Excerpted from the

Titan Lake Probe Final Study Review

March 23, 2010

Jet Propulsion Laboratory, California Institute of Technology

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Scientific Traceability

Scientific Goals

The primary scientific goals of the Titan Lake Probe are:

SGa: To understand the formation and evolution of Titan and its atmosphere

SGb: To study the lake-atmosphere interaction in order to determine the role of Titan's lakes in the methane cycle

SGc: To study the target lake as a laboratory for pre-biotic organic chemistry in both water (or NH3 enriched water) solutions and non-water solvents

SGd: To understand if Titan has an interior ocean

Traceability to Surveys and Reports

These goals and objectives can be directly mapped to the Decadal Survey:

1. Learn how the Sun's retinue of planets originated and evolved – SGa, SGb, SGc, SGd.
2. Discover how the basic laws of physics and chemistry, acting over eons, can lead to the diverse phenomena observed in complex systems such as planets - SGa, SGb, SGc, SGd.
3. Understand how physical and chemical processes determine the main characteristics of the planets, and their environments, thereby illuminating the workings of the Earth – SGa, SGb, SGc.
4. Determine how life developed in the solar system, where it may have existed, whether extant life forms exist beyond Earth, and in what ways life modifies planetary environments – SGc.

And to the SSE Roadmap:

1. How did the Sun's family of planets and minor bodies originate? SGa, SGb, SGc, SGd
2. How did the solar system evolve to its current diverse state? SGa, SGb, SGc, SGd
3. What are the characteristics of the solar system that led to the origin of life? SGc
4. How did life begin and evolve on Earth and has it evolved elsewhere in the solar system? SGc

And to the NRC Report, "The Limits of Organic Life in Planetary Systems" – SGa and SGc.

Table 1. Composition of Liquid (Mole Fraction at Given Temperature)

Species	87 K	90 K	93.65 K	
N_2	1.22×10^{-2}	4.94×10^{-3}	2.96×10^{-3}	
CH_4	2.18×10^{-1}	9.74×10^{-2}	5.56×10^{-2}	
Ar	1.01×10^{-5}	4.95×10^{-6}	3.09×10^{-6}	
Xe	8.55×10^{-3}	1.52×10^{-3}	3.09×10^{-4}	
Kr	7.72×10^{-9}	3.13×10^{-9}	1.92×10^{-9}	
CO	1.24×10^{-6}	4.25×10^{-7}	2.05×10^{-7}	
H_2	2.94×10^{-11}	4.08×10^{-11}	5.12×10^{-11}	
C_2H_6	6.55×10^{-1}	7.62×10^{-1}	7.95×10^{-1}	
C_3H_8	6.36×10^{-2}	7.40×10^{-2}	7.71×10^{-2}	
C_4H_8	1.19×10^{-2}	1.39×10^{-2}	1.45×10^{-2}	
HCN	9.06×10^{-3}	2.08×10^{-2}	2.89×10^{-2}	(s)
C_4H_{10}	1.04×10^{-2}	1.21×10^{-2}	1.26×10^{-2}	(ns)
C_2H_2	9.83×10^{-3}	1.14×10^{-2}	1.19×10^{-2}	(ns)
CH_3CN	8.48×10^{-4}	9.87×10^{-4}	1.03×10^{-3}	(ns)
CO_2	2.50×10^{-4}	2.92×10^{-4}	3.04×10^{-4}	(ns)
C_6H_6	1.93×10^{-4}	2.24×10^{-4}	2.34×10^{-4}	(ns)

Notes. From HCN to C_6H_6, compounds are in the solid state in precipitates and assumed to dissolve when they reach the liquid phase. (s): saturated; (ns): non saturated. Ar is the total argon contained in all isotopes.

Analytical Chemistry

- Adequate mass resolution/separation to untangle the mass range from 24 to 30 which includes HCN, C_2H_2, C_2H_6, C_2H_4, and N_2 and their isotopes.
  - Allows us to trace the chemical pathways of the methane conversion process
- Adequate sensitivity to determine the pattern of organic compounds and their isotopologues to a level of 1 ppm and determine their C, H, N, and O isotopic ratios to <1 per mil.
  - Identify patterns of trace species and their origins either in the atmosphere or in the hydrocarbon sea
  - Search for self-organizing organic chemical pathways
- Measure the concentration of noble gases to determine the chemical origin of the atmosphere.

Table 3. Key Measurements Needed to Achieve Science Goal

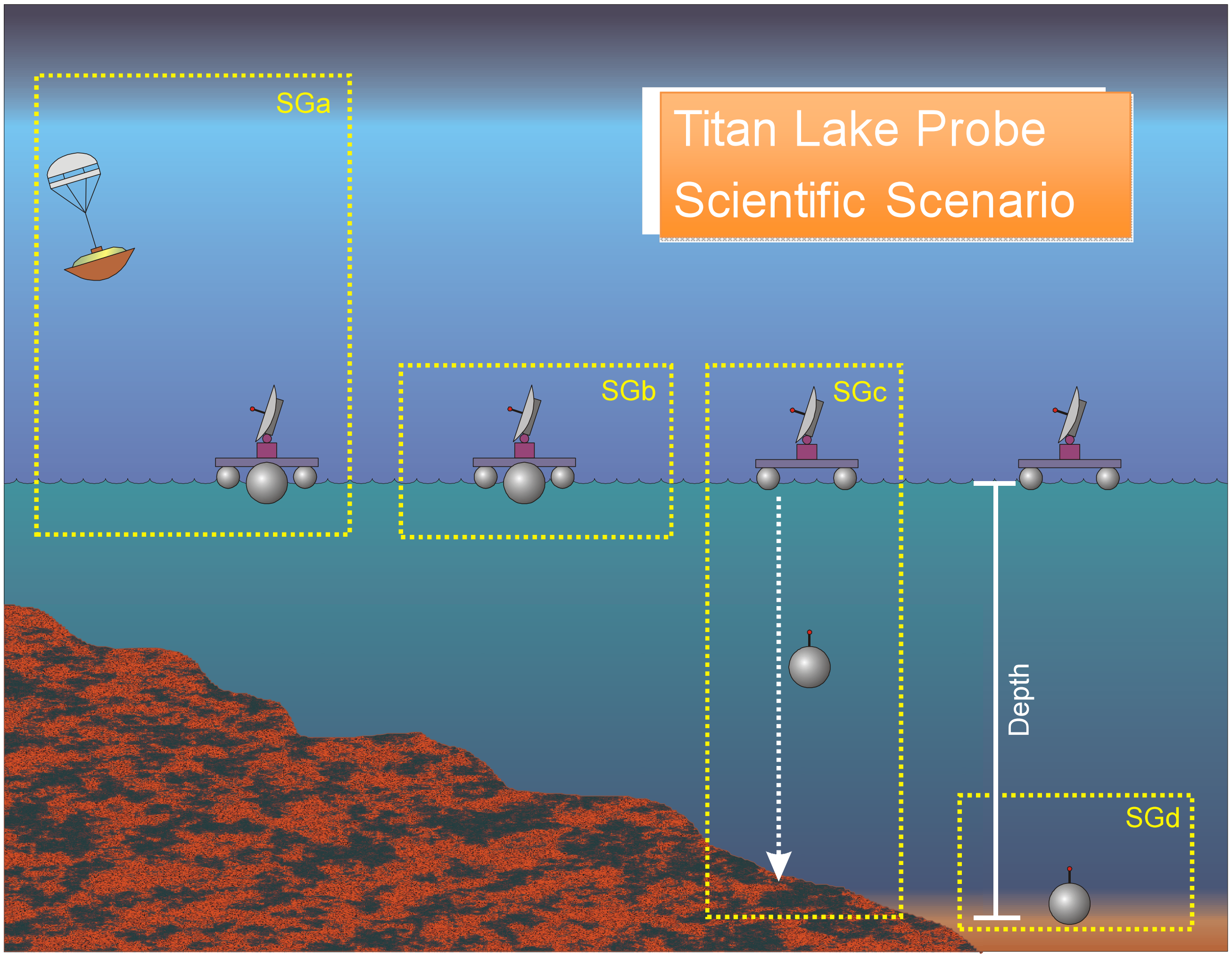
Parameter	Use	Range	Sensitivity/ Accuracy	Rate
Surface Lake Temperature, .	Calculate saturation vapor pressure; Surface heat flux	80-110 K	0.1 K	~0.1 Hz
Pressure*, *p*	Calculation of potential temperature, θ as a function of *T*.	1000-2000 hPa (altitude dependent)	1 hPa	~1 hr^{-1}
u*,v*,w*	3-D mean wind for structure functions and eddy covariances.	0-10 m/s	0.1 m/s u,v 0.01 m/s w	10 Hz
Atmospheric Temperature, *T**	Calculation of θ as function of p for structure function and bulk heat flux calculation.	80-110 K	0.1 K	10 Hz
Volatile abundance* (CxHy)	Calculation of structure functions and bulk volatile flux calculation	0-100% RH	1% RH	10 Hz
Lake Composition	Establish saturation vapor pressure of CxHy for bulk volatile flux calculation	?	?	?
Solar Flux, F↓	Radiative heating	0-5 W m^{-2}	0.1 W m^{-2}	~1 hr^{-1}
IR↓	Radiative Heating	0-5 W m^{-2}	0.1 W m^{-2}	~1 hr^{-1}
Rain rate^{+}	Mass return to lake	0-2 m hr^{-1}	1 cm/s	0.1 Hz (when raining)

* Taken at a minimum of three heights (e.g., 0.3 m, 0.6 m, 1.0 m).
\+ Not a floor requirement, but technically part of lake-atmosphere surface budget.

Meteorological Measurements

- Determine the thermodynamic state of the sea and atmosphere (P,T)
- Measure the three dimensional winds at three different heights to determine eddy co-variance
- Measure composition of C_xH_y in the sea and air to determine the chemical interchange of the sea and atmosphere.

General Mission Overview



Science Instrumentation

- **SGa: Atmospheric Evolution**
  - Lake Composition Analyzer **(LCA)**
- **SGb: Lake/atmosphere interaction**
  - Other Properties **(OP)**
  - Meteorological Package **(MP)**
- **SGc: Lake chemistry**
  - Lake Composition Analyzer **(LCA)**
  - Lake Properties Package **(LPP)**
  - Other Properties **(OP)**
- **SGd: Interior structure**
  - Lake Properties Package **(LPP)**

OP
- Dielectric constant
- Speed of sound sensor
- Temperature sensor
- Pressure sensor
- Refractive index
- Turbidimiter
- Densitometer
- Accelerometer

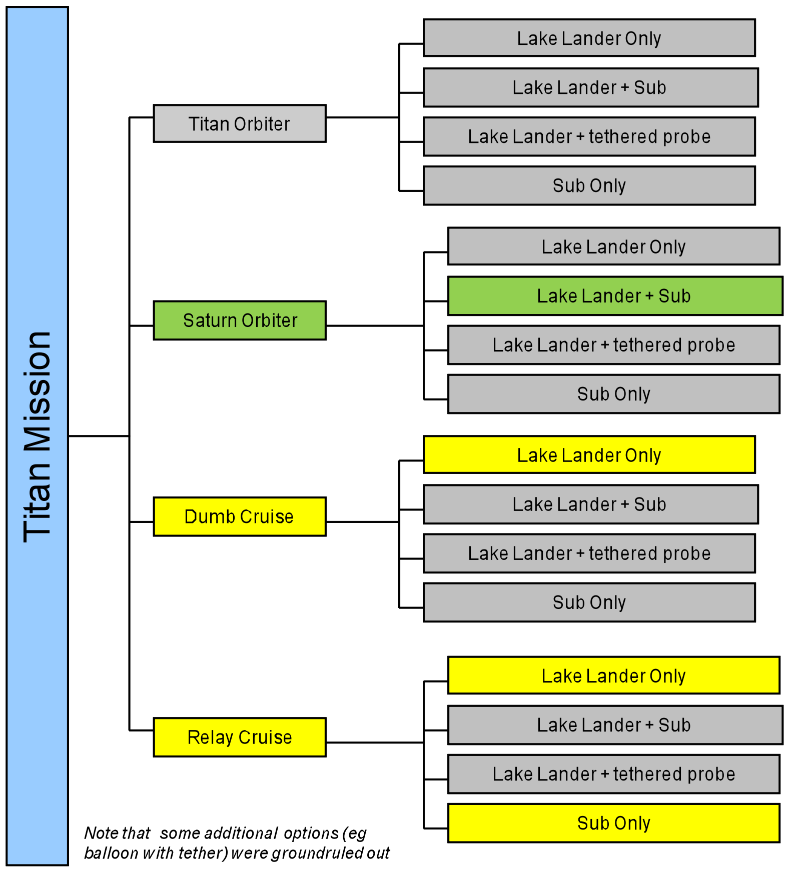
MP
- TDL spectrometer
- Temperature sensors
- Wind speed and direction sensors
- Cameras – Descent, Surface and Zenith
- Atmospheric pressure
- Radar altimeter
- Rain gauge
- Spectral radiometer

LCA
- GC x GC MS
- FTIR spectrometer

LPP
- GC x GC MS
- Temperature sensor
- Refractive index
- Speed of Sound sensor
- Turbidimeter
- Permittivity meter
- Echo sounder
- Refractive index
- Accelerometer
- Magnetometer

Architecture Trades

Architectural Options



Option Selection Rationale

Titan Orbiter:

Titan Orbiter too high cost for NF

Flagship mission assumed TSSM-like carrier, with delivery during Saturn orbit phase of mission

Saturn Orbiter:

- Lake Lander Only: Not considered sufficient for Flagship mission
- Lake Lander + Sub: Combination allows meeting greatest number of science objectives **Option 1**
- Lake Lander + tethered probe: Tether increases complexity, would likely interfere with sonar measurements
- Sub Only: Not considered sufficient for Flagship mission

Dumb Cruise:

- Lake Lander Only: Floater required for DTE implementation **Option 2**
- Lake Lander + Sub: Deemed too costly for NF mission
- Lake Lander + tethered probe: Tether increases complexity, would likely interfere with sonar measurements. Two elements would increase cost
- Sub Only: Not amenable to DTE solution

Relay Cruise:

- Lake Lander Only: Possibly lowest cost option **Option 4**
- Lake Lander + Sub: Deemed too costly for NF mission
- Lake Lander + tethered probe: Tether increases complexity, would likely interfere with sonar measurements. Two elements would increase cost
- Sub Only: Highest science return for lowest cost **Option 3**

Legend: (green) *Preferred Mission Architecture for Flagship* (yellow) *Preferred Mission Architecture for NF* (grey) *Not selected*

Mission Architectures and Assumptions

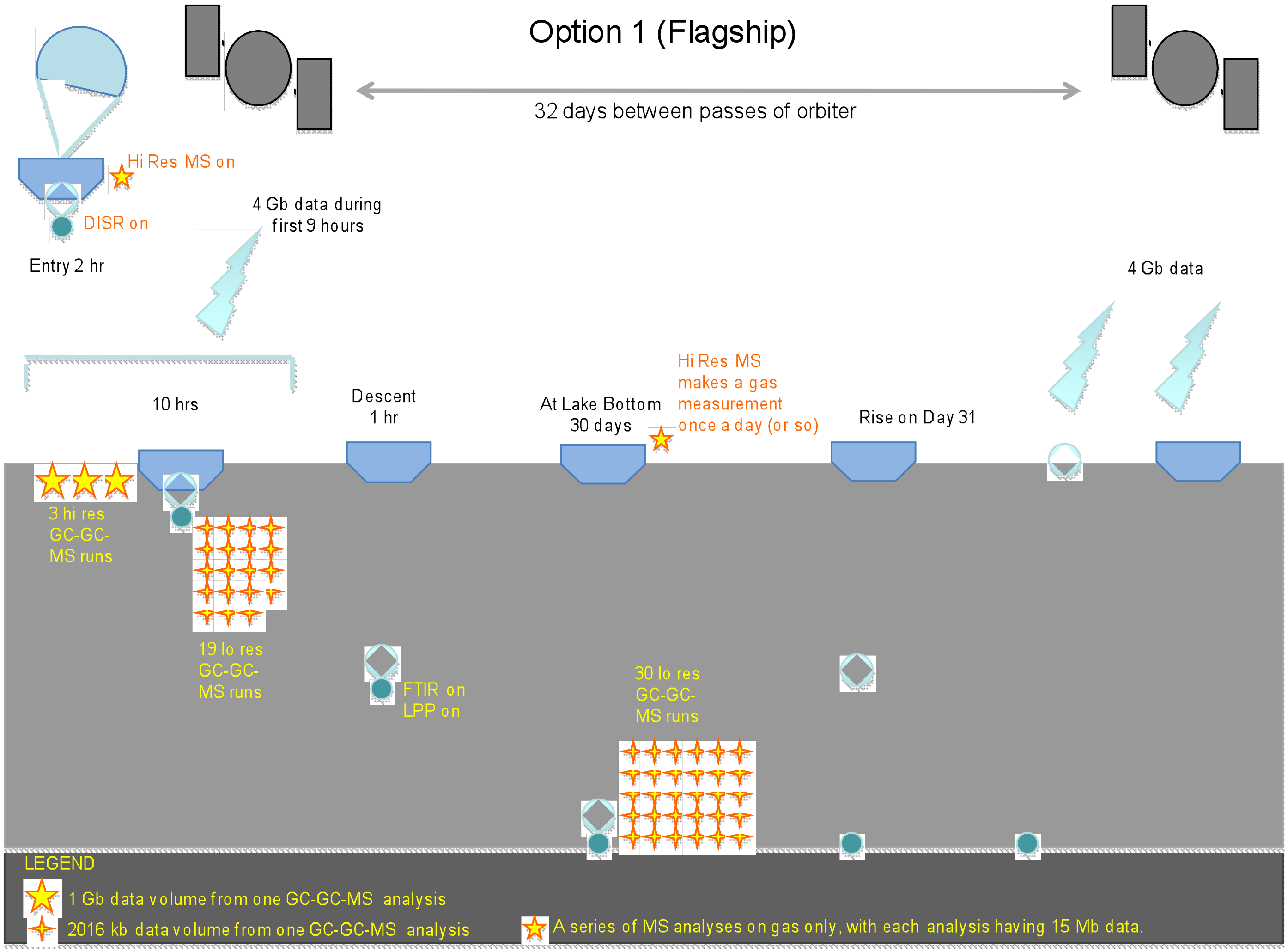
- Four options were studied, here I present only the flagship option:

  - **Option 1:** The collaborating trade team supplied Team X with a completed design for a Titan lake lander including both a floating ASRG-powered probe as well as a two-part battery-powered submersible. The submersible and floater relay data through a spacecraft in Saturn orbit with periodic swing-bys of Titan. The landed mission would run for a minimum of 32 days. Team X estimated the cost for the lander and submersible, and designed and estimated the EDL system. The overall mission was assumed to be a multi-billion dollar flagship class mission.

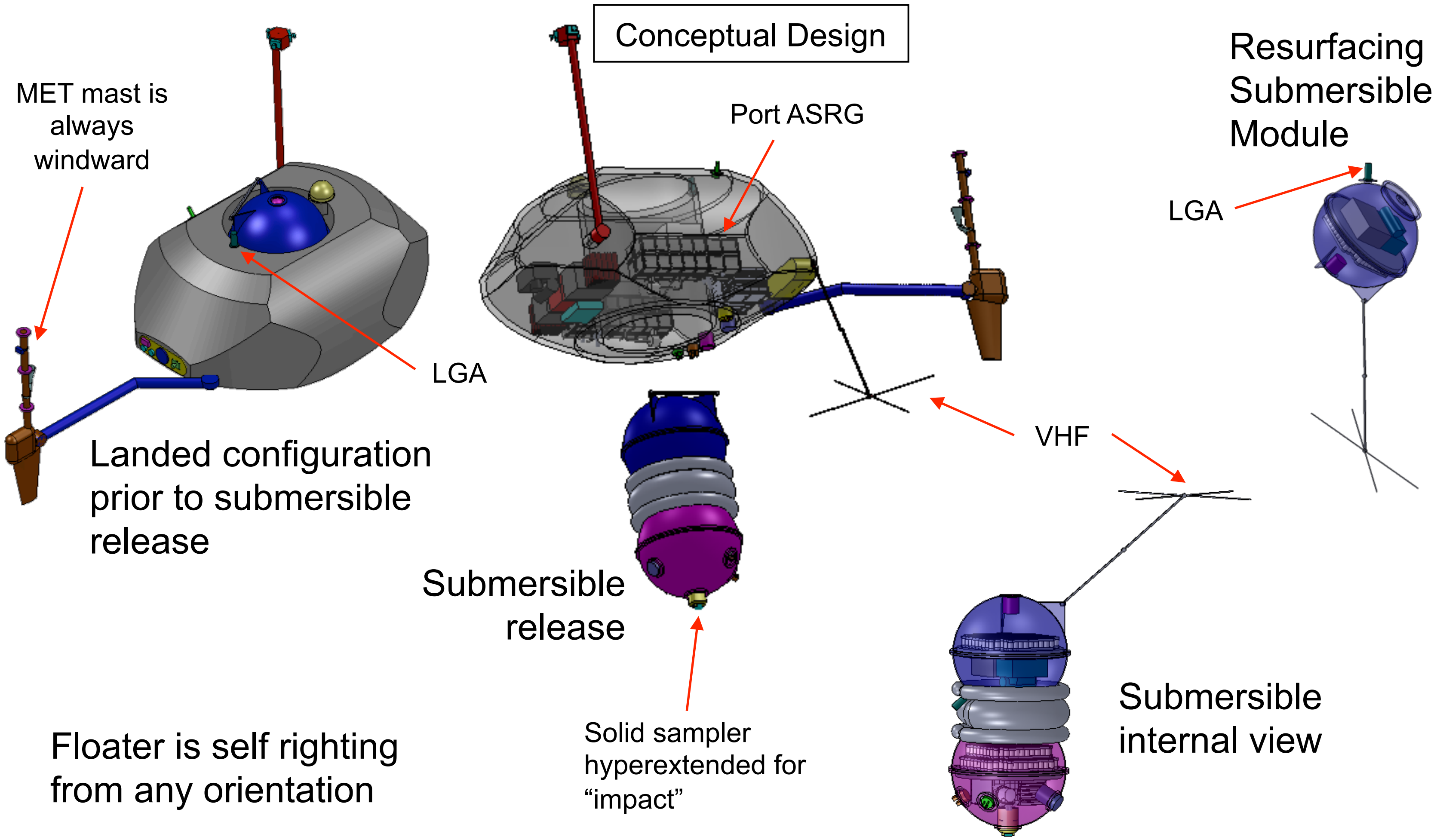
Option 1 Overview

- Team X estimated the cost of the trade team's design for a floater and submersible lake lander
  - No mission costing performed
- Aimed at a flagship-class mission
- Design addressed all four areas of scientific interest
  - Atmospheric evolution
  - Atmosphere-lake interaction
  - Lake chemistry
  - Interior structure
- Reaches Kraken Mare after sunset – must relay data through spacecraft in Saturn orbit
- 2 ASRGs on the floater
- This option was not be included in the input to the Independent Cost Estimate (ICE) and therefore could not be included in the decadal survey.

Option 1 - Flagship



Option 1 Configuration



Option Mass Comparison

		Options			
		1	2	3	4
Sub.	Instruments	38 kg		31 kg	
	Vehicle	160 kg		195 kg	
	Margin/ Contingency	*85 kg*		*97 kg*	
	Submersible Total	**283 kg**		**324 kg**	
Floater	Instruments	68 kg	56 kg		29 kg
	Payload	283 kg	0 kg		0 kg
	Vehicle	315 kg	302 kg		167 kg
	Margin/ Contingency	*165 kg*	*154 kg*		*85 kg*
	Floater Total	**831 kg**	**512 kg**		**281 kg**
Entry System	Payload	831 kg	512 kg	324 kg	281 kg
	Vehicle	389 kg	248 kg	227 kg	152 kg
	Margin/ Contingency	*167 kg*	*107 kg*	*97 kg*	*66 kg*
	EDL Total	**1387 kg**	**867 kg**	**648 kg**	**499 kg**
Spacecraft	Payload		867 kg	648 kg	499 kg
	Vehicle		509 kg	496 kg	438 kg
	Margin/ Contingency		*219 kg*	*213 kg*	*188 kg*
	Spacecraft Total (Dry)		**1595 kg**	**1357 kg**	**1125 kg**
	Propellant		2255 kg	702 kg	517 kg
	Spacecraft Total (Wet)		**3850 kg**	**2058 kg**	**1642 kg**
Launch Vehicle Capability		n/a	3883 kg	2645 kg	2645 kg
Launch Vehicle		n/a	Atlas 551	Atlas 401	Atlas 401

Technology Development Summary

- Huygens instruments do not need technology development *per se* but could benefit from redesign using current technology.
- Many of the instruments have been developed for Earth applications but need modifications and testing at T= 95K for use Titan's cryogenic lakes.
- Overall TRL of several of the instrument systems range from 2-4, with some higher TRL instruments previously flown on Huygens that need modernization and testing.
- Development of these instruments takes from 1-3 years, depending on their current state, and need adequate funding.
- Sample Acquisition and handling is costed but until designed it is a very rough estimate. Methods and techniques will be adapted from Earth applications in the ocean.
- In situ instruments are competitively funded, so an instrument program to fund Mid-TRL level is necessary.
- All instrument development efforts would need test facilities to test the instruments under Titan conditions. No such chamber exists. Some of the atmospheric instruments could use LN_2 chambers, but for the instruments that sample the lake they would need modification to be able to house liquid methane/ethane. This is not included in the Tech. Dev. Cost. Such a facility is conservatively estimated to cost ~$5M.

Lander Study/Team X Participants

NRC Panel Science Team		
Panel Lead	John Spencer	spencer@boulder.swri.edu
Science Champion	Hunter Waite	hwaite@swri.edu
Science	Tom Spilker	Thomas.R.Spilker@jpl.nasa.gov
Science	Zibi Turtle	Elizabeth.Turtle@jhuapl.edu
Science	Caitlin Griffith	griffith@lpl.arizona.edu
Science	Chris McKay	chris.mckay@nasa.gov

Other Decadal Survey Support		
JPL DS Lead	Kim Reh	Kim.R.Reh@jpl.nasa.gov
NASA Panel POC	Curt Neibur	Curt.Niebur@nasa.gov

Lander Study Team		
Study Lead	John Elliott	John.O.Elliott@jpl.nasa.gov
ACS	Bob Kinsey	Robert.J.Kinsey@jpl.nasa.gov
CDH	Dwight Geer	Dwight.A.Geer@jpl.nasa.gov
EEIS/GSE	Joe Smith	Joseph.F.Smith@jpl.nasa.gov
Instruments	Tim Brockwell	Tim.Brockwell@swri.org
Instruments	Luther Beegle	Luther.W.Beegle@jpl.nasa.gov
Instruments	Pat Beauchamp	Patricia.M.Beauchamp@jpl.nasa.gov
Instruments	Peter Willis	Peter.A.Willis@jpl.nasa.gov
Instruments	Rob Hodyss	Robert.P.Hodyss@jpl.nasa.gov
Instruments	Peter Tsou	Peter.Tsou@jpl.nasa.gov
Landed Sys Config	Joe Melko	Joseph.P.Melko@jpl.nasa.gov
Mission Design	Nathan Strange	Nathan.J.Strange@jpl.nasa.gov
Planetary Protection	Andy Spry	James.A.Spry@jpl.nasa.gov
Power	Paul Timmerman	Paul.J.Timmerman@jpl.nasa.gov
Support SE	Jared Lang	Jared.Lang@jpl.nasa.gov
Telecom	Michael Pugh	Michael.P.Pugh@jpl.nasa.gov
Thermal	Chris Paine	Christopher.G.Paine@jpl.nasa.gov

Team X		
Team X Study Lead	Keith Warfield	Keith.R.Warfield@jpl.nasa.gov
ACS	Robert Kinsey	Robert.J.Kinsey@jpl.nasa.gov
ACS	Ryan Lim	Ryan.S.Lim@jpl.nasa.gov
CDS	Dwight Geer	Dwight.A.Geer@jpl.nasa.gov
Configuration	Jamie Piacentine	Jamie.S.Piacentine@jpl.nasa.gov
Cost	Daniel Harvey	Daniel.G.Harvey@jpl.nasa.gov
Deputy SE	Mohammed Khan	Mohammed.O.Khan@jpl.nasa.gov
EDL	Evgeniy Sklyanskiy	Evgeniy.Sklyanskiy@jpl.nasa.gov
Ground Systems	Douglas Equils	Douglas.J.Equils@jpl.nasa.gov
Instruments	Marc Walch	Marc.J.Walch@jpl.nasa.gov
Logistics	Melissa Vick	Melissa.L.Vick@jpl.nasa.gov
Mechanical	Matthew Spaulding	Matthew.D.Spaulding@jpl.nasa.gov
Mission Design	George Carlisle	George.L.Carlisle@jpl.nasa.gov
Planetary Protection	Laura Newlin	Laura.E.Newlin@jpl.nasa.gov
Power	Keith Chin	Keith.B.Chin@jpl.nasa.gov
Programmatics/Risk	Jairus Hihn	Jairus.M.Hihn@jpl.nasa.gov
Propulsion	Masashi Mizukami	Masashi.Mizukami@jpl.nasa.gov
Science	William Smythe	William.D.Smythe@jpl.nasa.gov
Software	Ashton Vaughs	Ashton.G.Vaughs@jpl.nasa.gov
Software	Harry Balian	Harry.Balian@jpl.nasa.gov
Systems Engineer	Jared Lang	Jared.Lang@jpl.nasa.gov
Telecom Systems	David Hansen	David.M.Hansen@jpl.nasa.gov
Telecom Systems	Michael Pugh	Michael.P.Pugh@jpl.nasa.gov
Thermal	Robert Miyake	Robert.N.Miyake@jpl.nasa.gov

Table 5. Instrument Specifications

Item	Units	Hi-Res GC-GC MS	LPP Instrument	Echo Sounder	Turbidimeter	Relative Humidity (TDL-Mast Mounted)	Atmospheric Structure Instrument (ASI-Mast Mounted)	Descent Instrument (DISR)	Surface Cameras	Magnetometer	Low-Res GC-GC MS	FTIR Spectrometer	Descent Cameras
Volume of the instrument	cm^3	33,000	785	250	200	204	47,235	396	480	200	33,000	–	320
Instrument mass without contingency (CBE*)	kg	25.0	4.0	5.0	2.0	6	4.53	8	1.4	5	25.0	2	0.6
Instrument mass contingency	%	30	30	30	30	30%	30%	30	30	30	30	30	30
Instrument mass with contingency (CBE+Reserve)	kg	32.5	5.2	6.5	2.6	7.8	5.9	10.4	1.8	6.5	32.5	2.6	0.8
Instrument average payload power without contingency	W	150	10	5	10	30	6.75	11	13	2	150	10	22
Instrument average payload power contingency	%	30	30	30	30	30%	30%	30	30	30	30	30	30
Instrument average payload power with contingency	W	195	13	6.5	13	39	8.8	14.3	16.9	2.6	195	13	28.5
Instrument average science data rate^ without contingency	kbps	1,000	100	0.1	0.1	100	1	100	1,000	10	1,000	10	1,000
Instrument average science data^ rate contingency	%	30	30	30	30	30	30%	30	30	30	30	30	30
Instrument average science data^ rate with contingency	kbps	1,300	130	0.13	0.13	130	1.3	130	1,300	13	1,300	13	1,300

Backup Slides

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Option Cost Comparison

WBS Elements	Option 1	Option 2	Option 3	Option 4
Project Cost (including Launch Vehicle)	**$1430.0 M**	**$1540.0 M**	**$1440.0 M**	**$1370.0 M**
Development Cost (Phases A - D)	**$1340.0 M**	**$1150.0 M**	**$1080.0 M**	**$1010.0 M**
Proj. Mgmt. / Sys. Eng. / MA	**$40.0 M**	**$100.0 M**	**$90.0 M**	**$90.0 M**
Science	**$60.0 M**	**$20.0 M**	**$20.0 M**	**$20.0 M**
Payload System	**$290.0 M**	**$160.0 M**	**$100.0 M**	**$90.0 M**
Floating Lander	$220.0 M	$150.0 M	-	$80.0 M
Submersible	$50.0 M	-	$90.0 M	-
Flight System	**$500.0 M**	**$400.0 M**	**$420.0 M**	**$400.0 M**
Floating Lander	$260.0 M	$200.0 M	-	$80.0 M
Submersible	$100.0 M	-	$100.0 M	-
Entry System	$80.0 M	$60.0 M	$60.0 M	$60.0 M
Cruise Stage	-	$90.0 M	$200.0 M	$200.0 M
Mission Ops and Ground Sys. Dev.	**-**	**$50.0 M**	**$60.0 M**	**$50.0 M**
ATLO	**-**	**$40.0 M**	**$30.0 M**	**$30.0 M**
Education and Public Outreach	**$2.0 M**	**$2.0 M**	**$2.0 M**	**$2.0 M**
Development Reserves	**$450.0 M**	**$380.0 M**	**$360.0 M**	**$330.0 M**
Operations Cost (Phases E - F)	**$90.0 M**	**$110.0 M**	**$160.0 M**	**$160.0 M**
Launch Vehicle	**-**	**$280.0 M**	**$200.0 M**	**$200.0 M**

Study Overview

- This study was conducted in two phases: (1) an initial examination of the architecture tradespace 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 concurrent engineering team – Team X.
- The tradespace work and landed designs were developed during December 2009 and January 2010. The architectures of interest centered on a floater/ submersible portion of a large (Flagship-class) unspecified mission with emphasis on achieving all science objectives identified on the initial Panel questionnaire response, and two full missions (1 floater and 1 submersible) targeted at a New Frontiers-class cost constraint.
- Team X took this output and completed designs for the two missions assuming a launch date around 2022. Team X also estimated the cost of the landed package for the Flagship-sized mission. All options focused on lake landings on Titan's Kraken Mare. The study was held from January 19 to January 22.
- Based on the results of the initial study, the science panel and technical team felt that a simpler architecture could better represent a true floor mission and requested that Team X hold one more session to look at a variation to one of the earlier options. That option was another floater mission aimed again at New Frontiers. This mission was designed and estimated on February 4.

Driving Mission Requirements

- Land on, and preferably explore, the lake at depth while communicating data back to Earth
  - Understand the feasibility of different mission architectures as a function of launch date given that sub-earth and sub-solar points shift to Titan's southern hemisphere from 2025 to 2038, while Titan's largest lakes are at high northern latitudes
- Thermal design must allow sustained (>32 days) sampling of the 94K lake environment
- Sample acquisition and handling system must deliver samples to the inlet of the mass spectrometer, allowing representative sampling of gas, liquid and solids from the 94K environment

Findings

- While options 2 through 4 fit within the launch and programmatic constraints of the New Frontiers-class mission, none succeeded in clearly reaching the cost constraint. Adjusting the last New Frontiers cost cap requirement for differences in the Decadal Survey guidelines, we would expect a New Frontiers mission to be about $1B ($FY15). All options exceed this number (although all are also significantly less than past outer planets flagship missions).
- Exploration of Titan will require varying degrees of technical and engineering development depending on the type of in-situ vehicles used. The technical expertise for entry systems, spacecraft, and landed systems is within the range of present, demonstrated, technology. For the missions described in this report development of cryogenic instruments and sampling systems will require moderate additional technology development to bring to maturity
  - Cryogenic testing facilities are not presently available and will be important for development of many components of the mission
- Large Northern hemisphere lakes (e.g. Kraken Mare) are the preferred targets. Southern hemisphere lakes (e.g. Ontario Lacus) were determined to be too small to ensure a lake landing with an acceptable risk given current understanding of Titan winds and seasonal lake variation

Findings

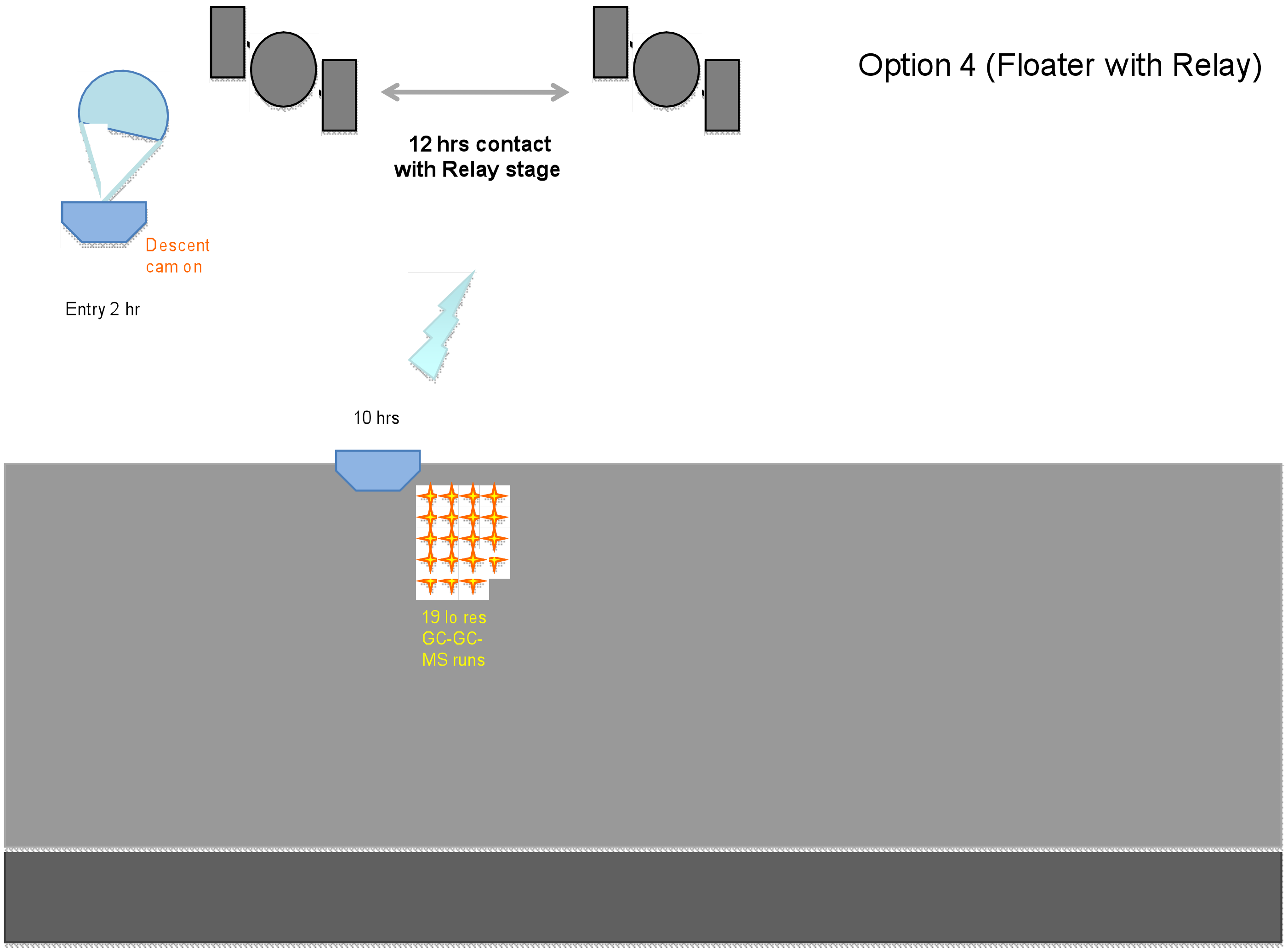
- Launch dates are less favorable for the 2022 opportunity. Any option contemplating DTE communication from a northern hemisphere lake must complete its mission prior to early 2029, requiring trip times on the order of ~6 yr. Jupiter will be out of position for a gravity assist during this next likely New Frontiers launch period, resulting in large delta V requirement to reduce transit times, otherwise long (~9 yr) cruise phases must be accommodated.
- Atmospheric attenuation makes Ka-band unfavorable for DTE options. X-band communications link provides significantly better performance
- Use of SEP, while potentially reducing transit time, was not found to be economically favorable

Option 4 Overview

- Team X designed the spacecraft and EDL system, and estimated the cost of the entire mission including the trade team's design for a floating lake lander
- Aimed at a New Frontiers sized mission
  - Exceeded likely cost level
- Design addressed two of four areas of scientific interest
  - Atmospheric evolution
  - Lake chemistry
- Reaches Kraken Mare after sunset – data relay is required
  - Over 9 year cruise
- Two ASRGs on the relay spacecraft
- Requires an Atlas 401 or equivalent

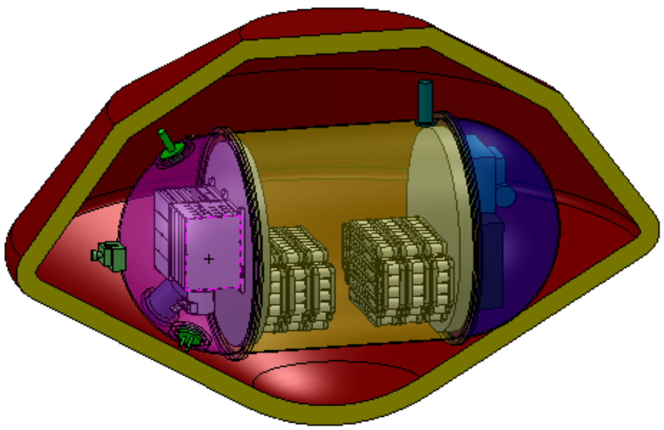
Option 4 – Floater Relay

Option 4 (Floater with Relay)

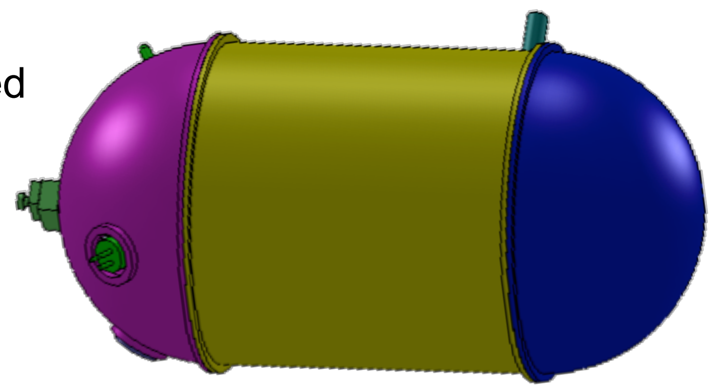


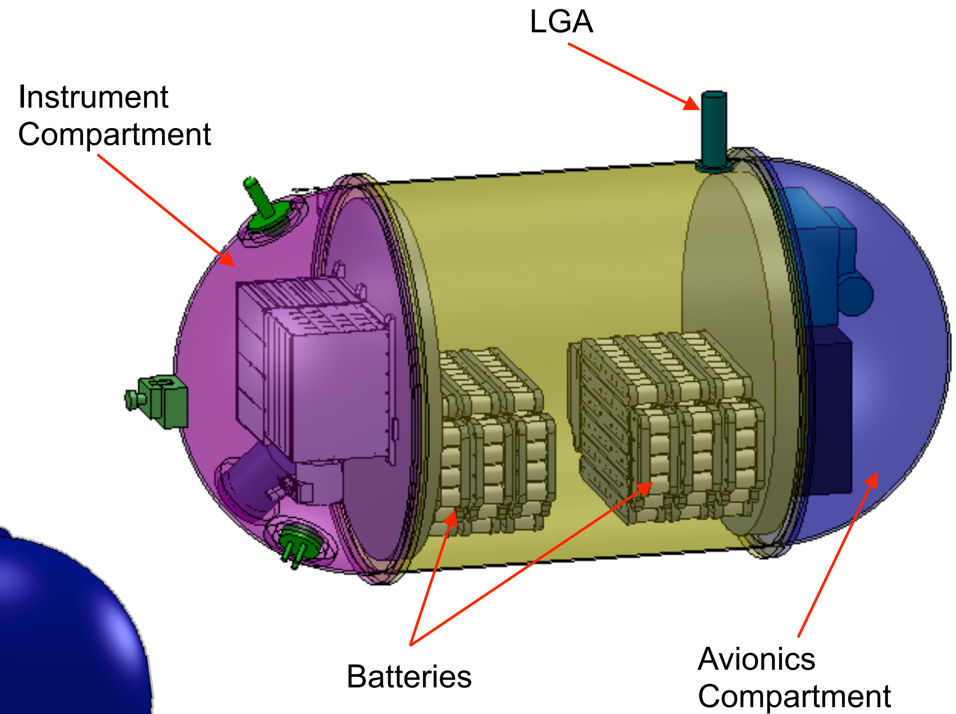
Option 4 - Surface Configuration

Stowed configuration in aeroshell



Deployed Floater





Conceptual Design

Instrument Summary

Instrument	Comments	Options				Platform	
		1	2	3	4	Floater	Sub.
Hi rez GC-GC MS	Two GC columns Analyze gas/liquids/solids via sample handling system	x	x	x	x	x	x[1]
Radar altimeter	Measures lander's altitude	x				x	
Rain gauge	Passive cup with graduations. Camera looks at level	x	x			x	
Surface cameras	3 x 120º azimuth, -80° to +40° elevation cameras for panoramic coverage	x	x			x	
Descent cameras	40° FOV	x	x	x[2]	x[2]	x	x[1]
Turbidimeter	Measures suspended particulates	x	x			x	x[3]
Echo sounder	24 pings/hr, 12kHz	x	x			x	x[5]
Magnetometers		x				x	
LPP instruments	Refractive index (1.250-1.450 range), speed of sound sensor (2,000 m/s max), liquid temperature, permittivity meter (250-275pF range)	x	x	x	x	x	x[1,4]
Relative Humidity	Methane/Ethane measurements (at 0.3 m AGL, 0.6 m AGL, 1.0 m AGL)	x	x			x	
Wind speed/press/temp		x	x			x	
Descent instruments	Violet photometers, IR & visible spectrometers, solar aureole	x	x			x	
Low rez GC-GC MS	2 GC columns Analyze liquids/solids via sample handling system	x					x
FTIR spectrometer	4000-400cm-1, 2cm-1 resolution	x		x			x

1. Instrument included on submersible in option 3
2. Single descent camera on both options 3 and 4
3. Turbidimeters are on both the floater and submersible in option 1
4. LPP instruments are on both the floater and submersible in option 1
5. Echo sounders are on both floater and submersible in option 1

Study Purpose

- As stated in the initial Study Questionnaire document:

The purpose of the study is to determine the technical feasibility and cost of a lake probe mission both as an element of a future Titan flagship mission and as a standalone New Frontiers mission. A secondary objective is to identify the technology developments required to make such a mission possible in the next decade