ORACLE: A Sample-Return Mission to Titan

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With a hazy atmosphere, a hydrocarbon cycle, seasons, and a diverse set of surface features, Titan is one of the most unique objects in the Solar System. Further exploration of Titan can elucidate its geologic activity, chemical history, and astrobiological potential. While one-way missions can provide a wealth of information about Titan through remote sensing, in-situ measurements, and communication relays back to Earth, returning samples from Titan allows for unparalleled scientific analysis. Here, we propose a novel mission concept to explore and analyze Titan *in situ* and return samples from its hydrocarbon lakes. Within ORACLE, a separate lander and orbiter segment will perform all the scientific investigations and collect the hydrocarbon lake samples. After collection of the samples, another segment will return the samples to Earth while the lander and orbiter continue investigating Titan. This mission concept demonstrates novel Titan lake sampling technology and incorporates sample return and in-situ scientific investigation to significantly increase our understanding of Titan, with far broader planetary science implications.

I. Nomenclature

C_3 = characteristic energy
ΔV = delta-v

II. Introduction

Titan's hazy atmosphere hosts a unique hydrologic cycle, raining hydrocarbons onto one of the most geologically and chemically dynamic bodies in our Solar System. With latitudinally stratified surface features, Titan is the only accessible site of surface liquids in the Solar System outside of Earth. Further exploration of Titan's rich liquid organic chemistry can help improve current astrobiological hypotheses about the environments and conditions that are potentially hospitable to life. While one-way surface missions can provide valuable information about Titan, the propulsive and thermal engineering challenges involved restrict the delivered scientific instrumentation to a small, fixed set that may be unable to identify complex or foreign biomarkers. In-situ analysis paired with sample return to Earth yields transformative scientific discovery. We propose a novel mission concept to explore and analyze Titan *in situ* and return samples from its hydrocarbon lakes for further analysis: The Orbit, Return, and Analysis of a hydroCarbon Lake sample Expedition (ORACLE). Within ORACLE, separate lander and orbiter segments work together to conduct scientific investigations of Titan's polar lake regions and collect solid, liquid and gaseous samples from and around the hydrocarbon lake Ligeia Mare. After collection and analysis, the samples are returned to Earth, while the lander and orbiter conduct a multi-year exploration of Titan.

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This is a peer reviewed, accepted author manuscript of the following conference contribution: Marlin, T. C., Gentgen, C., Fodde, I., Groshaus, J., Hennig, A., Hudson, B., Lin, A., Pabarcius, L., Smith, E., Vilchis Lagunes, N., Wall, M., Jiang, R., Mahendrakar, T., Shimane, Y., Christuraj, E., & Gammill, M. E. (2022). ORACLE: A sample-return mission to Titan. In ASCEND 2022 [4372] American Institute of Aeronautics and Astronautics Inc. (AIAA). https://doi.org/10.2514/6.2022-4372

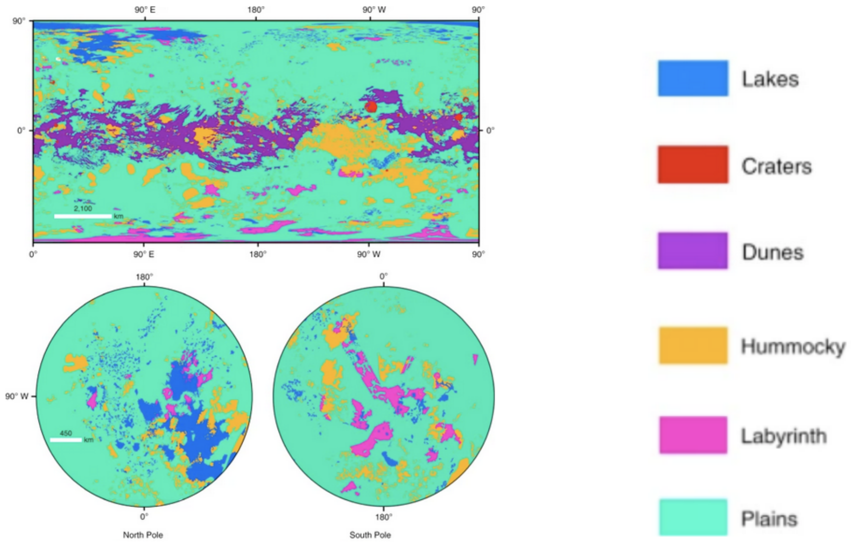


Fig. 1 Global geomorphological map of Titan's entire surface (top) and two polar regions (bottom). Figure from Lopes et al., 2020 [2].

III. Science

A. Titan: A Dynamic Wonderland

In the early 1980s, the two *Voyager* spacecraft took the first "close-up" images of Saturn's largest moon Titan, revealing a surface shrouded in haze. Several decades later, the *Cassini* orbiter became the first spacecraft to orbit in the Saturnian system, conducting 126 flybys of Titan and revolutionizing our understanding of this moon. The partner ESA probe, *Huygens*, descended to Titan's surface in 2005, taking atmospheric measurements during descent and relaying the first in-situ images of Titan's surface. The *Dragonfly* spacecraft is planned to land in and navigate around Titan's equatorial regions in 2034.

Cassini's infrared and radar instruments allowed first glimpses at the surface beneath Titan's dense atmosphere. With the Synthetic Aperture Radar instrument of *Cassini*, approximately 46% of Titan's surface was able to be mapped to relatively high resolution (less than 1 km) [1]. Paired with less sensitive instrumentation (the Imaging Science Subsystem and the Visible and Infrared Mapping Spectrometer), a global geomorphological map of Titan was created, revealing a world unlike any other in our solar system (Fig. 1) [2]. Strikingly, the reconstructed map of Titan reveals a latitudinally stratified world. Dunes and "hummocky" (mountainous) terrain dominate equatorial regions, while hydrocarbon lakes and highly dissected labyrinth terrain appear at the poles.

Titan is very sparsely cratered; the number of potential impact crater sites numbers less than one hundred [3], indicating a young and geologically active surface. This is a stark contrast to many solar system satellites, which are so heavily cratered that new cratering sites are layered on top of pre-existing crater sites [4].

Titan feels remarkably like Earth in some aspects, and yet completely foreign in others. Titan is the only moon with a substantial atmosphere; at 1.5 bars, Titan's surface pressure exceeds that of Earth. Like Earth, Titan's atmosphere is dominated by nitrogen gas (N_2- roughly 95% on Titan [5] vs. 78% on Earth). Whereas the second dominant species in Earth's atmosphere is oxygen at 21%, Titan's atmosphere is oxygen-free, instead containing methane (CH_4) as the secondary species [5]. Titan's atmosphere is a potential early Earth analog, as Earth's atmosphere was once oxygen-free as well prior to the Great Oxygenation Event [6].

Although nitrogen and methane in themselves are not extremely reactive, sunlight and energetic particles hitting the atmosphere cause dissociation and ionization. Subsequent recombination leads to photochemical synthesis of complex organic species, as shown in Fig. 2. Heavier species drift lower in the atmosphere, and it is hypothesized that they eventually deposit on the surface [7].

Due to its axial tilt, Titan experiences seasons just as Earth does. At a distance of 9-10 AU, Titan receives a very small fraction of the insolation that Earth does. Titan is relatively isothermal, with surface temperatures varying between 89 and 95 K regardless of season and latitude. The low surface temperature and high surface pressure of Titan

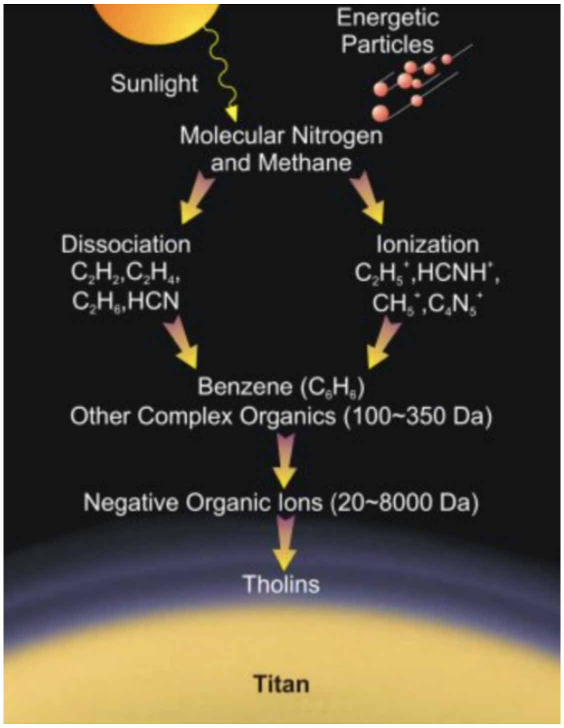


Fig. 2 Photochemistry occurring in Titan's atmosphere. Figure from Waite et al., 2007 [7].

lead to a unique phenomenon: Titan's surface conditions are near the triple point of methane, just as Earth's surface conditions are near the triple point of water. Thus, Titan is the only other known body in our solar system to experience a hydrologic cycle: rain, clouds, storms, and surface liquid bodies of hydrocarbons.

Titan is perhaps the most compelling astrobiological target in our solar system. With both a subsurface water ocean and surface bodies of hydrocarbon liquids, Titan offers two unique types of solvents in which life could exist. Biosignatures from life in the deep subsurface water ocean could potentially be brought up to the surface via impact melt or cryovolcanism; *Dragonfly* will search for these in the equatorial regions [8].

However, neither *Dragonfly* nor *Huygens* focus(ed) on the hydrocarbon lake-containing polar regions of Titan. While we would expect life in Titan's subsurface water ocean to be fairly Earth-like, the same cannot be said for potential life in the non-polar surface bodies of liquid. These lakes offer a compelling target for astrobiology, understanding non-Earth hydrology, and contextualizing geodynamic processes elsewhere in the solar system. Above all, Titan is an integrated world, where geology, hydro(-carbon-)ology, and photochemistry combine in an endlessly dynamic dance.

B. Background: *Cassini* and Ligeia Mare

Cassini's RADAR instrument gathered data of the northern lake Ligeia Mare through nine separate flybys conducted between February 2007 and January 2015 [9]. These efforts allowed the eventual construction of a topographic map of Ligeia Mare [8]. Of the Titan flybys that targeted Ligeia Mare, all but one were conducted using the synthetic aperture radar mode of the instrument. However, one flyby – the 91st Titan flyby conducted on September 23, 2013 – instead leveraged the RADAR altimeter to perform bathymetry on Titan's Ligeia Mare.

The T91 flyby sliced across a narrow segment of Ligeia Mare, accounting for less than 1% of the sea's surface area (Fig. 3) [9]. The time difference between echoes from the surface and the bottom of the sea allowed for determination of the depth of the sea as a function of latitude as *Cassini* passed by Titan. Data from the T91 flyby also allowed derivation of the dielectric constant throughout the flyby path. The data from this flyby is consistent with a sea composition that is dominated by methane [9].

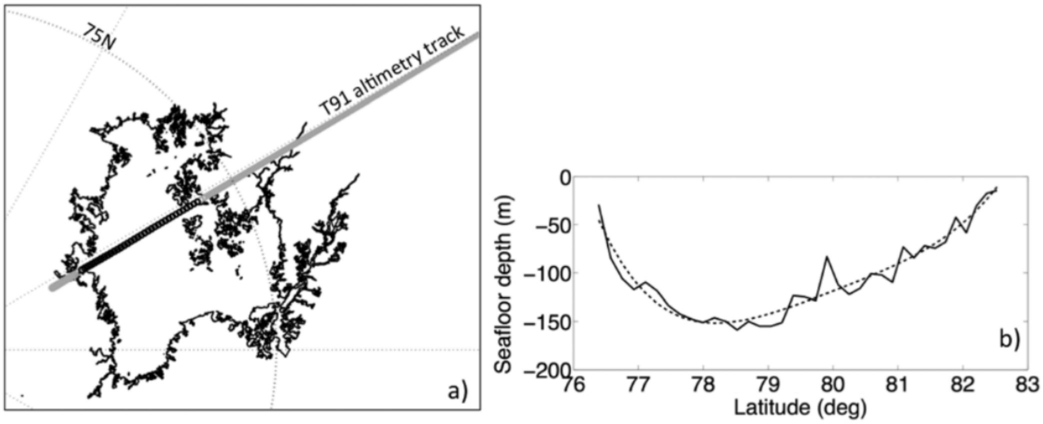


Fig. 3 ***Cassini*** **altimetry flyby of Titan's Ligeia Mare and corresponding derived seafloor depth. Figure from Le Gall et al., 2016 [10].**

C. Science Goal 1: Sample return

Science target: Collect solid, liquid, and gaseous samples from an outer solar system planetary body and return them to Earth for further scientific analysis.

The instrumentation and capabilities that are contained within an in-situ spacecraft are necessarily limited compared to the capabilities that scientists have in laboratories on Earth. To date, we have never returned a sample of any type from the outer solar system. The unique characteristics of Titan make it a high-priority target for sample return. This mission will ***return the first suite of samples – solid, liquid, and gas phase –*** from Titan to Earth for further scientific analysis.

D. Science Goal 2: Profile of a Titan sea

Science target: Conduct a thorough characterization of Ligeia Mare, Titan's second largest body of surface liquid, to constrain its habitability and prebiotic potentials, using a small suite of instruments.

Current literature is in agreement that Ligeia Mare is predominantly methane, but the estimates for the exact methane-ethane-nitrogen compositional ratio vary widely [10, 11]. We will ***investigate the precise composition of the sea liquid at varying depths***. The differing densities of methane and ethane suggest a potentially non-homogenous composition with depth, highlighting the importance of taking measurements at various depths. Additionally, seafloor depth and distance from the shore likely play a role in the dominant processes, so the derivation of a profile spanning both breadth and depth of the sea is critical. Understanding hydrocarbon compositional ratios and how they vary with depth and spatial position throughout the sea offers insight into the interchange and balance among hydrological, photochemical, and geological processes that are prevalent on Titan.

Corresponding atmospheric measurements will be taken from the air immediately above the lake. Although the air above the lake is expected to be more or less spatially and compositionally homogeneous, studying the air above the lake is critical to understand the environment with which the sea is directly interacting [12].

Although Titan's hydrocarbon lakes are predominantly composed of hydrocarbons (methane and ethane) and potentially dissolved nitrogen, no singular feature of Titan is isolated. The possibility of deposition and subsequent dissolution of photochemical species from the atmosphere into the lakes, seas, and rivers should not be discounted.

Laboratory studies of various Titan-relevant photochemical species and their solubilities in liquid methane and ethane yield varying results. Modeling suggests that Titan lakes are likely not saturated in species with higher solubility, instead having distributions and abundances that may vary throughout seasons and weather patterns [13].

Conversely, species with lower solubilities (such as benzene and its derivatives) may saturate more readily. Laboratory work suggests that a hydrocarbon lake could be saturated with benzene on Titan and thus have a layer of condensed benzene "sludge" at the bottom of the lake [14]. Organic species layering on lake/ocean floor beds could also be influenced by fluvial transport [10].

Characterizing the dissolved organics species levels in the sea and their distribution with depth and spatial layout in the lake is critical to understanding the interactions between Titan's hydrology, fluvial character, geology, and photochemistry. Comparison of samples taken at different depths in the sea will inform deposition trajectories and studying varying places in the lake will allow an understanding of the interplay between fluvial transport and atmospheric deposition of organics.

Stable isotope measurements (hydrogen, carbon, and noble gas) provide insight into the origins and modification of Titan's unique atmosphere as well as the habitability potential of Titan's lakes and seas. Titan's non-polar lakes and seas present a fascinating alternative solvent for life. Modeling work has proposed the possibility of "azotosome" membranes on Titan: inverted membranes with non-polar head groups and polar tails [15]. Although the chemistry and biology of microbial life in a non-polar solvent would be inherently different than life found on Earth, the elements are the same and some universal governing principles can be reasonably expected.

Life on Earth preferentially incorporates the lighter carbon isotope. This preference can be characterized when comparing the ^{13}C/^{12}C ratios in a biotic sample to a standard sample [16]. The δ^{13}C in the lake could serve as a biosignature detection mechanism. If a significant variation in δ^{13}C is observed relative to the atmospheric ratio or there are spatial differences throughout the lake, this could suggest extant microbial life in Titan's surface lakes.

IV. Mission Overview

A. System Architecture

A multi-vehicle architecture is used to conduct the sample return and an ongoing five-year science mission around Titan. As the primary objective of ORACLE is sample return, to mitigate the probability of failure, the sample collection phase of the mission is only six months before Titan ascent and return to Earth is initiated. In order to maximize the outputs of a mission which will have a 17-year round trip, a Titan Orbital Element (TOE) is proposed which remains in orbit after the transfer vehicle has departed for Earth. This spacecraft will continue science operations and provide communications support for the systems still on the surface of Ligeia Mare. Table 1 presents the primary system elements included as part of ORACLE. Although the mission proposal is complex, the architecture provides the maximum scientific benefit for what would require huge investment as a flagship program while primarily utilizing proven technologies that have been demonstrated on past missions. The vehicles presented in Table 1 are stacked vertically for launch and the Earth-Titan transfer using multiple separation systems.

Table 1 ORACLE primary system elements

System	Primary Role	Wet Mass (kg)	Key Features
Interplanetary Transfer Vehicle (ITV)	Sample-return interplanetary transfer	10300	3-axis stabilized, chemical bi-propellant propulsion, Earth Entry Vehicle (EEV) for sample Entry, Descent & Landing (EDL) on Earth
Titan Orbital Element (TOE)	5 year science mission in Titan Polar Orbit	1400	3-axis stabilized, chemical bi-propellant propulsion, RADAR & Spectrometer instruments
Titan Entry Vehicle (TEV)	Titan EDL	760	4.6 m, ablative thermal protection system and parachute to perform splashdown in Ligeia Mare
TitAn Lake Explorer and Sampler (TALES)	Floating science platform, sample collection & in-situ measurements	1100	Stowed within the TEV. Hosts redundant Sample Acquisition Submersibles (SAS) & the Titan Ascent Vehicle (TAV) to launch sample container into Titan orbit

The mass allocation for the ORACLE mission has been derived based on launch vehicle capabilities and the required propellant mass to conduct an Earth-Titan transit using a chemical bi-propellant propulsion system with a typical specific impulse of 300 s. The approximate wet mass given for each vehicle includes a conservative 50% margin to reflect the preliminary nature of this proposal.

Table 2 Science Instrument Suite Across Architecture Elements

Segment / Section	Instruments	Use	Heritage	Goal 1	Goal 2
TOE / Titan Mapping Suite	Mapping RADAR (RAD)	Creating surface and terrain maps	*Cassini*	X	X
	Visible and Infrared Mapping Spectometer (VIMS)	Creating hyperspectral images of the surface	*Cassini*	X	X
TEV / TALES	High Definition Camera (CAM)	Contextualizing samples and general imaging	*Huygens*, M2020	X	X
	Gas Chromatograph Mass Spectrometer (GCMS)	Characterizing chemical properties of air, liquid, and solids after sample return	*Cassini*, *Huygens*, MSL	X	
	Sonar/Acoustic Sounder (SON)	Mapping and studying the undersea structure		X	
TEV / SAS	Undersea Imager (USI)	Context of the samples and bottom of the sea		X	X
	Attenuated Total Reflectance Spectrometer (ATR)	Rapid characterization of liquid and semi-solids		X	X

As Titan is ~ 9.5 times farther away from the Sun than the Earth, the solar flux in Titan orbit is on average 14.1 W/m^2, approximately 100 times lower than that experienced in Earth orbit. Subsequently, the spacecraft would utilize a radioisotope thermoelectric generator (RTG) power solution as the solar panel area necessary to meet the power requirements of such a mission would be unfeasible when considering that they must be deployable structures, able to fit inside of a launch vehicle fairing. Use of RTGs is in keeping with the power system architecture of the original *Cassini* mission to the Saturnian System [17]. Based on a preliminary estimation of the power budget for the ITV and TOE spacecraft, each vehicle would have a maximum power requirement of 700 W and 400 W, respectively. These estimations include significant 50% margins resulting in power requirements comparable to the *Cassini-Huygens* mission of 641 W at the end-of-life [17].

Table 2 summarises the instrument suite included as part of the ORACLE mission payload. These instruments are based on upgraded heritage systems flown on similar missions or commercial off-the-shelf devices that could be employed in the liquid environment of Ligeia Mare. Across its primary elements, the ORACLE mission will:

1) Extensively map the Titan surface from orbit, improving upon the partial surface imagery provided by *Cassini*
2) Characterize and contextualize samples before return to Earth by using the attenuated total reflectance spectrometer (ATR) and undersea imager (USI)
3) Continue to characterize the structure of Ligeia Mare after sample return activities by using the same instruments in addition to a Gas Chromatograph/Mass Spectrometer (GCMS)

B. Concept of Operations (ConOps)

Depicted in Fig. 4 is an overview of the ORACLE mission architecture and the operations carried out in the Titan system. Assuming a launch in 2036, Titan's EDL operations will begin in 2045, followed by a six-month sample collection period on Titan. Ascent from Titan is expected to start in August 2045, with Earth's return transfer in 2046 and EDL and sample return to Earth in 2053.

The sample-return transfer is segmented into the interplanetary outbound, inbound, and the Titan capture/escape portions. A full interplanetary trajectory has been designed and optimized to minimize transfer time and ΔV. Given the targeted science schedule, an Earth to Saturn transit with a Jupiter flyby for the outbound transfer is utilized. For the return journey, a direct Saturn to Earth transit is selected. The full capabilities of NASA's Space Launch System (SLS) have been assumed with $C_3 = 90\ \mathrm{km}^2/\mathrm{s}^2$. ΔV is further reduced with multiple Deep Space Maneuvers (DSM) in the form of gravity assists upon Titan arrival and departure from the Saturnian system. For Titan orbit insertion, an aerobraking maneuver is utilized. The full ΔV budget for the mission is summarized in Table 3, not including the contributions from the upper stage of the SLS. Figure 5 illustrates the outbound and inbound interplanetary transfer

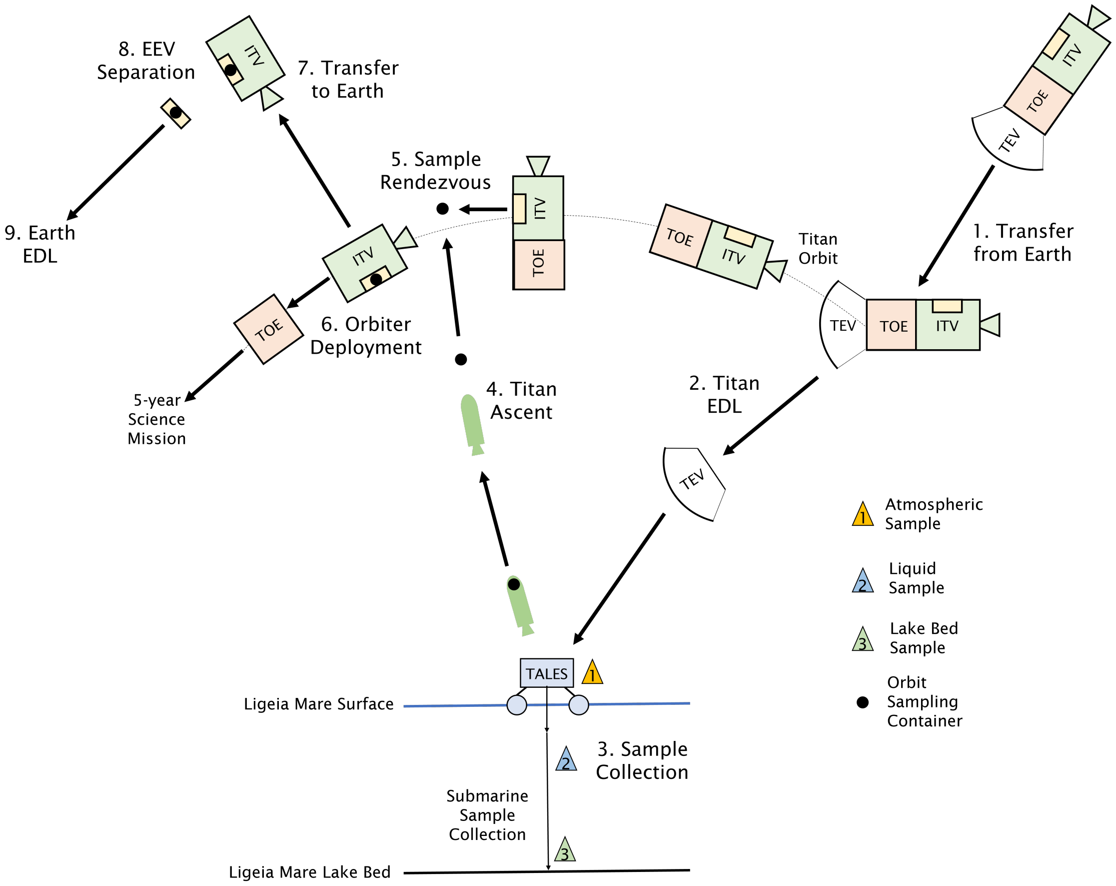


Fig. 4 ORACLE mission architecture and summary of operations at Titan

design. Figure 6 shows the Titan flyby trajectory used upon arrival to the Saturnian system.

Upon arrival to Titan, the TEV is deployed, allowing it to conduct EDL with TALES safely stowed inside. The combined TOE/ITV stack provides support in the form of communications and meteorological monitoring for the six month sample collection period. Once the samples have been retrieved and processed for the return journey, the TOE/ITV conducts rendezvous and capture of the sample container after Titan ascent has been performed. The TOE is subsequently deployed, allowing it to begin its science mission while the ITV initiates the transfer back to Earth.

Table 3 Summary of ΔV requirements

Maneuver	Cost, km/s
Outbound interplanetary DSM total	0.234
Titan Capture phase	1.165
Titan Escape phase	0.628
Inbound interplanetary DSM total	2.000

Communication with Earth is conducted through the Deep Space Network (DSN) using high-gain X- and Ka-band transceivers on the ITV and TOE, respectively. As has been demonstrated by *Cassini* and the recent *Juno* mission to Jupiter, use of X-band with a high gain antenna is more than sufficient for command and downlink of platform telemetry [18]. However, unlike *Cassini*, ORACLE will use the more recent upgrade of the DSN to Ka-band. It is envisaged that the higher data rate achievable over this link will be sufficient to downlink orbital payload data such as radar imagery from the TOE. *Cassini* was capable of transmitting radar data over the X-band and therefore it is reasonable to assume

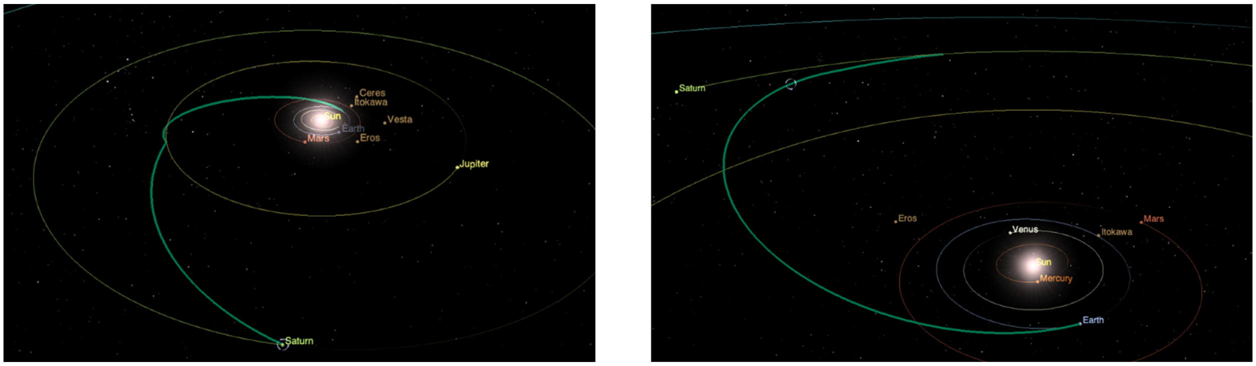


Fig. 5 Earth-Titan transfer with Jupiter flyby (Left). Return trajectory using direct transfer (right)

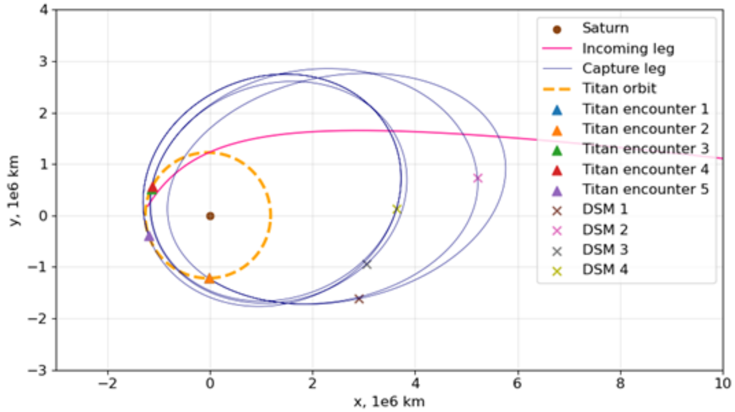


Fig. 6 Titan flyby trajectory upon arrival

that an upgrade to Ka will support downlink of higher resolution images and other science products [17]. TALES is capable of data relay through the orbiting spacecraft and direct communication with Earth via an X-band. This direct-to-Earth communication capability ensures that the science operations of TALES are not limited by the lifetime of the TOE.

C. Comparison to Other Proposed Titan Missions

There are numerous other proposed missions to Titan, all looking to explore the larger hydrodynamic cycle and evolution of the organic chemistry environment of this large moon. Of note is the Titan Mare Explorer, one of the three Discovery Mission finalists in 2011 (which eventually lost out to InSight, which would explore Mars' geology) [19]. This mission would land in Ligeia Mare, like our mission, and conduct experiments designed to understand the lake surface, local atmospheric environment, and interactions between the two. In comparison, our mission would focus more on sample return and characterization at the lake surface, below the surface, and at the solid-liquid interface at the lake bottom. Another proposed mission, the Titan Saturn System Mission, included an orbiter, a six-month balloon payload, and a lake lander [20]. Our mission profile bears many similarities with the long-duration orbiter and lake explorer in Ligeia Mare, but our focus is on the sample return aspects rather than a secondary balloon payload.

V. Entry, Descent, and Landing

The Titan EDL section of the mission relies on heritage from both the *Huygens* and *Dragonfly* missions [21, 22]. Due to the long parachute flight, it is essential to consider the winds during descent as they significantly influence the landing ellipse. From an analysis of the descent of *Huygens*, strong winds (around 100 m/s [21]) were found in the upper atmosphere, which have a significant effect on the motion of the TEV. This results in an uncertainty ellipse for the landing location of around 150 km [22]. As Ligeia Mare is larger than the landing uncertainty ellipse, the landing can take place in the lake without significant risk of landing on a hard surface. Thus, no controlled landing maneuver is required. The final parachute will descend the lander to the lake's surface to avoid hard impact. Thrusters are avoided due to the potential to heat the lake or cause excessive bubbling. As the parachute and backshell are still attached after landing, a mortar is used to separate them from the lander, ejecting them upwards and to the side. The mass of the backshell is sufficient to carry the parachute away from the lander, preventing it from collapsing on top of the vehicle.

VI. Main Subsystems

A. TitAn Lake Explorer and Sampler (TALES)

TALES is an integrated and mobile floating science platform, hosting the two redundant SAS, a suite of instruments to perform in-situ measurements, and the TAV. TALES is equipped with an MMRTG and supplemental batteries for power, propellers for locomotion, and an avionics suite (communication system, on-board computer, and guidance and navigation system).

Concept of Operations. After a soft landing on the surface of Ligeia Mare, TALES can propel itself to different sampling locations, selected using radar mapping from TOE and on-board sonar data. Once it has arrived at a sampling location, TALES will use its propellers to counteract any current and maintain its position in the lake. Next, one of two SAS will be deployed on a winch to collect samples from the air above the lake, the lake itself, or the lake bed. After winching up the SAS, TALES can transfer the SAS samples either to the Orbit Sampling Container (OSC) to prepare for launch or to the on-board mass spectrometer for analysis. TALES will also continuously collect data through its panoramic camera. Once the samples are loaded into the OSC and the OSC is sealed, TALES will launch the TAV into the air using pneumatic actuators, and the TAV will ignite and ascend into orbit. After launching the TAV, TALES will remain on the lake and continue performing in-situ science operations.

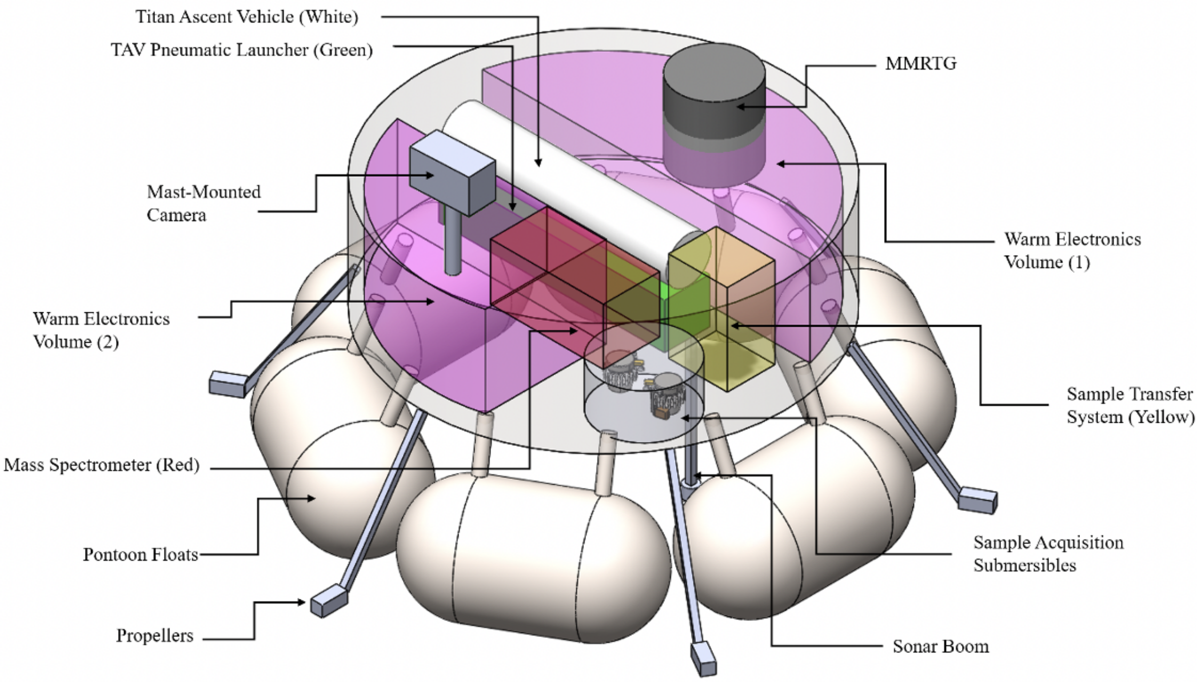


Fig. 7 TALES Design Layout.

External Design. The TALES vehicle, shown in Fig. 7, consists of a short cylindrical main body connected to six pill shaped-pontoons and was chosen to minimize thermal transfer between TALES and the lake and to maximize stability in the lake. TALES has a total height of 2.2 m, a diameter of 4.5 m (including the pontoons), and a total landing mass of approximately 1200 kg (with margin). The cylindrical main body is 1 m tall and 3.2 m in diameter and contains all of TALES' internal systems. Mounted on the top surface of TALES are the mast-mounted camera, the MMRTG, communication antennae (not shown), and thermal control radiators (not shown). A deployable sonar boom is mounted to the bottom of the main body.

TALES floats using six hexagonally-arranged pill-shaped pontoons. This arrangement is designed to maximize resistance to pitching and rolling moments, which could otherwise flip TALES. The six pontoons are each internally divided into 24 sealed compartments, ensuring that any lifetime damage has limited effect on overall buoyancy. Together, the six pontoons displace twice the volume necessary for TALES to float, ensuring that TALES will remain buoyant even if the pontoons are significantly degraded. The main body is elevated above the pontoons and connects to the pontoons by a set of beams. This limits conductive heat transfer from the lander to the lake and enables the SAS to collect atmospheric samples from just above the lake surface. TALES has six deployable propellers arranged between the pontoons, each of which can generate forward or reverse thrust, providing exceptional redundancy for locomotion on the lake surface.

Internal Layout. TALES' internal layout has been driven by stability and thermal considerations. The center of mass of the platform is as low and centered as possible. Since the launch of the TAV must not compromise stability, the TAV is also positioned such that its center of gravity is at the center of the platform. This ensures that the VECTOR-style lofting mechanism will not impart a large moment to our capsule [23]. Subsystems are positioned on two levels within the platform: level 1 (bottom) contains the TAV launching mechanism and the SAS on their rotating platform. Level 2 (top) contains the TAV, the RTG and batteries, the instruments suite, and the avionics. Regarding thermal management, parts of the platform with sensitive electronics are maintained at 298K (warm areas), while others are at ambient Titan temperature of 95K (cold areas). Excess heat is evacuated on the top of the platform through a radiator, while the rest of the boat is highly insulated in order to minimize thermal transfer to the lake.

B. Sample Acquisition Submersible (SAS)

The SAS is a non-propelled, negatively buoyant vehicle tethered to TALES that collects and delivers the three sample types. The SAS descends to the lake floor, taking atmospheric and liquid samples by hermetically sealing open sample tubes. There are two identical SAS aboard TALES to ensure mission success and reduce risks.

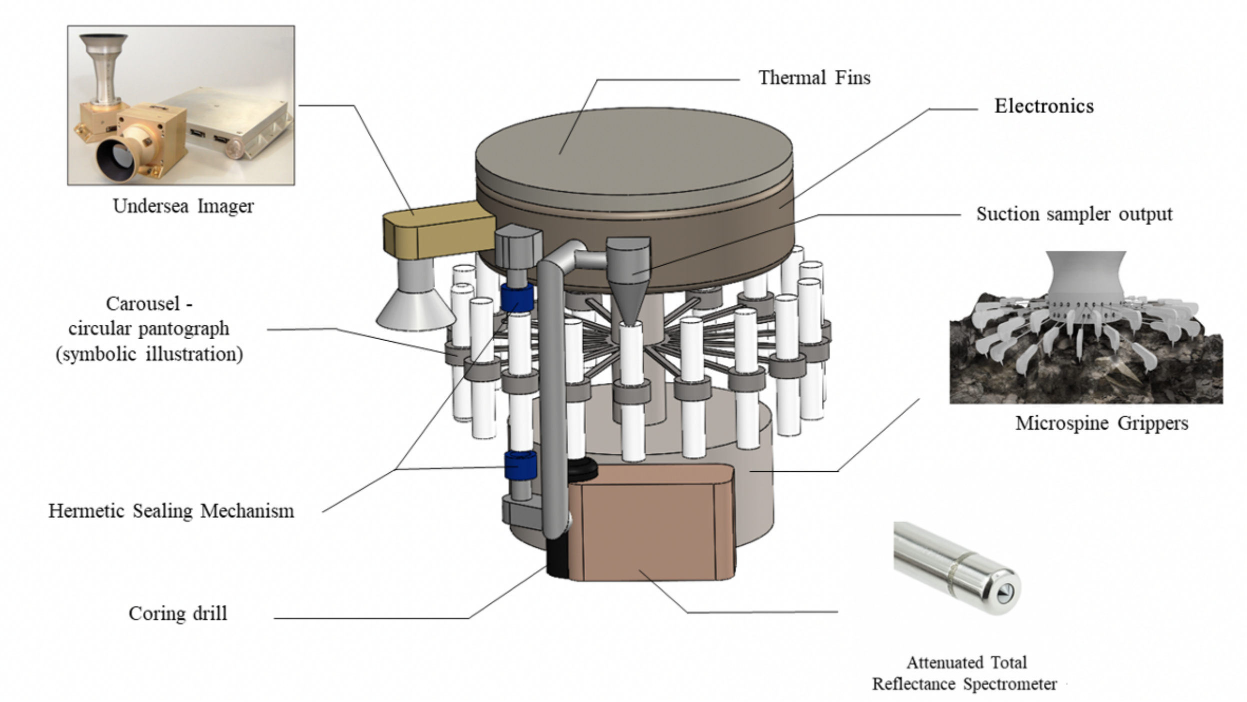


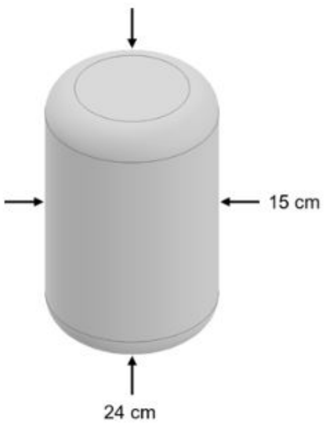
Fig. 8 Sample Acquisition Submersible

Concept of Operations. The SAS descends on a data-and-power-transmitting tether via a winch on TALES. The SAS collects atmospheric samples from just above the lake's surface when first released from TALES. The SAS then descends into Titan's lake to take liquid samples at various depths. An acoustic sounder and penetrometer are used to determine the hardness of the lake floor and dictate the method of sample collection. If drilling is necessary, the SAS anchors itself to the lake floor. In order to minimize power and thermal loads, the SAS waits to cool down between actuated maneuvers. The nominal timeline for all Titan activities prior to sample return is 60 days. This limit can be met with a significant margin with two days allotted to each of the 18 return samples. Once samples are collected and in-situ measurements of the lake are taken, the winch on TALES reels the SAS back up. Collected samples are delivered to the OSC and into the TAV for delivery back to Earth. After initial samples are collected and returned to Earth, the SAS continues to perform sample collection for in-situ analysis of the samples using an Attenuated Total Reflectance Spectrometer (ATR) as well as the gas chromatograph-mass spectrometer (GCMS) on TALES.

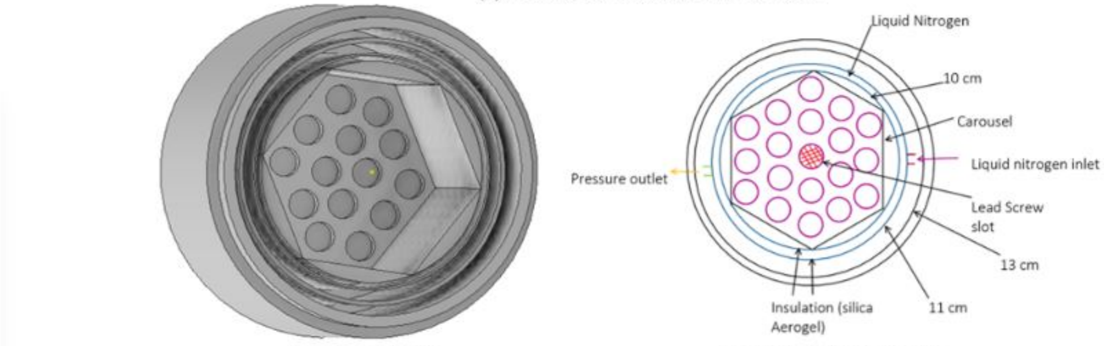
Design. Summarized in Fig. 8, the SAS arranges sample tubes in a circular carousel. The base of this carousel can fix itself to a hard lake floor via microspines [24]. A suite of robotic tools moves around the carousel on a rotating carriage. These tools include a percussive coring drill and a hermetic sealing tool, both modeled after Mars 2020 [25], and a suction sampler modeled after *Dragonfly*'s DrACO [26]. Finally, the tool carousel contains the ATR for inspecting samples *in situ* during and directly after acquisition.

Cold electronics are stored in a centralized location at the top of the SAS, connected to the tool carriage, cooled by the ambient lake fluid via high-surface-area radiator fins, and insulated from the samples. The tether mounts to the top of the SAS and transmits power and data via a copper wire. The sample carousel can un-dock from the tool carriage. In a fault scenario where the tool carriage cannot be retrieved (e.g. coring drill becomes stuck in the lake floor), the sample carousel can be retrieved via a contingency (unpowered) tether. Nominally, once the earth-return sample carousel undocks aboard TALES, the sample storage is made compact via contracting a radial pantograph mechanism comprising the structure of the carousel itself.

C. Orbit Sampling Container (OSC)



(a) The outer structure of the OSC



(b) Inner View (c) Inner View Details

Fig. 9 OSC Overview

The OSC, present in the TAV, is designed to house 18 samples collected by the SAS at the sample's native environmental conditions while they are transported back to Earth. The OSC is also designed to assist with the rendezvous and capture operations performed by the TOE.

Design. The compact carousel is inserted into the OSC with the help of a lead screw and is latched in place using a mechanical switch that triggers when the carousel approaches the OSC, shown in Fig. 9.

Thermal Management. One of the most critical tasks of the OSC is thermal management of the samples during Titan ascent. The surface temperature of Titan is exceptionally stable, and the samples must be kept within a narrow range of 85 - 95 Kelvin to maintain sample integrity. On Titan, sample integrity is maintained by keeping the samples in equilibrium with the Titan thermal environment. In transit back to Earth, the temperature of the OSC is maintained by exposure to deep space on the ITV. During a brief period from Titan ascent to rendezvous with the ITV in Titan orbit, the OSC must maintain an acceptable internal temperature for the sample tubes.

During Titan ascent, the OSC is exposed to all the layers of Titan's atmosphere, which have temperatures ranging from 80 to 200 K. It is also subjected to heating from the ascent itself, and to solar radiation in Titan orbit prior to rendezvous with the ITV. The OSC maintains an internal temperature at or below 95 K using a multi-layer passive thermal control system that combines thermal insulation with an evaporative cryostat system. The walls of the OSC contain a jacket of liquid nitrogen, pressurized such that the saturation temperature is 95 K. (This liquid nitrogen is supplied to the OSC by TALES, which carries a small 4-liter actively-refrigerated LN2 supply.) Any heat flux into the OSC causes liquid nitrogen to vaporize, and the excess gas is vented through a pressure relief valve. This thermo-mechanical system requires no electronics to operate, and is capable of maintaining OSC temperature during ascent and for 12 hours in orbit before the liquid nitrogen supply is depleted. This provides significant margin on the expected 4.5 hours the OSC will spend in Titan orbit prior to being picked up by the ITV. The thermal management system is shown in Fig. 10.

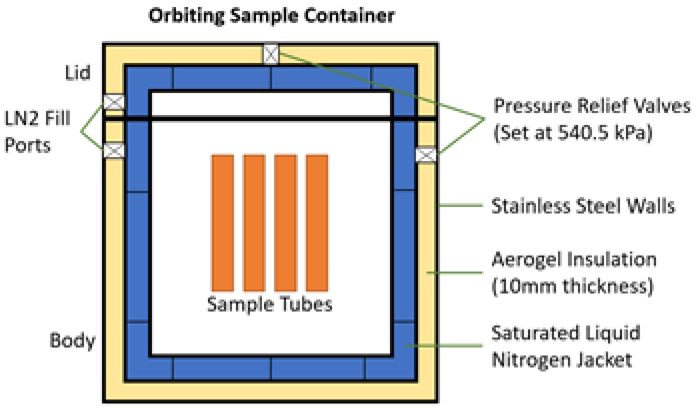


Fig. 10 Thermal Management - OSC

Electronics. To support ITV-OSC rendezvous and capture operations, the OSC will be equipped with a primary lithium-ion battery to power a radar beacon and a bow-tie patch antenna. The battery and the beacon are stored in the lid and the base of the OSC. The antenna is mounted around the structure of the OSC, similar to the Mars sample return canister described in [27].

VII. Ascent and Return

The samples in the OSC are loaded into the TAV, which is a single-stage rocket that takes the samples to orbit. This vehicle is based on the design proposed by Karp et al. [28] which uses a hybrid rocket design. The TAV needs to be capable of 4 km/s of ΔV, based on calculations from [29]. Considering the OSC mass of 15 kg, the TAV is roughly 250 kg, which is in line with what Karp et al. found. The TAV is lofted above the lander with a pneumatic arm that is based on heritage from the current Mars Sample Return system, VECTOR [30].

When the samples reach orbit, the Sample Capture Mechanism (SCM) receives the samples on the TOE. This design is based on a simplified Mars Sample Return concept described in [31]. As illustrated in Fig. 11, SCM consists of a funnel to capture the OSC and a mechanical door to contain the OSC after capture. Procedures are designed to ensure planetary protection protocols can be followed. The OSC is then moved into a container inside the EEV to protect it from the environment. After closing the container in the EEV, the SCM is detached from the EEV to allow the heatshield to be closed before Earth entry and remove the contact point between the OSC and the return vehicle.

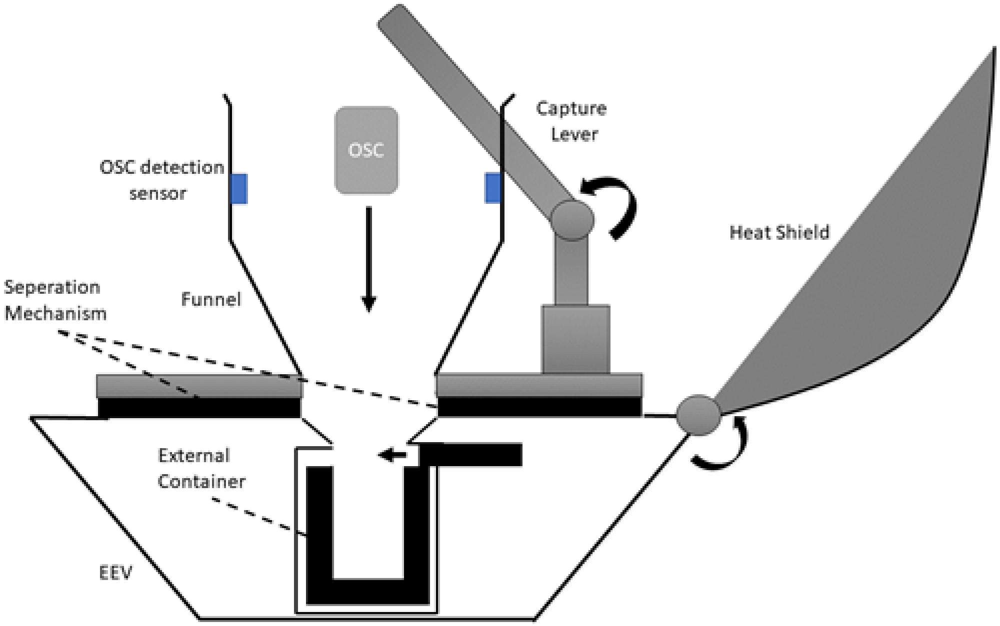


Fig. 11 Sample Capture Mechanism

Following the interplanetary trip from Titan to Earth, the samples reenter the Earth at roughly 14.5 - 15 km/s and land in the Utah desert. The reentry vehicle will be based on heritage from the Mars Sample Return capsule, which is currently proposed to be constructed from carbon-carbon and a secondary ablative thermal protection system. The samples will crash into the ground without a parachute before being recovered. Excluding a parachute will remove complexity from the vehicle.

VIII. Mission Cost

To estimate the mission's cost, we apply a hybrid top-down estimation methodology, first using a parametric model to approximate total mission cost, then analogy-based rough order of magnitude estimates for specific cost categories. Using the Planetary Exploration Budget Dataset [32], which catalogs and publishes cost data for NASA's robotic planetary missions since 1960, we regress total mission costs of 40 major historical planetary exploration missions against launch mass. We define launch mass as the mass of the payload and spacecraft and the mission cost as launch and development costs. Numbers are inflation-adjusted, and costs are represented in base year 2022. The regression in Fig. 12 shows mission cost can be roughly linearly correlated with launch mass. Given a maximum expected mass of 11,905 kg, we can expect total mission cost, excluding estimated launch costs of \$4.1B, to be around \$4B.

Specific cost categories are forecasted based on a percentage of total mission cost from analogous missions. Historical analogies show that the cost of the entire flight system (bus + propulsion + structures of our spacecraft system) is around 40% of the total mission cost. We estimate specific subsystem costs as a percentage of total flight system cost based on its mass ratio to total flight system mass, leveraging the same assumption that cost is roughly a linear function of launch mass. Payload mass, which is primarily scientific instrumentation, is calculated using the Class B Instrument \$/kg rough order of magnitude estimate of \$1M/kg. We also apply a TRL multiplier of 2 to account for TRL level 1/2 scientific instrumentation, giving us a total payload cost of \$415M, which is 16% of our total mission development cost, the average of comparable mission estimates. Other programmatic and operational costs are calculated using a % of total mission cost from analogous missions. The projected cost for each major development category is shown in Table 4. As a cross-check, our forecasted cost compositions are in line with those of comparable missions.

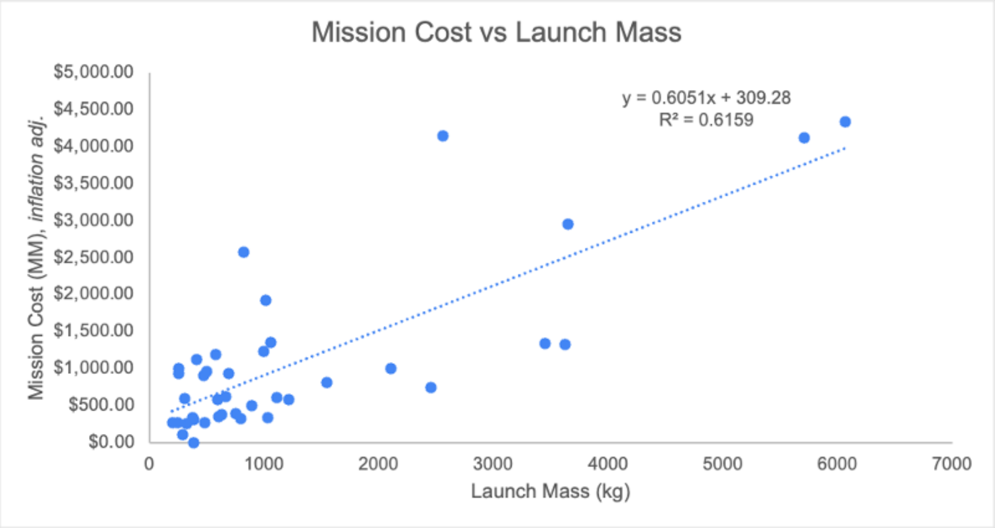


Fig. 12 Historical trend of mission cost against launch mass

Table 4 Total Mission Cost Breakdown

Cost Category (Phase A-D)	Projected Cost ($M)
Project Management	125
Systems Engineering	133
Safety and Mission Assurance	113
Science and Technology	326
Payloads	415
Flight System (Total = 1094 kg) :	
- TAV	45
- SAS	18
- TALES Power	22
- TALES Structure + Propulsion	124
- TEV Bus + Structure + Propulsion	142
- TOE Bus + Structure	237
- ITV Bus + Structure	495
- OSC	11
Ground Data System	116
Mission Operations System	493
System Integration and Test	78
Education and Public Outreach	25
DSN Service	33
Mission Design	135
Subtotal	3086
Reserve (30% of Subtotal)	926
Total Mission Cost	4012

IX. Conclusion

The ORACLE mission will expand the scientific body of knowledge surrounding Titan's hydrological cycle, the interactions of its dynamic surface processes, and its habitability potential. The mission will return samples from an outer solar system planetary body for the first time, conduct hydrology measurements over an extended period of time, and explore how rivers and lakes interact on Titan. The science from this mission supports and augments the scientific successes of *Cassini* and the anticipated scientific gains from *Dragonfly*.

The mission utilizes an orbital element, mobile floating science platform, and submersible samplers to collect solid, liquid, and gaseous samples from a Titan lake and send them back to earth for analysis. To maximize value from this mission, the elements deployed on and around Titan will conduct an extended science mission for thorough characterization of Titan's hydrocarbon lakes and the regions surrounding them. This mission concept combines heritage from other missions and novel innovations to make invaluable scientific progress.

Acknowledgments

The authors, Team Explorer, would like to give special thanks to the Caltech Space Challenge organizers for the opportunity to take part in the 2022 edition and for their planning and coordination before and during the week of the Challenge. We would also like to express deep gratitude to all the mentors and speakers who helped orient our team and guided us through the mission design process. Finally, we would like to acknowledge the Challenge sponsors for their support and contributions to help make this event possible.

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