and even provides more power than the five-MMRTG case). A fifth ASRG is carried as an onboard spare for redundancy.
OpNav camera	**Include OpNav** vs. no OpNav	Optical navigation is needed to determine the orbit of Enceladus to sufficient accuracy to enable low-altitude flybys. Without optical navigation, the altitude of these flybys would likely be limited to 500 km; with optical navigation these flybys could go as low as 25 km (as demonstrated in Cassini's Equinox Mission).
Fine attitude control	**RWAs** vs. MIT thrusters	RWAs were chosen to perform 3-axis control because, while the micro-impulse thrusters (MITs) require less power (by ~35 W) and will potentially cost less, they may require a large mass hit in hydrazine propellant. The RWAs will provide slightly better pointing control, especially with respect to pointing stability. The MITs have uncertain development and qualification costs at this time.
IMU	MIMU vs. **SIRU**	Although the micro-inertial measurement unit (MIMU) is less massive and costly (even though two are required for redundancy), there are concerns with the MIMU's lifetime. The internally redundant space inertial reference unit (SIRU) was selected for its longer life capability. This trade will be revisited in Phase A.
Thruster layout	**Coupled** vs. uncoupled thrusters	Coupled thrusters were used in the TSSM design to avoid accumulation of unwanted ΔV errors. Additionally, during the release of the in-situ elements, coupled thrusters provide double the control authority, and therefore higher reliability.
Main engine	**Single** vs. dual	Two engines for redundancy introduce complexities that have not yet been worked. It was deemed that implementation of this redundancy was not the best use of resources (i.e., cost and mass) at this time. This will be revisited in Phase A.
Thrust control	**Gimbaled main engine** vs. TVC thrusters	A propulsion system table top review concluded that, though a gimbaled main engine is more costly, it is a more robust design. Gimbaling provides a wider range for the center of gravity, which is especially important with the release of two large in-situ elements.
Engine cover	**Include engine cover** vs. no engine cover	There was concern that particulates may damage the engine during Saturn ring crossings, Enceladus plume flybys, and engine-first Titan aerobraking segments of the mission, as well as the long lifetime requirement on the engine.
Propellant tank material	Titanium vs. **COPV**	Composite overwrapped pressure vessel (COPV) tanks are industry standard and are significantly less massive and less expensive than traditional Titanium tanks.
Propellant tank configuration	**Tank mass** vs. spacecraft stack height	Although a trade was conducted to determine system-level mass savings for increasing tank width (and therefore mass) and reducing spacecraft stack height (and therefore decreasing overall system mass), ultimately the stack height was not reduced due to in-situ accommodation needs.

Trade Name	Trade Options*	Discussion
HGA pointing	Monopulse tracking vs. **spacecraft pointing w/ stiff antenna**	TSSM has a Mars Reconnaisance Orbiter (MRO)-derived antenna design for maximum stiffness. This includes a body-fixed gimbal platform for the antenna. The open-loop spacecraft pointing design using the stiff antenna was considered the more robust, lower cost option when compared to closed-loop monopulse tracking. Additionally, spacecraft pointing requires a lower demand on DSN resources.
HGA diameter and articulation	3 m vs. **4 m, gimbaled** vs. bodyfixed	The 2007 Titan Explorer study made use of a 3 m HGA, but this earlier study assumed 70 m receiving stations. As a result of the 2008 guideline to not assume 70 m stations, it was decided to adopt the larger antenna to recapture some of the data rate that would be lost by relying on the 34 m ground stations. To fit within the confines of the LV fairing, the antenna was positioned on the top deck of the orbiter. This axial location has the added benefits of protecting the spacecraft during ring crossings, serving as a sun shade, and acting as an aerodynamic stabilizer during aerobraking. Deciding to articulate the high gain antenna (HGA) (instead of putting the instruments on a scan platform or body-fixing the antenna and instruments like Cassini) came out of the operations lessons-learned activity.
Radio science and relay communication	**UST** vs. SDST	The universal space transponder (UST) accomplishes orbiter-to-Earth communication, relay communication with the *in situ* elements, and Ka-uplink (a science requirement) in a single unit, thus taking the place of a small deep space transponder (SDST), an Electra, and a Ka translator. While the SDST is flight proven, it is currently out of production. The UST is under development, and will be monitored carefully throughout Phase A.
Safe mode communication	USO vs. **USO not required for communication**	An ultra-stable oscillator (USO) is not required for flight-system safe-mode operations (an initial concern), but was included in the design for science purposes because it enables radio occultations in Titan's atmosphere.
C&DH system interfaces	**MSIA Card** vs. MREU	MSAP system interface assembly (MSIA) is the card used in the multimission system architecture platform (MSAP) C&DH architecture to interface with other spacecraft systems (in TSSM's case, the in-situ elements and the OpNav camera), but the MSIA uses significant power. An alternative architecture using a MSAP remote engineering unit (MREU) in place of the MSIA was investigated, but did not realize the power savings originally hoped for and complicated the design.
Memory type	Flash vs. **SDRAM** vs. SRAM	Flash memory is very sensitive to radiation (tolerant to only 7 krad), and would therefore require significant shielding to meet even the modest radiation requirements of this mission. SDRAM was chosen for its rad hard availability and because it provides more memory when compared to a SRAM card with the same sized footprint
Instrument interface type	SpaceWire vs. **diversified interfaces**	The goal of the TSSM C&DH design was to maximize the use of current MSAP designs. To use a SpaceWire-only system (a high-speed, low-error-rate interface) would have resulted in modifications to the current MSAP SFC card, which has only four SpaceWire ports. The current TSSM design utilizes SpaceWire and RSB for instrument interfaces and 1553 to interface with other spacecraft subsystems.

* = Chosen option indicated in bold.

3. Technical Overview

Instrument Payload Description

See Titan Saturn System Mission Study 2008: Final Report [1], Section 4.2

Baseline Orbiter Payload

See Titan Saturn System Mission Study 2008: Final Report [1], Section 4.2

Table 3-1. Baseline Instrument Specifications—Orbiter

	Units	**High Resolution Imager and Spectrometer (HiRIS)**	**Titan Penetrating Radar and Altimeter (TiPRA)**	**Polymer Mass Spectrometer (PMS)**	**Submillimeter Spectrometer (SMS)**	**Thermal Infrared Spectrometer (TIRS)**	**MAPP-Magnetometer**	**MAPP-Energetic Particle Spectrometer (EPS)**	**MAPP-Langmuir Probe**	**MAPP-Plasma Spectrometer**	**Radio Science and Accelerometer (RSA)**
Number of channels		3/410	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Size/dimensions (for each instrument)	m x m x m	0.3 x 0.5 x 0.6 plus electronics box: 0.07 x 0.15 x 0.20	2 10-m dipole antennae, each stowed 1.5 x 0.3 x 0.2	TBD	0.2 x 0.2 x 0.2 plus 15 cm parabolic dish	0.3 x 0.4 x 0.5	3.6 m boom	TBD	TBD	TBD	TBD
Instrument mass **without** contingency (CBE*)	kg	28.4	11	29.2	12.3	16.5	2.2	1.5	1.5	5.0	0
Instrument mass contingency	%	30	30	30	30	30	30	30	30	30	30
Instrument mass **with** contingency (CBE+Reserve)	kg	36.9	14.3	38	16	21.5	2.9	2.0	2.0	6.5	0
Instrument average payload power **without** contingency	w	28 (1 operating) or 32 (both operating)	25	25 (low mass range) or 47 (high mass range)	45	17	3	2.5	1	9	0
Instrument average payload power contingency	%	30	30	30	30	30	30	30	30	30	30
Instrument average payload power **with** contingency	w	36.4	32.5	32.5	58.5	22.1	3.9	3.3	1.3	11.7	0
Instrument average science data rate^ **without** contingency	kbps	77 (imager) or 225 (spec)	20–30 (alt mode) or 280 (sounder) or 20,000 (burst)	2.5–60 (depends on data rate mode)	14	10	4	5	0.1	1–10 (depends on data rate mode)	TBD
Instrument average science data^ rate contingency	%	0	0	0	0	0	0	0	0	0	0
Instrument average science data^ rate **with** contingency	kbps	77 (imager) or 225 (spec)	20–30 (alt mode) or 280 (sounder) or 20,000 (burst)	2.5–60 (depends on data rate mode)	14	10	4	5	0.1	1–10 (depends on data rate mode)	TBD
Instrument fields of view (if appropriate)	degrees	20	N/A	Mounted on a rotating platform. Closed ion source: two 60 half-angle centered on each gas ram direction. Open ion source: two 7.5 half-angle FOVs in the same directions.	N/A	Mid-IR: 3 Far-IR: 4.3	N/A	N/A	N/A	N/A	N/A
Pointing requirements (knowledge)	µrad	200	100	2	1	1	5	5	N/A	N/A	N/A
Pointing requirements (control)	millirad	1	100	5	5	3	10	10	N/A	N/A	N/A
Pointing requirements (stability)	µrad /sec	60/1	N/A	1,000/1	1,000/60	1,000/120	1,000/1	1,000/1	N/A	N/A	N/A

*CBE = Current best estimate

^Instrument data rate defined as science data rate prior to on-board processing

Table 3-2. Baseline Payload Mass and Power—Orbiter

Instrument	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
HiRIS	28.4	30	36.9	28 (1 operating) or 32 (2 operating)	30	36.4
TiPRA	11.0	30	14.3	25	30	32.5
PMS	29.2	30	38.0	25 (low mass range) or 47 (high mass range)	30	32.5
SMS	12.3	30	16.0	45	30	58.5
TIRS	16.5	30	21.5	17	30	22.1
MAPP-MAG	2.2	30	2.9	3	30	3.9
MAPP-EPS	1.5	30	2.0	2.5	30	3.3
MAPP-Langmuir probe	1.5	30	2.0	1	30	1.3
MAPP-plasma spectrometer	5.0	30	6.5	9	30	11.7
RSA	0.0	30	0	0.0	30	0
Total Payload Mass	**107.6**	–	**140.1**	**155.5***	–	**202.2***

*The instruments are not operated at the same time, so the spacecraft is not required to supply the total payload power or total payload downlink rate. Maximum instantaneous power supply with margin is 165 W.

Baseline Montgolfière Payload

See TSSM In Situ Elements 2008 Assessment Study Report [2], Sections 3.4.3.1 and 4.3.1, and 2008 CDF Study Report Tandem Study of a Two-Probe Mission to Titan [3], Section 7.1.1.

Montgolfière instrument mass contingencies are 20%, consistent with ESA practice for items requiring redesign.

Table 3-3. Baseline Instrument Specifications—Montgolfière

	Units	Balloon Imaging Spectrometer (BIS)	Visual Imaging System for Titan Balloon (Vista-B)	Atmospheric Structure Instrument/ Meteorological Package (ASI/Met)	Titan Electric Environment Package (TEEP-B)	Titan Radar Sounder (TRS)	Titan Montgolfière Chemical Analyser (TMCA)	Magnetometer (MAG)	Montgolfière Radio Science Transmitter (MRST)
Number of channels		N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Size/dimensions (for each instrument)	m x m x m	0.26 x 0.24 x 0.15 (optics) 0.2 x 0.3 x 0.1 (electronics)	TBD	0.2 x 0.2 x 0.2	0.1 x 0.1 x 0.02 0.05 x 0.004 x 0.001 (antenna)	0.37 x 0.25 x 0.13 1 m antenna	0.35 x 0.25 x 0.15	Two sensors@ 0.11 x 0.07 x 0.05 and electronics @ 0.1 x 0.12 x 0.03	TBD
Instrument mass **without** contingency (CBE*)	kg	3.0	2	1.0	1.0	8.0	6.0	0.5	1.0
Instrument mass contingency	%	20	20	20	20	20	20	20	20
Instrument mass **with** contingency (CBE+Reserve)	kg	3.6	2.4	1.2	1.2	9.6	7.2	0.6	1.2
Instrument average payload power **without** contingency	W	10	5	5	2.0	15	15	1.5	–
Instrument average payload power contingency	%	20	20	20	1	20	20	20	20
Instrument average payload power **with** contingency	W	12	6	6	20	18	18	1.8	–
Instrument average science data rate^ **without** contingency	kbps	740	10,240	0.15	1.2	TBD	5	0.8	TBD (very low)
Instrument average science data^ rate contingency	%	0	0	0	0	0	0	0	0
Instrument average science data^ rate **with** contingency	kbps	740	10,240	0.15	1.2	TBD	5	0.8	TBD (very low)
Instrument fields of view (if appropriate)	degrees	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pointing requirements (knowledge)	µrad	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pointing requirements (control)	millirad	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pointing requirements (stability)	µrad /sec	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

*CBE = Current best estimate

^Instrument data rate defined as science data rate prior to on-board processing

Table 3-4. Baseline Payload Mass and Power—Montgolfière

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
BIS	3.0	20	3.6	10	20	12
Vista-B	2.0	20	2.4	5	20	6
ASI/Met	1.0	20	1.2	5	20	6
TEEP-B	1.0	20	1.2	1	20	1.2
TRS	8.0	20	9.6	15	20	18
TMCA	6.0	20	7.2	8	20	9.6
MAG	0.5	20	0.6	1.5	20	1.8
MRST	–	20	–	–	20	–
Total Payload Mass	**21.5**	–	**25.8**	**45.5**	–	**54.6**

Baseline Lake Lander Payload

See TSSM In Situ Elements 2008 Assessment Study Report [2], Sections 3.4.3.2 and 4.3.2, and 2008 CDF Study Report Tandem Study of a Two-Probe Mission to Titan [3], Section 9.1.1.

Table 3-5. Baseline Instrument Specifications—Lake Lander

	Units	Titan Lander Chemical Analyzer (TLCA)	Titan Probe Imager (TiPI)	ASI/Met-TEEP-L	Surface Properties Package	Lander Radio Science Transponder (LRST)
Number of channels		N/A	N/A	N/A	N/A	N/A
Size/dimensions (for each instrument)	m x m x m	0.3 x 0.25 x 0.15	TBD	TBD	TBD	TBD
Instrument mass **without** contingency (CBE*)	kg	23	1.0	1.5	1.5	2.0
Instrument mass contingency	%	20	20	20	20	20
Instrument mass **with** contingency (CBE+Reserve)	kg	27.6	1.2	1.8	1.8	2.4
Instrument average payload power **without** contingency	W	75	7.0	5.5	10	20
Instrument average payload power contingency	%	20	20	20	20	20
Instrument average payload power **with** contingency	W	90	8.4	6.6	13.2	24
Instrument average science data rate^ **without** contingency	kbps	5.0	10	2.15	16.0	TBD (very low)
Instrument average science data^ rate contingency	%	0	0	0	0	0
Instrument average science data^ rate **with** contingency	kbps	5.0	10	2.15	16.0	TBD (very low)
Instrument fields of view (if appropriate)	degrees	N/A	N/A	N/A	N/A	N/A
Pointing requirements (knowledge)	μrad	N/A	N/A	N/A	N/A	N/A
Pointing requirements (control)	millirad	N/A	N/A	N/A	N/A	N/A
Pointing requirements (stability)	μrad /sec	N/A	N/A	N/A	N/A	N/A

*CBE = Current best estimate

^Instrument data rate defined as science data rate prior to on-board processing

Table 3-6. Baseline Payload Mass and Power—Lake Lander

	Mass			Average Power		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
TLCA	23	20	27.6	75	20	90
TiPI	1	20	1.2	7	20	8.4
ASI/Met-TEEP-L	1.5	20	1.8	5.5	20	6.6
Surface Properties Package	1.5	20	1.8	11	20	13.2
LRST	–	20	–	–	20	–
Total Payload Mass	**27.0**	**20**	**32.4**	**98.5**	**20**	**118.2**

Baseline Flight System

Baseline Orbiter Flight System

See Titan Saturn System Mission Study 2008: Final Report [1], Section 4.4.

Table 3-7. Flight System Element Mass and Power—Orbiter

	Mass			Average Power		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures and mechanisms	350	30	456	15	49	22
Thermal control	82	30	106	33	49	49
Propulsion (dry mass)	154	27	196	76	49	113
Attitude control	53	21	64	90	49	134
Command & data handling	32	17	37	58	49	86
Telecommunications	64	27	82	99	49	148
Power w/o RPS RPS Power	64 107	30 49	83 160	20	49	30
Cabling	68	30	89	28	49	42
SEP stage power accommodation	–	–	–	54	49	80
Total Flight Element Dry Bus Mass	**974**	**31**	**1,273**	**473***	**49**	**704***

*Power amounts are not simultaneous. See Titan Saturn System Mission Study 2008: Final Report [1], Section 4.4, Table 4.4-5 for details.

Table 3-8. Flight System Element Characteristics—Orbiter

Flight System Element Parameters (as appropriate)	Value/ Summary, units
General	
Design life, months	61 month SEP Cruise 58 month Chemical Cruise 24 month Saturn Tour 3 month Aerobraking 20 month Titan Orbit

Structure	
Structures material (aluminum, exotic, composite, etc.)	Graphite composite, aluminum honeycomb
Number of articulated structures	2
Number of deployed structures	0
Aeroshell diameter, m	N/A
Thermal Control	
Type of thermal control used	MLI, thermal surfaces, thermal conduction control, electrical heaters, and RHUs, both fixed and variable
Propulsion	
Estimated delta-V budget, m/s	2,377
Propulsion type(s) and associated propellant(s)/oxidizer(s)	Dual-mode
Number of thrusters and tanks	1 biprop main plus 16 monoprop
Specific impulse of each propulsion mode, seconds	323 biprop, 217 mono-prop
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.).	3-axis
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Sun sensors,star trackers, IMU
Attitude control capability, degrees	±0.7 mrad (3σ, radial)
Attitude knowledge limit, degrees	0.15 mrad
Agility requirements (maneuvers, scanning, etc.)	
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	2 axes for both HGA and main engine
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	4 RWAs with 25 Nms of angular storage, 16 4.5-N RCS thrusters
Command & Data Handling	
Flight element housekeeping data rate, kbps	10
Data storage capacity, Mbits	32,000
Maximum storage record rate, kbps	40,000
Maximum storage playback rate, kbps	200
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	5 ASRGs (4 operating; 1 spare)
Array size, meters x meters	N/A
Solar cell type (Si, GaAs, multi-junction GaAs, concentrators)	N/A
Expected power generation at beginning of life (BOL) and end of life (EOL), watts	600 (BOL) 540 (EOL)*
On-orbit average power consumption, watts	394
Battery type (NiCd, NiH, Li-ion)	Li-ion
Battery storage capacity, amp-hours	Two 25-Amp-hours

*Four ASRGs. Fifth ASRG included as a spare.

Baseline Solar Electric Propulsion (SEP) Flight System

See Titan Saturn System Mission Study 2008: Final Report [1], Section 4.4.4.

Table 3-9. Flight System Element Mass and Power—SEP Stage

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Structures and mechanisms	154	29	199	N/A	N/A	N/A
Thermal control	38	47	56	N/A	N/A	N/A
Propulsion (dry mass)	168	30	218	14,000	N/A	14,000
Attitude control	3	10	3	N/A	N/A	N/A
Command & data handling	8	18	10	N/A	N/A	N/A
Telecommunications	N/A	N/A	N/A	N/A	N/A	N/A
Power	96	30	124	15,000	N/A	150,000
Cabling	34	30	44	N/A	N/A	N/A
Total Flight Element Dry Bus Mass	**502**	**31**	**655**	**–**	**N/A**	**–**

Table 3-10. Flight System Element Characteristics—SEP Stage

Flight System Element Parameters (as appropriate)	Value/ Summary, units
General	
Design life, months	61 months
Structure	
Structures material (aluminum, exotic, composite, etc.)	Aluminum
Number of articulated structures	0
Number of deployed structures	Two solar array wings
Aeroshell diameter, m	N/A
Thermal Control	
Type of thermal control used	MLI, heaters
Propulsion	
Estimated delta-V budget, m/s	2,750
Propulsion type(s) and associated propellant(s)/oxidizer(s)	SEP
Number of thrusters and tanks	3
Specific impulse of each propulsion mode, seconds	>4,100*
Attitude Control	N/A
Control method (3-axis, spinner, grav-gradient, etc.).	N/A
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	N/A
Attitude control capability, degrees	N/A
Attitude knowledge limit, degrees	N/A
Agility requirements (maneuvers, scanning, etc.)	N/A
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	Three 2-axis gimbals on thrusters

Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	
Command & Data Handling	N/A
Flight element housekeeping data rate, kbps	N/A
Data storage capacity, Mbits	N/A
Maximum storage record rate, kbps	N/A
Maximum storage playback rate, kbps	N/A
Power	N/A
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	Two 7.5-kW Ultraflex wings
Array size, meters x meters	6 m diam
Solar cell type (Si, GaAs, multi-junction GaAs, concentrators)	Triple-junction GaAs
Expected power generation at beginning of life (BOL) and end of life (EOL), watts	15 kW
On-orbit average power consumption, watts	15 kW during thrusting
Battery type (NiCd, NiH, Li-ion)	N/A
Battery storage capacity, amp-hours	N/A

*NEXT Ion Propulsion System Development Status and Capabilities, Michael J. Patterson and Scott W. Benson, NASA Glenn Research Center, http://esto.nasa.gov/conferences/nstc2007/papers/Patterson_Michael_D10P3_NSTC-07-0014.pdf

Baseline Montgolfière Flight System with Spin Eject

See 2008 CDF Study Report Tandem Study of a Two-Probe Mission to Titan [3], Section 7.2.4.

Table 3-11. Flight System Element Mass and Power—Montgolfière

	Mass			Average Power		
	CBE (kg)	**% Cont.**	**MEV (kg)**	**CBE (W)**	**% Cont.**	**MEV (W)**
Structures	114.9	20	137.9	0	0	0
Balloon	109.9	0	109.9	0	0	0
Thermal control	93.3	5.9	98.8	0	0	0
Mechanisms	25.8	11.5	28.7	0	0	0
Attitude control	5.3	13.9	6.0	6	0	6
Command & data handling	7.9	10.0	8.6	10	0	10
Telecommunications	17.4	17.2	18.7	70	0	70
Power	4.2	16.5	5.0	–	0	–
DLS (front and back shields)	18.2	10.0	20.0	0	0	0
Harness	16	20.0	19.2	11	0	11
Total Flight Element Dry Bus Mass	**412.9**	**–**	**452.8***	**97****	**0****	**97****

*ESA carried 20% margin on top of subsystem contingency for a total of 548.1 kg

**The Montgolfière power system was designed for a simultaneous maximum power of 100 W. This is accomplished with load sharing. The maximum simultaneous load is calculated as 92 W.

Table 3-12. Flight System Element Characteristics—Montgolfière

Flight System Element Parameters (as appropriate)	Value/ Summary, units
General	
Design life, months	6 months after arrival
Structure	
Structures material (aluminum, exotic, composite, etc.)	Carbon fiber reinforced plastic Honey Comb Shells
Number of articulated structures	1
Number of deployed structures	6
Aeroshell diameter, m	2.6
Thermal Control	
Type of thermal control used	RHUs, waste heat
Propulsion	
Estimated delta-V budget, m/s	N/A
Propulsion type(s) and associated propellant(s)/oxidizer(s)	Parachute
Number of thrusters and tanks	N/A
Specific impulse of each propulsion mode, seconds	N/A
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.).	Spinner/gravity-gradient
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	N/A
Attitude control capability, degrees	N/A
Attitude knowledge limit, degrees	1
Agility requirements (maneuvers, scanning, etc.)	N/A
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	N/A
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	3 accelerometers, 2 G-switches, 3 coarse gyros, 3 sun/Saturn sensor, IMU, pressure sensor
Command & Data Handling	
Flight element housekeeping data rate, kbps	TBD
Data storage capacity, Mbits	32,000
Maximum storage record rate, kbps	200,000
Maximum storage playback rate, kbps	TBD
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	1 MMRTG
Array size, meters x meters	N/A
Solar cell type (Si, GaAs, multi-junction GaAs, concentrators)	N/A
Expected power generation at beginning of life (BOL) and end of life (EOL), watts	100 electrical, 1,690 thermal (EOL)
On-orbit average power consumption, watts	92 electrical, 1,000 thermal
Battery type (NiCd, NiH, Li-ion)	N/A
Battery storage capacity, amp-hours	0

Baseline Lake Lander Flight System with Spin Eject

See 2008 CDF Study Report Tandem Study of a Two-Probe Mission to Titan [3], Section 9.2.5.

Table 3-13. Flight System Element Mass and Power—Lake Lander

	Mass			Average Power		
	CBE (kg)	% Cont.	MEV (kg)	CBE (W)	% Cont.	MEV (W)
Structures	30.7	20	36.8	0	0	0
Mechanisms	20.5	10	22.6	0	0	0
Thermal control	29.9	1.3	30.3	0	0	0
Propulsion (dry mass)	0	0	0	0	0	0
Attitude control (AOCS)	1.7	12.7	2.0	5	0	5
Command & data handling (DHS)	6.1	10	6.7	12	0	12
Telecommunications	9.3	7	10.0	25	0	25
Power	6.9	13.2	7.8	13	0	13
DLS	13.5	10	14.86	0	0	0
Harness	11	20	13.2	0	0	0
Total Flight Element Dry Bus Mass	**129.6**	**–**	**144.1**	**55**	**0**	**55**

Table 3-14. Flight System Element Characteristics—Lake Lander

Flight System Element Parameters (as appropriate)	Value/ Summary, units
General	
Design life, months	9 hours after arrival
Structure	
Structures material (aluminum, exotic, composite, etc.)	Carbon fiber reinforced plastic Honey Comb Shells, impact attenuation foam
Number of articulated structures	0
Number of deployed structures	3
Aeroshell diameter, m	1.8
Thermal Control	
Type of thermal control used	RHUs
Propulsion	
Estimated delta-V budget, m/s	N/A
Propulsion type(s) and associated propellant(s)/oxidizer(s)	Parachutes
Number of thrusters and tanks	N/A
Specific impulse of each propulsion mode, seconds	N/A
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.).	Spinner/gravity-gradient
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	N/A
Attitude control capability, degrees	N/A
Attitude knowledge limit, degrees	N/A
Agility requirements (maneuvers, scanning, etc.)	N/A
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	N/A

Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	3 accelerometers, 1 gyro, 2 pressure sensors, 4-gswitch sensors
Command & Data Handling	
Flight element housekeeping data rate, kbps	Small-TBD
Data storage capacity, Mbits	14,000
Maximum storage record rate, kbps	200,000
Maximum storage playback rate, kbps	
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	Primary batteries
Array size, meters x meters	N/A
Solar cell type (Si, GaAs, multi-junction GaAs, concentrators)	N/A
Expected power generation at beginning of life (BOL) and end of life (EOL), watts	0
On-orbit average power consumption, watts	1.6
Battery type (NiCd, NiH, Li-ion)	SAFT $LiSO_2$
Battery storage capacity, amp-hours	806

Baseline Concept of Operations and Mission Design

See Titan Saturn System Mission Study 2008: Final Report [1], Sections 4.3, 4.5.1, 4.6.4, and Appendix C.

Table 3-15. Mission Design

Parameter	Value	Units
Orbit parameters (apogee, perigee, inclination, etc.)	Orbiter Titan orbit only 1,500 circular 85 Descending node LST 11:30 a.m. to 9 a.m.	km deg
Mission lifetime	61 SEP Cruise 58 Chemical Cruise 24 Saturn Tour 2 Aerobraking 20 Titan Orbit Total: 165	mos
Maximum eclipse period	N/A	min
Launch site	ETR	
Total flight element #1 mass **with** contingency (includes instruments)—orbiter	1,613	kg
Total flight element #2 mass **with** contingency (includes instruments)—SEP stage	655	kg
Total flight element #3 mass **with** contingency (includes instruments)—montgolfiére	571	kg
Total flight element #4 mass **with** contingency (includes instruments)—lake lander	190	kg
Propellant mass **without** contingency	2,528 bi-prop 410 (SEP)	kg

Propellant contingency	0 bi-prop 10 (SEP)	%
Propellant mass **with** contingency	2,528 bi-prop 451 SEP fuel	kg
Launch adapter mass **with** contingency	26	kg
Total launch mass	6,203	kg
Launch vehicle	Atlas V 551	type
Launch vehicle lift capability	6,265	kg
Launch vehicle mass margin	62	kg
Launch vehicle mass margin (%)	35	%

Baseline Orbiter Concept of Operations and Mission Design

The orbiter relays data to Earth for both the montgolfière and lake lander as the primary data-link.

Table 3-16. Mission Operations and Ground Data Systems—Orbiter

Downlink Information	SEP Cruise	Cruise	Saturn Tour	Aerobraking	Titan Orbit
Number of contacts per week	1–1.5	0.5 -21	14	21	14
Number of weeks for mission phase, weeks	264	251	104	9	95
Downlink frequency band, GHz	8.425/32.05	8.425/32.05	8.425/32.05	8.425/32.05	8.425/32.05
Sci & telemetry data rate(s), kbps	0.01	0.01	10(x)-200(Ka)	10(x)-200(Ka)	10(x)-200(Ka)
Transmitting antenna type(s) and gain(s), DBi	MGA-X 22 4 m HGA-X; 48.4 4 m HGA-Ka, 60.7	MGA-X 22 4 m HGA-X; 48.4 4 m HGA-Ka, 60.7	MGA-X 22 4 m HGA-X; 48.4 4 m HGA-Ka, 60.7	MGA-X 22 4 m HGA-X; 48.4 4 m HGA-Ka, 60.7	MGA-X 22 4 m HGA-X 48.4; 4 m HGA-Ka, 60.7
Transmitter peak power, watts(DC)	69	69	79	69	99
Downlink receiving antenna gain, DBi	DSS-25 68.4 X; 79 Ka	DSS-25 68.4 X; 79 Ka	DSS-25 68.4 X; 79 Ka	DSS-25 68.4 X; 79 Ka	DSS-25 68.4 X; 79 Ka
Transmitting power amplifier output, watts (RF)	25	25	25-X/35-Ka	25-X/35-Ka	25-X/35-Ka
Total daily data volume (MB/day)	**<1**	**<1**	**15,000 Max**	**16.9**	**14,440**
Uplink Information					
Number of uplinks per day	0.14	0.07	1	1	1
Uplink frequency band, GHz	7.17	7.17	7.17/34.33	7.17/34.33	7.17/34.33
Telecommand data rate, kbps	140	140	140	140	140
Receiving antenna type(s) and gain(s), DBi	MGA, 21.5	MGA, 21.5	4 m HGA-X, 47.0; 4 m HGA-Ka, 61.3	4m HGA-X, 47.0; 4 m HGA-Ka, 61.3	4m HGA-X, 47.0; 4 m HGA-Ka, 61.3

Baseline Montgolfière Concept of Operations and Mission Design

Montgolfiére data is relayed to the orbiter, although low data rate direct-to-Earth contact is possible.

Table 3-17. Mission Operations and Ground Data Systems—Montgolfière

Downlink Information	Balloon Science Phase
Number of contacts per week	Varies depending on orbiter distance
Number of weeks for mission phase, weeks	26
Downlink frequency band, GHz	8.45
Telemetry data rate(s), kbps	10–1,000
Transmitting antenna type(s) and gain(s), DBi	50 cm HGA, 31
Transmitter peak power, watts	45
Downlink receiving antenna gain, DBi	47
Transmitting power amplifier output, watts	25
Total daily data volume, (MB/day)	**TBD**
Uplink Information	
Number of uplinks per day	Varies depending on orbiter distance
Uplink frequency band, GHz	7.17
Telecommand data rate, kbps	Varies depending on orbiter distance
Receiving antenna type(s) and gain(s), DBi	4 m HGA X, 47

Baseline Lake Lander Concept of Operations and Mission Design

The lake lander sends data continuously to the orbiter during its nine hour mission.

Table 3-18. Mission Operations and Ground Data Systems—Lander

Downlink Information	Mission Phase 1
Number of contacts per week	Continuous
Number of weeks for mission phase	9 hours
Downlink frequency band, GHz	8.45
Telemetry data rate(s), kbps	1,024
Transmitting antenna type(s) and gain(s), DBi	MGA, 0
Transmitter peak power, watts	15
Downlink receiving antenna gain, DBi	47
Transmitting power amplifier output, watts	8
Total daily data volume, (MB/day)	**3,400**
Uplink Information	
Number of uplinks per day	Continuous
Uplink frequency band, GHz	7.17
Telecommand data rate, kbps	Varies depending on orbiter distance
Receiving antenna type(s) and gain(s), DBi	4 m HGA X, 47

Planetary Protection

See Titan Saturn System Mission Study 2008: Final Report [1], Section 4.7 and Section 4.10.6.

Risk List

See Titan Saturn System Mission Study 2008: Final Report [1], Section 4.10.

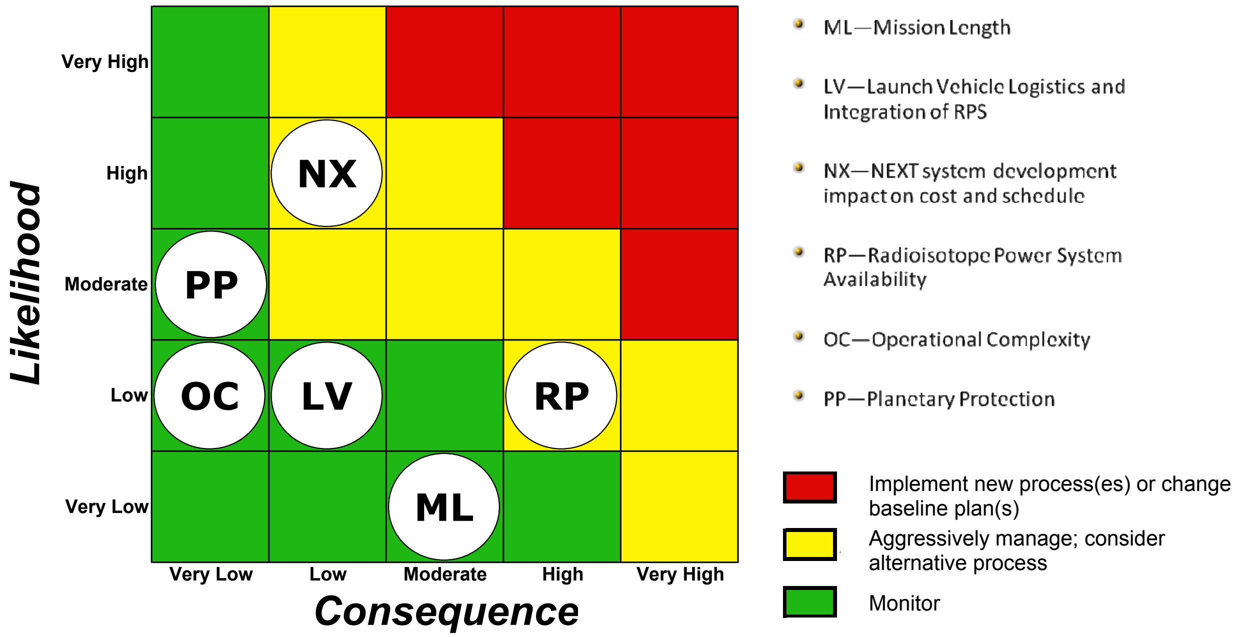

Figure 3-1. Risk Matrix

4. Development Schedule and Schedule Constraints

High-Level Mission Schedule

See Titan Saturn System Mission Study 2008: Final Report [1], Section 4.11.6, and TSSM In Situ Elements [2], Section 12.6.

Orbiter / Mission Schedule

Table 4-1. Key Phase Duration—Orbiter

Project Phase	Duration (Months)
Phase A – Conceptual Design	18
Phase B – Preliminary Design	18
Phase C – Detailed Design	24
Phase D – Integration & Test	28
Phase E – Primary Mission Operations	153
Phase F – Extended Mission Operations	6
Start of Phase B to PDR	16
Start of Phase B to CDR	28
Start of Phase B to delivery of instrument #1	45
Start of Phase B to delivery of instrument #2	45
Start of Phase B to delivery of instrument #n	45
Start of Phase B to delivery of flight element #1—orbiter	53
Start of Phase B to delivery of flight element #2—SEP stage	54
Start of Phase B to delivery of flight element #3—montgolfiére	46
Start of Phase B to delivery of flight element #4—lake lander	46
System-level integration & test	26
Project total funded schedule reserve	8.5
Total development time Phase B–D	70

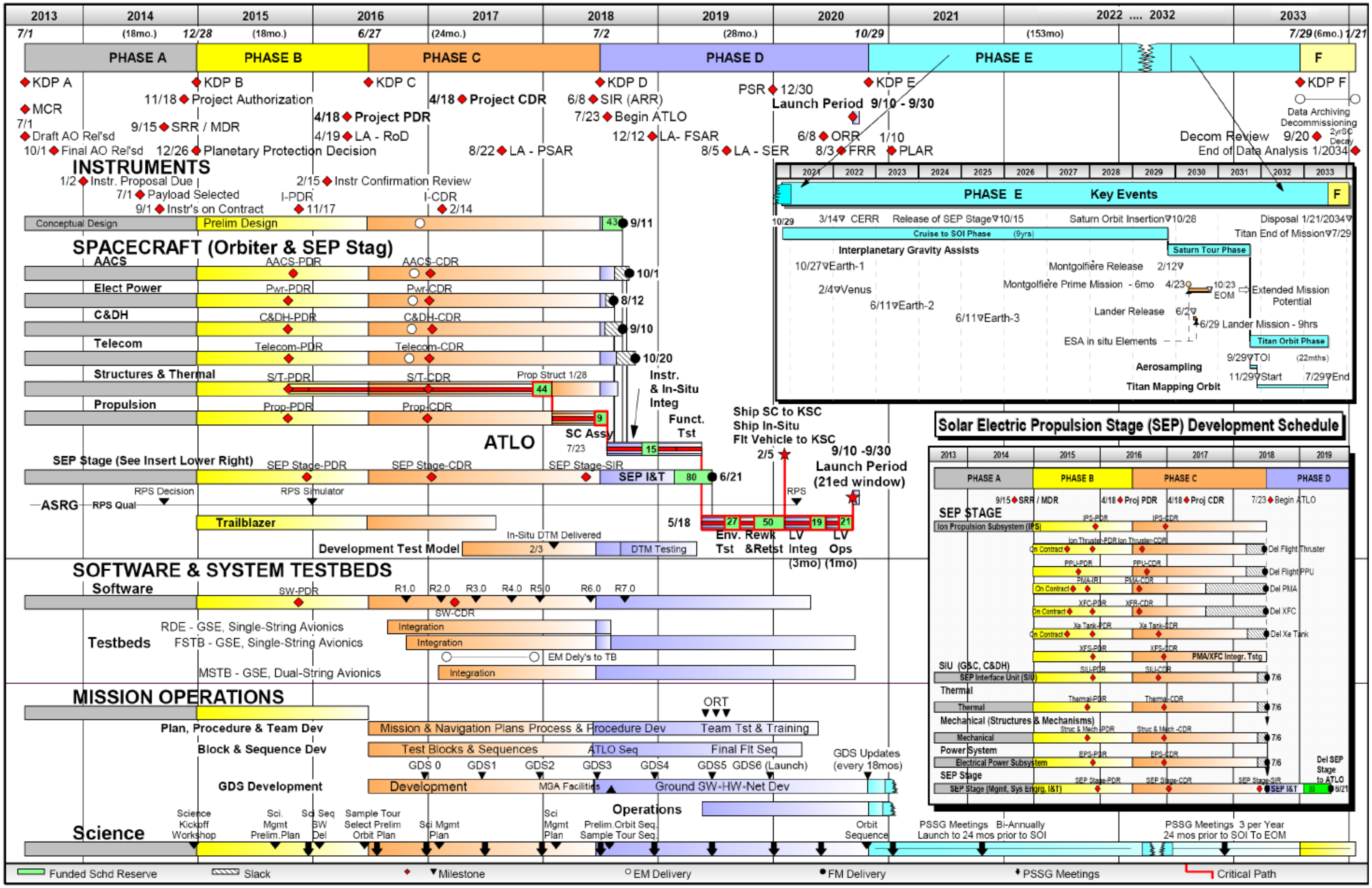

Figure 4-1. Schedule—Orbiter

Montgolfière / Lake Lander Schedule

Table 4-2. Key Phase Duration—Montgolfière and Lake Lander

Project Phase	Duration (Months)
Conceptual Design	45
Preliminary Design	21
Phase C – Detailed Design	30
Phase D – Integration & Test	36
Start of Preliminary Design to PDR	21
Start of Preliminary Design to CDR	51
Start of Preliminary Design to Delivery of Instruments	78
Total development time Preliminary Design—Delivery to Project	81

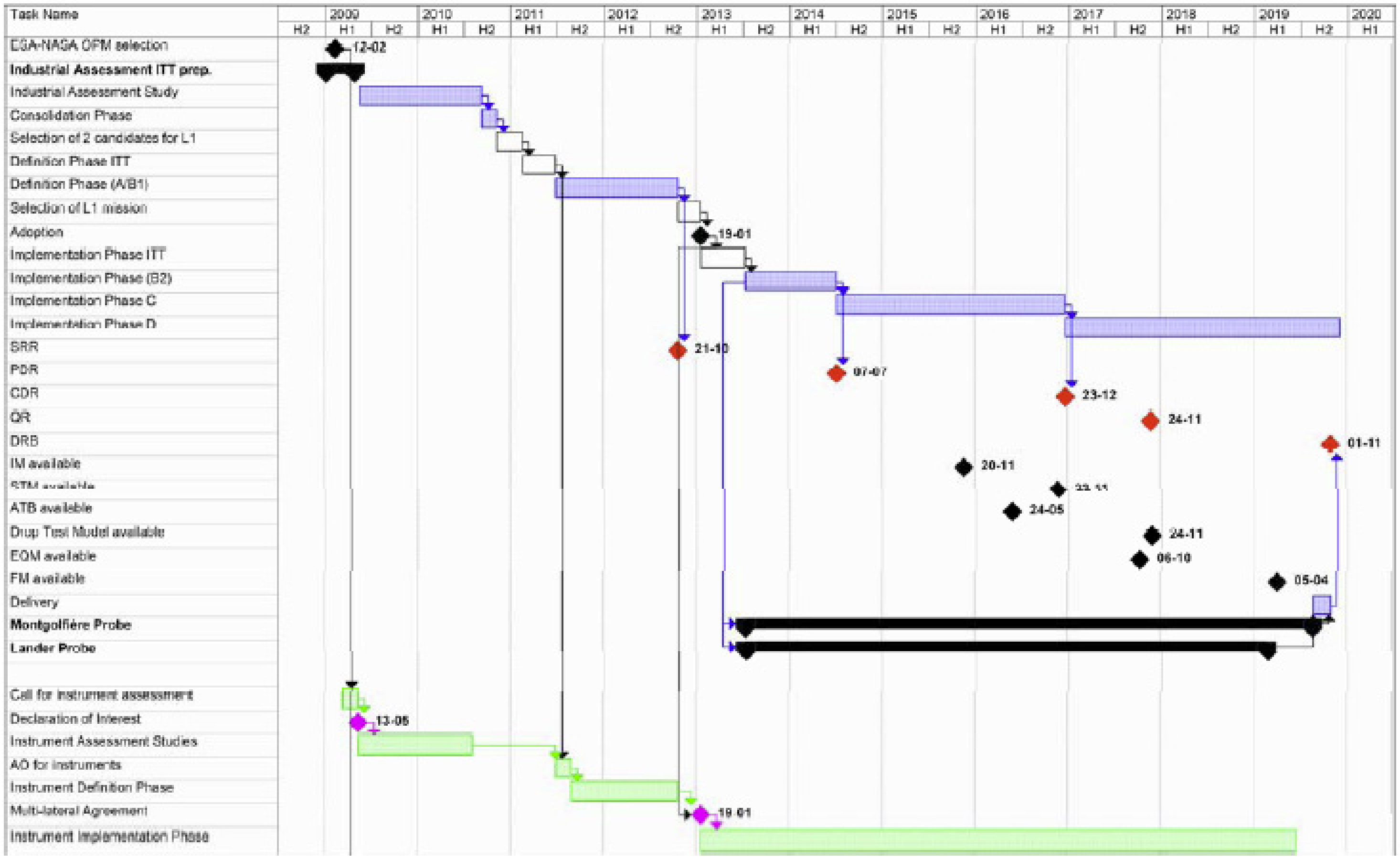

Figure 4-2. Schedule—Montgolfière / Lake Lander

Technology Development Plan

See Titan Saturn System Mission Study 2008: Final Report [1], Section 4.9.

Development Schedule and Constraints

See Titan Saturn System Mission Study 2008: Final Report [1], Section 4.3.11, 4.4.2, and 4.4.6.

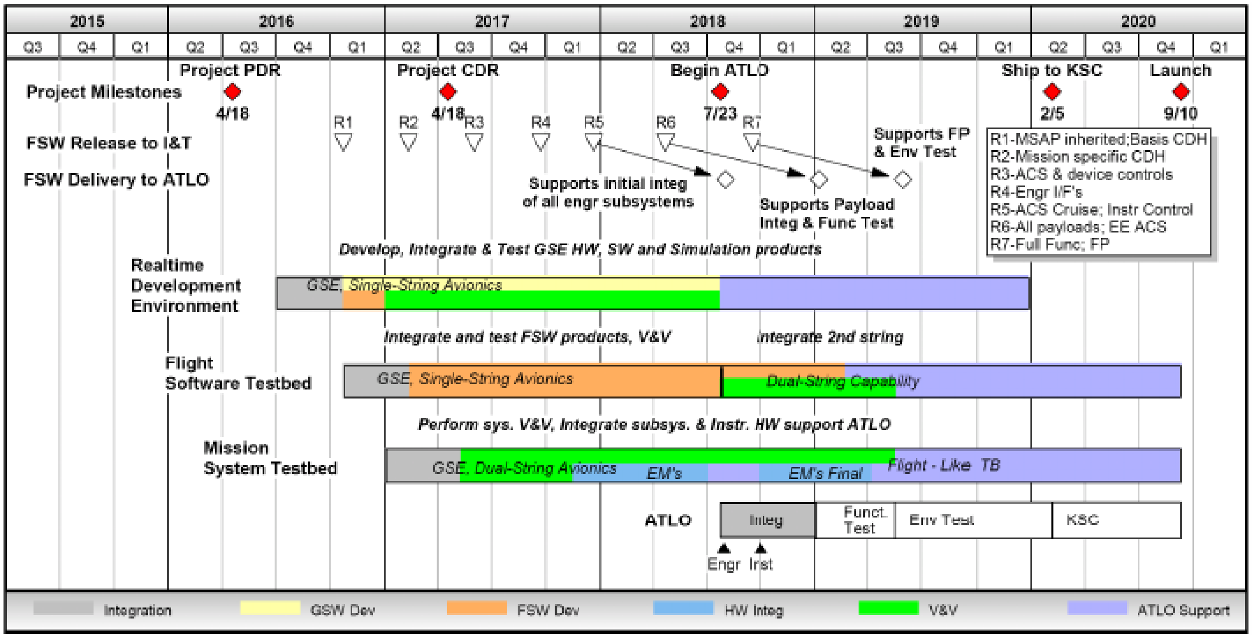

Figure 4-3. Schedule—Orbiter Testbed / ATLO

5. Mission Life-Cycle Cost

See Titan Saturn System Mission Study 2008: Final Report [1], Section 4.11.7 and Appendix D.

Costing Methodology and Basis of Estimate

The NASA portion of the TSSM cost estimate presented here is the total mission cost for the complete project life cycle from Phase A through Phase F as presented in Table 5-1. Notice that the real year (RY) cost profile is provided for an assumed 2020 launch. The total costs per year and by phase are also presented in 2015 then-year dollars. Note that the total costs per year at the bottom of the table shows costs based on the reserve posture determined in the 2008 study as well as the reserve requirements specified in the NASA ground rules (50% cost reserves for Phases A–D and 25% cost reserves for Phase E).

Cost Estimates

Orbiter Cost Estimates

See Titan Saturn System Mission Study 2008: Final Report [1], Appendix D.

The cost to NASA for the orbiter flight system, SEP stage, accommodation of in-situ elements, launch, and operations is shown in Table 5-1.

Table 5-1. Total Mission Cost Funding Profile—Orbiter

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

	Phase A				Phase B			Phase C/D						
	FY 2013	FY 2014	FY 2015	Total	FY 2015	FY 2016	Total	FY 2016	FY 2017	FY 2018	FY 2019	FY 2020	FY 2021	Total
01 Project Management	1,026	6,510	1,698	**9,235**	14,970	15,806	**30,777**	5,291	21,299	17,601	15,058	14,800	1,084	**75,133**
02 Project System Engineering	333	2,744	822	**3,899**	3,923	5,032	**8,955**	1,786	7,750	8,470	8,615	8,606	600	**35,827**
03 Safety & Mission Assurance	701	2,331	738	**3,770**	7,277	10,837	**18,114**	5,307	21,134	19,737	10,370	7,756	479	**64,784**
04 Science & Technology	250	1,034	253	**1,537**	4,117	4,181	**8,297**	3,742	15,532	14,192	8,337	8,621	726	**51,151**
04.01 Sci Mgmt	81	334	82	**497**	1,024	1,042	**2,066**	391	1,622	1,702	1,737	1,797	152	**7,402**
04.02 Sci Implement	156	646	158	**960**	2,381	2,416	**4,797**	3,111	12,916	11,280	4,865	5,033	423	**37,627**
04.03 Sci Support	0	1	0	**1**	4	4	**8**	2	10	10	8	8	1	**39**
05 Payload System	306	1,365	350	**2,021**	11,893	13,210	**25,103**	24,582	101,223	85,189	28,306	28,284	2,356	**269,941**
05.01 PL Sys Mgmt	220	1,010	263	**1,492**	853	866	**1,719**	320	1,329	1,400	1,426	1,476	124	**6,075**
05.02 PL System Eng	86	356	86	**528**	838	1,841	**2,679**	651	2,703	2,850	2,491	1,735	84	**10,512**
05.04 HiRIS	-	-	-	**-**	2,156	2,215	**4,371**	4,983	20,489	17,051	5,155	5,300	454	**53,432**
05.05 MAPP Combined Cost	-	-	-	**-**	1,416	1,454	**2,869**	3,271	13,450	11,193	3,384	3,479	298	**35,075**
05.06 TIRS	-	-	-	**-**	1,747	1,794	**3,541**	4,037	16,598	13,813	4,176	4,293	368	**43,286**
05.07 PMS	-	-	-	**-**	1,222	1,255	**2,478**	2,825	11,615	9,666	2,923	3,004	257	**30,291**
05.08 TiPRA	-	-	-	**-**	2,192	2,251	**4,443**	5,065	20,829	17,334	5,241	5,388	462	**54,318**
05.09 RSA	-	-	-	**-**	-	-	**-**	-	-	-	-	-	-	**-**
05.10 SMS	-	-	-	**-**	1,468	1,508	**2,976**	3,393	13,950	11,609	3,510	3,608	309	**36,380**
05.30 Sci Inst Purge	-	-	-	**-**	-	27	**27**	39	259	274	-	-	-	**572**
06 Spacecraft System	11,140	28,501	9,683	**49,324**	103,294	130,735	**234,029**	54,614	210,076	154,866	59,748	40,237	1,742	**521,282**
06.01 SC Mgmt	183	1,275	366	**1,824**	1,193	1,211	**2,404**	402	1,670	1,762	1,794	1,859	136	**7,622**
06.02 SC Sys Eng	403	3,149	1,143	**4,696**	6,321	7,718	**14,039**	2,561	9,527	8,740	6,538	4,282	223	**31,872**
06a Orbiter	10,275	22,821	7,790	**40,885**	76,334	104,372	**180,706**	32,344	156,159	117,446	37,649	30,526	1,196	**375,321**
06a.4 Power SS	246	1,614	686	**2,546**	5,446	15,967	**21,413**	1,976	21,785	7,006	1,352	2,133	118	**34,370**
06a.5 C&DH SS	41	2,404	1,487	**3,932**	10,211	17,199	**27,410**	4,569	14,885	5,896	477	420	-	**26,247**
06a.6 Telecom SS	7,785	6,115	728	**14,628**	24,511	11,861	**36,372**	3,433	18,712	7,035	2,138	2,019	312	**33,649**
06a.7 Mechanical SS	176	1,330	1,183	**2,689**	11,273	18,213	**29,486**	6,946	44,260	43,930	6,047	5,685	-	**106,869**
06a.8 Thermal SS	375	1,658	802	**2,835**	5,328	4,640	**9,968**	950	4,633	7,775	4,546	2,562	99	**20,566**
06a.9 Propulsion SS	891	5,857	1,285	**8,032**	9,888	14,937	**24,824**	4,832	6,069	8,035	1,824	3,140	194	**24,096**
06a.10 GN&C SS	740	3,545	1,226	**5,511**	6,475	14,355	**20,829**	6,039	22,523	9,066	3,369	3,184	-	**44,181**
06a.11 Harness	-	27	85	**112**	882	1,120	**2,001**	372	3,006	4,928	1,913	1,777	-	**11,995**
06a.12 Flight Software	-	165	266	**431**	2,008	4,259	**6,266**	2,126	14,138	16,307	11,771	7,058	474	**51,874**
06a.13 Materials & Proc	21	106	41	**168**	239	793	**1,032**	273	1,134	1,109	483	126	-	**3,125**
06a.14 Flight System Testbeds	-	-	-	**-**	74	1,030	**1,104**	828	4,249	4,765	2,802	2,421	-	**15,064**
06a.18 Trailblazer	-	-	-	**-**	-	-	**-**	-	766	1,594	927	-	-	**3,287**
06b SEP Stage	279	1,255	384	**1,919**	19,446	17,434	**36,880**	19,307	42,720	26,918	13,766	3,570	187	**106,467**
06b.3 IPS Subsystem	44	181	44	**268**	11,260	7,047	**18,307**	11,346	19,632	5,943	1,419	497	71	**38,909**
06b.4 Power System	17	171	101	**289**	6,339	7,206	**13,544**	2,294	9,409	7,036	707	677	36	**20,160**
06b.5 Mechanical	-	-	-	**-**	131	1,199	**1,330**	863	9,006	6,036	4,926	-	-	**20,831**
06b.6 Thermal	111	460	129	**699**	933	1,068	**2,001**	390	1,715	3,063	2,687	1,548	18	**9,421**
06b.7 GN&C	107	444	110	**662**	480	574	**1,054**	264	1,356	665	330	326	18	**2,959**
06b.8 C&DH	-	-	-	**-**	-	-	**-**	3,865	-	531	-	-	-	**4,396**
06b.9 I&T	-	-	-	**-**	303	340	**643**	283	1,602	3,643	3,698	522	44	**9,792**
07 Mission Operations System	140	1,298	471	**1,910**	1,865	4,508	**6,373**	1,801	8,404	9,961	12,612	22,262	2,333	**57,374**
08 Launch Services (see below)														
09 Ground Data System	331	1,530	424	**2,286**	1,473	4,122	**5,595**	1,605	8,839	10,342	11,656	13,573	729	**46,744**
10 Project System Integration & Test	-	145	191	**336**	1,572	4,676	**6,248**	2,295	8,217	10,109	20,114	19,873	108	**60,717**
11 Education & Public Outreach	74	245	78	**396**	764	972	**1,736**	507	2,013	1,648	871	814	50	**5,903**
12 Mission Design	556	3,781	1,032	**5,370**	3,470	2,991	**6,460**	906	3,755	3,931	3,881	3,946	251	**16,670**
Subtotal before Reserves	**14,858**	**49,485**	**15,741**	**80,083**	**154,617**	**197,069**	**351,686**	**102,438**	**408,242**	**336,046**	**179,569**	**168,773**	**10,458**	**1,205,525**
Reserves as determined in 2008 study	1,478	4,924	1,566	**7,969**	53,849	80,279	**134,128**	39,192	156,637	146,763	77,822	58,785	3,643	**482,843**
Total NASA Phase A-F Cost (No LV)	**16,336**	**54,408**	**17,307**	**88,052**	**208,466**	**277,348**	**485,814**	**141,629**	**564,879**	**482,810**	**257,391**	**227,558**	**14,100**	**1,688,368**
06a.17 Orbiter RPS	-	-	-	**-**	-	21,882	**21,882**	7,294	29,993	61,665	31,696	-	-	**130,648**
06c Lander RPS	-	-	-	**-**	-	1,568	**1,568**	-	-	-	-	-	-	**-**
06d Balloon RPS	-	-	-	**-**	-	9,821	**9,821**	2,751	11,313	23,260	11,956	-	-	**49,280**
DSN Aperture	-	-	-	**-**	-	-	**-**	-	-	-	-	-	3,522	**3,522**
Launch Vehicle	-	-	-	**-**	-	-	**-**	-	32,412	133,279	102,758	-	-	**268,448**
Total NASA Phase A-F Cost (With LV)	**16,336**	**54,408**	**17,307**	**88,052**	**208,466**	**310,619**	**519,085**	**151,674**	**638,598**	**701,014**	**403,800**	**227,558**	**17,622**	**2,140,266**
Titan estimate updated with new reserve requirement (50% Phase A-D, 25% Phase E-F)														
Subtotal before Reserves	**14,858**	**49,485**	**15,741**	**80,083**	**154,617**	**197,069**	**351,686**	**102,438**	**408,242**	**336,046**	**179,569**	**168,773**	**10,458**	**1,205,525**
Reserves of 50% A-D and 25% E as required by NASA SS2012 PS Decadal	7,429	24,742	7,870	**40,041**	77,309	98,534	**175,843**	51,219	204,121	168,023	89,784	84,386	5,229	**602,762**
Total NASA Phase A-F Cost (No LV)	**22,286**	**74,227**	**23,611**	**120,124**	**231,926**	**295,603**	**527,529**	**153,657**	**612,363**	**504,070**	**269,353**	**253,159**	**15,686**	**1,808,287**
06a.17 Orbiter RPS	-	-	-	**-**	-	21,882	**21,882**	7,294	29,993	61,665	31,696	-	-	**130,648**
06c Lander RPS	-	-	-	**-**	-	1,568	**1,568**	-	-	-	-	-	-	**-**
06d Balloon RPS	-	-	-	**-**	-	9,821	**9,821**	2,751	11,313	23,260	11,956	-	-	**49,280**
DSN Aperture	-	-	-	**-**	-	-	**-**	-	-	-	-	-	3,522	**3,522**
Launch Vehicle	-	-	-	**-**	-	-	**-**	-	32,412	133,279	102,758	-	-	**268,448**
Total NASA Phase A-F Cost (With LV)	**22,286**	**74,227**	**23,611**	**120,124**	**231,926**	**328,874**	**560,800**	**163,702**	**686,081**	**722,273**	**415,762**	**253,159**	**19,208**	**2,260,186**

	Phase E														Phase F			Total $RY	Total $FY15
	FY 2021	FY 2022	FY 2023	FY 2024	FY 2025	FY 2026	FY 2027	FY 2028	FY 2029	FY 2030	FY 2031	FY 2032	FY 2033	Total	FY 2033	FY 2034	Total	All Phases	All Phases
01 Project Management	6,956	4,700	4,493	4,515	4,655	4,667	4,700	4,900	5,416	5,688	5,959	6,091	4,922	**67,660**	234	357	**591**	**183,394**	**158,488**
02 Project System Engineering	628	707	732	775	785	812	832	862	963	985	1,019	1,056	922	**11,078**	25	57	**83**	**59,841**	**53,534**
03 Safety & Mission Assurance	815	797	760	647	706	632	591	633	956	1,093	1,837	1,901	1,556	**12,924**	275	642	**917**	**100,510**	**91,335**
04 Science & Technology	6,225	7,011	7,253	7,650	7,766	8,023	8,224	8,514	8,979	9,139	46,144	51,123	44,503	**220,552**	4,145	9,148	**13,293**	**294,831**	**214,404**
04.01 Sci Mgmt	1,709	1,926	1,993	2,098	2,134	2,205	2,263	2,343	2,467	2,515	5,277	5,697	4,930	**37,558**	473	1,014	**1,487**	**49,008**	**36,609**
04.02 Sci Implement	3,266	3,679	3,808	4,024	4,081	4,217	4,321	4,475	4,729	4,809	33,459	37,267	32,516	**144,652**	2,997	6,684	**9,681**	**197,718**	**143,239**
04.03 Sci Support	1,250	1,406	1,452	1,528	1,551	1,600	1,639	1,695	1,783	1,814	7,409	8,158	7,057	**38,342**	675	1,450	**2,126**	**40,517**	**27,554**
05 Payload System														**-**			**-**	**297,065**	**277,592**
05.01 PL Sys Mgmt														**-**			**-**	**9,287**	**8,772**
05.02 PL System Eng														**-**			**-**	**13,719**	**12,828**
05.04 HiRIS														**-**			**-**	**57,803**	**53,991**
05.05 MAPP Combined Cost														**-**			**-**	**37,944**	**35,442**
05.06 TIRS														**-**			**-**	**46,827**	**43,739**
05.07 PMS														**-**			**-**	**32,769**	**30,608**
05.08 TiPRA														**-**			**-**	**58,762**	**54,887**
05.09 RSA														**-**			**-**	**-**	**-**
05.10 SMS														**-**			**-**	**39,356**	**36,761**
05.30 Sci Inst Purge																		**599**	**562**
06 Spacecraft System														**-**			**-**	**804,634**	**767,029**
06.01 SC Mgmt														**-**			**-**	**11,851**	**11,197**
06.02 SC Sys Eng														**-**			**-**	**50,607**	**48,050**
06a Orbiter														**-**			**-**	**596,911**	**569,581**
06a.4 Power SS														**-**			**-**	**58,329**	**55,825**
06a.5 C&DH SS														**-**			**-**	**57,589**	**55,758**
06a.6 Telecom SS														**-**			**-**	**84,649**	**82,813**
06a.7 Mechanical SS														**-**			**-**	**139,043**	**131,436**
06a.8 Thermal SS														**-**			**-**	**33,369**	**31,656**
06a.9 Propulsion SS														**-**			**-**	**56,953**	**55,103**
06a.10 GN&C SS														**-**			**-**	**70,521**	**67,519**
06a.11 Harness														**-**			**-**	**14,109**	**13,121**
06a.12 Flight Software														**-**			**-**	**58,572**	**54,282**
06a.13 Materials & Proc														**-**			**-**	**4,324**	**4,092**
06a.14 Flight System Testbeds														**-**			**-**	**16,168**	**14,947**
06a.18 Trailblazer														**-**			**-**	**3,287**	**3,031**
06b SEP Stage														**-**			**-**	**145,265**	**138,200**
06b.3 IPS Subsystem														**-**			**-**	**57,484**	**55,317**
06b.4 Power System														**-**			**-**	**33,994**	**32,559**
06b.5 Mechanical														**-**			**-**	**22,161**	**20,678**
06b.6 Thermal														**-**			**-**	**12,121**	**11,310**
06b.7 GN&C														**-**			**-**	**4,674**	**4,472**
06b.8 C&DH														**-**			**-**	**4,396**	**4,254**
06b.9 I&T														**-**			**-**	**10,435**	**9,610**
07 Mission Operations System	24,775	25,477	23,730	18,013	21,327	17,283	15,512	17,254	32,664	39,508	42,709	42,037	32,256	**352,547**	3,703	2,164	**5,868**	**424,071**	**315,411**
08 Launch Services (see below)																			
09 Ground Data System	3,189	3,320	3,406	2,982	2,797	2,816	2,378	2,597	3,921	4,532	4,445	4,044	3,380	**43,808**	258	355	**613**	**99,046**	**82,360**
10 Project System Integration & Test	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**	-	-	**-**	**67,300**	**61,390**
11 Education & Public Outreach	832	813	775	660	720	645	603	646	975	1,115	1,874	1,939	1,587	**13,182**	157	232	**389**	**21,605**	**17,128**
12 Mission Design	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**	-	-	**-**	**28,500**	**27,112**
Subtotal before Reserves	**43,419**	**42,824**	**41,149**	**35,242**	**38,758**	**34,877**	**32,840**	**35,406**	**53,873**	**62,060**	**103,988**	**108,190**	**89,126**	**721,752**	**8,798**	**12,955**	**21,753**	**2,380,798**	**2,065,782**
Reserves as determined in 2008 study	6,388	6,302	6,056	5,187	5,706	5,135	4,836	5,214	7,935	9,142	15,317	15,938	13,131	**106,285**	1,296	1,908	**3,205**	**734,429**	**663,735**
Total NASA Phase A-F Cost (No LV)	**49,807**	**49,126**	**47,205**	**40,429**	**44,464**	**40,012**	**37,675**	**40,620**	**61,808**	**71,202**	**119,305**	**124,128**	**102,257**	**828,037**	**10,094**	**14,863**	**24,957**	**3,115,227**	**2,729,517**
06a.17 Orbiter RPS														**-**			**-**	**152,530**	**142,266**
06c Lander RPS														**-**			**-**	**1,568**	**1,526**
06d Balloon RPS														**-**			**-**	**59,101**	**55,188**
DSN Aperture	671	747	768	3,574	812	683	407	419	8,177	13,445	21,143	31,595	25,067	**107,508**	-	-	**-**	**111,030**	**73,407**
Launch Vehicle																		**268,448**	**246,141**
Total NASA Phase A-F Cost (With LV)	**50,478**	**49,873**	**47,973**	**44,003**	**45,275**	**40,695**	**38,083**	**41,039**	**69,985**	**84,647**	**140,448**	**155,722**	**127,324**	**935,545**	**10,094**	**14,863**	**24,957**	**3,707,905**	**3,248,046**
Titan estimate updated with new reserve requirement (50% Phase A-D, 25% Phase E-F)																			
Subtotal before Reserves	**43,419**	**42,824**	**41,149**	**35,242**	**38,758**	**34,877**	**32,840**	**35,406**	**53,873**	**62,060**	**103,988**	**108,190**	**89,126**	**721,752**	**8,798**	**12,955**	**21,753**	**2,380,798**	**2,065,782**
Reserves of 50% A-D and 25% E as required by NASA SS2012 PS Decadal	10,855	10,706	10,287	8,810	9,689	8,719	8,210	8,851	13,468	15,515	25,997	27,047	22,281	**180,438**	2,199	3,239	**5,438**	**1,004,523**	**871,609**
Total NASA Phase A-F Cost (No LV)	**54,273**	**53,531**	**51,437**	**44,052**	**48,447**	**43,596**	**41,049**	**44,257**	**67,341**	**77,575**	**129,985**	**135,237**	**111,407**	**902,190**	**10,997**	**16,193**	**27,191**	**3,385,321**	**2,937,392**
06a.17 Orbiter RPS														**-**			**-**	**152,530**	**142,266**
06c Lander RPS														**-**			**-**	**1,568**	**1,526**
06d Balloon RPS														**-**			**-**	**59,101**	**55,188**
DSN Aperture	671	747	768	3,574	812	683	407	419	8,177	13,445	21,143	31,595	25,067	**107,508**	-	-	**-**	**111,030**	**73,407**
Launch Vehicle																		**268,448**	**246,141**
Total NASA Phase A-F Cost (With LV)	**54,944**	**54,278**	**52,205**	**47,626**	**49,259**	**44,279**	**41,457**	**44,676**	**75,518**	**91,020**	**151,128**	**166,832**	**136,475**	**1,009,697**	**10,997**	**16,193**	**27,191**	**3,977,999**	**3,455,921**

Montgolfière and Lake Lander Cost Estimates

The European Space Agency (ESA) *Cosmic Vision 2015–25* call for mission ideas allocated 650 M€ for the cost to ESA for an L-class mission proposal. This was equivalent to approximately $1B US in 2008. Preliminary cost estimates, conducted by ESA and not validated by NASA, confirmed that this limit will not be exceeded provided the following assumptions are correct:

- The balloon technology development and balloon material for flight will be provided by CNES without additional ESA contribution.
- The NASA-provided orbiter would carry and release the ESA in-situ elements.
- The MMRTG and all RHUs would be provided by NASA at no cost to ESA.
- The instruments would be contributed by ESA member states

Additional margin was taken into account by ESA to provide for an expected cost increase, if more stringent planetary protection requirements arise should Titan be elevated to category IV.

Appendix A. Acronyms

AO	announcement of opportunity
ASI	Italian Space Agency
ASRG	advanced stirling radioisotope generators
ATLO	assembly, test, and launch operations
BIS	balloon imaging spectrometer
CBE	current best estimate
COPV	composite overwrapped pressure vessel
CML	concept maturity level
DSN	Deep Space Network
HGA	high gain antenna
HiRIS	high-resolution imager and spectrometer
I&T	integration and test
JSDT	Joint Science Definition Team
LV	launch vehicle
MAG	magnetometer
MAPP	magnetometer and plasma package
MEV	maximum expected value
MIMU	micro-inertial measurement unit
MIT	micro-impulse thrusters
MMRTGs	multimission radioisotope thermoelectric generator
MREU	MSAP remote engineering unit
MRO	Mars Reconnaisance Orbiter
MSAP	multimission system architecture platform
MSIA	MSAP system interface assembly
NRC	National Research Council
OPFM	Outer Planet Flagship Mission
PMS	polymer mass spectrometer
RPS	radioisotope power systems
RSA	radio science and accelerometer
RWA	reaction wheel assembly
RY	real year
SDST	small deep space transponder
SEP	solar electric propulsion
SIRU	space inertial reference unit
SMS	sub-millimeter sounder
SOI	Saturn Orbit Insertion
SPP	surface properties package
SSE	Solar System Exploration
TEEP	Titan electronic environment package
TiPRA	Titan penetrating radar and altimeter
TIRS	Thermal IR spectrometer
TLCA	Titan lander chemical analyzer
TMCA	Titan montgolfière chemical analyzer
TRS	Titan radar sounder
TSSM	Titan Saturn System Mission
USO	ultra-stable oscillator
UST	universal space transponder
VISTA	visual imaging system Titan for balloon
V&V	verification and validation

Appendix B. References

[1] National Aeronautics and Space Administration, and European Space Agency. 30 January 2009. *Titan Saturn System Mission Final Report on the NASA Contribution to a Joint Mission with ESA.* Task Order #NM0710851.

[2] National Aeronautics and Space Administration, and European Space Agency. 12 February 2009. *TSSM In Situ Elements: ESA Contribution to the Titan Saturn System Mission Assessment Study Report.* ESA-SRE(2008)4, Issue 1, Revision 2.

[3] ESTEC Concurrent Design Facility Team. Christian Erd, Study Manager. August 2009. *2008 CDF Study Report Tandem Study of a Two-Probe Mission to Titan*. CDF 78A.