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A concept study for extraterrestrial sea exploration of Titan via Deployable And Versatile
Instrument Device (DAVID) Buoys

By
Mary Katelyn Smith

A Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Aerospace Engineering
in the Department of Aerospace Engineering

Mississippi State, Mississippi
August 2016
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2016
A concept study for extraterrestrial sea exploration of Titan via Deployable And Versatile Instrument Device (DAVID) Buoys

By

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Saturn’s moon, Titan, has been a scientific marvel since Cassini’s flyby discovered methane-ethane lakes in the northern hemisphere. Several science missions to explore these lakes have been proposed, but none have been launched. Using these previous mission designs, as well as the success of the Huygens probe, this paper will discuss the development of a deployable multi-buoy system with the intent of studying the methane-ethane lakes. The buoys will study the chemical makeup of the lakes, determine meteorology of Titan atmosphere, and map the depth and floor of the targeted lakes. This thesis is a concept study on the multi-buoy system that reviews briefly the concept and design.
I would like to dedicate this thesis to my father and mother, David and Cathy Smith, and my two brothers, Zachary and Duncan Smith, for their unconditional love and support from the very beginning of this crazy, space-filled adventure. I would not have been able to complete this thesis without their endless love and encouragement. I will always remember the sagely advice my father gave me the very beginning, “The pointy end goes up.”
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NOMENCLATURE

ASI  Atmospheric Structure Instrument
BMA  Buoy Mast Assembly
CAD  Computer Aided Design
CAP  Chemical Analysis Package
CCD  Charged-coupled Device
DAVID  Deployable And Versatile Instrument Device
EDL  Entry, Descent, & Landing
ESA  European Space Agency
MER  Mars Exploration Rover
MET  Meteorology
MP3  Meteorology & Physical Properties Package
NAI  NASA Astrobiology Institute
NASA  National Aeronautics and Space Administration
NIAC  NASA’s Innovative Advanced Concepts
TiME  Titan Mare Explorer
TSSM  Titan Saturn System Mission
PanCam  Panoramic Camera
SSP  Huygens Surface Science Package
q  Heat flow
k  Conductivity
A  Area
Ti  Internal Temperature
To  Outside Temperature
Q  Heat flow
η  Efficiency Ratio
P  Power
t  Thickness
c0,c1,c2  Constants
MLI  Multi-Layer Insulation
V  inertial Velocity Magnitude
R  Planetary radius
h  height above surface
r  $R + h = \text{radius from planetary center}$
s  down-range travel relative to nonrotating planet
$\lambda$  flight-path angle, positive above local horizon
m  vehicle mass
g  gravitational acceleration
D  drag force, parallel to flight path
L  lift force, normal to flight path
Saturn continues to be a marvel for all who look upon it. It is a planet that has always brought constant curiosity, and through the Cassini mission, the science communities were able to gain a glimpse at what secrets the Saturnian system holds. The Cassini orbiter via a flyby, and the Huygens Probe mission to Saturn’s largest moon, Titan in Figure 1[1], discovered an environment unlike anything anyone had ever seen. Through the haze of the atmosphere, planetary scientist found what appeared to be lakes of liquid methane pocketed throughout the northern pole region of this moon[2]. This discovery sparked such curiosity about Titan that several mission proposals were dedicated to being the first extraterrestrial sea voyage. The further exploration of Titan is
a high priority, as recommended by NASA’s Solar System Exploration Roadmap[3], NASA’s National Research Council [4], the NASA Decadal Survey [5], and the ESA’s Cosmic Vision Program Themes[5]. This identifies that missions to Titan should be developed for future data gathering missions to answer many questions derived from the Cassini/Huygens spacecraft[5]. The “high priority” stems from the potential benefits the moon holds with planetary science interests as well as the prebiotic chemistry potential. The benefits of looking into the astrobiology of Titan is the desire to understand the moon’s system and its potential for possible life[5].

The Deployable And Versatile Instrument Device (DAVID) Buoys are a multi-buoy system concept being studied for a preliminary look at the extraterrestrial seas of Titan. This terrestrial moon has been an area of interest since the 2006 Cassini flyby that photographed the sunlight glinting off of the methane lakes on Titan’s northern hemisphere. There have been several proposed missions to insert probes into the lakes the past few years, including a submarine[6]. This multi-buoy system is the latest in this series of studies. This paper summarizes some preliminary concepts currently under development for this concept study.
CHAPTER II
TITAN

2.1 Titan Overview

Titan is the only known natural satellite to have a dense atmosphere comparable to Earth and a climate with seasonal variations. Cassini observed, in 2007, that Titan possessed seas of hydrocarbon. Additional study revealed that the climate is a major cause of many topographical features found on Titan, such as dunes, rivers, lakes, seas and deltas[6]. The Earthlike system is subjected to stresses and modifications and likely cryovolcanism[7]. The synergistic science involved in Titan missions is abundant. It encourages a wide range of scientific disciplines that other satellites currently do not. In September 2008, the NASA Astrobiology Institute (NAI) Executive Council reaffirmed that Titan should be on the high priority list of astrobiological targets in the solar system.

The moons thick methane-nitrogen shield was first discovered from Earth in the 1940s and was then verified by Voyager 1 in 1980. The most intriguing question that came from the verification was the nature of how the dense atmosphere is developed. As the Titan Saturn System Mission (TSSM) document admitted, the simplest of possibilities would be an ocean of methane and its photochemical product ethane might cover the globe to develop the unique atmosphere. The Cassini-Huygens mission uncovered many of the complexities in 2004. A methane cycle was proposed to influence Titan as water influences Earth. Cassini observed methane and/or ethane carved channels as well as
lakes and seas. These seas have been compared to in shape and size of the North American Great Lakes. While the Cassini-Huygens mission discovered many of Titan’s features, the mission left the scientific community with many unanswered questions. These include where the methane is distinctly coming from and interacting with the atmosphere; how the lakes and seas are fed, such as rainfall or aquifers underground, what is the meteorology of the Titan surface; etc[4].

Scientist believe to have observed a greenhouse effect, similar to what happens on Earth. The surface temperature is 94 K (-179°C) due to the greenhouse warming of methane [7]. Methane makes 1.6% of the atmosphere, and nitrogen is 98.4% [7]. Due to the temperature and the amount of methane in the atmosphere, the triple point of methane forms clouds, hail and rain [7]. This greenhouse effect of methane is a condensable gas that ends up like water vapor on Earth. There is considerable speculation that this causes the methane rain. The limited sunlight produces sparse rain from the hydrocarbon cycle, making rainfall, a few centimeters per year, quite rare on Titan.

The climate of Titan is controlled by its 26° tilted rotation with respect to its spin axis. Titan’s large distance from the sun, 1.5x10^9 km, means it take this moon 29.5 Earth years to orbit the sun [6]. This orbit leads to long seasons on Titan. (Titan also requires 15.9 Earth days to complete one rotation about its own axis.)

An abundance of dark lakes and sea, discovered by the Cassini flyby 2007, were found to be typically 20 km (12.4 mi) across and at the 70° Latitude [6]. These lakes are considered to be located mostly in the northern hemisphere due to the Titan’s seasons and amount of sunlight received [7]. This results in less intense summers in the north, which has a longer time to rain and accumulate the liquid bodies in that region.
2.2 Titan Target Area

As previously noted, the most studied region of Titan is the northern hemisphere. This is a result of the timing of Cassini’s flybys with respect to Titan’s solar cycle. Because of the relatively better knowledge of this pole, the target areas chosen for this mission concept are three northern lakes--Kraken Mare (1,000 km wide), Ligeia Mare (300-400 km wide), and Punga Mare (~100 km wide). These lakes, as seen in Figure 2.1, are in the general area of one another, so landing multiple buoys in more than one lake has a high feasibility.

Figure 2.1 Radar image showing Titan’s northern lakes.

A: Ligeia Mare, B: Punga Mare, C: Kraken Mare (Photo Credit: NASA/JPL-Caltech/ASI/USGA)
CHAPTER III
PREVIOUS AND PROPOSED MISSIONS FOR TITAN EXPLORATION

The driven curiosity and desire to study Titan is for scientific value as well as seeking signs of life has sparked the minds of many. The Cassini-Huygens spacecraft was the first and only mission to have visited Titan. Opportunities to involve a variety of scientific disciplines is abundant with the further exploration. The moon provides a chance to explore a terrestrial body that is similar to Earth and has the first evidence of stable bodies of liquid on the surface. The unique challenge of exploring Titan has been shown through the previously proposed missions concepts and proposals. Since 2009, there have had several mission designs proposed to return to Titan and build on what Cassini-Huygens spacecraft discovered. Chapter III will discuss the Cassini/Huygen mission as well as the aforementioned mission proposals.

3.1 Previous Mission

3.1.1 Cassini Spacecraft

The unmanned spacecraft Cassini/Huygens, launched in 1997 and is still in operation, was a flagship class spacecraft [2] sent to Saturn. This being the fourth space probe mission to visit Saturn and the first to enter orbit of the planet, the Cassini-Huygens spacecraft was a joint endeavor led by NASA and ESA. The Cassini Saturn Orbiter was designed to deliver the Huygens Probe to Saturn’s largest moon, Titan, and to perform mission objectives such as taking atmospheric and surface property data. This
challenging mission offered a higher operation complexity than many previous robotic exploration missions [2]. The sophistication of Cassini-Huygens spacecraft provided an opportunity to gain an extremely rich scientific output [2]. The continued exploration of the Saturnian system continues, however, the Cassini Saturn Orbiter will be decommissioned in September 2017 [8]. The success of the Cassini/Huygens spacecraft was regarded as “both an engineering and scientific victory” by former NASA Administrator O’Keefe [9]. ESA supplied and designed the Huygens probe to take scientific data during its mission on Titan. The valuable feat of the Huygen probe, and why it is relevant to this thesis’ mission design, was proving the ability to deliver a probe/lander during a flyby mission of another planet or moon.

3.1.2 Huygens Probe

The ESA’s first ever atmospheric entry probe was the Huygens Probe. The probe entered Titan’s atmosphere in 2005, taking approximately three hours to descend to the surface [10]. The Probe transmitted data more than 90 minutes after reaching the surface [9], where the probe mission objectives were to observe the meteorology of the moon, measure winds and global temperatures, determine topography and composition of the surface [11]. This Probe had a particularly unique system requirements that were needed for its mission on Titan [12]. The instrumentation on board delivered data and photographs of Titan that no one had ever seen. In figure 3.1, shows just one of the 350 photos the probe transmitted back to Earth.
3.2  Proposed Missions

3.2.1  Titan Saturn System Mission (TSSM)

TSSM was a joint mission, like the Cassini/Huygens spacecraft, proposed by NASA/ESA. The mission study was to explore Titan and Enceladus’ environments involving several science disciplines in one collaboration [4]. Specifically looking at the Titan portion of the TSSM mission, shown in Figure 3.2, the mission included an orbiter similar to Cassini, a balloon explorer called the Montgolfiere and a lake lander similar to Huygens. The lander, like the buoys, was targeted to study the methane lakes of Titan, while the balloon was to study the atmosphere. The lander was proposed to target the northern lake, Kraken Mare, and have a 9 hour nominal mission duration via battery power. The lake lander would relay data to Earth via the orbiter [4]. The lander was designed to be similar to Huygens and could land on either a liquid or solid surface. The
lake lander’s principle mission was to obtain information regarding the origin and evolution of Titan.

Figure 3.2  Artist interpretation of TSSM mission.

(Credit: TSSM Joint Document)

3.2.2  **Titan Mare Explorer (TiME)**

The Titan Mare Explorer (TiME), shown in Figure 3.3 [4], was chosen as one of the NASA Discovery Mission finalists to develop a concept study of the mission [13]. TiME was similar to the TSSM proposal of a lake lander to explore a targeted lake on Titan. The mission goals were similar to TSSM as well, looking into the origin and evolution of moon. TiME underwent a preliminary analysis study to be considered for the Discovery Mission. The Explorer Entry, Descent, Landing (EDL) design was also similar to that of Huygens probe. The TiME mission was to have a 3-6 month duration [13]. This mission was not chosen to move forward due to Mars exploration interest that ramped up around Mars Science Laboratory (Curiosity).
3.2.3 Titan Submarine

The most recently proposed mission was the conceptual design of a submersible science platform to explore the Titan seas. This submarine mission was funded by NASA’s Innovative Advanced Concepts (NIAC) in 2014 [6]. The challenge of this design was determining how to design a submarine-like structure to produce extensive scientific outputs, as proposed landers. The Titan submarine, shown in figure 3.4, is the most uniquely different of the previously proposed missions, including the use of a glider similar to the X-37 for EDL instead of a capsule such as used by Huygens. The Titan Submarine mission proposal is quite recent and further along in development than this concept study, there are large risks with this submarine mission associated with the unknowns of lake debris and lake depth [6]. The proposed multi-buoy system would provide a preliminary look at the seas of Titan to determine if a costly mission, such as the submarine, would hold merit.
Figure 3.4 Artist interpretation of the Titan submarine exploring the methane seas of Titan.

(Photo Credit: NASA)
CHAPTER IV
DEPLOYABLE AND VERSATILE INSTRUMENTED DEVICE (DAVID) BUOYS

The purpose of the mission is to use a multi-buoy system to explore the methane lakes on Titan providing crucial data for future missions. This chapter discusses the details of the buoys and the buoy subsystems.

4.1 Concept of Operations

The buoys will be deployed from a Huygens-like ‘mothership’. The reason for adopting the Huygens Probe heritage is that it has many benefits. These benefits specifically include design time and costs savings of the Huygens capsule/aeroshell design. This reduces the mission risk and enhances the overall technology readiness level. The mothership can be utilized as a science vessel as the Huygens Probe did during descent and landing. Using this heritage, leads to a minimal design component required for this particular concept. The buoys shall be deployed during the mothership’s slow descent (2.5 hours), as shown in Figure 4.1. The buoys will have a time varied release from the mothership. Once they are deployed, each buoy’s recovery system will deploy an autonomous paraglider, to assist in directing the probe to the targeted lake. The buoys will be designed to survive a landing on a solid surface and acquire data even if the
desired lake target is not reached. The buoys will have time varied activation times to take data for three (3) Titan days (~16 Earth Days or 384 Earth Hours).

Figure 4.1 DAVID Buoy parachute deploy/splashdown

4.2 Buoy Novelty

While there have been previously proposed missions with the same goal to study Titan’s methane lakes, this mission provides a novel and innovative way to take a preliminary look at what lies beneath the liquid hydrocarbon lakes. The mission will not only be the first extraterrestrial sea exploration, but also develop a multi-buoy deployment system that uses heritage from the Huygens probe to explore multiple lakes in a singular mission. The buoys shall be equipped with the first autonomous paragliding system for space use to direct the buoys during descent. The guided descent concept will be described in length during this chapter.
4.3 **Mission Requirements**

The mission requirements include (i) Relay science data from buoys to Earth (ii) Minimum mission duration of two (2) Titan days (iii) Minimize mass due to buoy constraints and (iv) Sonar mapping of the targeted lake of each individual buoy.

4.4 **Buoy Structural Design**

The buoys shall be constrained by the Huygens-like Mothership. The Mothership shall have a science platform for the five buoys to sit during cruise stage to Titan. The mothership platform for the buoys will have a diameter of 1.3 m like Huygens. Each buoy will be 0.4 m in diameter, 0.3 m in length with a volume of 0.034 m$^3$. In order for each buoy to stay buoyant on the liquid methane lakes (density 422.36 kg/m$^3$). Due to these constraints, the mass of the buoy does seem to appear quite small, around 8 kg. However, with the continued advancement in technology, the instrumentation and other packaging can be custom built to the buoy specifications. The instrumentation and other packaging included in the buoy have all been based off of already developed systems. The desire is to discuss the concept, since the feasibility of the packaging is already more or less determined. Figure 4.2 presents a rudimentary CAD drawing of the buoy structure.
4.5 **Science Objectives**

The scheduled decommissioning of Cassini in 2017 will leave much unknown about Titan. The observations made by Cassini have sparked great interest in exploring the lakes and determining their physical/chemical properties.

The science objectives for the current proposal are based on those of the previously proposed missions, particularly those of the 2007 Titan Explorer Flagship Mission Study. The DAVID Buoy science objectives are: (i) measure the lake/sea chemistry and compare it with Earth and other bodies (ii) measure the sea depth and determine organic inventory (iii) study the sea circulation and the sea surface (iv) determine sea and atmospheric meteorology (v) determine the process responsible for the organic chemistry and complexity in both the lakes and atmosphere and (vi) Constrain prebiotic chemistry in the sea, comparing with Earth biological material [7].
4.6 Science Instruments

4.6.1 Science Overview

The scientific goals for the DAVID Buoy mission have been developed from the 2007 Titan Explorer Flagship study and can be viewed in Table 4.1. The Titan seas were discovered during the flagship study, however the objectives encompass enough to remain endorsed in other previous studies such as the Decadal Survey, TSSM, TiME and Titan Submarine.

Table 4.1 Scientific Objectives and Goals of the 2007 Titan Explorer Flagship Study

| Objective 1: Titan: An Evolving Earthlike System | Objective 2: Titan's Organic Inventory: A Path to Prebiological Molecules |
| How does Titan function as a system? How do we explain the similarities and differences among Titan, Earth, and other solar system bodies? To what extent are these controlled by the conditions of Titan's formation and to what extent by the complex interplay of ongoing processes of geodynamics, geology, hydrology, meteorology, and aeronomy in the Titan system? | What are the processes responsible for the complexity of Titan's organic chemistry in the atmosphere, within its lakes, on its surface, and in its subsurface water ocean? How far has this chemical evolution progressed over time? How does this inventory differ from known abiotic organic material in meteorites and biological material on Earth? |

4.6.2 Science Requirements

Shown in Table 4.2, the scientific goals of the buoys can be found. They are the same as those of the Decadal Survey lake lander and Titan Submarine, but modified to fit the constraints of the buoys unique ability to deliver multiple units and explore different regions at one time. There is a growing interest in the Titan Submarine, and with the buoys there can be a preliminary study of the diverse shorelines and the depth of the sea floors can be uncovered for future exploration missions.
### Table 4.2  DAVID Buoy Science Payload

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Mass</th>
<th>Dimensions</th>
<th>Power</th>
<th>Heritage</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panoramic Camera (PanCam)/Mast Assembly</td>
<td>4kg</td>
<td>Lens: 44mm</td>
<td>10W</td>
<td>MER/Titan Submarine</td>
<td>Photograph the sea surface and shoreline to explore geological history, measure physical characteristics</td>
</tr>
<tr>
<td>Mass Spectrometer (MS)</td>
<td>1.48kg</td>
<td>220x185x76mm</td>
<td>5W</td>
<td>TSSM/TiME</td>
<td>Measure isotopic ratios of noble gases and organics to constrain origin and evolution of Titan</td>
</tr>
<tr>
<td>Meteorology Package (MP3)</td>
<td>3kg</td>
<td>5.5mm diameter</td>
<td>6W</td>
<td>TIME/Pathfinder ASI/MET/Titan Submarine</td>
<td>Measure the sea surface and atmospheric meteorology weather activity and air-sea exchange</td>
</tr>
<tr>
<td>Sonar Device (MP3)</td>
<td>.5kg</td>
<td>56x68x79mm</td>
<td>2W</td>
<td>TIME/Commercial Fish Finders/Titan Submarine</td>
<td>Explore the depth of the lakes/seas to understand the history of the seabed and basin. Possibly discover more about deposits of sediments</td>
</tr>
<tr>
<td>Physical Properties Package (MP3)</td>
<td>2kg</td>
<td>5.5mm diameter</td>
<td>6W</td>
<td>Huygens Surface Science Package (SSP)/ TiME/ Titan Submarine</td>
<td>Measure the organics in the sea, prebiotic chemistry</td>
</tr>
</tbody>
</table>

#### 4.6.3 Proposed Instruments

The science requirements give a stronger idea on what should be listed for each buoy’s payload. The curiosity surrounding the chemical composition of the seas has a complexity that desires unique instrumentation. The chemical analysis desired for this mission has not been specified. Like the Titan submarine’s Chemical Analysis Package (CAP) [6]. It might include a mass spectrometry system similar to that of the Huygens Probe or an analyzer for broad chemical characterization and isotopic measurement. The astrobiological interests drive the techniques to gather specific data. Overall, the goal is to consider on previously space flown instruments for this thesis, but there is a need for unique instrumentation to be developed to fit the buoy unique packaging constraints.

#### 4.6.3.1 Panoramic Camera (PanCam)

Through the success of MER, the Pancam assembly would be desirable for each buoy. The lightweight cameras produce highly beneficial information while still fitting within the Buoy package constraints. Two Pancams shall be mounted on a bar atop the
Buoy Mast Assembly (BMA). The cameras offer a way to stitch a multispectral panoramas of the area surrounding the buoys. This can provide a full three-dimensional model of the surrounding terrain. The benefits of this form of imaging is the information provided on the morphology, lithology, distribution, and shapes of the nearby shoreline [15]. Possibly distinguish dunes and other rock forms on Titan. The Pancam shall view the surface around the buoy, using two high resolution stereo cameras to survey the surrounding area. The total mass of each Pancam is around .27kg. This includes the filter wheel and electronics. The Pancam will require +7.1V and -10.4 V from the power supply [15]. The total power usage during the full-frame imaging is 1.4W (idle), 2.4W (integration and readout), and 3.8 W maximum (during CCD flush) [15].

![Assembled Pancam for MER before mounting on mast assembly.](image)

CCD/Optics/filter assembly is in the foreground and the electronic box is in the background. (Photo Credit: Cornell University)

### 4.6.3.2 Mass Spectrometer

A mass spectrometer would be developed to acquire samples of sea liquid and volatilize them for study in a quadruple mass analyzer. This will acquire materials for
analysis that are far simpler for a liquid surface than a solid surface. The ability to ingest liquid at ambient temperature and seal it for subsequent heating requires an innovative thermal design. Extensive design and testing of the inlet system was proposed in the TiME phase A development. The successful sampling of cryogenic liquids was provided by Goddard Space Flight Center[13]. In addition, the function of valve seats over multiple operations and with particulate laden liquids was demonstrated[13]. The mass range and sensitivity of the instrument would substantially exceed that of the Huygens mass spectrometer which operated on surface of Titan in 2005, and would accurately characterize the organic composition of the sea as well as isotopic ratios and noble gases[16]. Further development on this instrument is required under the buoy size constraints. There is no foreseeable complication with buoy constraints with the current development of the mass spectrometer proposed for the TiME mission. For this thesis purpose, the 908 devices mass spectrometer, M908, specifications will be used for preliminary power and packaging development.

4.6.3.3 Meteorology and Physical Properties Package (MP3)

The MP3 experiment is designed to obtain measurements of the Titan atmosphere during the entry, descent and landed phases of the DAVID Buoy mission. This instrument was first proposed by TiME and was developed using Atmospheric Structure and Meteorolgy Package (ASI/MET) that JPL designed for Mars Pathfinder mission[13]. The instrument underwent its original design when the TiME proposal was still being developed. The background research and development of the MP3 serves as a useful device to achieve the desired mission goals of this mission. The MP3 has small, simple sensors in an integrated suite with the ability to function as a traditional meteorology
package with liquid physical properties and depth-sounding[6]. The package follows the concept of the Huygens Surface Science Package [17]. The MP3 design is to have an unprecedented, long-term measurement opportunity to fully excavate the environment and explore the surrounding area of each buoy. The Titan seas provide a scientifically-rich environment where even the simple measurements serve great value. The on-surface meteorology sensors (wind, pressure, and temperature) will yield data to determine Titan circulation models[6]. The undersea sensors would include temperature, optical, speed of sound in the liquid, depth sounder sonar to develop the undersea characteristics. A general overview of the sensors included in the MP3 can be found in Table 3. The overall scientific goals and measurement objectives for this instrument is to provide a stream of useful data in one integrated package. The MP3 will have a single electronics box inside each buoy to perform the data handling functions[6]. Further development of the MP3 system is needed to be determine as well as the power supply to operate the extent of the mission.
<table>
<thead>
<tr>
<th>Sensor</th>
<th>Type</th>
<th>Description</th>
<th>Heritage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Cryogenic</td>
<td>Installed in multiple locations throughout the buoys and placed above/below waterline. Compare surface and undersea temperatures</td>
<td>Huygens</td>
</tr>
<tr>
<td>Pressure</td>
<td>Barometer</td>
<td>Mounted in buoy vehicle connected to the exterior via pitot tube</td>
<td>Huygens</td>
</tr>
<tr>
<td>Methane</td>
<td>Methane Humidity</td>
<td>Gauge methane humidity, like fog. Uses a simple 2-channel differential absorption spectrophotometer.</td>
<td>New</td>
</tr>
<tr>
<td>Wind</td>
<td>Speed/Direction</td>
<td>An ultrasonic anemometer, mounted on BMA</td>
<td>MER</td>
</tr>
<tr>
<td>Chemical</td>
<td>Dielectric</td>
<td>Fills with liquid, measures dielectric constant. Sensitive to the methane/ethane ratio, as well as possible presence of nitriles (HCN)</td>
<td>New</td>
</tr>
<tr>
<td>Speed of sound</td>
<td>Ultrasound Transducers</td>
<td>Measure the speed of sound in the liquid, function of methane/ethane ratio. Facilitates interpretation of the sonar</td>
<td>New</td>
</tr>
<tr>
<td>Sonar</td>
<td>Piezoelectric Transducer</td>
<td>Down-looking depth-sounder to measure Titan's sea depth. Echo recorder will also indicate scatters and the presence of bubble or precipitation noise at the sea surface.</td>
<td>Earth Fish finder technology</td>
</tr>
<tr>
<td>Turbidity</td>
<td>Optical Fibers</td>
<td>Visible light beam passed via optical fibers across the liquid and the direct and scattered intensity is measured. Which determines the solar heat with depth and temperature structure of the liquid.</td>
<td>Earth Deep Ocean Exploration</td>
</tr>
</tbody>
</table>
4.6.4 **Payload Packaging**

The packaging of the buoys is exampled in Figure 4.4. The packaging considerations is still sizing of the instrumentation and stability. Due to some of the proposed instrumentation not being fully developed mean the cross-sectional view of the buoy is an estimated guess based off of similar systems.

![Preliminary cross-section of buoy with instrumentation packages.](image)

(Not to scale)

**4.7 Electrical Power Subsystem**

The buoys require a robust and lightweight system that can power the buoy for its mission while on Titan. The subsystem shall power the buoys in “on-off” cycles for a total of 255 hrs for each buoy. Each buoy will have staggered activation to maximize the data collection for three full Titan days (384 Earth hours). This will also help gather a range of data on Titan. In figure 4.5, It shows a timeline of when each buoy is active. The
timeline exhibits the buoy’s “On” cycle with the small red/grey stripes. This is where the buoy will run for 1 hour at a maximum of 30W. The lighter areas show when the buoy is “off”. However, the buoy will not be fully powered off due to the need for system check-ups in-between “on” cycles. There will be 1 W during this 16hr “Off” cycle.

Figure 4.5  Buoy Mission Power Timeline

4.7.1  Power Requirements

The maximum power during the buoy’s “on” phase is 30W. This is contingent on the power requirements of the science payload and data relay to the mothership. While the buoy might not use a full 30W during each “On” cycle, designing with the maximum requirement in mind will ensure enough power is allocated for the mission.
Table 4.4  Buoy Power Specifications

<table>
<thead>
<tr>
<th>Buoy Power Supply Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of &quot;on/off&quot; cycles</td>
<td>15</td>
</tr>
<tr>
<td>Buoy &quot;on&quot;</td>
<td>1hr</td>
</tr>
<tr>
<td>Buoy &quot;off&quot;</td>
<td>16hr</td>
</tr>
<tr>
<td>W-hr Total</td>
<td>690W-hr</td>
</tr>
<tr>
<td>Buoy Total Life</td>
<td>255hr</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Battery Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Lithium Carbon Monofloride</td>
</tr>
<tr>
<td>Number of cells per buoy</td>
<td>8 cells</td>
</tr>
<tr>
<td>Voltage</td>
<td>12V</td>
</tr>
<tr>
<td>Cell Strings</td>
<td>2</td>
</tr>
</tbody>
</table>

Due to the distance from the sun, solar arrays and re-chargeability is not possible for this mission. Therefore, the batteries will provide electrical power to the mission. The W-hr required for the mission is a total of 690 W-hr. Therefore, the power system will have two strings with four cells each to make up the power supply. The power supply and battery specifications can be found in Table 4.4. The battery will consist of two modules of four Lithium Carbon Monofloride cells in series. The expected utilization of the available battery energy during the mission shall satisfy the instrumentation requirements.

4.8   Thermal Subsystem

The thermal system for the mothership and buoys during the 7.5 year cruise to Titan shall use the orbiter. The orbiter can thermally control the systems to maintain the temperatures met during transit. This way the mothership and buoys will be partially
thermally insulated before reaching Titan. Once the buoys have been ejected, the thermal subsystem must insulate from the extremely low temperatures of Titan while staying lightweight for buoyancy concerns.

We begin an estimation of the insulation required by assuming linear heat conduction through the buoy walls and negligible heat transfer due to the radiation and convection. Therefore,

$$q = kA \frac{T_i - T_o}{\text{thickness}}$$

(4.1)

It can also be assumed that the internal temperature, Ti, stays constant with time, meaning that heat lost through the walls must be balanced by heat generated internally.

$$q = Q_{\text{internal}}$$

(4.2)

The internal heat can be assumed to come entirely from power dissipated in the buoy vessel, and the power dissipated is some fraction, \(\eta\), of the power, in this case 30 W, being used.

$$Q_{\text{internal}} = \eta P$$

(4.3)

Therefore,

$$\eta P = kA \frac{T_i - T_o}{\text{thickness}}$$

(4.4)

Now we need to find the desired thickness required to satisfy the energy balance, for a given type of insulation material. Conductivity, \(k\), is assumed a linear function of the number of layers needed.

$$k = c_0 + c_1 \ast \text{number of layers}$$

(4.5)

We can assume thickness is directly proportional to the number of layers.

$$t = c_2 \ast \text{number of layers}$$

(4.6)
To find the constants $c_0$, $c_1$, and $c_2$, we will use the empirical data from Brown [18] that provides information on $k$ as a function of number of layers. An in-house physical MLI sample provides information on the thickness as a function of number of layers. With the information from these sources we can solve for the thickness required and for the corresponding number of layers. Finally, we use additional data from Brown [18] to estimate the mass as a function of the number of layers.

The Multi-Layer Insulation (MLI) blankets seem to be the best fit to aid with keeping the payload at the required internal temperature, $T_i$, of 0°C. This internal temperature is decided based on the operational temperature ranges given for instrumentation, due to sensitive and vulnerable components. The MLI blankets can be made to specification depending on how many layers the blanket needs to be. Carrying out the procedure described above, the thickness needed is 17.1mm to keep the buoys insulated using the minimum power of the batteries at 1W in the Titan environment. This is quite thick, however, the sizing and packaging of the buoys within the structure means that the buoys should have room for such a thick MLI blanket. The layers can be solved using the sample MLI blanket as a base and the 17.1mm thickness. The buoys will need 69 layers to keep insulated.

To determine how much mass the MLI blanket will hold. The mass of each buoy MLI blanket comes out to be 0.065kg. This is a desired mass due to mass budget concerns and buoyancy.
4.9 Communication Subsystem

The buoy communication system is modeled after the Huygens-Cassini system [DESCANSO]. Except during the glide from the Mothership, the buoys communicate directly with the Titan orbiter.

The basic communication protocol is Code Division Multiple Access (CDMA) with Binary Phase Shift Keying (BPSK) of a nominal 2 GHz carrier. The very slow physical processes on Titan due to its 360 hour day and its 15 Earth year orbital period about the Sun allow low data rates to be used with no significant loss of meaningful measurements. The nominal total transmission rate is 8 kbps with a bit error rate (BER) of $10^{-5}$ and an energy per bit per noise margin of 5 dB.

The communication system is designed to accommodate large view angles between each buoy and the orbiter. A link can be established at a spacecraft elevation of 10°, with a pointing error of 15°. This large error accounts for uncertainties in buoy orientation if a buoy happens to come to rest on land, or, if a buoy experiences wave motion in a lake. For the orbit in a nominal 1500 km altitude orbit above Titan, the slant range at 10° is 2700 km. This is the range used in the link analysis.

The buoys are provided with an S-band patch antenna on their top surface. This antenna has a boresight gain of 2 dB and a “3 dB down” edge gain of -1 dB. The edge gain is used in the link budget. The antenna efficiency is 50%. The S-band transmitter can provide 10 W RF power to this antenna. During the paraglide this transmitter/antenna combination, along with an S-band receiver, will communicate with the Mothership. The Mothership receive system uses a Cassegrain antenna with a gain of 30 dB. The receiver total system noise temperature is 250 K.
With the parameters described above, and accounting for miscellaneous losses, the link table shown below results. Even with only 1 Watt RF power, there is a significant excess signal to noise ratio at the receiver for successful communication.

Table 4.5 The Buoy to Orbiter Communication Data

<table>
<thead>
<tr>
<th>Buoy to Orbiter</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>2.0 GHz</td>
</tr>
<tr>
<td>BER</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Range @ 10° Elevation</td>
<td>2700 km</td>
</tr>
<tr>
<td>Total Data Rate</td>
<td>8.0 kbps</td>
</tr>
<tr>
<td>Tx Pointing Error</td>
<td>15.0 deg</td>
</tr>
<tr>
<td>Tx Gain (Patch Antenna)</td>
<td>2.0 dB</td>
</tr>
<tr>
<td>Tx Efficiency</td>
<td>0.5 –</td>
</tr>
<tr>
<td>Tx Power</td>
<td>1.0 W</td>
</tr>
<tr>
<td>Modulation Type</td>
<td>BPSK –</td>
</tr>
<tr>
<td>Modulation Loss</td>
<td>-1.0 dB</td>
</tr>
<tr>
<td>Cable and Filter Losses</td>
<td>-0.5 dB</td>
</tr>
<tr>
<td>EIRP</td>
<td>32.6 dBW</td>
</tr>
<tr>
<td>path loss @ 10° elevation</td>
<td>-168 dB</td>
</tr>
<tr>
<td>polarization loss, circ/circ</td>
<td>-0.5 dB</td>
</tr>
<tr>
<td>Rx gain (based on Cassini Cassegrain antenna)</td>
<td>30.0 dB</td>
</tr>
<tr>
<td>received power</td>
<td>-122 dBmW</td>
</tr>
<tr>
<td>received energy/bit, $E_b$</td>
<td>-150 dBmJ</td>
</tr>
<tr>
<td>system noise temperature (from DESCANSO-Cassini)</td>
<td>250 K</td>
</tr>
<tr>
<td>noise density, $N_0$</td>
<td>-175 dBmW/Hz</td>
</tr>
<tr>
<td>received $E_b/N_0$</td>
<td>25 dB</td>
</tr>
<tr>
<td>required $E_b/N_0$ for BPSK mod (theory, SMAD)</td>
<td>10.0 dB</td>
</tr>
<tr>
<td>Implementation Loss</td>
<td>1.4 dB</td>
</tr>
<tr>
<td>Required Margin</td>
<td>5.0 dB</td>
</tr>
<tr>
<td>Actual Required $E_b/N_0$</td>
<td>16.4 dB</td>
</tr>
<tr>
<td>Excess Margin</td>
<td>8.7 dB</td>
</tr>
</tbody>
</table>

4.10 Entry, Descent, and Landing

4.10.1 Mothership Descent and Buoy Deployment

As specified earlier in this chapter, the buoys will be packaged in a ‘Mothership’ similar to the Huygens probe. The Mothership and multi-buoy system will use the
Cassini-Huygens heritage as a reference for developing their descent profiles. The science platform shown in Figure 4.6 will hold five (5) buoys. These buoys will have a time varied release at a predicted altitude of around 80 km. The mothership will not only hold the buoys, but will house the navigational system for the autonomous paraglider system.

![Exploded view of mothership (Grey) / Buoy packaging (Orange)](image)

The descent is calculated assuming planar entry into the atmosphere of a spherical, non-rotating planet. The equations of motion parallel to and normal to the velocity vector and the kinematic relations are, respectively, [19]

\[
\frac{dv}{dt} = -\frac{D}{m} - g\sin\gamma \tag{4.7}
\]

\[
\frac{v dy}{dt} = \frac{L}{m} - \left(g - \frac{v^2}{r}\right)\cos\gamma \tag{4.8}
\]

\[
\frac{ds}{dt} = \left(\frac{R}{r}\right)V\cos\gamma \tag{4.9}
\]

\[
\frac{dr}{dt} = \frac{dh}{dt} = V\sin\gamma \tag{4.10}
\]
The atmospheric density is determined from a simple exponential profile based on Yelle 97 [19]. This model is shown in Figure 4.7. Gravity is described by a spherically symmetric $r^2$ model. The lift and drag coefficients are held constant.

![Titan Density model](image)

**Figure 4.7** Titan Density model

These equations have been integrated with a fixed time step 4th order Runge-Kutta solver with the following conditions

**Table 4.6** Initial Conditions

<table>
<thead>
<tr>
<th>Mothership Initial Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Altitude</td>
</tr>
<tr>
<td>Entry Speed</td>
</tr>
<tr>
<td>Flight Path Angle</td>
</tr>
<tr>
<td>Density Scale Height</td>
</tr>
<tr>
<td>Mass</td>
</tr>
<tr>
<td>Reference Area</td>
</tr>
<tr>
<td>Lift Coefficient</td>
</tr>
<tr>
<td>Drag Coefficient</td>
</tr>
</tbody>
</table>
The results for these conditions are shown in Figures 4.8 and 4.9. The Table shows that it takes 160 mins to reach the Titan surface. This can be compared to the Huygens entry reconstruction where it took 150 mins to reach the surface. We can estimate the best altitude for the buoys to be released. At 80 km, the descent is slow enough, but also gives the buoys enough time to achieve their targeted lake region.

The two figures below, Figure 4.9 and Figure 4.10 are a comparison of the deceleration event for the Huygens probe and the Mothership. As shown, the scale of events for the Mothership is not quite the same as the Huygens profile, however, it is believed that with more accurate data on the Mothership, the figures would be more similar. The current calculation has the Mothership’s main parachute 1 m across, and the Huygens main parachute is 8 m across. This could be why the deceleration profiles don’t fully match.
Figure 4.9  Mothership’s deceleration under main parachute

Figure 4.10  Huygens deceleration under main parachute
4.10.2 Autonomous Paragliders

Unmanned Aerial Vehicles (UAVs) have become a specific area of interest the past few years, due to this, there has been work with an autonomous paraglider system. Much like the way a person can direct their parachute as they land, there is a development of a system to provide an autonomous paraglider. Tapping into this research and development, the buoy recovery subsystem will be designed with an autonomous paraglider. The reason for this novel system is to achieve each buoy’s specific target region. The buoys will be ejected from the mothership at varied intervals of time, giving the buoy enough time to clear the mothership and have enough room to eject the paraglider. While this paraglider system has not been space qualified, this approach to descend through automated parachute guidance could prove quite useful for future outer solar system missions.

The University of Adelaide in Australia researched and developed such a system. Exhibiting the low cost, power and weight and demonstrating a working system. With Titan’s lower gravity and higher density the exampled paraglider translates well with the
buoy constraints[20]. Figure 4.11 is the University of Adelaide’s autonomous paraglider and illustrates the feasibility of this particular system working in tandem with the buoy mission.

As mentioned earlier, the autonomous paragliders will be guided by the navigational system on board the mothership. The navigation system shall track the five buoys as they descend to their target area.
CHAPTER V

FUTURE WORK & CONSIDERATIONS (OR CHALLENGES & FUTURE WORK?)

5.1 Challenges of the Buoy mission

There are many challenges that face such a novel mission. The obvious challenge is to overcome the mass and power budget constraints. The current instrumentation payload and other systems exceed the 8 kg buoy limit. The hope to correct for this is that over time technology will improve and lessen in mass. Instrumentation provided in this thesis is also based off of previously space flown or proposed missions. Many instruments can lessen mass if the instrument is custom built for to fit within the constraints. Another challenge to overcome is the autonomous paraglider system. This system has never been flown on any mission and is in the early development stages, however, the documentation available is evident that it is well within feasibility.

5.2 Next Step

The next step for this concept study of the mission is verification of constraints such as mass and power, if these budgets cannot be reasonably met, there is a option of a simple redesign. The redesign option would scaling the buoys up. This entales the mission have three (3) buoys as opposed to five (5) and target one (1) lake instead of three (3). This would allow more a large mass and still achieve the novelty and purpose of this mission.
In conclusion, this multi-buoy system concept is novel and scalable. The system has the potential to be useful for other exploration missions and capitalizes on heritage technology. It also directly targets the NASA Roadmap and the NASA Decadal objectives regarding Titan.

The feasibility to explore Titan’s extraterrestrial seas is evidenced by the amount of research and concept studies done from previous proposals and other papers. The DAVID Buoy concept takes a novel approach for a preliminary study of the hydrocarbon
seas. This multi-buoy system enables a broad study of the northern Titan lakes by exploring multiple lakes during one mission. The scientific and engineering benefits from this mission will be used for future exploration of Titan as well as exploration of other worlds. The fact that so many proposals and papers have been written and inspired by Titan proves this is a pioneering effort and scientifically relevant.
REFERENCES


