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In-Situ Missions for the Exploration of Titan's Lakes

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Abstract. The lakes of Titan represent an increasingly tantalizing target for future exploration. As Cassini continues to reveal more details the lakes appear to offer a particularly rich reservoir of knowledge that could provide insights to Titan's formation and evolution, as well as an ideal location to explore Titan's potential for pre-biotic chemistry. A recent study of Titan Lake Probe missions was undertaken as one of several dozen studies commissioned by the National Research Council (NRC) Planetary Decadal Survey to explore the technical readiness, feasibility and affordability of scientifically promising mission scenarios. This in-depth study focused on an in-situ examination of a hydrocarbon lake on the Saturnian moon Titan—a target that presents unique scientific opportunities as well as several unique engineering challenges (e.g., submersion systems and cryogenic sampling) to enable those measurements. Per direction from the NRC Planetary Decadal Survey Satellites Panel, and after an initial trade-space examination, study architectures focused on three possible New Frontiers–class missions and a more ambitious Flagship-class lander intended as the in-situ portion of a larger collaborative mission. Detailed point designs were developed to explore these four potential mission options, including consideration of flight system and mission designs, as well as operations on and under the lake's surface and scenarios for data return. In this paper we present an overview of the science objectives of the missions, the mission architecture and surface element trades, and the detailed point designs chosen for in-depth analysis.

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INTRODUCTION

As part of NASA's support to the National Research Council (NRC) SS2012 Planetary Decadal Survey, the Jet Propulsion Laboratory (JPL) was assigned the task of developing several mission point designs aimed at in-situ science on and in one of the ethane/methane lakes of Saturn's moon Titan. Initial prioritized science requirements were supplied by the NRC Satellites Panel. The panel was specifically interested in a mission that would fit within NASA's New Frontiers proposal constraints as well as consideration as the landed portion of a larger Flagship mission. Architecture trade-space analyses and detailed point designs were to be performed by JPL. To meet this study's needs, the work was divided into two phases: (1) an initial examination of the architecture trade space and detailed point designs of the landed elements of the candidate architectures by a stand-alone study team; and (2) detailed designs and cost estimates of the total mission architectures by JPL's Advanced Projects Design Team (Team X). This arrangement allowed for a more free-ranging exploration of possible mission and landed element architectures by a team of specialists chosen for their relevant knowledge to the problem, while leveraging the efficiency and experience of Team X with the entry, descent, and landing (EDL) and spacecraft portions of the mission—areas routinely handled by this team. This work was done in close coordination with the Decadal Survey's Satellites Sub-panel with several panel members providing active guidance on the design process and decisions to JPL's two study teams.

The study designs were all developed to the same set of assumptions and constraints. The first level of constraints was specified in NASA-supplied ground rules and included details on cost reserves, advanced Stirling radioisotope generators (ASRG) performance and cost, Ka-band telecommunications usage, and launch vehicle costs—all of which were adhered to within the studies. The second level of constraints and assumptions were internal JPL best practices as specified in JPL Design Principles [1] and Flight Project Practices [2]. These documents covered margin and contingency levels as well as redundancy practices. Finally, since a primary goal of the study was to examine the compatibility of the different options with a possible future New Frontiers announcement of opportunity (AO) call, initial assumptions of a launch date sometime after January 1, 2021 and before December 31, 2023, and a complete mission cost cap of approximately $1B were also assumed. The latter assumption came from adjusting the cost cap on this latest New Frontiers AO for differences between that AO's cost assumptions and the currently specified Decadal Survey assumptions.

SCIENCE GOALS AND OBJECTIVES

The global methane cycle at Titan embodies both a short-term (years to thousands of years) hydrological and a long-term (millions of years to hundreds of millions of years) chemical transformation of methane to higher order organics. The Titan Lake Probe mission would be designed to study the role of Titan's lakes in the global methane cycle—from both a hydrological and chemical transformation perspective. In the hydrological cycle, the lakes are tightly coupled to Titan's lower atmosphere, exchanging both methane and ethane in gas, liquid, and perhaps solid states. The role of the lakes in the longer chemical transformation cycle is less direct. In this case, the lakes serve both as a repository of accumulated "organic rain" from the upper atmosphere and a potential source of oxygen in the form of water due to the interaction of the lake with ice on the shore and lake bottom. This lake-based chemical transformation can significantly modify the chemistry creating many important pre-biological molecules. Furthermore, the lakes may sequester noble gases such as argon, krypton, and xenon that hold important clues about the outgassing of Titan's primary volatiles (molecular nitrogen and methane) over geological time.

The scientific objectives established by the science team for the Titan Lake Probe mission are:

1. To understand the formation and evolution of Titan and its atmosphere through measurement of the composition of the target lake (e.g., Kraken Mare), with particular emphasis on the isotopic composition of dissolved minor species and on dissolved noble gases.
2. To study the lake-atmosphere interaction in order to determine the role of Titan's lakes in the methane cycle.
3. To study the target lake as a laboratory for both pre-biotic organic chemistry in water (or ammonia-enriched water) solutions and non-water solvents.
4. To understand if Titan has an interior ocean by measuring tidal changes in the level of the lake over the course of Titan's 16-day orbit.

Previous Titan mission studies [3,4] have demonstrated that it is possible to place a landing ellipse in the center of Kraken Mare or another one of Titan's large lakes from a range of trajectories, including Saturn flyby, Saturn orbital, or Titan orbital. Suggested mission concepts have included boats [4] and submersible lake probes [5]. Both concepts allow first-order characterization of the lake composition and provide information about the lake-atmosphere interaction. These studies agree that a well-equipped chemical analysis system that includes noble gas, organics, and CHON isotopic determination are the first measurement priority and that a meteorological package that measures the relative humidity of methane and ethane, the static stability, the wind vector, the height of the boundary layer and other parameters relevant to modeling the evaporation from the lake, is a necessary secondary payload, as well as imaging sonar to determine the lake morphology and examine the diurnal tides.
Specific scientific measurements to meet the mission objectives would include 1) determination of the lake's vertical structure (temperature and pressure), 2) determination of changes in lake composition and chemistry as a function of depth, 3) measurement of the lake tides from a fixed platform at the bottom of the lake, which in conjunction with (1) would allow determination of the Titan lake tides with an accuracy of ~10 cm (expected tidal range is ~1 m), and 4) characterization of the lake sediment composition. These additional objectives would require the payload to be augmented by a lake temperature and pressure sensor, as well as an upward-looking sonar.

ARCHITECTURE TRADES

Once scientific objectives were established mission architectures for detailed study were evaluated as shown in Figure 1. For delivery of the in-situ vehicle to Titan four options were considered. These consisted of delivery by orbiters, either from Titan orbit or in orbit around Saturn, as well as options that involved direct delivery to Titan by spacecraft that would continue on flyby trajectories. These latter options were divided into delivery by "dumb" cruise stages, in which the cruise stage operates only as a propulsion and support vehicle with all control functions provided by the in-situ vehicle, and a cruise/relay option in which the cruise stage is a fully capable spacecraft that would provide telemetry relay during the science mission. In-situ options were divided into four categories. The simplest mission would involve a lake lander only. As mentioned in the Science Objectives, the best chance of meeting all of the defined science goals would be an in-situ mission involving both a lake lander and an independent submersible, and this was the second option. A third option discussed by the team would be the use of a tethered probe lowered from the lander for measurements at depth as a potentially simpler alternative to the independent vehicle. Finally, the team considered an implementation consisting of a submersible-only in-situ mission.

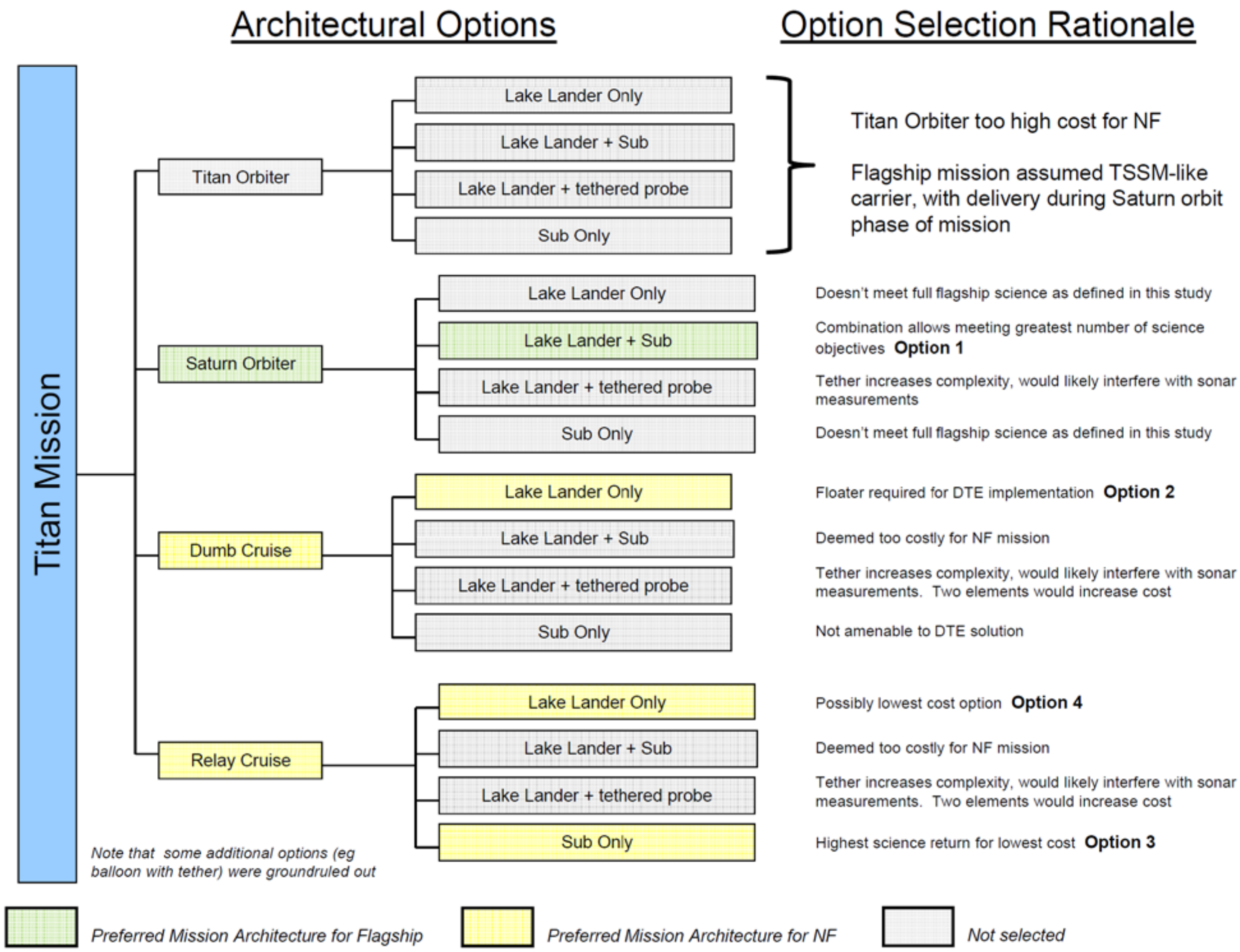

FIGURE 1. Architecture Trade Tree.

To simplify the architecture trade space, the team decided that the flagship option would use a TSSM-like mission as its model. TSSM, while ultimately planned to enter Titan orbit, would deliver its in-situ payloads from Saturn orbit, during a ~2 year Saturn tour phase of the mission. Telecom passes for data return would be available during orbiter flybys of Titan that would occur approximately every 32 days. Additionally, for the Flagship option it was decided that the full complement of in-situ vehicles (lander and submersible) should be assumed, as this mission option was meant to investigate a mission architecture capable of achieving all the science objectives. This architecture was designated as Option 1 for detailed mission study. For the New Frontiers (NF) mission options, it was decided that orbiters would be unaffordable within the cost cap, so the focus was directed to the flyby options. The study team wished to evaluate the case of a direct-to-earth (DTE) communications architecture, as well as relay communications. The most likely platform for a DTE system was felt to be the lake lander. For the NF options it was determined that only a single in-situ element would be affordable, hence the second mission option chosen for detailed study was a DTE lander-only architecture, delivered by a “dumb” cruise stage. Finally, two cruise/relay options were chosen for study; one involving delivery of a submersible only (Option 3), and one delivering a lake lander (Option 4).

Each of the four mission options was measured against its intrinsic scientific value in terms of how well each option addressed the science goals. A numerical value was given to each option by assigning the following maximum values to each of the science objectives: A—10 points, B—7.5 points, C—5.0 points, and D—2.5 points, i.e.,

- Goal A (10 points): To understand Titan via measurement of the composition of the lake
- Goal B (7.5 points): To study the lake-atmosphere interaction
- Goal C (5 points): To study the lake as a laboratory for pre-biotic organic chemistry
- Goal D (2.5 points): To understand if Titan has an interior ocean

MISSION CONCEPTS

The four mission architecture options chosen were developed into full mission point designs by the team. Descriptions of each option studied are provided below:

Option 1: Flagship Mission (Scientific Value: 25/25)

This configuration was considered as a US contribution to a possible international mission. The in-situ component would represent a major portion of the mission’s science return, but it would not be the only science. The most likely Flagship configuration would involve a carrier/relay spacecraft in Saturn orbit carrying out other science investigations throughout the Saturnian system (much like the TSSM proposal). As such, the in-situ portion of a major venture to Saturn would need to carry out extensive investigations to advance beyond Cassini/Huygens and to justify inclusion. Accordingly, the lake lander, submersible, and a nominal 32-day mission were all viewed as necessary to advance science in all four investigation areas (atmospheric evolution, atmosphere-lake interaction, lake chemistry, and interior structure) identified as science goals. The extensive payload on the floating lander, 32 days of operations, and limited link opportunities with the Saturn-orbiting relay spacecraft resulted in a design that would benefit from the use of ASRGs on for power. A major trade for this option involved the question of how to handle the submersible data retrieval. A tethered probe was considered but dismissed because the drifting floating lander would likely drag the submersible and interfere with the lake depth measurements needed for Titan interior science. Reliance on a submersible-to-lander VHF data relay was also considered but this too would be limited by the drifting lake lander. The final adopted architecture included a submersible that could transmit data to the floating lander while in range then resurface at the end of the 32-day mission to transmit directly to the relay spacecraft. The mission would launch around 2025, reaching the Kraken Mare landing site after sunset but this was not seen as an issue since the carrying spacecraft would provide the data downlink.

The Flagship architecture would include two in-situ elements—a floating lander and a submersible (see Figure 2)—packaged together in a single aeroshell and delivered to Titan from Saturn orbit by a Flagship-class carrier spacecraft (not designed as part of this study).

Flagship Submersible

The Flagship submersible would be delivered by the Saturn orbiter to the Titan lake integrated with the floating element. The submersible would take a limited number of surface science measurements before descending to the bottom of the lake. During descent, the submersible would take compositional lake measurements at different depths while returning science data via VHF link through the lake medium to the floating element. Once on the bottom of the lake, the submersible would collect and analyze sediment samples. The submersible would remain at the bottom of the lake for 30 days, taking compositional samples and acquiring sonar data before returning to the surface and sending data to the Saturn orbiter on its second Titan flyby.

The submersible design consists of two 0.7 m diameter metal spheres connected by a thin cylindrical tube containing the cabling from one sphere to the other. Science instruments and most of the batteries would be housed in the upper

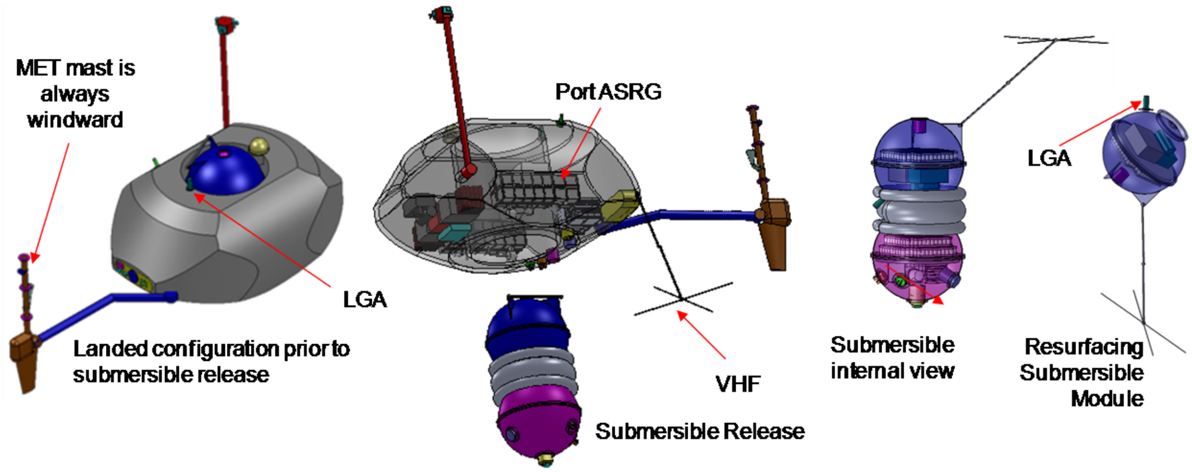

FIGURE 2. Flagship Floating Lander and Submersible Configurations (*conceptual designs*)

sphere, while the telecom system, C&DH, and power electronics would be in the lower. When connected, the submersible mass outweighs the displaced fluid, causing it to sink to the lake bottom at a rate of approximately 1 m/s. At the end of 30 days, the sphere containing the instrumentation would be released, remaining at the lake bottom while the upper sphere would return to the surface to transmit data to the orbiter. Although the liquid medium is not fully known, the structural components were designed with margin to ensure descent and resurfacing occurs given the widest expected range of possible lake densities.

The submersible power system would be comprised of lithium-carbon monoflouride (Li CFx) primary batteries. There would be no power generation located on the submersible. A new, small-format, modular approach would be used for the electronics allowing a combination of C&DH and electrical power system (EPS) functions in a single-integrated avionics assembly. An event timer module (ETM) would be designed for the submersible, providing the timing and control functionality while minimizing power. Instrument control and sequence event timing would be loaded into the ETM prior to separation from the floating lander.

All versions of the Titan lake floating landers and submersibles would utilize the same thermal control approach to reject heat during cruise, while decoupling from the cold environment during and following EDL. Radioisotope heating units (RHUs) would be used for heat generation to keep the battery-powered submersible at operating temperature. To maintain operational temperature of the instruments in the cryogenic Titan environment, the interiors of the probes would be insulated from the exterior shells. The submersibles would be hermetically sealed vessels, which would be maintained with vacuum inside and insulated by multilayer insulation (MLI). The vessels would be evacuated prior to launch, and all materials would be low-outgassing as far as practical. During cruise, vacuum would be maintained by refirable getters, which must be reactivated as vacuum degrades; this is done by passing an electric current through the getter body, which incorporates a resistive heater. The last reactivation of the getter package would be done shortly before separation of the entry vehicle from the Saturn orbiter. Upon entry into the cold Titan atmosphere and lake, absorptive getters located on the inner surface of the hermetic shell would maintain vacuum inside the probe.

The submersible would utilize two methods of relaying data taken from the lake depths—through the medium to the floating element as well as directly to an orbiting spacecraft upon resurfacing. For through-the-medium communication during the initial descent, a transmit-only VHF system would use a 1 m deployable crossed dipole antenna attached to the exterior of the submersible to transmit to the floating element. This information can be stored onboard the floating element to be sent back to the orbiter if an anomaly occurs and the submersible is unable to resurface. Due to the uncertainty regarding currents and surface winds, the line of communication between the two elements may not be reliable for long after submersible descent. Therefore, primary data return would be provided by an X-band system using a single zenith-pointed low-gain antenna (LGA), allowing communication directly to the Saturn orbiter upon resurfacing. Two independent Universal Space Transponders (USTs) would serve as the radios for both the VHF and the X-band systems providing functional redundancy for the telecom system. The UST is a software-defined radio currently under development at JPL as the next-generation deep space transponder. The UST has a reprogrammable baseband processor, which is link-frequency independent, as well as frequency-dependent circuit slices, which support the RF-processing functions. More than one set of circuit slices can be connected to the baseband processor, thus enabling simultaneous operation in more than one frequency band.

Flagship Floating Lander

The floating lander structure has been designed to accommodate the submersible as shown in Figure 2, carrying it to the surface and distributing the loads of lake impact. In order to do so, the lander is designed to enter the lake stern-first, to minimize the surface area that would impact the lake surface, much like a diver entering the pool after a dive. This method of descent reduces the added structure required to absorb the impact of landing. In order to mitigate any atmospheric disturbances that may occur due to the floating lander, booms containing the atmospheric instrumentation would be mounted in such a way as to always be up wind of the floating lander. This is achieved by placing a small keel at one end of the lander to act as a pivot point orienting the bulk of the lander downwind.

The power system of the floating lander would utilize two ASRGs for power generation. During launch and cruise, the power would be shunted and the heat would be rejected by external radiators to prevent overheating. In addition to ASRG power generation, the power system would include multiple advanced Li-Ion primary batteries to meet the temporary additional loads required for telecom and science operations. The floating lander is required to control all in-situ elements of the Flagship option. The floating lander's C&DH subsystem design is based on JPL's MSAP architecture. The computer and memory would provide sequencing under flight software control and additional storage for science data. The critical relay controller board would provide hardware protection for critical functions.

The floating lander would utilize a redundant, two-way X-band system for communication to the orbiting spacecraft and a redundant, receive-only VHF system for submersible communication. The floating lander telecommunication subsystem is very similar to the submersible, using the same types of antennas as well as the UST as the radio for both telecom bands.

Thermal control would be similar to the design used for the submersible with the exception of heat generation. Waste heat from the ASRGs would be distributed throughout the lander, eliminating the need for RHUs. The floating lander would not be a hermetically sealed volume; it would be vented in a controlled fashion during atmospheric descent to allow pressure equilibration with the surrounding atmosphere, which is mostly N2. The floating lander would be insulated with a layer of aerogel on the inner surface of the shell, which would provide sufficient insulation to maintain inner temperature.

Science requires knowledge of wind direction, which in turn requires knowledge of the floating lander heading angle. The Flagship mission would operate during Titan night at the target lake, where sun sensors are not an option. Instead, a Saturn camera would be developed for this mission. Its heritage HgCdTe detector would be sensitive in the 2 to 5 micron range, taking advantage of "windows" in Titan's atmosphere at those wavelengths.

Option 2: New Frontiers Floating Lander with DTE Communications (Scientific Value: 20/25)

The DTE New Frontiers–class mission was developed to determine the feasibility of a mission using DTE communication from the Titan surface. In order to communicate with Earth, the mission must be flown during daylight at the target lake, significantly constraining the timeline as well as adding new requirements on the flight system. This option would consist of a floating lake lander with a DTE communication capability that would be carried to Titan by a simple carrier stage, which would rely on the lander for much of its avionics and would have no function once the lander is released. The removal of the submersible and several instruments eliminated the interior structure objective (Goal D) and reduced achievable science in the other three focus areas. DTE link requirements drove a decision to design the lander with ASRG power which would enable long term downlinks of probe data. The DTE requirement coupled with the New Frontiers launch date (2022) also drove the mission to a six-year cruise to ensure arrival at a time when Kraken Mare would remain in view of Earth. This high-performance trajectory would require a large bi-propellant propulsion system on the carrier, putting the mission on the largest Atlas V launch vehicle.

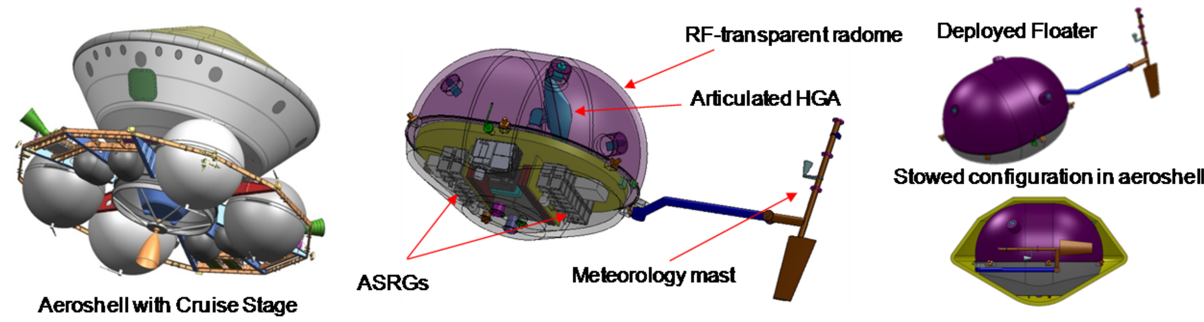

FIGURE 3. DTE Floating Lander Configuration (*conceptual designs*)

Much like the Flagship mission, the New Frontiers DTE lander would be delivered to the surface by parachute in such a way that would minimize the surface area impact when entering the lake. However, unlike the Flagship lander, the structure of the floating lander must house a 0.8 m HGA required for communication with Earth. This antenna would be housed within a RF-transparent shell and would be used throughout surface operations (Figure 3). The RF-transparent radome containing the relay antenna would utilize thermal insulation in the inner surface of the shell. The interior of the shell would contain Titan atmosphere, mostly N2, at ~290 K and ~1.6 bar. The insulation would be designed to retain sufficient heat to maintain the instruments and avionics at operational temperature, with the 1 KW (thermal) waste heat from the ASRGs providing the heat source, and the outer surface at ~94 K. A 25 mm thick layer of aerogel on the inner surface would maintain the interior volume at 290 K while attenuating an X-band signal by <3%.

The lander would have a redundant, two-way X-band communications system. USTs would be used as the telecom subsystem's radio; however only an X-band RF slice would be needed since there would be no Ka-band communication. Two 35 W RF travelling wave tube amplifiers (TWTAs) would power the downlink. An X-band LGA would allow EDL carrier tracking by a radio telescope, but for data return, a gimbaled 0.8 m X-band HGA would be used. Due to the rocking motion of the moving liquid, a gimbaled system similar to that used on terrestrial ocean-going ships would orient the antenna, maintaining lock on Earth with the help of a DSN uplink beacon. The floating lander's inertial orientation would be used to determine where to point the HGA for DTE communications. An uplink beacon sensed by the HGA would be used for auto-tracking after acquisition.

While the floating lander is on the lake surface, gyros, accelerometers, and sun sensors would be used to sense orientation, and the floating lander would be passively stable. A redundant set of IMUs and six JPL advanced-integrated micro-sun sensors (AIMS) would be used for redundant hemispherical coverage. Accounting for atmospheric absorption, solar intensity on the surface appears to be comparable to solar intensity in space at 30 AU. JPL AIMS sun sensors are qualified for up to 30 AU. With the sun direction, nadir direction (from accelerometer measurements), and accurate ephemeris information, the inertial orientation of the floating lander can be determined.

The floating lander would utilize two ASRGs for power generation. Power control would be accomplished through a shunt regulator / shunt radiator system. Power switching would be provided for the lander subsystems, including C&DH, telecom, thermal control, mechanisms, and instruments. The lander would also contain an MSAP avionics design similar to the Flagship floating lander.

Option 3: New Frontiers Submersible with Relay Communication (Scientific Value: 21/25)

The third option would not require DTE and could be accommodated with a much smaller launch vehicle and a little over a nine-year cruise phase (assuming a launch date similar to Option 2). The two-day surface mission would consist of a single probe that would briefly float on the lake's surface while making surface measurements, then submerge and conduct measurements at depth for about six hours, and finally resurface the part of the probe containing the telecom and data storage subsystems to transmit its collected data to the flyby carrier/relay spacecraft. The instrument payload was further reduced for this option to a two-dimensional gas chromatograph mass spectrometer (GC-GC MS), Fourier transform infrared (FTIR) spectrometer, lake properties instruments, and a descent camera. The science largely became focused on just two areas: atmospheric evolution and lake chemistry. The submersible would be delivered to Titan surface packaged in a 2.1 m aeroshell.

The operational scenario puts some constraints on the structural design, requiring the submersible to float before submerging. This constraint was not necessary in the Flagship mission, where the floating lander would keep the submersible afloat prior to release. In order to address this constraint, small-evacuated floats would be attached to the submersible in such an orientation as to keep the lander upright during surface operations. Once the surface operations have been completed, the floats would be opened, filling with liquid to decrease buoyancy of the vehicle and allow it to sink.

As shown in Figure 4, the primary structural design consists of two 0.7 m diameter metal spheres connected by a thin cylindrical tube containing the cabling from one sphere to the other. As with the Flagship submersible, science instruments and most of the batteries would be housed in the lower sphere, while the telecom system and necessary electronics would be housed in the upper. When connected after the floats are flooded, the submersible mass would outweigh the displaced fluid, causing it to sink. At the end of the submerged science operations, the sphere containing the instrumentation would be released, remaining at the lake bottom while the upper sphere would return to the surface to transmit data to the cruise/relay stage during its flyby.

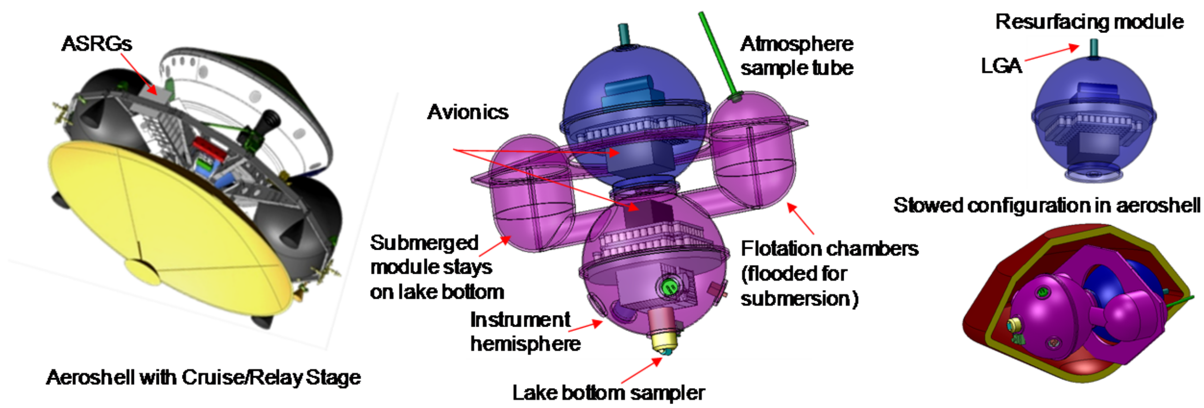

FIGURE 4. Relay Submersible Configuration (*conceptual designs*)

As with the Flagship submersible, this option's power source would be Li CFx primary batteries. The same ETMs described in the Flagship submersible design would be employed for the New Frontiers submersible. Two ETMs would be designed specifically for the mission. Thermal design would also be the same as the Flagship submersible. The hermetically sealed submersible would use vacuum getters to maintain vacuum while RHUs would provide the necessary heat to keep the instruments and avionics at operating temperature. High-conductance structure, heat straps, and switches would be used to moderate the thermal connections to the shell wall.

The submersible would use a redundant X-band system with X-band-only USTs and 15 W solid-state power amplifiers (SSPAs). The system would use a single X-band LGA for communications. The submersible would carry out science operations while the cruise/relay stage approaches Titan. After six hours at the bottom of the lake, the submersible would return to the surface and relay all data to the cruise stage during the four hours of closest approach. The cruise/relay spacecraft would return all mission data (~2Gb) to Earth over the following week.

Option 4: New Frontiers Floating Lander with Relay Communication (Scientific Value: 16/25)

The fourth and final option examined was a floating probe carrying only three instruments delivered by a flyby carrier/relay spacecraft. Surface operations for this option would be reduced to 12 hours. The mission trajectory design would be similar to that of Option 3, but probe release would only be two months before entry (three months in Option 3). The instrumentation would be further reduced to a GC-GC MS, lake properties instruments, and a descent camera. The flyby spacecraft would be identical to the spacecraft used in Option 3. The design of the lander leverages that produced for the New Frontiers relay submersible with a shorter mission timeline and a descoped set of science instruments. The lander would be delivered to Titan using the same entry system as the submersible.

The floating lander was designed with simplicity in mind. Figure 5 shows the configuraton. Shaped like a barrel, the masses of the subsystems are distributed in such a way as to be self-righting when immersed in the liquid. The masses of the instrumentation and batteries would be located on the same side of the barrel in order to cause that side always to be oriented down. This design has the added benefit of dampening any motion that may be caused by surface chop in the liquid, ensuring a stable platform for telemetry and science operations.

Thermal control for the lander would be very similar to the battery-powered submersibles. As with the submersibles,

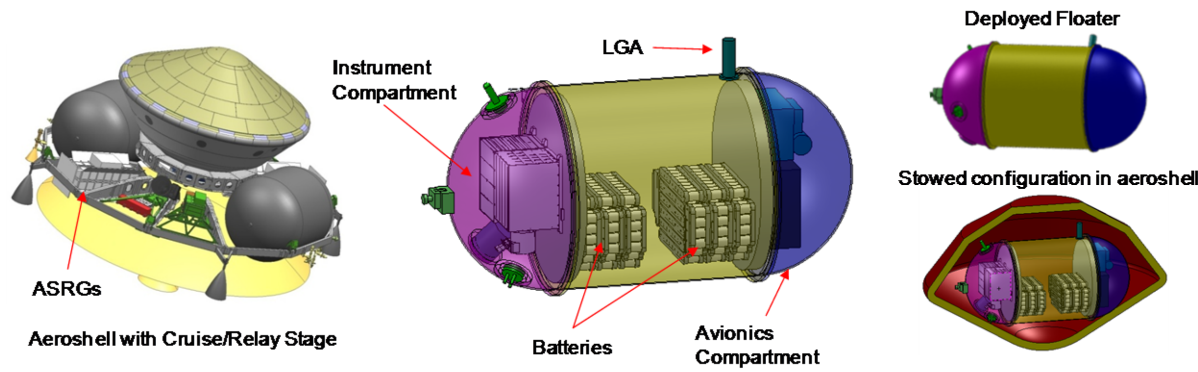

FIGURE 5. New Frontiers Relay Floating Lander Configuration (*conceptual designs*)

the floating lander would be a hermetically sealed vessel, maintained with internal vacuum and insulated by MLI. Vacuum would be maintained by refirable getters and heating would be provided by RHUs.

Lithium-carbon monoflouride primary batteries would power the lander. The lander power electronics suite would include power distribution and regulation as well as ETM functions. No power control is required for a primary battery powered system, as discharge voltage alone suffices. Power switching would be provided for the lander subsystems, including C&DH, telecom, thermal control, mechanisms, and instruments. The lander's avionics suite would consist of two ETMs to handle spacecraft operations as in Option 3. The floating lander would utilize the same communication strategy as the New Frontiers submersible. Communication to the relay spacecraft may be possible at a very low rate beginning at entry, and would extend until the relay spacecraft goes over the horizon approximately 12 hours later. A redundant X-band system with X-band-only USTs and 15 W SSPAs transmitting through a zenith pointed LGA would relay up to 2 Gb of science data to the flyby spacecraft during the 12 hour pass.

CRUISE STAGE DESIGN

The New Frontiers DTE mission would use a "dumb" cruise stage to deliver the lander to Titan as illustrated in Figure 3. Using the avionics and power from the lander, the cruise stage would effectively be a large propulsion system. A large dual-mode bipropellant propulsion system would be necessary to accommodate the high delta-V requirement to get to Titan while Earth is in view. One 110 lbf Hi-PAT bipropellant thruster would be used for large propulsive maneuvers while twelve 0.2 lbf monopropellant thrusters would utilize the propulsion system's fuel to provide attitude control and small delta-V maneuvers. The lander's ASRGs would provide power generation for the cruise stage during cruise. Propulsion drivers and power conditioning units would be mounted aboard the cruise stage to run the propulsion system. All other control would be handled by the avionics aboard the landed element.

The New Frontiers carrier/relay stage would be used for Options 3 and 4 as illustrated in Figures 4 and 5. Unlike the "dumb" cruise stage used for Option 2, this stage must perform all the functions of a free-flying spacecraft and thus would include all the necessary avionics both to control itself and to act as a communication relay for the in-situ vehicle. The longer cruise times associated with these missions would bring the benefit of a reduction in the amount of delta V required relative to Option 2, allowing for a cheaper blowdown monopropellant hydrazine system to be used. The propulsion subsystem would include four 50 lbf thrusters used for deep-space maneuvers (DSMs). All engines would be fired simultaneously to reduce the duration of the maneuver. Twelve 0.2 lbf thrusters would be used in pairs for attitude control maneuvers. An X-band relay system would allow periodic checkouts of the lander/entry system during its detached cruise and would be able to receive semaphore tones from the lander during EDL. The lander would carry out science operations while the cruise stage approaches Titan and would then relay all data to the cruise stage at X-band during the four hours of closest approach. The cruise stage would have a redundant X- and Ka-band system. Two USTs would transmit and receive at X-band for either relay or DTE communication and would transmit only at Ka-band for DTE communication. Amplifiers would include 15 W RF X-band SSPAs and 25 W RF Ka-band TWTAs. A 3 m X- and Ka-band HGA would be used for relay and high-rate DTE communication, an MGA would be used for safe mode out to 7 AU, and two LGAs would provide early cruise communications. The power system for the relay cruise stage would be similar to the DTE version with the exception of the location of the ASRGs. These power generation units would be housed aboard the cruise stage itself rather than on the landers. This architecture would force the landers to be completely battery-powered; however, would significantly reduce the cabling required to transport power.

CONCLUSION

The exploration of Titan's lakes offers a rich opportunity for lifting the veil on that enigmatic world. The mission concepts presented in this document represent several possible options for beginning this exploration. Architectures explored by the team indicate that a flagship mission, capable of achieving all Decadal science goals for Titan lake exploration should be feasible with support from a Saturn orbiter. The field of possible New Frontiers mission candidates is relatively broad, with implementations varying in complexity and capability. These missions should be able to achieve many of the lake science objectives using currently available technologies for their flight systems, although development would likely be required in the areas of instruments and sampling systems able to function in the Titan lake environment. Major challenges for these New Frontiers examples would lie in the area of keeping costs within the caps imposed by that competition.

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