Titan Saturn System Mission

Kim R. Reh
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-635-9730

Abstract—[1,2,3]

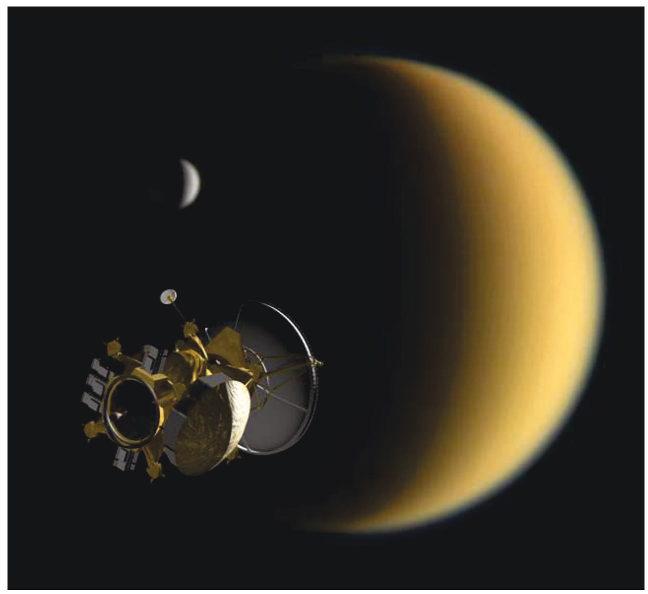
Titan is a high priority for exploration, as recommended by NASA's 2006 Solar System Exploration (SSE) Roadmap (NASA 2006), NASA's 2003 National Research Council (NRC) Decadal Survey (NRC Space Studies Board 2003) and ESA's Cosmic Vision Program Themes. Recent revolutionary Cassini-Huygens discoveries 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.

Following 50 years of space exploration, 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 planet mission.

Although the scope of science possible at Titan covers the entire range of planetary science disciplines, the TSSM team has developed a mission 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) can be done at acceptable risk within the specified budgetary constraints and can proceed now.

1.0 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 does 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.

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- Define a NASA-only mission and Floor mission that can 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.

2.0 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 of developing a focused, cost-effective TSSM (**Figure 2-1**). 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. 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.

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 concept preserves all flight elements except the SEP stage with the impact of taking as much as 1.5 years longer to reach Saturn.

3.0 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.

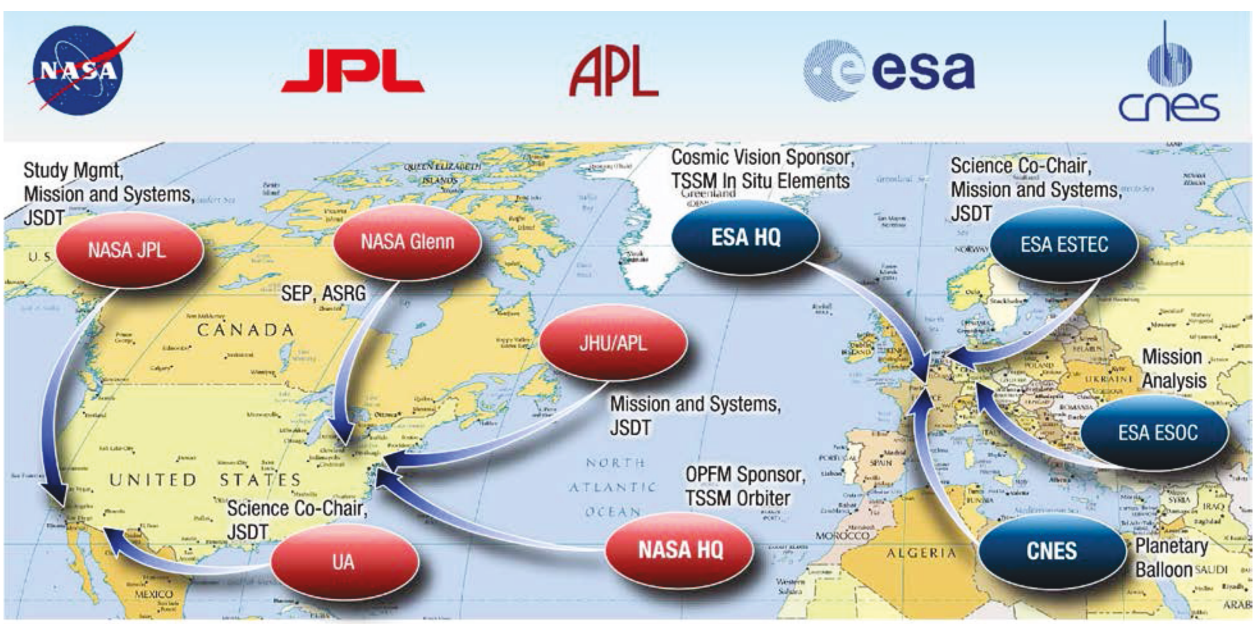

Figure 2-1. NASA/ESA geographically diverse team operates as a seamless integrated unit incorporating lessons learned from the Cassini-Huygens model.

Titan, a complex, Earth-like moon of Saturn 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 could 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 would be 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.

Figure 3-1. *The TSSM orbiter will have multiple opportunities to sample Enceladus' plumes.*

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 3-1**). 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 3-1** 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 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.

Table 3-1. *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?

3.1 Mission Architecture Assessment

A robust architecture has been developed that enables 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 3-2** indicate that the combination of orbiter, solar electric propulsion, lander, and montgolfière provides the highest science value per unit of currency invested.

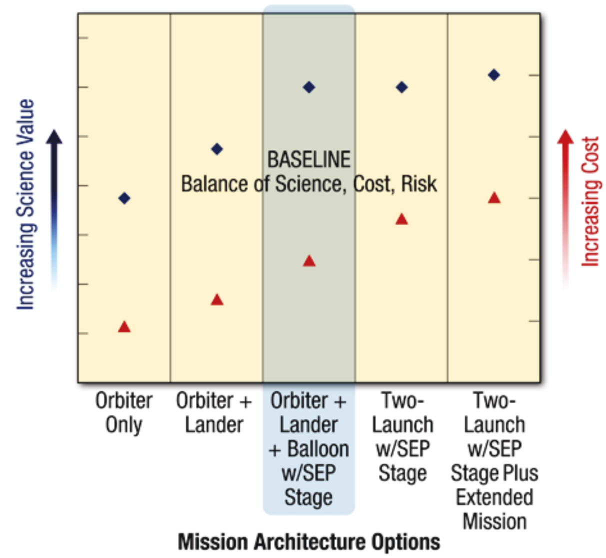

Figure 3-2. *TSSM's Baseline architecture maximizes science return to investment ratio within NASA and ESA resources, at risk comparable to Cassini-Huygens.*

This Baseline mission architecture provides descope options for both NASA and ESA to a scientifically attractive NASA/ESA Floor mission (as shown in **Figure 3-3**), 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

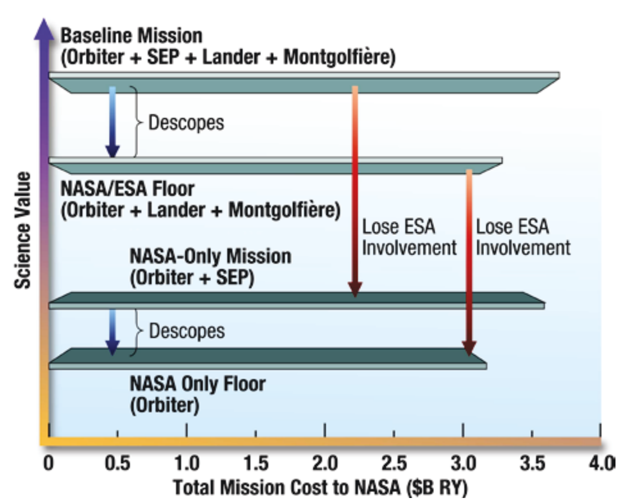

Figure 3-3. *NASA/ESA and NASA-only missions include robust descopes while remaining above the science floor.*

other potential descopes 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. Investigating NASA provided *in situ* elements was beyond the scope of this study and therefore the orbiter-only option was assessed. An orbiter-only mission with the instrument complement described here would provide 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.

3.2 Mission Implementation

TSSM implementation options would 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 and Exomars missions.

The flight elements shown in **Figure 3-4** 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 will 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

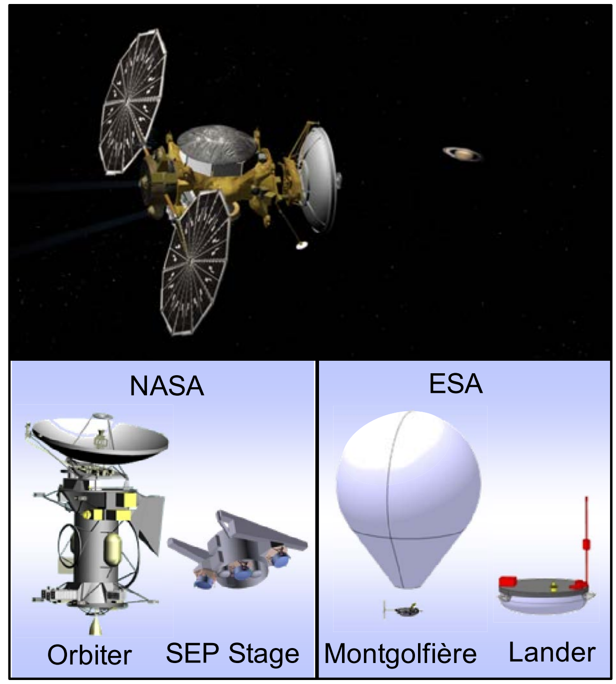

Figure 3-4. *Baseline mission concept includes coordinated orbital observation and in situ elements.*

raise burn to achieve a 1500-km circular, 85° polar-mapping orbit. This Circular Orbit Phase would last 20 months.

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 3-2** lists major characteristics of the Baseline mission. NASA will decide which Radioisotope Power System (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.

3.3 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 3-3**, 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

Table 3-2. *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

L-class mission of the Cosmic Vision 2015–2025 program (650M€ FY07 Cost-at-Completion). These ESA costs do not include the development and delivery of the balloon envelope, which will 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 excluding 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 **Figures 3-5a and b.** 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 would be 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 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, and ExoMars experience and lessons learned, the technical development, and cost risks are well understood.

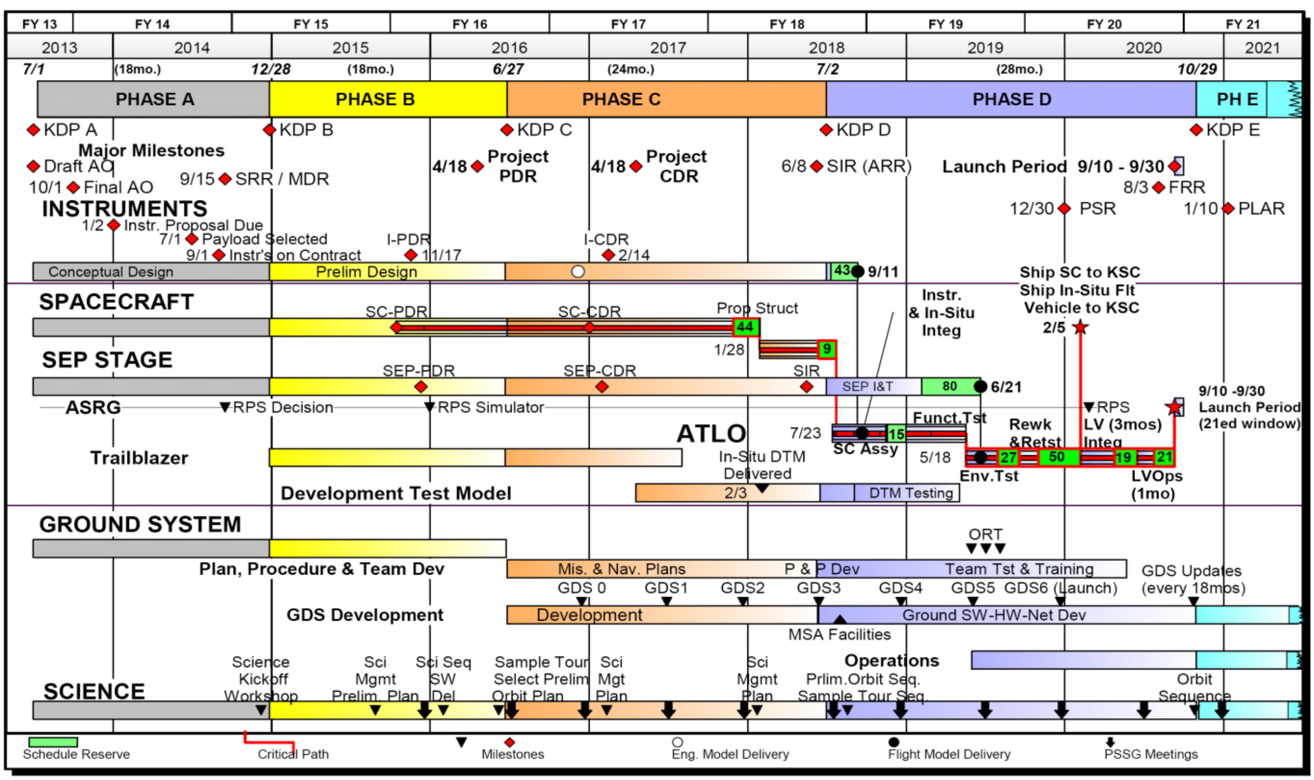

Figure 3.5a. Top-level mission Development timeline.

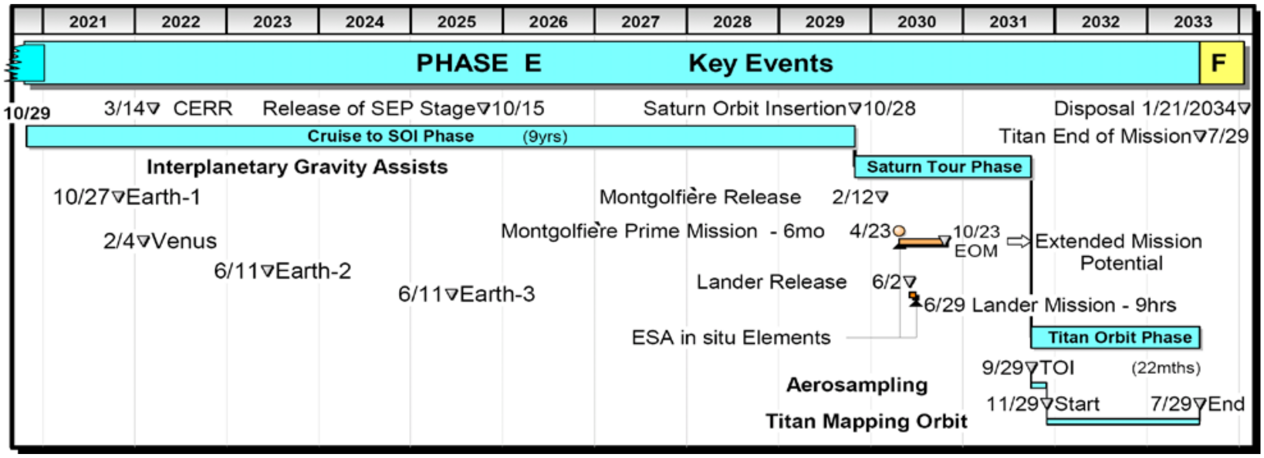

Figure 3-5b. *Top-level mission Operational timeline.*

3.4 Summary and Conclusions

Important science questions are now well established for Titan and Enceladus. The time is right to initiate a dedicated robust mission to answer them.

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. 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. With these recent discoveries, the high priority of Titan is reinforced.

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 scientific advance beyond Cassini-Huygens.
- Covers the full range of planetary science disciplines.
- 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 and 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 would provide a revolutionary kind of planetary exploration ideally suited to the environment of Titan.

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BIOGRAPHY

Kim R. Reh has a broad base of program, project and line organization experience that spans project Formulation through Implementation. His experience includes significant interaction with the science community, working with international partners and implementing projects according to NASA requirements for management of flight projects.

Kim is currently a Pre-Project Manager at JPL leading pre-Phase A concept studies and strategic technology investments for solar system exploration missions. He is the Study Lead for a collaborative NASA/ESA outer planet flagship mission that targets two icy moons of Saturn, Titan and Enceladus.

Kim received his BSE from the University of Michigan, MSE from California State Polytechnic University, Business Management Certificate from the University of California Riverside and Certificate of Executive Management at Caltech. Additionally, Kim has taken many continuing education courses in technical and management fields.