National Aeronautics and
Space Administration

Titan Orbiter + Probe

Mission Concept Report
for the Planetary Science and Astrobiology Decadal Survey

11 June 2021

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Disclaimers/Acknowledgements

This document is intended to support the 2023–2032 Planetary Science and Astrobiology Decadal Survey.

Pre-Decisional Information – For Planning and Discussion Purposes Only.

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

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Titan Orbiter and Probe

Exploring an organic world of two oceans

Titan is an Ocean World with an atmosphere resembling the Early Earth's, an active hydrological cycle and hydrocarbon lakes likely to contain prebiotic molecules. Titan Orbiter and Probe seeks to explore the Geology, Geophysics, Astrobiology and Atmosphere of this fascinating world.

Geology: understand the processes actively shaping Titan's surface

Geophysics: understand Titan's interior structure and surface-interior exchange

Astrobiology: understand Titan's organic/prebiotic chemistry

Atmosphere: understand Titan's climate as a source of surface modification

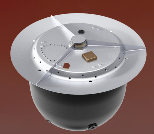
The Orbiter carries an IR camera, Radar Altimeter and Mass Spectrometer along with Radio Science for gravity. The Sea Probe carries a Mass Spectrometer, Environmental Package and Visible Camera and will splashdown in Kraken Mare, Titan's biggest sea.

Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12

Titan Orbiter and Probe is responsive to the majority of Decadal Survey questions. It will probe Titan's surface & interior (Q5), atmosphere (Q6) , formation (Q2), bombardment history (Q4) while probing its potential for habitability (Q10) and informing our understanding of life's appearance on Earth (Q9). This mission will also address questions centered on characterizing Saturn (Q7), Saturnian system interactions (Q8), prebiotic chemistry (Q11), and investigating processes relevant to exoplanets such as haze production (Q12).

MISSION OVERVIEW

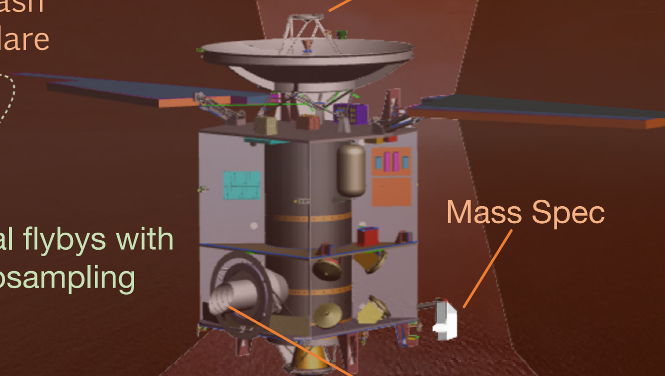
- High performance ELV with 4 m fairing
- 10-year interplanetary cruise to Saturn
- Saturn Tour Phase (2 years)
- In-Situ Exploration of a Titan Sea
- Titan Orbit Phase (2 years)
- 1500-km, circular orbit around Titan



Sea Probe will splash down in Kraken Mare

SPACECRAFT CHARACTERISTICS

- 11.5 meter dia. MegaFlex arrays
- Bipropulsion system
- X, Ka-Band
- 400 Gbits mission data volume



ORBITER PAYLOAD

Mass Spec
Multi-stage MS with 1000 amu range

IR Camera
3 band images with ≤ 70 m resolution at 5 μm

Radar Altimeter
Surface topography at 1 m vertical resolution

+ Gravity Science from Navigation Data
Crustal mass anomalies & global water ocean

SEA PROBE PAYLOAD

Mass Spectrometer
Multi-stage MS with 1000 amu range

Visible Camera
Provides 360 deg panoramic coverage

Environmental Suite
Pressure, Temperature, Methane Humidity, and Accelerometers

	PHASE A-D (FY22 $M)
Cost without reserves	776
Reserves (30%)	232
Reserves (50%)	388
Total PI-MM Cost (30% Reserves)	1008
Total PI-MM Cost (50% Reserves)	1164

MARGINS

- Power margin 34% at Saturn
- Dry mass margin 27%
- Data storage margin >2000%
- CPU margin 50%

INTERPLANETARY CRUISE PHASE					SATURN ENTRY PHASE		PLANE CHANGE + PUMP-DOWN TOUR	TITAN SCIENCE PHASE	
Launch	Earth Flyby	Venus Flyby	Earth Flyby	Earth Flyby	Saturn Orbit Insertion	Periapsis Raise	Probe Splash Down	Titan Orbit Insertion + Aerobraking	EOM
	L+≈1 year	L+≈1.5 years	L+≈2.5 years	L+≈5.5 years	L+≈10 years	L+≈10 years	L+≈11 years	L+≈12 years	L+≈14 years

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EXECUTIVE SUMMARY

Titan is a world of extraordinary complexity, containing an atmospheric factory producing complex prebiotic molecules, hydrocarbon lakes and seas partaking in a hydrological cycle and Earth-like climate system, and a subsurface water ocean that may periodically erupt liquid onto an organically rich surface. Titan Orbiter + Probe will investigate four aspects of this complex world (Geology, Geophysics, Astrobiology, and Atmosphere) and provide a global synoptic context to complement the local and regional-scale in-situ measurements acquired by Dragonfly.

The mission's science goals are Geology (understand the processes actively shaping Titan's surface); Geophysics (understand Titan's interior structure and surface-interior exchange processes); Astrobiology/Chemistry (understand Titan's organic chemistry and path to prebiotic molecules); and Atmosphere (understand Titan's climate as a source of surface modification).

Interplanetary cruise to Saturn Orbit Insertion (SOI) takes approximately ten years and, depending on launch year, includes some number of Venus and Earth flybys. The spacecraft consists of two components: the Orbiter, carrying a NIR imager, a mass spectrometer and a radar altimeter; and a Sea Probe, carrying a mass spectrometer, an imager and an environmental suite. Top-level Orbiter measurement requirements include: imaging more than half of Titan's surface at 25 m/pix or better; acquiring topographic measurements at a vertical precision of 1 m; measuring the tidal Love numbers k_2 and h_2 to a precision of 0.01; and measuring atmospheric compositions over a range of 2–1000 Da with a mass resolution (m/Dm) exceeding 1000. The main Sea Probe requirement is to measure the liquid composition and lower atmospheric composition over a range of 5–1000 Da.

The Orbiter is a solar-powered, three-axis stabilized body that will perform 18 flybys through Titan's atmosphere for sampling prior to settling into a two year, 1500-km-altitude circular polar mapping orbit. The battery-powered Sea Probe will be released a year after Saturn Orbit Insertion (SOI) and will descend by parachute to land in Kraken Mare, carrying out surface operations for a required 4 hours, and likely lasting a few Earth days.

A Titan orbiter mission (Oceanus) was submitted to the NF4 opportunity and was well-reviewed in terms of both technological readiness and cost risk. This concept, which captures years of technical analysis, trade studies and cost estimates, served as a reference for much of this report. The only significant difference is that this Mission Study includes a Sea Probe, in order to more thoroughly characterize the organic cycle on Titan and explore a vastly different environment than what the Dragonfly rotorcraft will encounter near Selk Crater in Titan's equatorial terrain.

1 SCIENCE OBJECTIVES

1.1 SCIENCE QUESTIONS AND OBJECTIVES

Saturn's moon, Titan, is unique in the solar system in that it is host to a dense atmosphere, complex chemistry in an early-earth-like environment, present-day terrestrial geologic processes, and an internal water ocean. **The scientific questions that can be addressed at Titan encompass nearly every aspect of planetary science and tie to many Earth science-based communities, from oceanography to organic and polymer chemistry.**

Titan serves as an unparalleled planetary laboratory that invites the study of fundamental science in a second environment. This includes the study of the intricate interplay between atmosphere, geology, geophysics and geomorphology, all occurring in different materials (largely organic) and in a different gravity compared to Earth. Titan appears to possess all of the organic chemical building blocks for life as we know it; exploration of the potential for prebiotic chemistry (and even biochemistry) in a planetary setting not already rife with biology may reveal the propensity for life to emerge on other worlds. The thick atmosphere is also enabling for atmospheric science investigations and exploration of climate evolution.

Titan hosts two completely different liquid environments — hydrocarbons on the surface and water in the subsurface — as well as a thick atmosphere and diverse terrains that rival Earth in geologic and chemical complexity. As a result, Titan science is by its very nature incredibly broad and can contribute meaningfully to nearly every fundamental question in planetary science, as well as serve as a bridge to Earth and exoplanetary science by investigating processes relevant to exoplanets such as haze production and climate stability.

Table 1. Titan Science

Property (General Audience)	Property	Scientific Importance
Only Moon with an atmosphere (second densest of all solid bodies in the solar system)	Dense atmosphere, haze layers	Photochemistry; Early Earth; exoplanet analog in our own cosmic backyard; climate change? Can also test aerobraking/aerocapture technologies.
Titan is like the Early Earth, which was not a 'pale blue dot' but a 'pale orange dot'	Complex organic chemistry in atmosphere, similar to Early Earth	Key insight into prebiotic chemistry no longer accessible on the Earth
Clouds, rain, lakes and seas of methane and ethane	Nonaqueous hydrologic system	Non-terrestrial material and environment provide unique insight into fundamental processes
Follow the Water	Subsurface liquid water ocean	Titan serves as a prebiotic chemical laboratory on a planetary scale; if complex organic molecules are reaching the subsurface ocean, this habitable environment could support life as we know it
Water isn't the only liquid	Two solvents	Titan has two solvents, one polar and one nonpolar, which drive different types of chemistry - do these systems (their products) interact? What are the implications for putative astrobiology?
Rocks made out of 'not rocks'	Cryominerals	Alien geology/petrology; important to understand intermolecular interactions between organics in a natural system (i.e., how universal are sediment transport and other aspects of geology if the rocks/grains are made out of different compounds?)
Volcanoes can be cold too	Areas of cryovolcanic activity where water/ammonia-based cryomagma may be present on the surface	Provides insight into interior composition and activity of an ocean world; transient liquid water on the surface could also lead to prebiotic chemistry with rich organics 'snowing' down from the atmosphere.
Methane-rich atmosphere	Methane atmospheric photochemistry	In situ observation of Titan's complex atmospheric photochemistry is key to understanding methane photolysis on many worlds, including Uranus, Neptune, Triton, Pluto, early Earth and early Mars, as well as exoplanets

While Titan's diversity enables investigations centered on geology, geophysics, astrobiology and chemistry, and atmosphere, these subfields are intimately linked and, when considered together, reveal Titan as a system. Below each investigation is described in detail, including the measurements made by both the Orbiter and the Sea Probe to achieve each science objective.

1.1.1 GEOLOGY: UNDERSTANDING THE PROCESSES ACTIVELY SHAPING TITAN'S SURFACE (EXPLORE TITAN, AN EARTH-LIKE SYSTEM)

Titan is host to the most Earth-like geology in the solar system, complete with an active hydrologic cycle (Mitchell and Lora, 2016; Hayes et al., 2018), aeolian processes (e.g., Lorenz et al., 2006), impact cratering (e.g., Wood et al., 2010), tectonism (e.g., Mitri et al., 2010), and potentially even cryovolcanism (e.g., Lopes et al., 2013). While these processes are familiar to us, the materials and environmental conditions are alien, allowing a unique opportunity to examine the underlying physics driving these fundamental geologic processes. These geologic processes also influence Titan's complex chemistry, transporting and mixing organic solids, dissolving and precipitating solid organics in alkane solvents, and mixing organics with transient pockets of liquid water.

While Cassini observations have provided a wealth of information regarding these processes, fundamental questions remain for which Cassini imaging and topography lack the spatial and temporal resolution and coverage to address. Cassini's sparse and coarse resolution therefore severely limits our understanding of how Titan's many landscapes have evolved. Titan Orbiter + Probe will collect the data necessary to make fundamental advances in Titan geology.

The main geology objective of this mission is to "**understand the processes actively shaping Titan's surfaces** (Explore Titan, an Earth-like System)". In detail, there are three sub-objectives:

1. Determine relative importance of the major geologic processes (i.e., aeolian, fluvial, pluvial, lacustrine, tectonic, cryovolcanic, and impact) modifying the surface today and in the past.
2. Understand how material is transported across Titan's surface and any modification it may undergo.
3. Explore the physical environment of a Titan sea.

These objectives are designed such that we could see Titan's landscapes as we have seen Earth's, to understand when, where and how material is transported across its surface, and how Titan's many landscapes are both modified today and how they have evolved through time. These three objectives could address two broad science questions that will not only be of interest to those studying Titan, but to those studying Earth, Mars, and exoplanets as well.

How are planetary climate & hydrologic cycles maintained through time?

Titan is the only world in our solar system, outside the Earth, that has an active hydrological cycle. This hydrologic cycle has given rise to a rich variety of landforms, and is intimately linked to the evolution of Titan's changing climate.

But Titan's atmosphere is not stable indefinitely, as methane is irreversibly destroyed high in the atmosphere. This implies one of two scenarios: (1) Titan's atmosphere is old, and methane is resupplied and/or exchanged within the near subsurface or (2) we are witnessing Titan's most recent atmosphere, and Titan's landscapes are transient over the age of the solar system. Cassini also revealed that over shorter timescales, analogous to glacial cycles on Earth, that Titan's climate is actively changing today. Stable liquids are seemingly restricted to the poles, in particular the north pole, while the equator looks to be a vast desert, with longitudinal dunes enveloping nearly the entire moon.

Understanding what stabilizes Titan's climate (or what does not), and how Titan's climate may be changing is critical to understanding not just Titan's landscapes and broader evolution, but planetary surfaces and climate in general. The silicate weathering cycle on Earth acts as a natural thermostat, stabilizing our climate over billions of years, the basic principles of which have been adapted by exoplanet scientists as more and more worlds, like Titan and Earth, continue to be discovered. Is there an analogous exchange process on Titan today that stabilizes its climate and might operate on exoplanets? Does methane have to be continuously replenished from the interior? Or is Titan's climate slowly drying out, such that stable hydrologic cycles like the Earth's are the exception, not the norm?

To resolve these questions, we need to understand the myriad of possible exchange processes between the solid surface and atmosphere. How are liquids transported across the surface and into the subsurface? How is sediment moved by these liquids, or in the absence of liquids? How do the liquids and sediment alter Titan's landscapes? What evidence from Titan's landscapes witness both the ongoing, orbitally driven climate change, and any putative longer-term loss of methane? High-resolution imaging and altimetry would allow us to answer many of these questions and lead to fundamental advances in our understanding of planetary hydrologic cycles.

Combined with improved understanding of Titan's atmospheric circulation/activity (discussed below), these imaging and topographic data would provide the inputs that needed to advance an integrated atmosphere-surface methane transport model, revealing for the first time the entirety of an extraterrestrial hydrological cycle.

What can observing Titan's active & simpler system teach us about current and past Earth and Mars?

The coupling between climate, tectonics, and erosion is fundamental control on Earth's topography, and the many feedbacks resulting from this coupling have been studied for decades. Yet much of our understanding of these processes, in particular how landscapes erode, are necessarily built on empiricisms made from field observations of specific landscapes, leaving us with a heavily Earth-centric bias.

Earth's land surface was also minimally biotically active for the first ~90% of its history, and so its landscapes evolved without the influence of vegetation or life. Such landscapes were the norm for most of Earth's history, yet that record is mostly lost, with only a few deposits remaining.

One place to study landscapes like those on the current and ancient Earth has been Mars: gravity is only slightly different and the materials are familiar, a natural extension that has been leveraged for decades. Yet the problem at Mars, as it is on Earth, is that those ancient hydrologic records are highly degraded and they are no longer active. We are therefore left to reconstruct past climatic conditions with incomplete information. Further, while the surface of ancient Mars was eroded like on Earth, its initial relief is likely dominated by the impact cratering process, and the materials are similar to terrestrial materials, providing little room for advancement in our general understanding of how landscapes and climate are coupled.

Titan offers the perfect opportunity to study landscape evolution as governed by a hydrologic cycle for three principal reasons: First, its environment is active today, and is a rather simple system compared with the Earth, lacking diverse climate zones, vegetation, and life. This means that the hillslopes and rivers on Titan today may not be unlike those on the early Earth and ancient Mars. Reconstructions are also unnecessary, as we could simply watch how the landscapes behave. Second, impacts are seemingly less important on Titan, meaning its relief is set by the same feedbacks that govern Earth's topography — *the only other world where that's the case*. Finally, the materials, timescales, and gravity are all far different from the Earth, allowing us to test assumptions we have had any need to, as of yet.

It is therefore both the familiar and alien nature of Titan's surface and environment that can be leveraged as an all-important second data point, one that is needed to break free from our reliance on empiricisms so prevalent in terrestrial geology and geomorphology. To do so requires studying Titan's landscapes and climate as we have studied the Earth's and Mars. Specifically, high resolution, repeat, color imaging, and topographic data will allow us to test the fundamental assumptions underlying much of terrestrial geology and geomorphology, and then use that knowledge to better understand processes on Earth and Mars, both today and in the distant past.

Orbiter

Addressing objectives 1 and 2 requires repeat high-resolution imaging (10s of meters per pixel), repeat, color imaging, and topography of the majority of Titan's surface (see Figure 1). Such a dataset would be comparable to early Landsat data (30 m/px), which were sufficient to characterize Earth's global landscapes. The Titan orbiter camera and altimeter instruments would provide these data.

Capabilities provided by such a dataset include the ability to: delineate watersheds, map putative landslides and hillslope structures, map channel networks to investigate the extent and timing of fluvial dissection and sediment transport, diagnose groundwater transport, and ascertain the location and areal extent of all surface liquids using specular reflections. Does Titan have meandering rivers, or are all of its large rivers braided, as on the Early Earth? Are Titan's hillslopes rocky, or are there new, yet unknown mechanisms through which to generate sediment and smooth a hillslope?

Further, imaging of Titan's polar seas and sedimentary basins would map shorelines and sedimentary deposits to constrain long-term climate and sea-level variations and evaluate how long its coastal environments have persisted (Tobie et al., 2006; Becerra et al., 2016). Repeat images of Titan's coasts could also reveal ongoing dynamics, while color images could track the transport of sediment along and toward coasts. Does Titan have beaches, and if so, where and how do they move? What can Titan's coastal sediments and deltas teach us about long-term climate change?

Images of Titan's equatorial longitudinal dunes would reveal if they are compound in form, like those on Earth, which would reveal shorter-term climatic shifts (Lancaster, 1995; Ewing et al., 2015) and would provide insight into the stability of Titan's climate over the past millions of years. Images would also reveal the stratigraphic relationships between dunes and fluvial deposits, allowing us to understand how Titan's climate is changing. Global color imaging would reveal sediment transport patterns, sources, and sinks, allowing for a full accounting of sediment across the moon. Are there new minerals/sediments that are unique to Titan because of its composition and liquids (e.g., co-crystals). Where do astrobiologically interesting sediments accumulate, and what modifications, if any, do they undergo during transport?

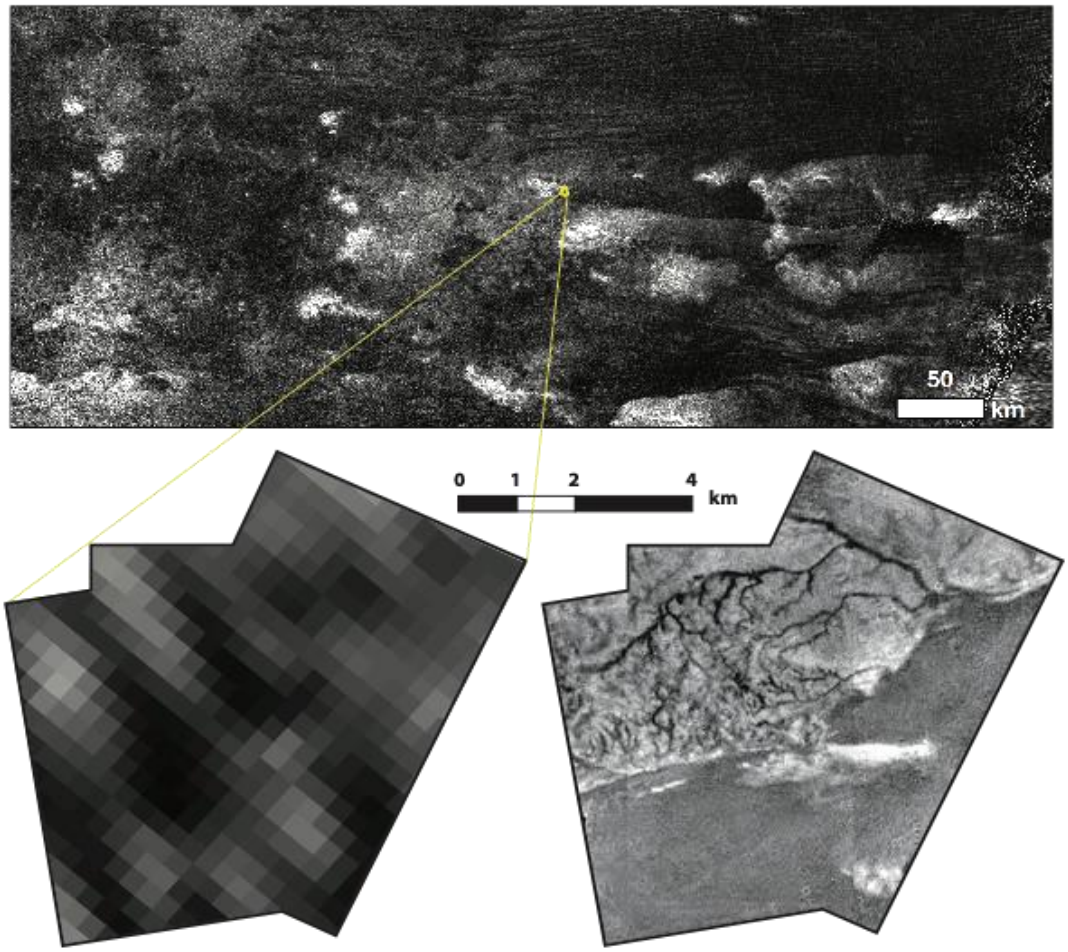


Figure 1: Demonstration of Titan Orbiter image quality. (Lower left) Typical Cassini SAR image, with ~1-km resolution. (Lower right) DISR mosaic at ~100-m resolution. The Orbiter will image more than half of Titan at 70-m resolution.

Finally, global high-resolution imaging and topography would allow for an understanding of how Titan's surface and climate are coupled to its interior. This would enable a global search for new cryovolcanic candidates and an evaluation of the merits of current candidates like Doom Mons (Lopes et al., 2013). How do such features interact with sedimentary materials, and are they sufficient to replenish Titan's atmospheric methane? Similarly, imaging and topography could also be used to map global and local tectonic stress patterns, to understand where Titan's lithosphere is undergoing extension and compression. What is the surface expression of faults, if any and what are the rates of vertical crustal movement that allow for the maintenance of relief?

Sea Probe

The Sea Probe will characterize the physical and chemical properties of a Titan lake necessary to understand how Titan's lakes evolve its landscape. The evolution of Titan's lakes and seas provides insight into the evolution of Titan's climate and redistribution of methane on 100,000-year timescales.

The Sea Probe will determine the amplitude and periodicity of any waves and tides, providing insight into the importance of wave activity on shaping Titan's lakes and seas. Evidence of dissolved materials in the liquids, through the liquid composition and turbidity, will provide insight into the importance of dissolution in shaping Titan's surface while detection of suspended sediments will provide insight into the importance of Titan's liquids mechanically eroding its landscape. The Sea Probe will also determine if there are any films or floating materials present on the surface.

1.1.2 GEOPHYSICS: UNDERSTAND TITAN'S INTERIOR STRUCTURE AND POTENTIAL ORGANIC TRANSPORT PATHWAYS BETWEEN THE SURFACE AND SUBSURFACE WATER OCEAN (ASSESS TITAN'S ASTROBIOLOGIC POTENTIAL)

Measurements of Titan's obliquity and tidal response strongly suggest the presence of a subsurface ocean. However, the characteristics of the ocean and the ice shell above are very uncertain. For instance, some authors argue for an ice shell a few tens of km thick (Tobie et al. 2006, Beghin et al. 2012) while others suggest a value of a few hundred km (Hemingway et al. 2013, Sohl et al. 2014). Similarly, it is entirely unclear whether the ice shell is convecting or not. Last, it is not clear whether Titan's surface topography is due to variations in ice shell thickness (Nimmo and Bills 2010), variations in surface density (Choukroun & Sotin 2012), or some other reason.

These uncertainties matter, because characteristics of the ice shell determine the extent to which the subsurface ocean might be habitable. For instance, a convecting ice shell would result in a much higher flux of organic materials from the surface to the ocean. A thin, conductive shell could be subject to fractures and transport via water-filled cracks, as occurs at Enceladus. Furthermore, because of the phase diagram of ice, a thin shell also implies an ocean in direct contact with the underlying silicates, increasing the likelihood of water-rock reactions. Conversely, a thick conductive shell would represent an impermeable barrier to vertical transport in either direction. Lastly, the variable surface density hypothesis implies a substantial subsurface circulation of ethane through a methane-clathrate crust, and a thinner crust overall, potentially facilitating transport to the ocean below.

Accordingly, the main geophysics objective is to **"understand Titan's interior structure and potential organic transport pathways between the surface and subsurface water ocean".** In detail, there are three sub-objectives:

1. Determine the thickness of the ice-crust (including spatial variations).
2. Determine if the ice-crust is conductive or convective.
3. Determine any lateral variations in ice shell thickness or density.

To meet objectives 1 and 2, the primary goal is to accurately measure Titan's tidal response. This is described by two dimensionless Love numbers: k_2, which measures the response of Titan's gravity; and h_2, which measures the surface deformation. These are measured by tracking of the spacecraft and altimetric measurements of the surface, respectively.

The combined quantity $1+k_2-h_2$ is sensitive to the thickness of the rigid part of the ice shell and relatively insensitive to other quantities such as ocean density (Wahr et al. 2006). For a conductive shell, the rigid shell provides a good approximation to the total shell thickness. For a convective shell, however, the convecting interior will be too warm to maintain rigidity at tidal frequencies. As a result, in this case the total layer thickness will be much greater than the rigid layer thickness, which is what $1+k_2-h_2$ measures. Fortunately, a convecting shell will exhibit a large phase lag in its response to the tidal potential, while a conductive shell will not. Thus, by measuring the phase lag in k_2, or equivalently the imaginary (out-of-phase) part of k_2, conductive and convective shells can be distinguished. Figure 2a shows the contrasting temperature structures for example conductive and convective shells; Figure 2b shows that by measuring both $1+k_2-h_2$ and the phase lag ($Im(k_2)$), the shell thickness and its nature (convecting or conducting) can be determined. Measurement of both the static gravity and topography can be used to determine the admittance, which provides an alternative way to estimate the thickness of the ice shell (Hemingway et al. 2013).

Whether the ocean is directly in contact with the silicates beneath will determine how much transfer of energy and chemicals from Titan's deep interior can take place. Knowing the shell thickness answers this question, because the shell thickness and the presence/absence of high-pressure ices directly above the silicates are linked via the ice phase diagram (e.g. Vance et al., 2014).

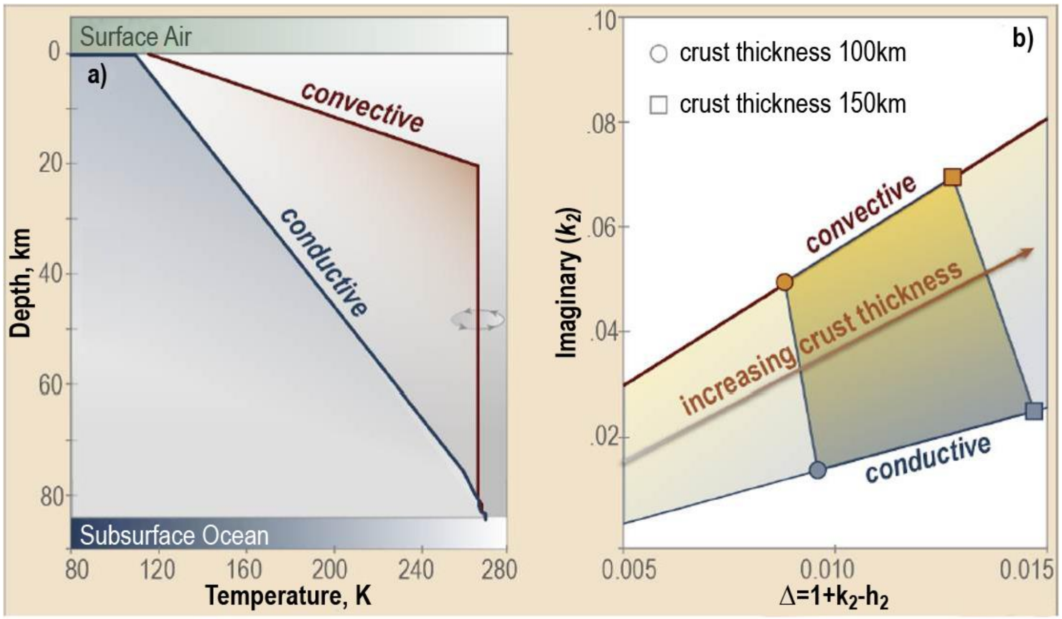


Figure 2. a) Hypothetical temperature structures for convective and conductive ice shells. b) Variation of $1+k_2-h_2$ and $Im(k_2)$ as a function of shell thickness for the conductive and convective cases.

Objective 3 is most readily answered by the static, rather than the time-varying, topography and gravity. The variable-thickness hypothesis makes predictions about the spatial pattern of topography (Bills & Nimmo 2010); furthermore, it predicts the size and pattern of the corresponding gravity anomalies. These anomalies will be larger than in the variable-density case, because in the latter case all the density variations are within the top few km of the ice shell.

1.1.3 ASTROBIOLOGY AND CHEMISTRY: UNDERSTAND TITAN'S ORGANIC INVENTORY AND PATH TO PREBIOTIC MOLECULES

Titan contains all of the necessary ingredients for habitability, in that it hosts "extended regions of liquid water, conditions favorable for the assembly of complex organic molecules, and energy source(s) to sustain metabolism" (Des Marais et al., 2008). However, it is not clear based on current data whether local environments are present on Titan where these ingredients coexist for extended periods. In concert with the geophysics and geology investigations, which will address potential transport pathways for organics into the subsurface liquid water ocean, the main astrobiology objective is to **obtain a complete and accurate inventory of the types and abundances of organic molecules present in Titan's atmosphere and on its surface**. Laboratory studies indicate that if certain organic molecules believed to be present on Titan come into contact with liquid water, chemical reactions (hydrolysis, etc.) would generate prebiotic molecules such as amino acids and nucleotides (Cleaves et al., 2014; Kawai et al., 2013; Neish et al., 2010). Importantly, Titan also allows investigation of life 'not as we know it' in that any biochemistry supported in the nonpolar hydrocarbon lakes would by definition be very different from that of aqueous-based systems. Assessment of the organic molecule inventory is an important step for either case, in identifying locations on Titan that may be habitats for astrobiological chemistry.

Orbiter

The main orbiter chemistry goal is therefore to "understand how and what organic molecules are synthesized in Titan's atmosphere, and identify pathways to prebiotic molecules." This involves three science objectives:

- 1.1 Determine the relative contributions of ion neutral vs. radical reaction pathways in the growth of large molecules and aerosols.
- 1.2 Determine the extent of oxygen incorporation in atmospheric organics.
- 1.3 Determine if there are large atmospheric molecules that are composed of repeating subunits.

The first objective establishes the primary chemical pathways through which large organic molecules are formed in Titan's atmosphere. In the upper atmosphere (above 750 km), methane and molecular nitrogen are broken down by various processes (photoionization, photodissociation, electron-ion recombination) to form ions and radicals, which then react to generate larger organic molecules. However, due to Cassini's narrow mass range and limited vertical access, it is not known if the reactions to form larger molecules are dominated by ion neutral chemistry or radical chemistry. Even percent-level efficiencies of radical chemistry can significantly alter the mass distribution of molecules, shifting abundances to larger molecules and potentially limiting the availability of small prebiotic molecules in the atmosphere and on the surface. By measuring the abundance of molecules as a function of molecular weight from 2–500 molecular mass units (Da) at multiple altitudes from 750 to 1100 km, the contribution of radical chemistry relative to ion neutral chemistry can be quantified. A decrease in the abundance of molecules in the range of 100–500 Da below 900 km would indicate significant radical chemistry is occurring.

The second objective addresses whether oxygen-containing organic molecules are being formed on Titan. Oxygen is important for life, as it is a key component of prebiotic molecules such as amino acids and nucleobases. In Titan's atmosphere, oxygen is primarily present as carbon monoxide (CO), and while laboratory experiments simulating Titan atmospheric chemistry indicate that prebiotic molecules can be formed (Horst et al., 2008), these molecules have not been definitively identified on Titan. Measurement of the abundance of molecules with characteristic fragment losses of H_2O, CO_2, or CO_2H versus molecular weight will definitively determine if oxygen is being incorporated into the large organic molecules in Titan's atmosphere. This is achieved using multi-stage mass spectrometry, where molecules of a given mass are trapped in the ion trap and fragmented, revealing repeating subunits in a mass spectrum that is no longer obscured by interfering peaks from other molecules.

The third objective determines if the molecules formed in Titan's atmosphere have ordered complexity from repeating subunits. Models of atmospheric chemistry on Titan vary; some indicate polycyclic aromatic hydrocarbons (PAHs) might be an important subunit, while others suggest polynitriles will dominate. By using multi-stage mass spectrometry, a 'fingerprint' of daughter fragments for a single trapped parent ion elucidates repeating chemical structures (Figure 3). The same technique is commonly used to identify biomolecules such as polypeptides. Identification of the common building blocks in Titan's organic molecules will enable prediction of the likely chemical structures and reactivity of large molecules, as well as the formation of possible biomolecules such as the DNA-base adenine (Carrasco et al., 2009).

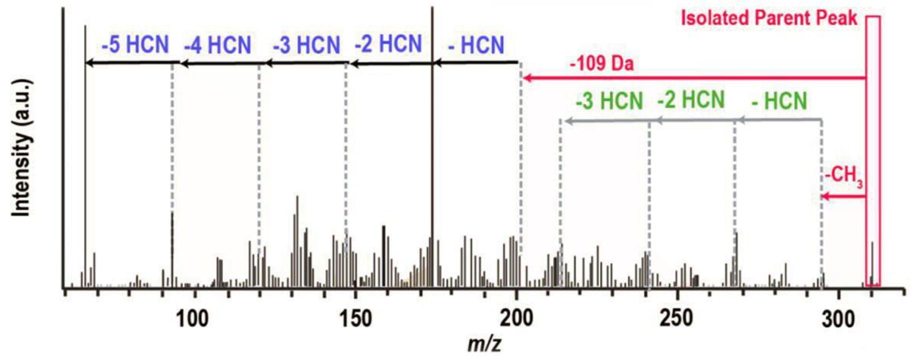


Figure 3. Multi-stage mass spectrometry can be utilized to identify repeating subunits in large organic molecules by trapping and fragmenting an isolated parent peak. Here, an ion at 310 Da is fragmented, generating a pattern of repeating HCN subunits (27 Da). [Carrasco et al., 2009].

Sea Probe

The Sea Probe will make key in situ measurements relevant to addressing questions about the history of volatile evolution at Titan, as well as the potential for prebiotic or even biotic chemistry.

The first goal of the Sea Probe is to understand the history and extent of volatile exchange in Titan's hydrologic system. In this case, 'hydrologic' refers not to water but hydrocarbons, primarily methane and ethane, as these comprise the liquid phase on Titan's surface. This requires four science objectives:

- 1.1 Determine how Titan's volatiles were delivered and if they were internally processed.
- 1.2 Determine the age of methane in Titan's present day atmosphere, and search for evidence of renewal via internal outgassing.
- 1.3 Determine the thermal and dynamical state of the atmosphere above Kraken Mare.
- 1.4 Determine the physical state and composition of a Titan sea.

Assessment of the origin of Titan's volatiles requires measurement of the abundance of noble gases (Ar, Ne, Kr and Xe) and their isotopes, both from the sea (Kraken Mare) and lower atmosphere. Measurements made with the Huygens probe indicate a strong depletion in primordial noble gases (Niemann et al., 2005). Theories for sequestration of these species include dissolution in the hydrocarbon lakes, as well as trapping within clathrates in the crust or haze layers in the atmosphere. In particular, Kr and Xe may be enriched in surface liquids relative to the atmosphere (Glein, 2015).

Photochemistry in Titan's atmosphere is destroying methane and converting it to larger molecules; this occurs at a rate such that all methane currently in the atmosphere should be fully depleted in ~10^7 years (Strobel, 1982). The fact that methane is still present implies a source to replenish it in the atmosphere, likely via internal outgassing. Comparison of the $^{12}C/^{13}C$ and D/H ratios of methane in the seas and atmosphere to protosolar / cometary values would indicate whether the CH_4 on Titan is exogenous or endogenous (generated via reduction of CO_2 or through geochemical / hydrothermal synthesis). Further, the abundances of rare isotopologues, such as $^{13}CH_3D$ and $^{12}CH_2D_2$ can constrain the temperature of CH_4 synthesis (Stolper et al., 2014).

Another unknown with respect to Titan's atmosphere is whether this moon has lost a significant amount of N_2 via atmospheric photochemistry and escape. This is important in understanding whether Titan's atmospheric N_2 is endogenous or exogenous. Measurement of tracers of potential atmospheric escape (He, H_2, $^{20}Ne/^{22}Ne$, $^{36}Ar/^{38}Ar$, etc.) would address this question.

In addition to assessing volatile exchange via delivery/processing of volatiles and outgassing, it is important to determine the thermal and dynamical state of the atmosphere above the hydrocarbon seas. Measurements of the wind profile, as well as vertical profiles of temperature, pressure, density, and methane and ethane abundance, will provide a deeper understanding of the exchange between the lakes and atmosphere.

The physical state and composition of a Titan sea is also critical to provide quantitative constraints on model parameters for volatile exchange. These measurements include identification of molecular constituents via multi-stage mass spectrometry, sound speed and permittivity of the sea liquid, constraints on sea depth and turbidity, and documentation of the presence or absence of wave activity, floating debris or films and possible currents.

The second primary goal of the Sea Probe is to investigate whether Titan's hydrocarbon seas support ongoing prebiotic and/or biotic processes. This can be accomplished with the following four objectives:

- 2.1 Determine if Titan's organic chemistry involves biogenic elements (e.g., phosphorus and sulfur).
- 2.2 Determine if reduced and/or oxidized organic species are available in the sea.
- 2.3 Determine if processes consistent with biochemistry are operating on organic molecules in sea liquid.
- 2.4 Determine the extent to which Titan's surface chemically communicates with its water-rich interior.

By measuring the elemental chemistry of organic molecules in Titan's atmosphere with multi-stage mass spectrometry, biogenic elements such as phosphorus and sulfur that are critical to life as we know it can be identified in molecules present in Titan's atmosphere, aerosols and sea. The same measurement technique can also be applied to determine the presence of reduced species (saturated hydrocarbons and amines) and oxidized species (acetylene, ethylene, nitriles) in the sea. The presence of both types of species may establish whether a putative biochemistry could be supported via redox gradients in this alien, nonpolar solvent.

Going one step further, measurement of isotopic ratios in alkanes and a search for organic molecules inconsistent with abiotic synthesis in the sea liquid could provide evidence of processes consistent with biochemistry operating on organic molecules in the sea liquid.

Finally, measurement of the abundance of radiogenically derived noble gases, such as ^{40}Ar and ^{21}Ne, in the sea liquids would determine the extent of communication between Titan's surface and its water-rich interior, which is important to constrain chemical pathways and transport available to support prebiotic or biotic chemistry.

1.1.4 ATMOSPHERE: UNDERSTAND TITAN'S CLIMATE AS A SOURCE OF SURFACE MODIFICATION

Beyond hosting complex prebiotic chemistry, Titan's atmosphere is dynamically active, with weather that plays critical roles in both transporting aerosols and volatiles across the body, and in shaping its surface (Mitchell & Lora, 2016; Faulk et al., 2017; Hayes et al. 2018). Understanding the longevity and chemical constituents of Titan's atmosphere provides insight to understanding the gas and ice giants, while the atmospheric dynamics, coupling between the atmosphere and surface, and active hydrologic cycle link Titan atmospheric science to Earth, Venus, Mars, and Pluto (MacKenzie et al., 2021).

The plethora of organic species produced from the atmospheric photochemistry make up Titan's haze. While unlike present-day Earth, this environment provides a window into what haze production may have been like on Early Earth. Moreover, Titan's atmosphere serves as a powerful backyard analog for hazy exoplanets—from understanding the formation, evolution, and impact of atmospheric aerosols to how we might best detect and observe them—as we have ground truth from both remote and in situ sensing (Robinson et al., 2014; Checlair et al., 2016; Lora et al., 2018).

The seasonal timing and magnitude of surface-atmosphere fluxes of methane, including observed clouds and rainstorms, are probably linked to existing surface and subsurface liquid reservoirs as well as controlled by the atmospheric dynamics (e.g., Turtle et al., 2018; Faulk et al., 2020). The episodic nature of Cassini flyby observations, however, have left a spatially and temporally incomplete picture of the seasonal changes occurring in Titan's atmosphere, greatly limiting our ability to constrain weather and climate models, the physical processes they simulate, and the underlying properties of Titan's hydrologic cycle.

The main atmospheric objective is to **"Understand Titan's weather as a source of surface modification"**. In detail, there are two sub-objectives:

- Determine the 3D distribution of aerosols & clouds (both methane clouds and other hydrocarbon and nitrile clouds that form in the stratosphere).
- Determine the atmospheric P/T/rho profile, and measure polar humidity and winds.
- Monitor surface for changes related to observed weather events.

These objectives will be met through a combination of remote sensing observations from the Orbiter and in situ measurements from the Sea Probe. And while the goals of these objectives bear directly on Titan today, the implications are far reaching.

Orbiter

The ability of the Orbiter to observe Titan's clouds and hazes at a higher cadence and consistency than Cassini will fundamentally change our understanding of Titan's atmosphere. Such data will fill in basic gaps in our current knowledge, such as the longevity of Titan's clouds and their 3-dimensional evolution, as well as begin to inform our understanding of climatic variability. The Orbiter will also provide global topography, which will allow us to investigate how mountains and topography affect Titan's weather and climate by modifying the atmospheric circulation.

Regular imaging of the surface will allow for detection of rainfall events on Titan that are both smaller and shorter-lived than those observed by Cassini's sporadic observations. Understanding the duration, frequency, and magnitude of storms on Titan provides critical constraints to general circulation models (GCMs) and cloud resolving models, as well as insight into the rates at which the methane cycle operates, including how readily it is replenished into the atmosphere.

These observations will allow us to determine how the seasonal trends in condensate distributions observed at high altitudes extend to lower altitudes, whether and how these affect sedimentation onto the surface, and the feedbacks between the atmospheric circulation and surface–atmosphere fluxes of methane.

Improved knowledge of the distribution, optical properties, and composition of Titan's hazes and clouds will provide the observational constraints needed to better understand the roles that microphysics and regional characteristics play in cloud and haze formation.

Sea Probe

We currently have one single datapoint in terms of a ground-truth atmospheric pressure, temperature, density, wind, and methane humidity profile: that of the Huygens probe. Extrapolating these measurements to different seasons and different latitudes introduces significant uncertainties and severely limits our ability to interpret Titan's atmosphere. Dragonfly and this NF Sea Probe would provide highly complementary information that would greatly improve our understanding of the variability of Titan's atmosphere: Dragonfly will improve our understanding of the temporal variability of Titan's atmosphere at a latitude that is very similar to the Huygens probe, while the Sea Probe would provide a second complete atmospheric profile at a dramatically different latitude.

SCIENCE TRACEABILITY MATRIX — ORBITER

Science Goal	Science Objective	Measurement Requirements: Physical Parameters	Measurement Requirements: Observables	Instrument Functional Requirements	Projected Performance	Mission Functional Requirements
1. Understand how and what organic molecules are synthesized in Titan's atmosphere and identify pathways to prebiotic molecules.	1.1. Determine the relative contributions of ion neutral vs. radical reaction pathways in the growth of large molecules and aerosols	Molecular abundance vs. weight and how the distribution varies above and below 900 km altitude	Mass abundance vs. molecular weight from 2-500 Da at altitudes from 750-1100 km with 50 km altitude resolution	Mass range: 2-500 Da Mass resolution: 2 (m/Δm) @ 2 Da and 500 (m/Δm) @ 500 Da Sensitivity: at least 0.005 counts molecule^{-1} cm^3 sec^{-1}	Orbiter MS Neutral closed source MS^n capable with 1 Da isolation width Mass range: 2-1000 Da Mass resolution: 20 (m/Δm) @ 2 Da 400 (m/Δm) @ 46 Da 1,000 (m/Δm) @ 500 Da 5,000 (m/Δm) @ 1000 Da Sensitivity: at least 0.05 counts molecule^{-1} cm^3 sec^{-1}	Perform 5 flybys of Titan from Saturn orbit at 1000 +/- 100 km above Titan surface Perform 4 (3+1 margin) MS scan passes through Titan atmosphere to altitudes below 800 km (Science Objective 1.1) Perform 6 (5+1 margin) MS^{2}passes through Titan atmosphere at altitudes of 800 to 900 km (Science Objective 1.2) Perform 2 (1+1 margin) MS^3 passes through Titan atmosphere at altitudes of 800 to 900 km (Science Objective 1.3) Support Mass Spec sampling and analysis during aerosampling passes from 750 to 1100 km
	1.2. Determine the extent of oxygen incorporation in atmospheric organics	Abundance of molecules with characteristic fragment losses of H_2O, CO_2, or CO_2H vs. molecular weight	Neutral fragment loss patterns as a function of 1 Da windows in an MS^2 experiment scanning parent ions from 46-500 Da	Mass range: 46-500 Da Capable of MS^2 with 1 Da isolation width MS^2 fragment mass window range is 50% of parent ion mass value Mass resolution: 46 (m/Δm) @ 46 Da and 500 (m/Δm) @ 500 Da Sensitivity: at least 0.005 counts molecule^{-1} cm^3 sec^{-1}		
	1.3. Determine if there are large atmospheric molecules that are composed of repeating subunits	Repeating subunits in the fragmentation patterns of 50 trapped ions	MS^3 fragment pattern and abundances from 50 parent/daughter ions in range of 46 -500 Da	Mass range: 46-500 Da Capable of MS^3 with 1 Da isolation width MS^3 fragment mass window range is 75% of parent ion mass value Mass resolution: 46 (m/Δm) @ 46 Da and 500 (m/Δm) @ 500 Da Sensitivity: at least 0.005 counts molecule^{-1} cm^3 sec^{-1}		
2. Understand Titan's Earth-like hydrocarbon-based hydrologic and sediment cycles	2.1. Determine the dominant transport and processing mechanisms of organic sediment across Titan's surface (past and present)	Distribution, morphology, and cross-cutting relationships of aeolian, fluvial, pluvial, lacustrine, tectonic, cryovolcanic and impact features.	Imaging at 100 m spatial resolution and topography at 20 m vertical precision of fluvial networks and deposits	Spatial resolution: 100 m Vertical topographic precision: 20 m SNR 50:1	Orbiter Camera Filters: 5, 2, & 1.3 µm Spatial resolution: 70 m (5 & 2 µm), better than 500 m (1.3 µm) Vertical topographic precision: 10 m SNR 100:1	Imaging of required areas (see Section D text) with solar incidence ≤ 70°. Stereo imaging with 27-30 degree convergence. Some targets require orbit inclination of 90° +/- 10°.
	2.2. Determine where past hydrocarbon seas and sedimentary organic materials are located on Titan's surface.	Existence of 5-µm bright unit that is a putative evaporite deposit	5, 2, & 1.3-µm imaging (to distinguish 5-micron bright unit from other spectral units) at 500 m spatial resolution of candidate paleosea basin	Filters: 5, 2, & 1.3 µm Spatial resolution: 500 m SNR 50:1		
		Existence of morphologic features such as paleoshorelines and hanging deltas	Imaging at 100 m spatial resolution and topography at 20 m vertical precision of candidate paleolake/paleosea basin	Spatial resolution: 100 m Vertical topographic precision: 20 m SNR 50:1		
3. Understand Titan's interior structure and surface-interior transport pathways	3.1 Determine if and where liquid water was present after impacts to hydrolyze organic molecules.	Impact melt volume and shape: Areal extent from morphology and 3-color spectral variability Thickness (lower limit) from fluvial valleys	Imaging at 100 m spatial resolution and topography at 20 m vertical precision of entire crater and ejecta area 5, 2, & 1.3-µm imaging at 500 m spatial resolution to determine exposed ice and whether fluvial valleys are in frozen ice-melt	Filters: 5, 2, & 1.3 µm Spatial resolution: 100 m (5 µm), 500 m (2 & 1.3 µm) Vertical topographic precision: 20 m SNR 50:1		
	3.2. Determine if and where cryvolcanism has occurred on Titan's surface.	Existence of cryovolcanic morphologic features such as flows, domes, calderas, and pits	Imaging at 100 m spatial resolution and topography at 20 m vertical precision of candidate cryovolcanic features	Spatial resolution: 100 m Vertical topographic precision: 20 m SNR 50:1		
	3.3. Determine if tectonic processes have operated that could have facilitated transport of organic material down through the upper layer of the ice-crust	Identify Titan tectonic regime using morphologic features such as thrust faults and folds (compression), horst and graben (extension) and lateral offsets (strike-slip) in ice-bedrock	Imaging at 100 m spatial resolution and topography at 50 m vertical precision of tectonic features 5, 2, & 1.3-µm imaging at 500 m spatial resolution to determine whether tectonic deformation includes ice-bedrock	Filters: 5, 2, & 1.3 µm Spatial resolution: 100 m (5 µm), 500 m (2 & 1.3 µm) Vertical topographic precision: 50 m SNR 50:1		
	3.4. Determine the ice-crust thickness to an accuracy of 10 km	Complex tidal Love numbers k2 (potential Love number) and h2 (shape Love number) to evaluate D=1+k2-h2 to an accuracy of 0.01	Spacecraft to Earth range-rate to an accuracy of 3 µm/s at 1000 s integration time, to determine spacecraft radial position with an accuracy of 1 m (3 sigma). This enables the determination of h2 to an accuracy of 0.01 and k2 to an accuracy of 0.0001 (both real and imaginary components). Spacecraft to Titan surface range to an accuracy of 3 m (3 sigma) to determine h2 to an accuracy of 0.01 (3 sigma)	Spacecraft to Earth range-rate accuracy: 3 µm/s at 1000 s integration Spacecraft to Titan surface range accuracy: 3 m	GRAVITY SCIENCE Spacecraft to Earth range-rate accuracy: 2.5 µm/s at 1000 s integration T-Alt Spacecraft to Titan surface range accuracy: 1 m Doppler tracking is conducted at both X & Ka-band via the HGA for 6 hours out of every 25 hour period while in Titan orbit.	6 hrs/day of coherent 2-way Doppler tracking for 1 year Orbit with inclination of 90° +/- 7° and LTAN (local time of ascending node) > 7:00 ~1000 crossovers of spacecraft to Titan surface range measurements at variable true anomalies that are geographically distributed Spacecraft position accuracy (relative to Titan center-of-mass) of 1 m (3 sigma) for each orbit
	3.5. Determine whether the "lower" ice-crust is conductive or convective.	Complex tidal Love numbers k2 (potential Love number) and h2 (shape Love number) to an accuracy of 0.01 (both real and imaginary components)				
	3.6. Determine any lateral variations in ice-crust thickness and/or density that could be indicative of variations in vertical transport or abundance of crustal organics.	Admittance (ratio of gravity to topography) at wavelengths greater than 2000 km (less than degree 8) to quantify the extent of compensation as a function of wavelength	Spacecraft to Earth range-rate to an accuracy of 3 µm/s at 1000 s integration Spacecraft to Titan surface range to determine elevation of every 22.5° latitude x 22.5° longitude box at 1 m vertical accuracy	Spacecraft to Earth range-rate accuracy: 3 µm/s at 1000 s integration Spacecraft to Titan surface range accuracy: 10 m		6 hrs/day of coherent 2-way Doppler tracking for 3 months Orbit with inclination of 90° +/- 10° and LTAN (local time of ascending node) > 7:00 100 radar altimetry measurements in every 22.5° latitude x 22.5° longitude box

SCIENCE TRACEABILITY MATRIX — SEA PROBE

Science Goal	Science Objective	Measurement Requirements: Physical Parameters	Measurement Requirements: Observables	Instrument functional requirements	Projected Performance	Mission Functional Requirements
1. Understand the history and extent of volatile exchange in Titan's hydrologic system	1.1. Determine how Titan's volatiles were delivered and if they were internally processed.	Abundance of noble gases (Ar, Ne, Kr, Xe) and their isotopes from mass spectra of the target sea and atmosphere.	Mass abundance vs. molecular weight from 2-200 Da of atmosphere at altitudes from 750-1100 km with 50 km altitude resolution; at sea level and in liquid from the target sea.	Mass range: 2-200 Da Capable of MS^2 with 1 Da isolation width MS^2 fragment mass window range is 50% of parent ion mass value Mass resolution: 2 ($m/\Delta m$) @ 2 Da and 200 ($m/\Delta m$) @ 200 Da Sensitivity: at least 0.005 counts $molecule^{-1}$ cm^3 sec^{-1}	Sea Probe MS redundant thermionic emission electron gun with redundant channel electron multipliers Mass range: 5-1000 Da Dynamic Range: 10^6 Resolution: up to 1000 (FWHM) Accuracy: +/-0.4 Da actual mass Sensitivity: at least 0.05 counts $molecule^{-1}$ cm^3 sec^{-1}	Requires noble gas enrichment Require aerosol collectors Requires measurements in atmosphere during descent (post parachute deployment) and sea liquid following splashdown
		Measure and compare isotopic ratios: $^{12}C/^{13}C$ and D/H in the alkanes in the sea and atmosphere.	Mass abundance vs. molecular weight from 2-100 Da of liquid from target sea. MS^2 analysis of isotopes of CH4, C_2H_2, C_2H_4, C_2H_6, C_3H_8, C_4H_{10}.			
	1.2. Determine the age of methane in Titan's present day atmosphere, and search for evidence of renewal via internal outgassing.	Measure and compare isotopic ratios: ($^{14}N/^{15}N$; $^{12}C/^{13}C$; D/H; $^{16}O/^{18}O$) from mass spectra of the sea and atmospheric aerosols / gas at several levels in the atmosphere during descent.	Mass abundance vs. molecular weight from 2-100 Da of liquid from target sea. MS^2 analysis of isotopes of N_2, CH_4, C_2H_2, C_2H_4, C_2H_6, C_3H_8, C_4H_{10}, CH_3CN, HCN, C_2N_2, CH_2CH_2CN, HC_3CN.			
		Measure abundance of methane, ethane, and propane in atmosphere and liquid from mass spectra and search for fractionation.	Mass abundance vs. molecular weight from 2-45 Da of atmosphere at altitudes from 750-1100 km with 50 km altitude resolution; at sea level and in liquid from the target sea.	Mass range: 2-45 Da Mass resolution: 45 ($m/\Delta m$) @ 45 Da Sensitivity: at least 0.005 counts $molecule^{-1}$ cm^3 sec^{-1}		
		Detect He and H_2 (via Ion trap).	Mass abundance vs. molecular weight from 2-4 Da of atmosphere at altitudes from 750-1100 km with 50 km altitude resolution; at sea level and in liquid from the target sea.	Mass range: 2-4 Da Mass resolution: 2 ($m/\Delta m$) @ 2 Da Sensitivity: at least 0.005 counts $molecule^{-1}$ cm^3 sec^{-1}		
	1.3 Determine the thermal and dynamical state of the atmosphere above Kraken Mare	Record wind profile (speed and direction) during descent and after splashdown.	Wind speed and direction measurements during descent and after splashdown.		Environmental Suite (T, Press, RH, Wind)	
		Document vertical profile of temperature, pressure, and density during descent.	Measure environmental parameters (temperature, pressure, density, and methane RH) during descent.		Environmental Suite (T, Press, RH, Wind)	
		Determine surface temperature of sea liquid to within 0.1 K.	Measure sea surface temperature to +/- 0.1 K.		Environmental Suite (T, Press, RH, Wind)	
		Measure vertical profile of methane and ethane abundance from mass spectra during descent.	Mass abundance vs. molecular weight from 2-31 Da of atmosphere over altitude transects (100 km spacing).		Sea Probe MS redundant thermionic emission electron gun with redundant channel electron multipliers	
	1.4 Determine the physical state and composition of a Titan sea.	Determine the composition of the sea	Mass abundance vs. molecular weight from 2-200 Da in sea liquid from the target sea.	Mass range: 2-200 Da Capable of MS2 with 1 Da isolation width MS2 fragment mass window range is 50% of parent ion mass value Mass resolution: 2 ($m/\Delta m$) @ 2 Da and 200 ($m/\Delta m$) @ 200 Da Sensitivity: at least 0.005 counts molecule-1 cm3 sec-1	Mass range: 5-1000 Da Dynamic Range: 10^6 Resolution: up to 1000 (FWHM) Accuracy: +/-0.4 Da actual mass Sensitivity: at least 0.05 counts molecule-1 cm3 se	Acquire during and after splash down for depth resolution
		Measure bulk properties of the sea liquid.	Sound speed and permittivity.	Measure sound speed to 1% sensitivity over range of 1000-2000 m/s Measure dielectric constant to +/-0.01 over range 1-3	0.2% sensitivity over range of 200-3000 m/s Dielectric constant to +/-0.005 over range 1-3	Acquire after splashdown
		Constrain sea depth and characterize noise levels from sonar measurement.	Depth to < 5m accuracy over range of 10 - 500 m.	< 50 dB/Pa2/Hz	< 40 dB/Pa2/Hz (2 m accuracy over range of 10 - 2000 km)	Illuminate above waterline
		Document presence or absence of wave activity, floating films/debris, and possible currents.	Images of sea surface and IMU measurement of probe attitude.		Sea Probe Camera IMU	
		Determine turbidity of sea liquids from optical extinction.	Images of LEDs illuminated below waterline.		Sea Probe Camera (TURB)	Illuminate underneath waterline
2. Investigate whether Titan's seas support on-going prebiotic and/or biotic processes	2.1 Determine if Titan's organic chemistry involves biogenic elements (e.g., phosphorus and sulfur)	Measure the elemental chemistry of organic molecules in Titan's atmosphere, aerosols, and sea using mass spectrometry.	Mass abundance vs. molecular weight from 2-100 Da of liquid from the target sea.	Sea Probe MS redundant thermionic emission electron gun with redundant channel electron multipliers Mass range: 5-1000 Da Dynamic Range: 10^6 Resolution: up to 1000 (FWHM) Accuracy: +/-0.4 Da actual mass Sensitivity: at least 0.05 counts molecule-1 cm3 sec		
	2.2. Determine if reduced and/or oxidized organic species are available in the sea.	Inventory reduced organic species (saturated hydrocarbons and amines) and oxidized organic species (acetylene, ethylene, low mass nitriles such as acetonitrile) in the sea.	Mass abundance vs. molecular weight from 2-100 Da of liquid from the target sea.			
	2.3 Determine if processes consistent with biochemistry are operating on organic molecules in sea liquid.	Measure and compare isotopic ratios: $^{12}C/^{13}C$ and D/H in the alkanes in the sea and atmosphere using mass spectrometry.	Mass abundance vs. molecular weight from 2-100 Da of liquid from target sea. MS2 analysis of isotopes of CH_4, C_2H_2, C_2H_4, C_2H_6, C_3H_8, C_4H_{10}.			
		Compare mass distribution of organic molecules to that expected from abiotic synthesis (e.g., Poisson vs. non-Poisson) in sea liquid as compared to the atmosphere	Mass abundance vs. molecular weight from 2-500 Da of atmosphere at altitudes from 750-1100 km with 50 km altitude resolution; at sea level and in liquid from the target sea.			
	2.4 Determine the extent to which Titan's surface chemically communicates with its water-rich interior.	Measure the abundance of radiogenically-derived noble gases (e.g., 40Ar, 21Ne) in the sea.	Mass abundance vs. molecular weight from 2-50 Da of liquid from the target sea.			

2 HIGH-LEVEL MISSION CONCEPT

The previous Decadal Survey describes Titan as the most accessible location in the solar system for studying planetary organic chemistry, including prebiotic and potentially exotic biochemistries (Squyres et al. 2011). Understanding the abiotic organic synthesis occurring in Titan's atmosphere will shed light on the conditions of early Earth when life emerged and will answer questions regarding life's potential origins on other worlds (Hayes et al. 2015). At the same time, Titan hosts a complex hydrocarbon-based climate system that provides a natural laboratory for studying how planetary climates evolve and interact through surface-atmosphere exchange processes (Hayes et al. 2018). Titan's organic-rich surface material is transported within a source-to-sink sediment transport system that may provide pathways leading to exchange between surface organics and liquid water from the moon's vast subsurface ocean. Following on from the discoveries of the *Cassini* mission, Titan Orbiter + Probe will revolutionize our understanding of Titan's atmospheric chemistry, surface geology, and interior structure. The sea probe will further address the history of volatile exchange between Titan's atmosphere and interior, and characterize the environment and chemistry of an alien sea.

Following up on *Cassini*, a Titan orbiter (Oceanus) was proposed in response to the Ocean Worlds Theme in NASA's New Frontiers 4 announcement of opportunity (Sotin et al. 2016). Titan Orbiter + Probe is based on this proposal. The Oceanus proposal originally included a sea probe, but this element was descoped prior to proposal submission. This decision was made late in the process, however, after the sea probe had been designed. In the NF4 competition, Oceanus was considered low risk from a technical maturity and cost perspective but ultimately not selected for Phase A study. Based on the previous experience provided by Oceanus, the concept maturity of the Titan Orbiter + Probe missions is at or possibly above CML5. The mission concept has been detailed to the subsystem level, and has been shown to meet New Frontiers requirements for mass, power, and cost margins. Key elements of the mission design include:

- Launch between 2031 and 2039 with a 10 year EVEE transfer to Saturn.
- Deliver a Sea Probe to Kraken Mare for >4 hours of in-situ sampling of a Titan sea.
- Conduct a 2-year Saturn tour of 20 Titan flybys (18 aerosampling), enabling T-MASS science and global imaging.
- Spend 2-years in Titan orbit to enable T-CAM, T-ALT, and T-GRAV observations.
- Flight system derived from high-heritage deep-space designs with robust technical margins.
- MegaFlex solar array with high-efficiency LILT-screen collar cells.

2.1 TECHNOLOGY MATURITY

With one exception, the Titan Orbiter + Probe science payload and spacecraft components are all TRL 6 or above. At the systems level, T-MASS is considered TRL 5 until prototype demonstration of functional performance in a relevant environment. The maturation plan for T-MASS is described below. The Titan Orbiter spacecraft and Sea Probe require no new technologies or advanced engineering developments.

2.2 KEY TRADES

Several trade studies were conducted during the design of the Titan Orbiter + Probe concept. While some decisions were made, others were put off for future proposers to consider. The key trades are listed in Table 2 below:

Table 2: Trade studies.

Trade Study	Options considered	Selected approach
Power Source	Both solar arrays and MMRTG or newer RTG are viable power options.	Megaflex solar arrays chosen, but the mission can be implemented with RTGs as well. Solar array orientation can be optimized while in inner solar system to minimize momentum accumulation. Newer solar cell technology can be considered.
Radar vs. Laser Altimeter	A 1 or 5 micron laser altimeter (similar to MOLA, but operating at a different frequency to penetrate Titan's atmosphere) could be used instead of a radar.	RADAR chosen for heritage concerns and interest in foreign contribution.
Use of SSPA instead of TWTA in T-ALT	SSPA could lower cost, shorten development schedule. Trade off is heritage, and reduced power efficiency.	TWTA maintained for heritage reasons.
Launch vehicle	Falcon Heavy or Atlas V551	Atlas chosen for NF4 implementation, but newer launch vehicles (e.g., Falcon Heavy) should be considered by future proposers.
Descope Probe	Removing the sea probe represents the primary descope option for Titan Orbiter + Probe.	The sea probe was descoped in the NF4 proposal but, given changes to AO parameters and intervening technology development, it is recommended to be included in future proposals and is included here.

3 TECHNICAL OVERVIEW

3.1 INSTRUMENT PAYLOAD DESCRIPTION

The concept payload for the Titan Orbiter features an in-situ instrument (T-MASS), two remote-sensing systems (T-CAM and T-ALT), and one investigation (T-GRAV). The Sea Probe features an in-situ instrument (S-MASS), a camera system (S-CAM), and an environmental suite (S-ENV). These instruments were selected to meet the requirements of the Science Traceability Matrix (Tables X and Y) while also satisfying additional mission constraints such as total mass and power consumption for the Orbiter and Sea Probe (Tables X and Y, respectively). All six payload elements can be built today using existing technologies and require no new technology development.

T-MASS: MASS SPECTROMETER: T-MASS is a compact, rugged mass spectrometer that will profile Titan's atmospheric constituents from 2 to 500 Da (performance 2–1000 Da) with high sensitivity (0.05 counts/molecule/cm^3/s) and accuracy (m/Δm from 20 at 2 Da to 5000 at 1000 Da), and features a multi-stage mass spectroscopy capability. T-MASS is based on a JPL's Quadrupole Ion Trap Mass Spectrometer (QITMS) that has been developed under both the NASA Instrument Concepts for Europa Exploration (ICEE) program (Darrach et al. 2015) and through substantial JPL strategic investment beginning in FY2012 and continuing to the present. All of the QITMS components are at TRL 6 or above and systems-level TRL 6 for Titan can readily be achieved by qualifying the instrument for hypervelocity sampling of Titan's atmosphere using the Hypervelocity testing facilities at Montana State University and the California Institute of Technology. The individual components of T-MASS can be seen in Figure 4.

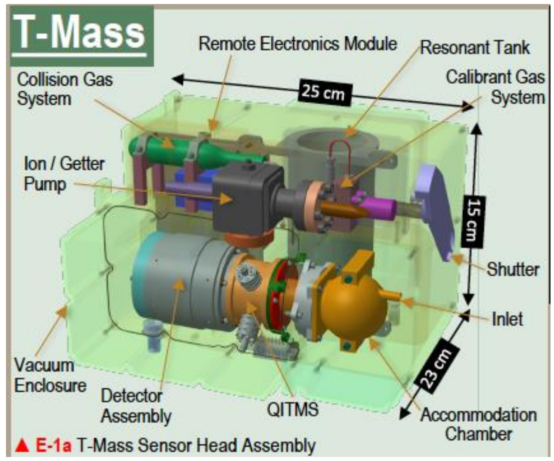


Figure 4: T-MASS Sensor Head Assembly.

T-CAM: INFRARED IMAGER: T-CAM observes Titan's surface at 25 m/pixel simultaneously at 5 and 2 µm yielding < 70 m resolution, and 1.3 µm yielding < 400 m resolution, revealing the geology of Titan's surface at spatial scales that are more than order of magnitude improved over the best observations from Cassini. Provided resolutions are comparable to Huygens DISR images (see Figure 5 at right). The instrument consists of a 40-cm aperture, f/2.7, three-mirror anastigmat (TMA) telescope coupled to a Teledyne 5.3-µm-cut-off 2kx2k-H2RG detector driven by Teledyne's SIDECAR ASIC Focal Plane Electronics package and a Xilinx Virtex-5 FPGA for digital processing. Filter strips are directly bonded to the detector. All subsystems are technologically mature (TRL 6 or greater) and T-CAM requires only standard engineering development. At 2 and 5 µm, T-

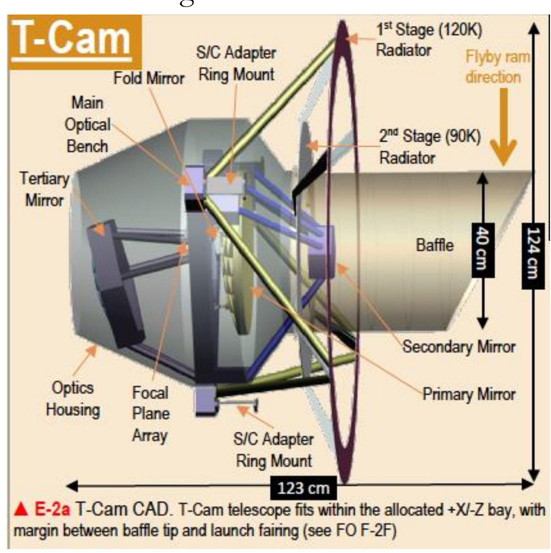


Figure 5: T-CAM CAD model.

CAM images are diffraction-limited as > 90% of unabsorbed photons escape from Titan's surface unscattered (Barnes et al. 2013). Digital Time Delay Integration (dTDI) is used to improve the T-CAM Signal-to-Noise Ratio (SNR). The Titan Orbiter maps from a 1500-km orbit with a 938 m/s ground speed. For T-CAMs' ~17 µrad Instantaneous Field of View (IFOV), this yields a scale of 25 m/pixel and a rate of 26.7 ms per line. To keep the solar arrays Sun-pointed during Titan orbit Oceanus rotates about the nadir vector, resulting in a slightly skewed scene movement relative to pixel columns/rows. T-CAM accounts for this by using diagonal TDI (McEwen et al. 2012). The DPU aligns images using the predicted scene range and angle.

T-ALT: RADAR ALTIMETER: T-ALT provides the data needed to derive Titan's geophysical parameters (e.g., Tidal Love Number) and produce a global-scale topographic map using mature technologies and heritage components. Altimetry data are acquired with an X-band (8.4 GHz) 100-MHz bandwidth pulsed linearly polarized radar altimeter. T-Alt's 100 W amplifier transmits bursts of 18 pulses to avoid range ambiguities while allowing Doppler processing. X-band was chosen so that T-ALT can share the telecom systems antenna/ feed and leverage the flight heritage of the X-band Travelling Wave Tube Assembly (TWTA). T-ALT shares the MRO-heritage 3 m antenna and combines the X/Ka-band feed horn with the telecon sub-system. T-ALT itself consists of a digital board assembly that performs waveform generation and onboard processing, a frequency synthesizer that generates clock signals, a power generation module, an X-band TWTA to amplify the signal, a high-power front end that directs the transmitted / received waveforms to / from the antenna, an upconverter / downconverter assembly that translates the output of the waveform generator to the final 8.4 GHz frequency and down-converts received echoes back to the 240 MHz baseband, and a power conversion unit. All of these components are mature and have substantial flight heritage (e.g., Cassini, SHARAD, MARSIS, etc.). To meet downlink constraints, T-ALT performs onboard processing and compression of the returned radar echoes. The primary processing mode takes echo data from each 18-pulse burst and compresses it using a matched filtering algorithm (Cumming and Wu, 2005), then coherently and incoherently combines the data into echo profiles. This results in 316 Mb per pulse train track (one per day) to be downlinked. For developmental debugging, infrequent onboard processor checkout, and data calibrations in flight, a different raw echo compression algorithm converts the 12-bit ADC data to 4 bits using a Block Adaptive Quantizer compression (BAQ) (Kwok and Johnson, 1989).

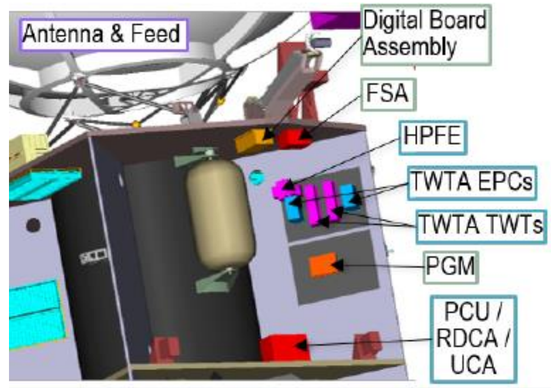


Figure 6: T-ALT CAD model, showing that the configuration accommodates thermal and proximity constraints and fits easily in the available space. Summed volume for all T-ALT boxes is 0.0222 m^3 vs. 1.3 m^3 available in the spacecraft instrument bay.

T-GRAV: GRAVITY SCIENCE: The T-GRAV investigation leverages the orbiter's telecom system to perform two-way S/C Doppler tracking, provide data to determine Titan's gravity field (and thus k2), and produce an accurate orbital ephemeris to supplement T-ALT investigations. T-GRAV imposes a requirement for spacecraft-to-Earth range-rate accuracy of 3.0 µm/s @ 1000 s integration (capability 2.5 µm/s; 20% margin) and produces its own set of science products. The requirement of 3.0 µm/s @ 1000 s integration implies the use of Advanced Water Vapor Radar (AWVR) at the DSN station. This equipment is currently available, and is in the process of being upgraded to support ESA's JUICE mission.

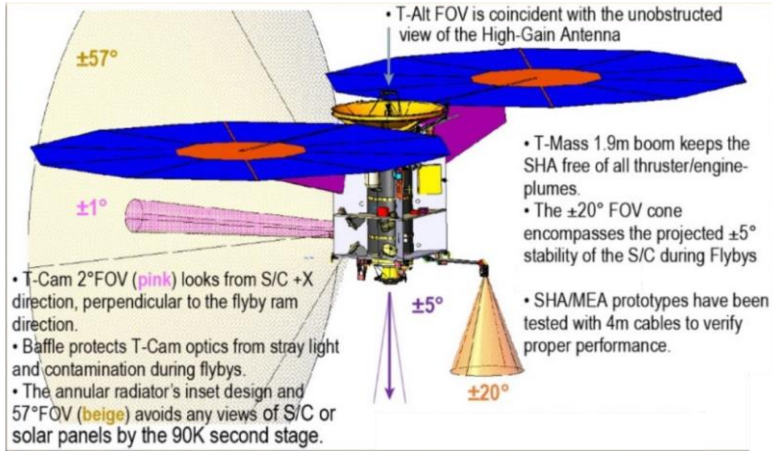


Figure 7: The orbiter provides unobstructed FOVs for the T-MASS inlet and T-CAM optics and radiator. The T-ALT FOV is coincident with the HGA and also has a clear view.

Table 3: Orbiter instrument parameters.

Item	T-MASS	T-CAM	T-ALT
Size / Dimensions (m^3)	0.086	0.20	0.022
Mass CBE (kg)	11.6	56.2	43.2
Operating Power (W) (Peak / Average)	75 / 55	52 / 29	166 / 166
Data Rate	112 Mb/flyby	319 Mb/day	316 Mb/day
Field of View	N/A	2°	4.3 km footprint

S-MASS: SEA PROBE MASS SPECTROMETER: The Sea Probe mass spectrometer utilizes ion trap gas chromatography to measure the trace components of a Titan sea, including noble gases and their isotopes, over the mass range of 5–1000 Da with a resolution (m/Δm) of up to 1000, Dynamic Range of 10^6, and accuracy of +/– 0.4 Da actual mass. It is based on a linear ion trap mass spectrometer developed by the NASA Goddard Space Flight Center (GSFC) and has substantial flight heritage. The fluid inlet system is based on a TRL 6 design developed for the Titan Mare Explorer (TiME) Discovery concept while everything else, including the gas inlet, processing, and pumping mechanisms, have heritage tracing back to the Huygens, SAM, and MOMA instruments. The gas chromatography heritage is SAM. A CAD model of the S-MASS system configuration is shown in Figure 8.

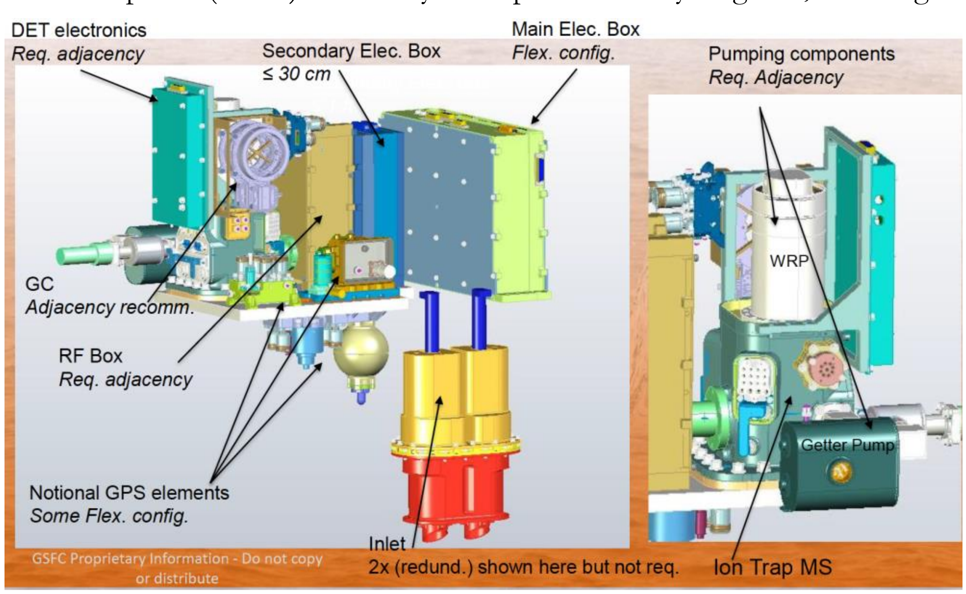


Figure 8: S-MASS System.

Figure 9: MSSS ECAM 50 DVR (left) and camera head (right).

S-CAM: SEA PROBE CAMERA: The Sea Probe camera is a high-heritage visible engineering camera based on the Malin Space Science System (MSSS) E-CAM product line. The camera will utilize a visible-band Aptina 5 MP CMOS detector driven by an MSSS Digital Video Recorder (DVR). The camera will look up through a window into an inverted parabolic mirror, providing a 360°of the probe's surroundings. All components of S-CAM are TRL-9 with substantial flight heritage. The detectors and electronics are the same as those flying on Dragonfly.

Table 4: S-ENV Characteristics

	Temperature	Pressure	Accel.
Manufacturer	Cernox	Honeywell	Honeywell
Model	SD-HT	PPT2-0050AKK_VEE	Q-Flex QA3000
Accuracy	+/- 18 mK	0.001% FS	< 0.04 mg
Range	20–325 K	0–3.45 bar	+/- 60 g
Mass	40 mg	125 g	71 g
Current	N/A	50 mA	< 16 mA
Unit Price	~$1K	$1.6k	~$1K

S-ENV: ENVIRONMENTAL SENSOR SUITE: S-ENV is a high-heritage Environmental Sensor Suite that will monitor temperature, pressure, and acceleration. The temperature series are based on the Cernox HR series with JWST heritage. The Honeywell PPT2 pressure sensor is space-qualified and has accuracy sufficient to make absolute pressure measurements comparable to those performed by the Huygens probe. The QA-3000 accelerometers have been flown on multiple missions (e.g., Phoenix, Rosetta, Curiosity, GRAIL, Juno, Maven, MRO, New Horizons, Perseverance, etc.).

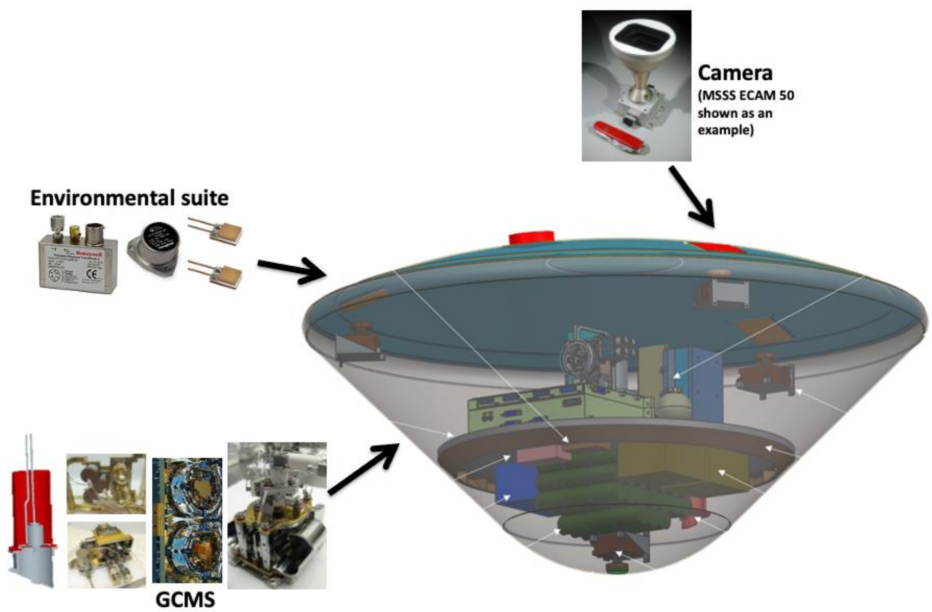
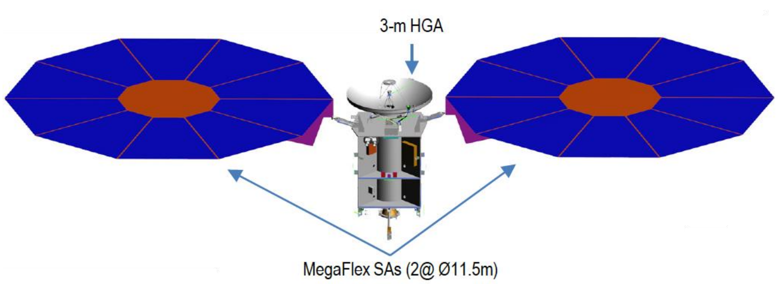


Figure 10: Sea Probe configuration showing the locations of S-MASS, S-CAM, and S-ENV.

3.2 FLIGHT SYSTEM

A representative spacecraft for the Titan Orbiter + Probe mission is shown in Figure 11. Subsystem mass and power for the Orbiter and Sea Probe are listed in Tables 5, 6, and 7, respectively. A particular mission will have many design choices for instrument accommodations that will result in adjustments to the spacecraft shown here. The representative flight system includes 11.5 m MegaFlex Solar Arrays for power, but the proposed mission architecture could easily accommodate Radioisotope Thermoelectric Generators (RTGs) or more advanced solar arrays. We view the representative spacecraft to be conservative on mass and power with multiple launch opportunities that provides many options to further reduce mass and power at low risk.



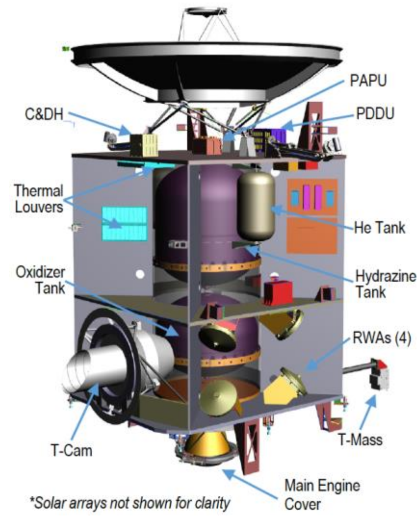


Figure 11: Example spacecraft configuration for the orbiter.

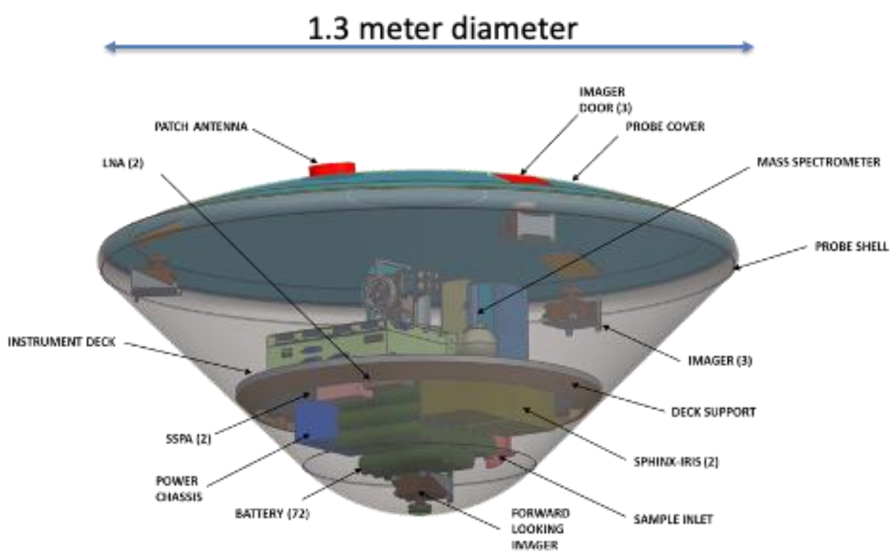


Figure 12: Example configuration for the Sea Probe.

Table 5: Orbiter Mass

Subsystem	Mass, kg		
	CBE	Contingency	MEV
C&DH	13.3	5.0%	13.9
EPS	371.2	8.1%	401.2
Telecom	52.7	6.5%	56.1
ACS	75.5	5.0%	79.2
Thermal Control	41.7	15.6%	48.2
Structures	219.9	18.6%	260.7
Mechanisms	41.9	21.9%	51.1
Propulsion	176.2	8.5%	191.3
Harness	70.7	24.8%	88.3
Science Payload	83.5	32.8%	111.0
Total Flight Sys. Dry Mass	**1146.4**	**13.5%**	**1300.9**
		Flight System Dry Mass Margin	27.3%
		Max. Attainable Dry Mass**	1655.4

Table 6: Orbiter Power System Characteristics

Type of array structure	MegaFlex
Solar array axes of rotation	Y-axis + Sweep along Z-axis
Array size	11.5 m dia
Solar cell type	ZTJ
Solar cell efficiency	34% at Saturn
Expected power at beginning of life	660.4 W @ 9.4 AU
Expected power at end of life	602.0 W @ 9.4 AU
Worst-case Sun incidence angle	0 degrees nominal
Battery type	Li-Ion
Battery storage capacity	78 Ahr
Worst-case battery depth of discharge	57% (Saturn Orbit Insertion)
S/C bus voltage	28 V

Table 7: Sea Probe Mass and Power Characteristics

Sea Probe	CBE Mass (kg)	Cont. (%)	Total Mass (kg)	Heritage/Comments
Instruments	15.8	18%	18.6	MOMA/Huygens/MSL
C&DH	0.5	23%	0.6	Sphynx dual string
Power	11.2	30%	14.5	Batteries
Telecom	7.3	25%	9.1	Electra
Structures	27.1	30%	35.3	
Thermal	2.9	29%	3.7	
Probe Total	**64.8**	**26%**	**81.9**	
System Margin			10.8	
Dry Mass Total		**43%**	**92.6**	
Entry System	113.0	0.3%	146.9	Aeroshell + parachutes
Probe Entry Mass Total			**239.5**	

Table 8: Flight System Characteristics

Flight System Element Parameters (as appropriate)	Value/ Summary, units
General	
Design Life, months	180
Structure	
Structures material (aluminum, exotic, composite, etc.)	Composite, Aluminum
Number of articulated structures	2 (Solar Arrays)
Number of deployed structures	2 (Solar Arrays)
Aeroshell diameter, m	1.3 (Sea Probe)
Thermal Control	
Type of thermal control used	Passive, MLI, Heat Pipes, Louvers
Propulsion	
Estimated delta-V budget, m/s	2055
Propulsion type(s) and associated propellant(s)/oxidizer(s)	Regulated bipropellant
Number of thrusters and tanks	16 ACS Thrusters 3 TCM Thrusters 1 Main Engine 2 Pressurant Tanks 1 Ox Tank 1 Fuel Tank
Specific impulse of each propulsion mode, seconds	Bi-prop: 318 s; Monoprop: 228 s
Attitude Control	
Control method (3-axis, spinner, grav-gradient, etc.).	3-axis
Control reference (solar, inertial, Earth-nadir, Earth-limb, etc.)	Inertial, Nadir, Solar
Attitude control capability, degrees	0.25 mrad
Attitude knowledge limit, degrees	< 30 arcseconds
Agility requirements (maneuvers, scanning, etc.)	DSM
Articulation/#–axes (solar arrays, antennas, gimbals, etc.)	2 axes for Solar Arrays
Sensor and actuator information (precision/errors, torque, momentum storage capabilities, etc.)	3 mm/s lateral, 2 mm/s axial (ME burn)
Command & Data Handling	
Flight Element housekeeping data rate, kbps	46.6 (X), 58.2 (Ka)
Data storage capacity, Mbits	64,000 (64 Gb)
Maximum storage record rate, kbps	30 Mbps per instrument (50 Mbs combined rate)
Maximum storage playback rate, kbps	300 Mbps internal, downlink data rates of 7.2 kbps (X-band) and 50 kbps (Ka-band)
Power	
Type of array structure (rigid, flexible, body mounted, deployed, articulated)	MegaFlex
Array size, meters x meters	11.5 m diameter
Solar cell type (Si, GaAs, Multi-junction GaAs, concentrators)	ZTJ
Expected power generation at Beginning of Life (BOL) and End of Life (EOL), watts	34% efficiency at Saturn, 660.4 W at 9 AU (BOL) and 602.0 W at 9 AU (EOL)
On-orbit average power consumption, watts	344.4 W
Battery type (NiCd, NiH, Li-ion)	Li-ion
Battery storage capacity, amp-hours	78 Ahr

3.3 CONCEPT OF OPERATIONS AND MISSION DESIGN

The Titan Orbiter + Probe mission includes a 10 year ballistic interplanetary cruise with flybys of Venus and Earth to reach Saturn. After Saturn Orbit Insertion (SOI), the spacecraft begins a 26-month Saturn tour phase including 20 flybys (18 aerosampling) of Titan at various altitudes to meet mission requirements. The Sea Probe will be released on the 3rd orbit around Saturn, ~350 days after SOI. After release, the probe coasts for 18 days prior to splashdown in Kraken Mare within a landing ellipse of 298 × 58 km (see Figure 13). The Sea Probe will enter Titan's atmosphere at ~4.4 km/s and an entry angle of ~70°. During an ~1.5 hour descent, the Sea Probe environmental sensor suite (S-ENV) will continuously monitor atmosphere temperature and pressure, while S-MASS will acquire one in-situ sample at 100 km altitude for detailed compositional analysis. For a sea density of ~500 kg/m^3, the probe will plunge to a depth of ~1.9 m upon landing prior to returning to the sea surface. Following splashdown the probe will operate for > 4 hours and communicate via one-way communication to the orbiter, transmitting at least 155 Mb of data.

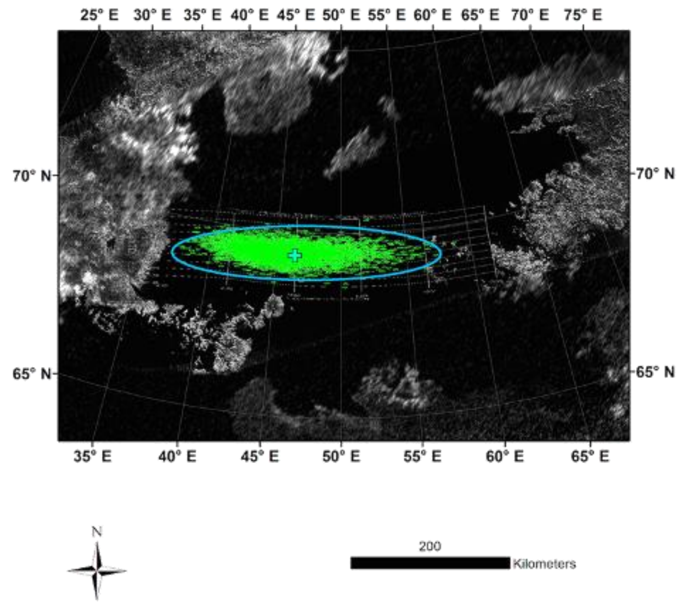


Figure 13: 3-Sigma landing ellipse for the sea probe in Kraken Mare from a Monte Carlo analysis using a variety of models for Titan's atmospheric winds.

At the end of the 2-year Saturn tour and T-MASS measurement campaign, the spacecraft will insert into a circular, near-polar (96°), 1500-km science orbit around Titan. The 27-month Titan orbit phase begins with an apparent Local Solar Time at Ascending Node (LTAN) of 8:30 am, which naturally progresses to 7:51 am by the end of the mission. The resulting Titan science orbit geometry avoids eclipses, ensures robust margins for power and downlink, and delivers excellent observing geometries for T-CAM, T-ALT, and T-GRAV measurements. Upon completion of the science mission, a small deorbit burn places the spacecraft into a controlled decay orbit, resulting in break-up within Titan's atmosphere.

4 DEVELOPMENT SCHEDULE AND SCHEDULE CONSTRAINTS

4.1 HIGH-LEVEL MISSION SCHEDULE

Table 9: Durations of key mission phases

Project Phase	Duration (Months)
Phase A - Conceptual Design	6
Phase B - Preliminary Design	16
Phase C - Detailed Design	19
Phase D - Integration and Test	17
Phase E - Primary Mission Operations	173
Phase F - Extended Mission Operations	TBD
Start of Phase B to PDR	13
Start of Phase B to CDR	25
Total Development time Phases B-D	52
Project Total Funded Schedule Reserve	3.8 (+26 months of schedule slack for T-MASS TRL6 development)

4.2 TECHNOLOGY DEVELOPMENT PLAN

Titan Orbiter + Probe required no new technologies or advanced engineering developments. A maturation plan for the T-MASS instrument, currently at a systems-level TRL 5, involves requalification of the instrument for the orbiter's hypervelocity sampling of Titan's atmosphere. Two activities are planned to bring T-MASS to TRL 6 prior to PDR. The first involves testing at the hypervelocity facilities at Montana Status University and California Institute of Technology to demonstrate that instrument performance exceeds expectations. The second involves the integration, environmental qualification, and performance validation of the full Sensor Head Assembly at JPL. The mission concept is designed around flight-proven systems, subsystems, components, verification methods, and operational procedures.

5 MISSION LIFE-CYCLE COST

Including 30% reserves, Titan Orbiter + Probe has a Phase A-D PI Managed Mission Cost of $1.0B in FY22 dollars (Table 10). Imposing the 50% reserves applied to lower maturity mission studies, the total Phase A-D cost would be $1.2B. These totals fit within the target New Frontiers cost outlined in the Decadal study guidelines. The primary descope option would be to remove the Probe, which would save $150M in direct costs with additional savings on reserves, operations, and mass.

Table 10: PI-Managed Mission Cost

Work Breakdown Structure	Titan Orbiter + Probe Cost (FY22 $M)
01 Project Management	**25**
02 Project Systems Engineering	**22**
03 Safety & Mission Assurance	**28**
04 Science and Technology	**32**
05 Payload (Orbiter Only)	**82**
T-MASS	40
T-CAM	28
T-ALT	14
06 Flight System (Orbiter + Probe)	**488**
Orbiter	372
Probe & Probe Payload	127
07 Mission Operations	**27**
09 Ground Data Systems	**22**
10 System I&T	**42**
Orbiter I&T	42
12 Mission Design & Nav	**8**
Subtotal (w/o reserves)	**776**
Reserves (30%)	232
Reserves (50%)	388
Total PI-MM Cost (30% Reserves)	**1008**
Total PI-MM Cost (50% Reserves)	**1164**

A ACRONYMS

BAQ	Block adaptive quantizer
BOL	Beginning of life
DNA	Deoxyribonucleic acid
dTDI	Digital time delay integration
EOL	End of life
FPGA	Field-programmable gate array
GCM	General circulation model
IFOV	Instantaneous field of view
LTAN	Local solar time at ascending node
MRO	Mars Reconnaissance Orbiter
NIR	Near infrared
PAHs	Polycyclic aromatic hydrocarbons
QITMS	Quadrupole ion trap mass spectrometer
RTG	Radioisotope thermoelectric generator
SOI	Saturn orbit insertion

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