TITAN SATURN SYSTEM MISSION INSTRUMENTATION

A. Coustenis[1], J. Lunine[2], K. Reh[3], J.-P. Lebreton[4], C. Erd[5], P. Beauchamp[3], C. Sotin[3] and D. Matson[3], [1]LESIA, Observatoire de Paris-Meudon, 92195 Meudon, France, Athena.coustenis@obspm.fr , [2]Cornell Univ., [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, [4]LPC2E/CNRS, Orléans, France, [5]ESA/ESTEC, Noordwijk, The Netherlands.

Introduction: Titan is a high priority for exploration, as recommended by NASA's 2006 Solar System Exploration (SSE) Roadmap [1], NASA's 2003 National Research Council (NRC) Decadal Survey [2] and ESA's Cosmic Vision Program Themes. Recent revolutionary Cassini-Huygens discoveries have dramatically escalated interest in Titan. We present here the results of a study as documented in the TSSM Final Report [3] and Titan Saturn System Mission (TSSM) NASA/ESA Joint Summary Report [4] and we briefly describe some later Titan mission studies.

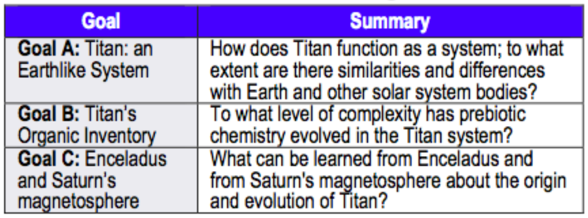
Figure 1. The release of the montgolfière from the TSSM orbiter

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. 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 and several concepts have been proposed in the past years : TSSM, but also JET (Journey to Titan and Enceladus), the Titan Aerial Explorer (TAE) and TiME, which we briefly describe in a later section.

Figure 2. The TSSM orbiter will have multiple opportunities to sample Enceladus' plumes.

The TSSM Science Goals as shown in Table 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 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?

Although the scope of science possible at Titan covers the entire range of planetary science disciplines, the TSSM team 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 in anear future.

Mission concept: The Baseline Mission concept developed by the study team included a NASA orbiter with Solar Electric Propulsion (SEP) stage and ESA-provided lander and montgolfière balloon. The floor for this collaborative 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.

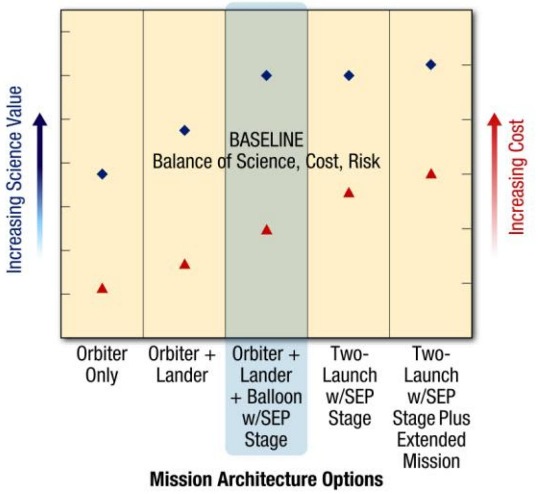


Figure 3. TSSM's Baseline architecture maximizes science return to investment.

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. Aerocapture concepts were not pursued as part of this study (because the study ground rules excluded it) 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 indicate that the combination of orbiter, solar electric propulsion, lander, and montgolfière provides the highest science value per unit of currency invested.

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 were planned for launch 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.

Table 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

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 concur- rent 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.

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 Joint Science Definition Team (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.

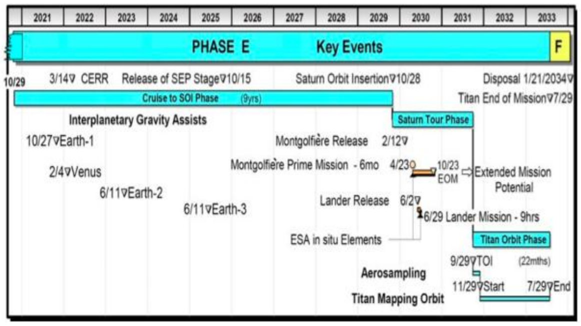


Figure 4. Top-level mission operational timeline.

TSSM benefited from proven experience, flight systems, 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 also compatible with Multimission RTGs. Table 2 lists major characteristics of the Baseline mission.

Payload: The orbiter, montgolfière and lake lander model instrumentation is described in Tables 3-4. Hereafter we focus on the model payload for the Montgolfiere. Several instruments could be placed aboard the gondola of the balloon in order to monitor atmospheric phenomena. Examples of measurements:

Chemical analysis to determine the methane and ethane mole fractions, measure the noble gas concentration, detect and characterize molecules and determine the concentration and bulk composition of aerosol particles. The need for high-resolution mass spectrometry could be satisfied through the development of the concept of mass analyser for space applications that is lightweight and provides ultrahigh resolving power capabilities (M/ΔM beyond 105 up to *m/z* 400): the Orbitrap.

Spectral-imaging with the Montgolfière

Near-infrared spectroscopy of the surface from the montgolfière provides high résolution views of the composition from reflectance spectroscopy across the organic (or organic-coated) dunes, outwash planes and channels, impact craters and any cryovolcanic features etc ; investigates the composition of the surface of Titan (ices, organics) at regional and local scale with a spectral sampling of 10.5 nm; maps the temperature of the surface of Titan; investigates the troposphere in an altitude range of 3-30 km on the surface and the composition and optical properties of the haze, as well as any variable features in the lower part of the troposphere (clouds, plumes if any). A unique feature of the montgolfière is its ability to circumnavigate the globe at low altitudes (10 km) so as to conduct very high resolution imaging of a broad sweep of terrains. The camera performs stereo panoramic and high-resolution geomorphological studies at resolutions of better than 10 m per pixel, with selected areas at a meter per pixel with a narrow angle camera.

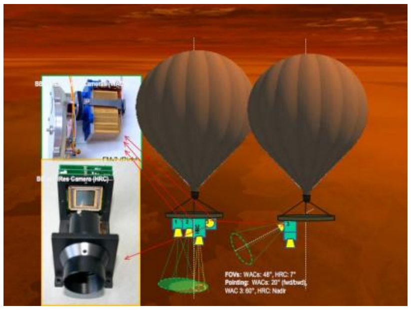


Figure 5. Imaging system on a Titan montgolfiere balloon. DLR/R. Jaumann.

Atmospheric structure with thermometer-barometer and electric package : In situ measurements are essential for the investigation of the atmospheric structure, dynamics, composition and meteorology. ASI/MET will monitor environmental physical properties of the atmosphere and the acceleration experienced by the entry module and probe during the whole descent.

Radar sounding : This instrument will help reconstruct the geological history of Titan characterizing and assessing the present day sedimentary environments and geomorphological features and identifying the stratigraphic relationships of ancient sedimentary units., It would allow one to detect sub-surface profiles and possible interfaces due to the presence of liquid or other structures (e.g. of tectonic or cryovolcanic origin). Also, it would help reconstruct their histories and provide altimetry at high/moderate resolution.

Magnetometry: The magnetometer will measure the magnetic field in the spacecraft and aso perform gradiometry measurements. Magnetometry aboard the montgolfière and lake lander allow for sensitive field measurements beneath Titan's screening ionosphere

Radio science: The goal of the Radio Science experiment is to provide signals to the Titan orbiter and direct-to-Earth, in order to make possible a precise estimation of the montgolfiere trajectory in Titan atmosphere. Gravitational measurements can be inferred from measurements of the relative velocity between the spacecraft and ground stations (Doppler shift). One-way radio link will also yield temperature-pressure profiles for Titan's atmosphere.

Table 3. Orbiter model science instruments and science contributions.

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

Table 4. Model instruments for the montgolfière.

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

Summary and conclusions: 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. 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 (Figure 6) offers high science return expectations in outer planets exploration with an adequate payload to ensure :

- 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 disciplines.

Table 5. Model instruments for the lake lander.

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

Other concepts for future Titan missions

Besides TSSM, future mission concepts include the Discovery **JET proposal** aimed at sending an orbiter to explore Titan with two instruments: a mid-infrared camera/thermal imager and a mass spectrometer : (*www.lpi.usra.edu/meetings/lpsc2011/pdf/1326.pdf*).

The TAE concept used a helium-filled super-pressure (or "pressurized") balloon (instead of a montgolfière) with the capability for ground-penetrating radar, radio science and multi-spectral imaging and spectroscopy, aerosol analyses, and possibly other instruments. The goal is to explore the processes that are at work on the surface on and near-surface of Titan with sufficient resolution and wavelength capability to quantify Titan's methane hydrologic cycle. These goals require combined in situ measurements, high-resolution surface studies, subsurface sounding, and regional- to global-scale coverage. This combination of requirements calls for a long-range balloon system (see http://users.sch.gr/gbabasides/joomla/). The aerostat would carry a camera to observe the surface of Titan, while spectra of the surface would be taken to map out the locations and extent of deposits of major organic products of the methane chemistry.

A radar sounder would probe the subsurface to look for evidence of layering associated with sedimentary deposition, cryovolcanism, tectonics, and other processes that might dominate the particular regional context elucidated by the imager. The aerostat, floating just at or below the methane cloud base, would also carry an instrument to sample the atmosphere looking for aerosols that nucleate methane-nitrogen cloud formation. It would measure ambient electric and magnetic fields to seek additional evidence for a subsurface water-ammonia ocean and determine the thickness of the ice crust above the ocean.

Finally, **the TiME mission**, planned to land in Ligeia Mare, is currently in competition among the Discovery missions and aims at constraining the role of lakes and seas in Titan's active carbon cycle and searching for signs of self-organizing organic chemistry.http://en.wikipedia.org/wiki/Titan_Mare_Explorer

The anticipated measurements and payload are :

- Determine the chemistry of a Titan lake to constrain Titan's methane cycle : *Mass Spectrometer*
- Determine the depth of a Titan lake: *Sonar*
- Characterize physical properties of lake liquids: *Physical Properties Package*
- Determine how the local meteorology over the lakes ties to the global methane cycle: *Meteorol. Package*
- Analyze the morphology of lake surfaces and shorelines, in order to constrain the kinetics of lake liquids and better understand the origin and evolution of Titan lakes: *Descent and Surface Imagers*

References: [1] NASA (2006), Solar System Explor. Roadmap for NASA's Science Mission Direct, NASA Science Missions Director.,Washington,DC, http://www.lpi.usra.edu/opag/road_map_final.pdf.

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[3] TSSM Final Report on the NASA Contribution to a Joint Mission with ESA, 3 November 2008, JPL D-48148, NASA Task Order NMO710851

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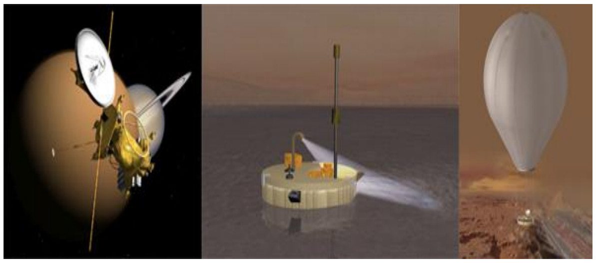

Figure 6. The mission elements accomplish comprehensive scientific exploration of Titan and Enceladus.