Earth Moon Planet (2009) 105:135–142
DOI 10.1007/s11038-009-9308-9

Earth-Based Support for the Titan Saturn System Mission

Athena Coustenis · Jonathan Lunine · Jean-Pierre Lebreton · Dennis Matson · Christian Erd · Kim Reh · Patricia Beauchamp · Ralph Lorenz · Hunter Waite · Christophe Sotin · Leonid Gurvits · Mathieu Hirtzig

Received: 22 January 2009 / Accepted: 9 April 2009 / Published online: 5 May 2009

Abstract The Titan Saturn System Mission (TSSM) concept is composed of a TSSM orbiter provided by NASA that wou\ld carry two Titan in situ elements provided by ESA: the montgolfière and the probe/lake lander. One overarching goal of TSSM is to explore in situ the atmosphere and surface of Titan. The mission has been prioritized as the second Outer Planets Flagship Mission, the first one being the Europa Jupiter System Mission (EJSM). TSSM would launch around 2023–2025 arriving at Saturn 9 years later followed by a 4-year science mission in the Saturn system. Following delivery of the in situ elements

Contribution to the workshop on "Future Ground Based Solar System Research: Synergies with Space Probes and Space Telescope", Portoferraio, Isola d'Elba, September 8–12, 2008.

A. Coustenis (✉) · M. Hirtzig
LESIA, Paris-Meudon Observatory, 5, place J. Janssen, 92195 Meudon, France
e-mail: Athena.coustenis@obspm.fr
URL: http://lesia/cosmicvision/tssm-public

J. Lunine
Department of Planetary Sciences, University of Arizona, Tucson, AZ 85721-0092, USA
e-mail: jlunine@lpl.arizona.edu

J.-P. Lebreton · C. Erd
ESA/ESTEC, SRE-SM, Keplerlaan 1, 2201 AZ, Noordwijk, The Netherlands

J.-P. Lebreton
e-mail: jean-pierre.lebreton@esa.int

D. Matson · K. Reh · P. Beauchamp · C. Sotin
Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

D. Matson
e-mail: dmatson@jpl.nasa.gov

K. Reh
e-mail: kim.r.reh@jpl.nasa.gov

P. Beauchamp
e-mail: patricia.m.beauchamp@jpl.nasa.gov

to Titan, the TSSM orbiter would explore the Saturn system via a 2-year tour that includes Enceladus and Titan flybys before entering into a dedicated orbit around Titan. The Titan montgolfière aerial vehicle under consideration will circumnavigate Titan at a latitude of $\sim 20°$ and at altitudes of ~ 10 km for a minimum of 6 months. The probe/lake lander will descend through Titan's atmosphere and land on the liquid surface of Kraken Mare ($\sim 75°$ north latitude). As for any planetary space science mission, and based on the Cassini–Huygens experience, Earth-based observations will be synergistic and enable scientific optimization of the return of such a mission. Some specific examples of how this can be achieved (through VLBI and Doppler tracking, continuous monitoring of atmospheric and surface features, and Direct-to-Earth transmission) are described in this paper.

Keywords Titan · Space mission · Probes · Balloons · Montgolfière · Lander

1 Introduction

A mission to return to Titan after Cassini–Huygens is a high priority for planetary exploration. In 2005, the Huygens Probe gave us a snapshot of a world tantalizingly like our own, yet frozen in its evolution on the threshold of life. 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 a rich world where organic compounds reside in surface repositories of methane, ethane and complex organic deposits, and where there are energy sources necessary to drive chemical evolution. In addition, Cassini–Huygens data suggests that a vast subsurface ocean of liquid water is also present in Titan. The Cassini discovery of active geysers on Enceladus adds yet a second target in the Saturn system for the considered mission, one that is synergistic with Titan in understanding planetary evolution and in adding a potential abode for life as we know it. With these recent discoveries, interest in Titan as the next scientific target in the outer Solar System is strongly reinforced (http://www.lpi.usra.edu/opag/).

In November 2007, a proposal for an L-class (large) mission called T and EM (for Titan and Enceladus Mission) was selected by ESA in the framework of the Cosmic Vision 2015–2025 Call (Coustenis et al. 2008). In parallel, NASA defined a mission called Titan Explorer in its 2007 Outer Planet Flagship studies (Leary et al. 2008). In 2008, NASA and ESA decided to merge the two missions into the Titan Saturn System Mission (TSSM), as part of the Outer Planet Mission Program (http://www.lesia.obspm.fr/cosmicvision/tssm/tssm-public/; http://sci.esa.int/science-e/www/area/index.cfm?fareaid=106; http://opfm.jpl.

C. Sotin
e-mail: csotin@jpl.nasa.gov

R. Lorenz
Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel, MD 20723-6099, USA
e-mail: Ralph.lorenz@jhuapl.edu

H. Waite
Southwest Research Institute, 6220 Culebra Rd, San Antonio, TX, USA
e-mail: hwaite@swri.edu

L. Gurvits
Joint Institute for VLBI in Europe, P. O. Box 2, 7990 AA, Dwingeloo, The Netherlands
e-mail: lgurvits@jive.nl

nasa.gov/titansaturnsystemmissiontssm/), which also includes the Europe Jupiter System Mission (EJSM).

In February 2009, the two space agencies prioritized the Outer Planet Missions with a first launch decided towards the Jupiter System, and a second one to follow 3–5 years later towards Saturn.

In responding to both the 2003 NASA Decadal Survey results (National Research Council Space Studies Board 2003) and the ESA Cosmic Vision Themes as defined in the 2007 calls and studies, TSSM would return brand new scientific insights — among other — on chemical composition and structure, meteorology, climatology, dynamics, geology, geophysics, hydrology, solar system physics. The in situ elements are clearly key to this mission that goes well beyond what was done by Cassini–Huygens. After a brief description of the mission hereafter, this article focuses on the additional support which could provided to such an exploration by Earth-based observations.

2 Scientific Objectives of the Titan Saturn System Mission (TSSM)

The TSSM concept is focused on remote sensing and in situ investigations of Titan primarily, but also of Enceladus's south polar region and Saturn's magnetosphere. The two satellites are linked by their locations and properties, whose remarkable nature have only been partly revealed by the ongoing Cassini–Huygens mission. These bodies hold mysteries that call for a comprehensive exploration using multiple complementary flight elements and instruments. TSSM will enable the study of Titan as a system, including its upper atmosphere, the interactions with Saturn's magnetosphere, the neutral atmosphere, surface, interior, origin and evolution, as well as its astrobiological potential. It is a mission to two of the most exciting and potentially rewarding bodies in the Solar System. TSSM is designed to build upon and exceed by far the scientific and technological accomplishments of the Cassini–Huygens mission, exploring Titan and Enceladus in ways that are not currently possible with Cassini–Huygens (including full close-up and in situ coverage over long periods of time for Titan, and multiple close flybys of Enceladus).

The TSSM goals can be summarized in three parts: (a) *understand Titan as a system, in the same way that one would ask this question about Venus, Mars, and the Earth.* How are the distinctions between Titan and other worlds in the solar systems understandable in the context of the complex interplay of geology, hydrology, meteorology, and aeronomy? Is Titan an analogue for some aspects of the Earth's history, past or future? Why is Titan endowed with an atmosphere whereas Ganymede—Jupiter's moon virtually identical in size and mass—is not? (b) *understand the chemical cycles that generate and destroy organics and assess the relevance of these processes to the origins of life.* Titan is rich in organic molecules—more so in its surface and atmosphere than any other place in the solar system, including Earth (excluding our vast carbonate sediments). These molecules were formed in the atmosphere, deposited on the surface and might, in coming into contact with liquid water, undergo an aqueous chemistry that could replicate aspects of life's origins.(c) *understand how Titan interacts with its Saturnian environment and what role Enceladus plays both in supplying material and in being by comparison a separate source of information for the interior composition of Titan.* Titan is a world embedded within the Saturnian magnetosphere (and sometimes the solar wind, as well). It receives energy from the magnetosphere, ions and neutrals that play a role in its chemistry (some of which may originate in Enceladus), and undergoes escape of major and minor constituents. TSSM will enable the investigation of those relationships.

3 Titan Saturn System Mission Architecture

The TSSM concept encompasses remote sensing and in situ investigations of Titan primarily, but also of Enceladus and Saturn's magnetosphere (TSSM Final Report 2008; ESA Assessment Study Report 2008; TSSM NASA/ESA Joint Summary report 2008). In the current mission architecture, TSSM consists of a 1600-kg orbiter (under NASA's responsibility) that would perform at least seven Enceladus and 16 Titan flybys en route to entering orbit around Titan. before orbiting Titan, and during the Saturn tour, the TSSM orbiter will deliver the in situ elements (a 588-kg montgolfière, or hot air balloon, and a 180-kg short-lived probe/lake lander), which are being studied by ESA. The balloon will circumnavigate Titan at $\sim$20°N latitude at an altitude of about 10 km and possibly lower for at least 6 months (Fig. 1). The short-lived (8–10 h) probe will descend through Titan's northern atmosphere and land on a liquid surface.

Following the recent NASA-ESA prioritization, the mission could be launched on an Atlas 551 in the 2023–2025 timeframe, travelling to Saturn using a Solar Electric Propulsion (SEP) gravity assist trajectory, and reaching Saturn approximately 9 years later. The SEP stage would be released approximately 6 years after launch well in advance of approaching Saturn (TSSM Final Report 2008). The main engine would then place the flight system into orbit around Saturn for a tour phase lasting approximately 2 years. During the first Titan flyby ($\sim$100 days after arrival at Saturn), the orbiter would release the lander to target one of the two large northern polar seas, Kraken Mare, at $\sim$75°N, and the montgolfière would be released on the second Titan flyby, targeting the near equatorial region.

During the tour phase, TSSM would accomplish Saturn system and Enceladus science (7 close-up Enceladus flybys with instrumentation for plume sampling and subsurface measurements well beyond Cassini's capability) while executing Titan pump down manoeuvres to minimize the amount of propellant needed for Titan orbit insertion (TSSM Final Report 2008). Following its Saturn system tour, the spacecraft would enter into a 950 km by 15,000 km elliptical orbit around Titan. The next phase would utilize

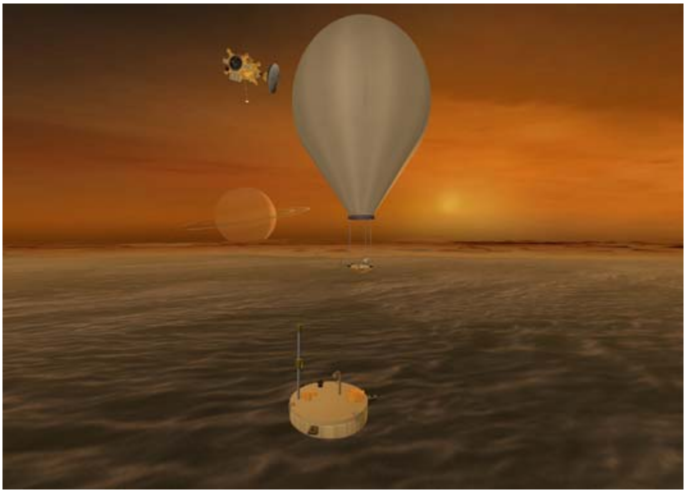

Fig. 1 Artist's view of the TSSM orbiter, montgolfière and lander. Credit: C. Waste/NASA/JPL

concurrent aerosampling and aerobraking in Titan's upper atmosphere (to depths as low as 600 km altitude), gradually circularizing the orbit. Using a small periapsis raise manoeuvre, the spacecraft would finally achieve at a 1,500 km circular, 85° inclined, polar-mapping orbit.

Instruments aboard the orbiter would map Titan's surface at better than 50 m resolution in the 5–6 micron window, provide a global data set of topography and sound the immediate subsurface to identify layers and porous (possibly liquid-filled) reservoirs, sample high molecular weight organics, provide detailed observations of the atmosphere at all levels, and quantify the interaction of Titan with the Saturn magnetospheric environment (TSSM Final Report 2008).

Instruments aboard the montgolfière would provide high-resolution vistas and make compositional measurements of the surface, detailed sounding of the subsurface, crustal layering, and chemical measurements of aerosols (ESA Assessment Study Report 2008). A magnetometer, unimpeded by Titan's ionosphere, would permit sensitive detection of induced or intrinsic fields.

The probe/lake lander would splash into a large northern sea and spend several hours floating (Fig. 1) during which it would carry out direct chemical and physical sampling, and analysis of the liquid for a host of dissolved organic species (ESA Assessment Study Report 2008). During its descent the probe would provide the in situ profile of the winter, northern-hemispheric atmosphere, quite different from the equatorial atmosphere where Huygens descended and where the montgolfière will fly. Radio scientific experiments aboard the orbiter and in situ elements would be capable of providing information on Titan's tidal response, and hence its crustal rigidity and thickness, as well as information about wind speeds.

4 Earth-Based Observations in Support of TSSM

Ground-based measurements play an important role in supporting space missions. Indeed, even a powerful mission like Cassini–Huygens benefits from complementary information from Earth-based or orbiting (Earth-bound) astronomical facilities. A post-Cassini–Huygens mission like TSSM will benefit from similar support. For example, even though the Huygens probe explored the surface at a single location, Earth-based measurements acquired simultaneously allowed for the Cassini–Huygens data to be extrapolated to the whole surface. This will also be the case for TSSM, especially since it will add information on a new region in the North and provide extended coverage at latitudes around the equator with the montgolfière. Furthermore, ground-based and Earth orbiting instruments can provide measurements and complementary observations for regions that are in night-time can be observed a few days later; data during times when the Earth orbiter is observing other objects to look for time-variable phenomena (cloud formation and decay); and measurements at wavelengths beyond the capabilities of the orbiter payload. Furthermore, Earth-based stellar occultations, and especially those yielding a central flash, may be valuable as they provide unique insight regarding the zonal wind regime around 250 km altitude. Monitoring such events might thus tell us how winds seasonally evolve with time.

The TSSM Earth-based observing campaign will follow the example of Cassini–Huygens mission. The data obtained by these observations will offer extremely valuable synergy with in situ TSSM measurements. A few examples are given hereafter:

4.1 VLBI and Doppler tracking

The Earth's global network of radio telescopes and processing facilities will conduct Planetary Radio Interferometry and Doppler Experiment (PRIDE) aiming to provide ultra-precise estimates of the state-vectors of the in situ elements. The approach will be based on the heritage of the Huygens Doppler Wind Experiment (DWE) and Very Large Baseline Interferometer (VLBI) tracking experiments. Today's technology and very conservative projection of capabilities of VLBI radio telescopes for the next two decades lead to the following guaranteed accuracy of positional measurements: 500 m based on S-band (2 GHz signal), 100 m at X-band (8 GHz) and 30 m at Ka-band (32 GHz). PRIDE poses minimal requirements for the on-board instrumentation. It can include the TSSM orbiter in the list of targets and enhance other types of radio science experiments in the Saturnian environment.

The position history of the montgolfière in particular will be of great scientific value, providing an indication of Titan's lower tropospheric winds, which are difficult to measure remotely. Additionally, analysis of the radio signals received at Earth when the latter is low on the balloon's horizon will be diagnostic of the refractivity profile of the atmosphere (like a radio occultation) and/or may probe the dielectric properties of the surface (bistatic radar).

4.2 Direct-to-Earth (DtE) Data Transmission

TSSM's nominal operational scenario assumes transmission of the scientific and house-keeping data from the Titan in situ elements via relay by the orbiter. Indeed, the amount of data produced by the Titan montgolfière (e.g. images) will require a high-capacity radio relay system. However, as an efficient backup able to provide support to critical mission operations and experiments, a low data-rate link can be achieved with the nominal transmission from the in situ elements and received by the large Earth-based radio telescopes. The most attractive option of DtE would involve the Square Kilometre Array (SKA, (http://www.skatelescope.org)) as the Earth-based facility able to operate at the S-band (2.3 GHz). This facility is expected to be fully operational in 2020. As shown by preliminary estimates, SKA will be able to receive data streams from the TSSM in situ elements at the rate of 30–100 bps.

4.3 Astronomical Observations

While the specific scientific programme of astronomical observations in support to TSSM is to reflect and enrich the mission programme and will be shaped up at a later stage of the project development, one should anticipate the following possibilities:

- Long-term seasonal monitoring of the Saturnian system objects;
- Characterisation of Titan's atmosphere using continuum (visual, IR) and spectral line (UV, visual, IR, mm and sub-mm wavelengths);
- Visual and IR characterisation of the surface of Enceladus;
- Multi-band monitoring of non-thermal radiation of the ionospheres and magneto-spheres of Saturn and other sources in the Saturnian system.

The astronomical observations will be conducted in many cases using national and international facilities, accessible via open proposal peer-review mechanism. TSSM will facilitate the coordination of the Earth-based astronomical observing campaign with the spacecraft investigations. In addition, future Earth-based studies could benefit from new facilities in operation during the preparatory and in-flight phases of TSSM. Indeed, observations from future large observatories like the next generation optical telescopes (e.g. ELT), the Atacama Large Millimeter/submillimeter Array (ALMA) and the Square Kilometre Array (SKA), as well as spacecraft like Herschel and SOFIA, will be able to add to our knowledge of—for instance–Titan's chemical composition, by extending the available Titan data in imaging and spectroscopy. Other such large, future, facilities that could potentially contribute to Titan science include the Expanded Very Large Array (EVLA), the Giant Segmented Mirror Telescope (GSMT), and the James Webb Space Telescope (JWST). Continuous monitoring from Earth will certainly help cover (between space-based missions) a full Titan year and return information on the satellite's complex seasonal phenomena.

5 Conclusions

Orbiting Titan, landing and floating on one of its seas, and ballooning in its atmosphere, all are parts of the vision for a new and exciting approach to planetary exploration. The TSSM architecture inherently provides the optimal balance between scientific return, risk, and cost. It has three guiding principles:

- *Achieve a scientific return well beyond the high bar set by Cassini–Huygens.* The TSSM orbiter, lander and balloon have been configured with complementary payloads and operational concepts exceeding by far the capabilities of Cassini–Huygens.
- *Build upon the successful design, operational experience, and lessons learned from Cassini–Huygens.* ESA has successful experience in designing and landing a probe on Titan (Huygens), as does NASA in implementing an orbiter at Saturn (Cassini).
- *Continue the proven international partnerships.* TSSM represents a rich and robust collaboration between NASA and ESA that is structured to provide the best possible mission at a reasonable cost. This partnership leverages resources to maximize scientific return, mitigate risk, and ensure technical readiness.

In conclusion, a new exploration of the Saturnian system and of Titan in particular, as proposed in TSSM, will revolutionize our understanding of Titan as a system. It will achieve science well beyond what Cassini–Huygens has done, including the full potential of the Cassini extended mission. Earth-based observations will be important in augmenting the TSSM in situ studies thereby maximizing the mission's potential scientific return.

References

http://www.lpi.usra.edu/opag/

A. Coustenis et al., Exp. Astron. **23**, 893–946 (2008). doi:10.1007/s10686-008-9103-z

J. Leary, R. Strain, R. Lorenz, J. H. Waite, Titan explorer flagship mission study, Public Report (2008) http://www.lpi.usra.edu/opag/Titan_Explorer_Public_Report.pdf

http://www.lesia.obspm.fr/cosmicvision/tssm/tssm-public/; http://sci.esa.int/science-e/www/area/index.cfm?fareaid=106; http://opfm.jpl.nasa.gov/titansaturnsystemmissiontssm/

National Research Council Space Studies Board, New frontiers in the solar system: an integrated exploration strategy (the first Decadal Survey Report). (National Academic Press, Washington, DC, (2003)

K. Reh, Ch. Erd, D. Matson, A. Coustenis, J. Lunine, J.-P. Lebreton, TSSM NASA/ESA Joint Summary Report, ESA-SRE(2008)3, JPL D-48442, NASA Task Order NMO710851, 15 November 2008
K. Reh, J. Lunine, D. Matson, T. Magner, J.-P. Lebreton, A. Coustenis, TSSM Final Report on the NASA Contribution to a Joint Mission with ESA, 3 November 2008, JPL D-48148, NASA Task Order NMO710851
Square Kilometre Array, http://www.skatelescope.org
TSSM in situ elements, ESA Assessment Study Report, ESA-SRE(2008)4