# A Comparison of Platforms for the Aerial Exploration of Titan

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**Exploration of Titan, envisioned as a follow-on to the highly successful Cassini-Huygens mission, is described in this paper. A mission blending measurements from a dedicated orbiter and an in-situ aerial explorer is discussed. Summary description of the science rationale and the mission architecture, including the orbiter, is provided. The mission has been sized to ensure it can be accommodated on an existing expendable heavy-lift launch vehicle. A launch to Titan in 2018 with a 6-year time of flight to Titan using a combination of Solar Electric Propulsion and aeroassist (direct entry and aerocapture) forms the basic mission architecture. A detailed assessment of different platforms for aerial exploration of Titan has been performed. A rationale for the selection of the airship as the baseline platform is provided. Detailed description of the airship, its subsystems, and its operational strategies are provided.**

## Nomenclature

| | | |
|---|---|---|
| *cm* | = | centimeter |
| *kg* | = | kilogram |
| *km* | = | kilometer |
| *m* | = | meter |
| *mm* | = | millimeter |
| *nm* | = | nanometer |
| *s* | = | second |
| *TRL* | = | Technology Readiness Level |
| *W* | = | Watts |

## I.   Introduction

ONE of the fundamental questions in all of science concerns the origin and evolution of life and the occurrence of life beyond Earth.  In the search for life in the Solar System, Titan holds a very unique position. Titan (radius: 2575 km) is slightly larger than Mercury (radius: 2439 km) and smaller than Mars (radius: 3393 km).  Like the terrestrial planets, Titan has a solid surface and a density that suggests it is composed of a mixture of rock and ice in almost equal amounts. Titan may provide the details to explain how life formed on Earth very early in its history, shortly after the Earth formed 4.6 billion years ago. The evolution of the Earth's atmosphere and plate tectonics have erased any early record of the primitive pre-biological Earth (the Earth's geological record begins with the oldest rocks on our planet, dated to be about 3.5 billion years old, about a billion years after the Earth formed).  The appearance on Earth of the first biological or living system, and the subsequent evolution of biological systems, were preceded by the process of prebiotic chemistry or "chemical evolution."  Chemical evolution is the formation of the complex organic compounds, the precursors of living system.  It is generally believed, that on Earth, chemical evolution occurred very soon after the Earth and its atmosphere formed.  It is further believed that the gases in the early atmosphere, including nitrogen, methane, water vapor, molecular hydrogen, etc. were the "raw" materials that chemically formed the complex organic molecules, the precursors for the first living system.

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Our knowledge and understanding of Titan, Saturn's largest moon, have increased significantly as a result of measurements obtained from the Cassini spacecraft following its orbital insertion around Saturn on June 30, 2004 and even more recently with the measurements obtained during the descent of the Huygens probe through the atmosphere and onto the surface of Titan on January 14, 2005. The Titan Explorer mission discussed in this paper is the next step in the exploration of this mysterious world. The Titan Explorer mission consists of an orbiter and an airship that traverses the atmosphere of Titan and can land on its surface. Alternative aerial vehicles considered include airplanes and helicopters. Summary assessments of these other aerial vehicles are included in conjunction with a detailed description of the airship (baseline) mission.

NASA selected this study effort to develop mission concepts for the exploration of Titan with a launch in the post 2015 time period. Primary emphasis of the study was to develop an integrated mission concept for a Flagship Class mission (total cost >$700M). Development of a science basis coupled with integration of the science payload into an investigative platform which could be delivered to Titan in a reasonable time period were key facets of this study. Detailed results of the study have been provided to NASA's Science Mission Directorate.[1]

## II.    Scientific Rationale for the Exploration of Titan

Characterizing the atmospheric chemistry, measuring the meteorology, and understanding the nature of the surface of Titan provide the focus areas of the scientific investigation. A coupled scientific approach, which combines orbital measurements with in-situ measurements, has been assumed. Use of an orbiter also reduces the overall complexity of returning the scientific measurements from the aerial vehicles. Devising a science strategy, coupled with selection of the preferred instruments, is the necessary first step towards developing a mission concept to perform the overall study.

### A. Investigation Timing – Assumed Implementation Time Scale

The NASA Research Announcement indicated the study should consider launch dates after 2015. For the purposes of this study, a launch in 2018 was assumed. A technology development (TRL $\geq$ 6) cutoff date of 2013 was also assumed. Using implementation dates such as this allow for detailed analysis of the Cassini/Huygens data to aid in defining an appropriate science investigation strategy.

### B. Science Investigation 1: The Atmosphere of Titan

Titan's atmosphere may hold answers to chemical evolution on the early Earth.[2, 3, 4] Titan is surrounded by a thick, opaque orange-colored atmosphere with a surface pressure of 1.5 bars-about 50% greater than the Earth's atmosphere. Similar to the Earth, molecular nitrogen ($N_2$) is the overwhelming constituent of the Titan atmosphere (about 95% by volume), with smaller amounts of methane ($CH_4$) and molecular hydrogen ($H_2$).[5] The stability of methane in Titan's atmosphere is puzzling, since the atmospheric lifetime of methane is controlled by its destruction by solar ultraviolet radiation, which is short on cosmic timescales ($10^7$ years). Hence, atmospheric methane on Titan appears to be buffered or re-supplied by a possible surface reservoir.

Photochemical and chemical reactions initiated by methane (and nitrogen) lead to the production of numerous hydrocarbons of increasing molecular complexity, beginning with ethane, hydrogen cyanide, etc., and leading to complex organic compounds such as purines, pyrimidines, and aldehydes, believed to be the chemical precursors of the first living systems on Earth.[2, 3, 4] The dominance of nitrogen on Titan, gives rise to the rich coupled chemistry between nitrogen and carbon. The variety of nitrile species on Titan appears to be unique in the Solar System.

The early history and evolution of the atmosphere of Titan is a key scientific question. Due to its low gravitational attraction (g = 135 cm/sec$^2$), Titan can easily lose atomic (H) and molecular ($H_2$) hydrogen to space. With the loss of hydrogen (both atomic and molecular), the production of complex hydrocarbons becomes irreversible. Measurements of the isotopic ratios of the carbon, hydrogen, nitrogen and chemically inert gases will provide important vital observations on the evolution of the atmosphere of Titan.

### C. Science Investigation 2: Meterology and Circulation

Titan's "hydrological" cycle involving the condensation, precipitation and evaporation of hydrocarbons may resemble the water hydrological cycle on Earth. Calculations indicate that Titan has roughly 100 times more latent heat available for fueling weather than does the Earth's atmosphere. Recent observations of the presence of clouds that form at the tropopause on Titan are evidence for hurricane-sized cloud systems. The nature and formation of the clouds, the origin of the large storm systems, and the effects of latent heat on cloud formation and atmospheric circulation are unknown.[7, 8]
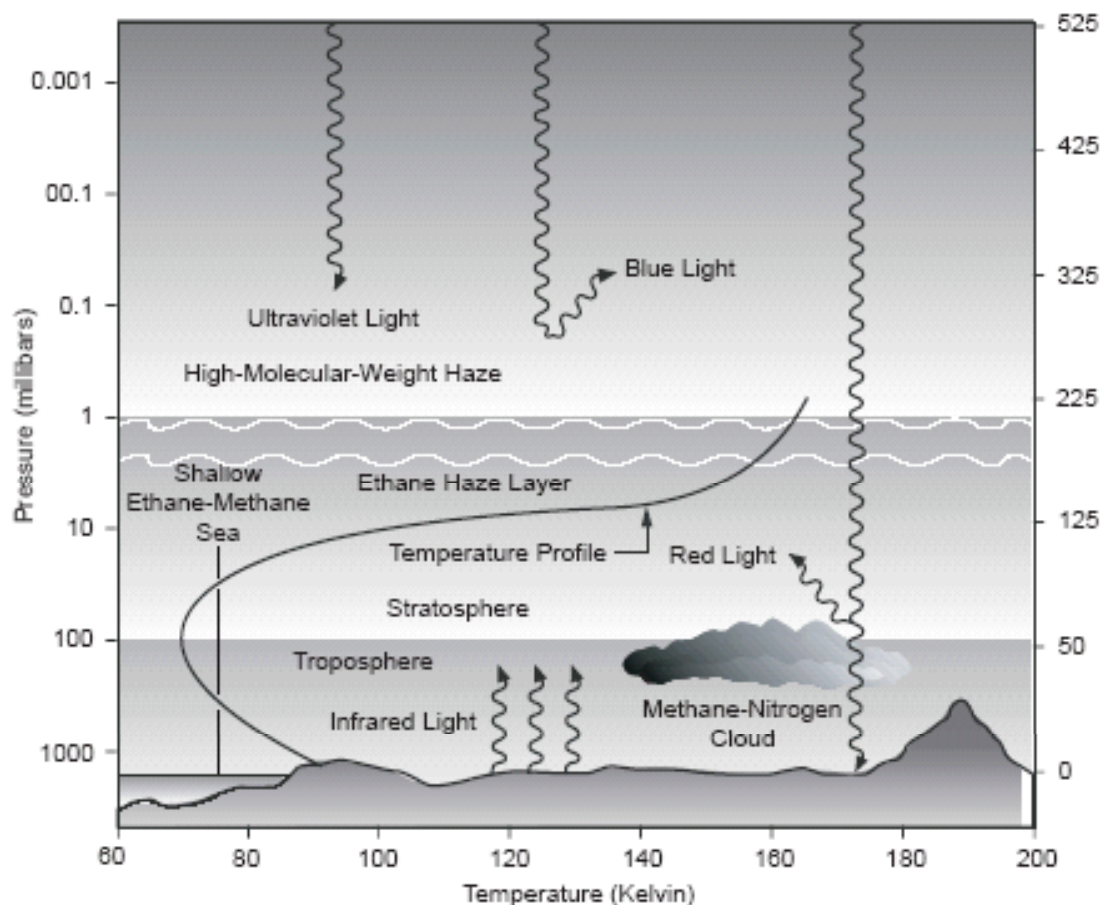
**Figure 1: Model of the atmosphere of Titan illustrating mechanisms for the atmospheric chemistry.[6]**

### D. Science Investigation 3: Determining the Nature of the Surface

Visible imaging of the surface of Titan is not feasible from orbit due to the thick layers of opaque haze and clouds in the atmosphere. Hydrocarbon lakes or oceans would serve a similar role as the lakes or oceans on the early Earth that led to the production via polymerization reactions of the first living systems. It has also been hypothesized that the tropopause of Titan acts as a "cold trap," where gaseous organic compounds condense out of the atmosphere and are, hence, removed from the atmosphere, followed by their deposition to the surface. For example, ethane precipitates out of the atmosphere onto the surface producing ponds, lakes or oceans of ethane (or ethane/methane). An ethane/methane ocean at the surface may be the source of the re-cycling of methane back into the atmosphere. The nature of the surface is best characterized through orbital measurements not in the visible spectrum as well as through near-surface, in-situ measurements.

## III. Science Payload for Titan Explorer

The Titan Explorer mission concept blends measurements from orbit with in-situ measurements to enable an extension of the current and future data sets from the Cassini and Huygens mission. Detailed measurements of the atmosphere, particulates in the atmosphere, the chemistry of the atmosphere, and characterizing the nature of the surface of Titan, are the basis of the aerial vehicle mission strategy. It is envisioned the aerial vehicle will provide almost a global scale set of measurements since its longevity is sufficient to permit at least one circumnavigation of Titan. Measurements of the atmosphere and surface of Titan are the primary emphasis of the orbiter. Serving as the telecommunications relay to and from the aerial vehicle is the secondary purpose of the orbiter.

The instruments selected for use in the study focus on providing data necessary to address the science questions as shown in Table 1. Detailed performance requirements for the instruments have not yet been derived from the

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science questions, however, instruments have been selected that have performed similar measurements and will provide enough data (power, mass, volume and data rate) to perform the systems study. The orbiter and aerial platform instruments are described below. Using either existing instruments, or those which can be realized near term, reduces the overall risk and provides the performance and mass upper bound for each platform.

## A. Measurements and Measurement Strategy

Significant advancements in our understanding of the atmosphere of Titan can be made from orbit, however, key science questions can only be answered with in-situ measurements. A three-year life is used with the orbiter while a minimum 4-month life is used for the aerial vehicle. A balance between science data, availability of electrical power, and ability to transmit the data from Titan to Earth is achieved with the selected mission implementation. Further, correlating the science data from the aerial vehicle with a position on Titan form the basis of the airship operational strategy.

**Table 1: Mapping of Titan Explorer science instruments with the science objectives.**

| Platform | Measurement Type | Science Objective |
|---|---|---|
| Orbiter | Solar occultation | Determine atmospheric composition and isotopic ratios |
| Orbiter | Radar Mapper | Determine nature of the surface |
| Orbiter | Magnetometer | Search for both planetary dipole and surface magnetism |
| Orbiter | Ultraviolet Spectrometer | Measure atomic and molecular hydrogen escape from the upper atmosphere of Titan |
| Orbiter | Visual and Infrared Mapping Spectrometer | Measure cloud layer, haze layer, and surface characteristics (IR) |
| Airship | Airship Imaging System | Investigate surface features, clouds, and haze |
| Airship | Mass Spectrometer | Measure atmospheric composition and isotopic ratios |
| Airship | Haze and cloud particle detector | Determine aerosol abundance and characterization |
| Airship | Surface Composition Spectrometer | Determine nature and composition of the surface |
| Airship | Sun-seeking spectrometer | Measure the opacity of the atmosphere of Titan |

## B. Orbiter Science Payload

Science payload for the orbiter consists of five instruments: a solar occultation instrument, a UV spectrometer, a Visible and IR mapping spectrometer, two magnetometers, and a radar altimeter. Summary level details of the instrument suite are provided in Table 2. Since the focus of this paper is on the aerial vehicle, the orbiter science payload is only briefly described to aid in establishing the overall mission context.

**Table 2: Orbiter science payload description and heritage.**

| Instrument | Description | Heritage | Mass (kg) | Power (W) | Data Rate (kbps) |
|---|---|---|---|---|---|
| Solar Occultation | Fourier Transform Spectrometer. Resolution 0.02 cm$^{-1}$. Spectral range of 2 to 13 microns. | ACE-SCISAT | 13 | 25 | 115 |
| UV Spectrometer | Spectral range of 55 to 190 nanometers. Push broom configuration with 1 pixel along track by 60 pixels cross track. Spectral dimension is 1024 pixels per spatial pixel. | Cassini UVIS | 8 | 6.5 | 32 |
| Visible & IR Mapping Spectrometer | Pair of imaging-grating spectrometers. Spectral range of 0.35 to 5.1 microns. | Cassini VIMS | 34 | 27 | 182 |
| Magnetometers | Two magnetometers – vector/scalar helium and fluxgate magnetometers. Both sensors mounted on a single 3 m long deployable boom. | MGS and STEREO | 8 | 2 | 4 |
| Radar Altimeter | Altimetry and scatterometer operations. X-band frequency; use 2.6 m diameter X-band high gain antenna on orbiter. | Magellan and Cassini | 15 | 200 | 1400 |

### C. In-Situ (Aerial) Science Payload

Science payload for the aerial vehicle consists of five instruments: a visible light imager, a mass spectrometer, a haze and cloud particle detector, a surface composition spectrometer, and a sun seeking spectrometer. A surface science payload allocation is also included in the overall science payload.

**Table 3: Airship science payload description and heritage.**

| Instrument | Heritage | Mass (kg) | Power (W) | Data Rate |
|---|---|---|---|---|
| Visible Light Imager | Clementine UVVIS | 1.3 | 5 | 1 Mbit per image |
| Mass Spectrometer | Cassini INMS | 10 | 28 | 1.5 kbps |
| Haze & Cloud Particle Detector | Pioneer Venus (LCPS) | 2.5 | 20 | 4 kbps |
| Surface Composition Spectrometer | Messenger (MASCS) | 5 | 5 | 5 kbps |
| Sun Seeking Spectrometer | Galileo (Net Flux Radiometer) | 3 | 11 | 4 kbps |
| Surface Science Payload | Not determined | 3 | -- | -- |

#### 1. Airship Imaging System - Visible Light Imager

An airship mounted imaging system is used to investigate surface features, clouds, and haze. The Clementine Ultraviolet/Visible camera (UV/Vis) was used as the baseline for the study. The detector and electronics can be used with a redesign of the optical assembly. Calculations were performed to determine the luminence level at the surface of Titan. An optics layout was developed using these luminence levels. The Airship Imaging System (AIS) consists of two identical cameras. Each camera provides a 45 degree by 45 degree field of view with a detector array consisting of 373 by 373 pixels, with each pixel being 0.02 mm. The imager provides a minimum SNR of 450 over the wavelength range of 450 to 900 nm. At the nominal cruise altitude of 5 km, the images are a 4 km by 4 km image with an approximate resolution of 20 meters. An integration time of 1.9 seconds is needed to achieve the desired SNR while meeting the 1/2 pixel smear limit at the maximum cruise velocity of 4 meters per second.

#### 2. Mass Spectrometer

Atmospheric composition and isotopic ratios are measured using the mass spectrometer (MS). The Cassini Ion and Neutral Mass Spectrometer (INMS) was used as a baseline for the study. It is intended to measure positive ion and neutral species composition and structure in the upper atmosphere of Titan, however, with some minor modifications to accommodate the significantly higher density and variability of species, it can ably serve as the in-situ mass spectrometer. The baseline mass spectrometer for the Titan Explorer can measure mass to charge ratios between 1 to 99 AMU's.

#### 3. Haze and Cloud Particle Detector

The lower altitude haze layers and cloud particulates are investigated using the haze and cloud particle (HCP) detector instrument. The small probe nephelometer used on the Pioneer Venus mission was used as a reference instrument for the study. The nephelometer can be used to measure the particle size and concentrations and locate and characterize UV absorption on the sunlit portion of the planet. The measurements can be used to document the optical properties of the atmosphere to attempt to infer the composition of particulate matter or gaseous absorbers in the atmosphere. The instrument contains two distinct, but physically integrated experiments, a backscattering nephelometer channel and a two-spectral channel radiometer. The nephelometer comprised of a pulsed laser, a detector to measure the scattered light, collimating and collecting optics, spectral filters, and analog and digital electronics and power supplies. The radiometer consisted of a set of detector-filter combinations, optics, internal calibration systems and signal processing electronics and power supplies.[9]

#### 4. Surface Composition Spectrometer

The nature and composition of the surface are determined using a spectrometer (SCS). The instrument will measure the unique spectral signatures for different molecules or minerals, since they only absorb and reflect certain wavelengths of light. By looking at what wavelengths are absorbed and reflected by a material, the minerals on the surface can be determined. The MESSENGER Mercury Atmospheric and Surface Composition Spectrometer (MASCS) was used as the baseline instrument. A similar design of the MASCS instrument can use ultraviolet, visible, and near-infrared spectrometry to search for iron-related minerals on the surface of Titan, as well as to profile the distribution of various species with altitude in the atmosphere. The MASCS experiment consists of two instruments, a UV/Visible Spectrometer (UVVS) and a Visible/IR Spectrograph (VIRS). A baffled 250 mm Cassegrain f/5 telescope focuses light through a common boresight to both instruments. The UVVS consists of an Ebert-Fastie diffraction grating spectrometer. An 1800 groove/mm grating gives an average spectral resolution of 1.0 nm (0.5 nm in the far ultraviolet). The grating is rotated in 0.25 nm steps for scanning. Three photomultiplier

tubes are situated behind separate slits, one covers the far ultraviolet (115-190 nm), one the middle ultraviolet (160-320 nm), and one the visible (250-600 nm).  The VIRS is designed to measure surface reflectance in the 300 to 1450 nm band with a spatial resolution of 100 m. The field of view is 0.023 by 0.023 degrees. Light reaches the detector through a fused silica fiber optic bundle. A concave holographic diffraction grating with 120 lines/mm and a dichroic beam splitter which separates the visible (300 to 1025 nm) and infrared (950 to 1450 nm) parts of the spectrum are used to focus the spectra on two detectors. The visible detector is a 512-pixel silicon line array with an absorption filter in front of the long-wavelength half to eliminate the second order spectrum. The infrared detector is a 256 pixel InGaAs line array which does not require cooling. Spectral resolution is 4 nm and data is digitized to 12 bits.

### 5. Sun Seeking Spectrometer

Atmospheric opacity of Titan is investigated using the Sun-Seeking Spectrometer (SSS) instrument. This instrument can be used to: (1) measure vertical distribution of net flux of solar energy and planetary emission in the region of the atmosphere, (2) determine the location of cloud layers, and (3) obtain evidence on the mixing ratios of selected constituents and the opacity of low altitude clouds and aerosols in the infrared. The Net-flux Radiometer used on the Galileo Probe was used for the study. A multi-channel radiometer measures flux in about 30 degree cones alternately centered plus or minus 45 degrees from horizontal. The radiometer has an onboard calibration system (two black bodies), a multi-detector array (with channels at approximately 0.3 to 3.0, 0.3 to 2000, 20 to 30, 30 to 40, and 40 to 60 micrometers), and an array of six pyroelectric detectors.

### 6. Surface Science Payload

An allocation for a surface science payload (SSP) was included in the study. A detailed assessment of the SSP was not performed. Allocations for mass as well as data volume were made. It was assumed the aerial vehicle would either drop or place this science payload on the surface of Titan. Data return would be by low power UHF and would necessitate the aerial vehicle remaining within 100 km of the SSP to receive the data.

## D. Data Collection and Return Strategy

Science instrument operation on the aerial vehicle is primarily constrained through communications bandwidth. A UHF communication system between the orbiter and the aerial vehicle has been assumed to leverage the extensive Mars data return heritage. Previous studies assessed a direct to earth link from an aerial vehicle and concluded it was feasible. Since this study was considering a Flagship class mission, and it was capable of being launched on a single existing, heavy-lift expendable launch vehicle, the mass savings inherent in not having a dedicated orbiter for data return were not addressed. Transmission of the data from Titan to Earth was baselined using an X-band system. Near term demonstrations of Ka-band for deep space data transmission to Earth will allow for this option to be added to the Titan Explorer with a resulting four-fold increase in returned orbiter data volume, however, this does not aid in increasing the data bandwidth between the aerial vehicle and the orbiter.

### 1. Airship Data Collection and Relay Strategy

Airship operations are structured around data collection and return with the perspective of correlating the data with a surface position. There is a 14-orbit cycle where the airship and orbiter can communicate from 35 to 75 minutes during each 5.2 hour orbit (1700 km circular orbit, inclined at 100 degrees). Then, there is a nominal 5 day period (average) where the airship and orbiter cannot communicate due to the precession of Titan beneath the orbiter. These two periods of time are used to define the airship operational architecture. Each of these categories is further divided into the time periods when the airship is on the side of Titan which is facing the Sun and when the airship is on the side which is not facing the Sun.

The operational cycle balances the available electrical power and the bandwidth of the UHF relay system. This operational cycle is then used to define the peak data storage needed on board the airship to ensure all data is ready for transmission when the orbiter is in view. Day-side operations result in a significantly larger data burden. The AIS, SCS, and SSS are only operated on the day-side, while the MS and the HCP are operated during both day-side and night-side scenarios. Based on the operational scenarios illustrated in Figure 2, the uncompressed data load is found to be 9.6 Mbits per hour for the day-side and 6.6 Mbits per hour for the night-side. The operational life for the day-side includes the nominal 5 days of no contact with the orbiter plus the final 5 orbits when only navigation data is transferred and the first 5 orbits when again only navigation data is transferred. This corresponds to a period of 173 hours of data storage coupled with 4 hours per orbit during the 4 science data transfer orbits. A total data storage volume of 1.81 Gbits (189 hours at 9.6 Mbits per hour) is needed.

Key science data which requires precise collection knowledge is the data from the AIS and the SCS instruments. While these measurements will be collected throughout the mission, those measurements collected during the 73 hours when the orbiter is providing navigated position updates form the heart of the science data return. Further, the

navigation uncertainty is such that 2 orbits before communication starts and 2 orbits after communication ends will still either retain sufficient navigated state knowledge, or be able to be corrected on the ground. These measurements will be collected during this time (73 hours). The remainder of the time when the orbiter is out of view, the MS, HCP, and SSS data will be collected. It has been estimated that the maximum position uncertainty when the orbiter is not providing navigated state updates is approximately plus or minus 48 km 2
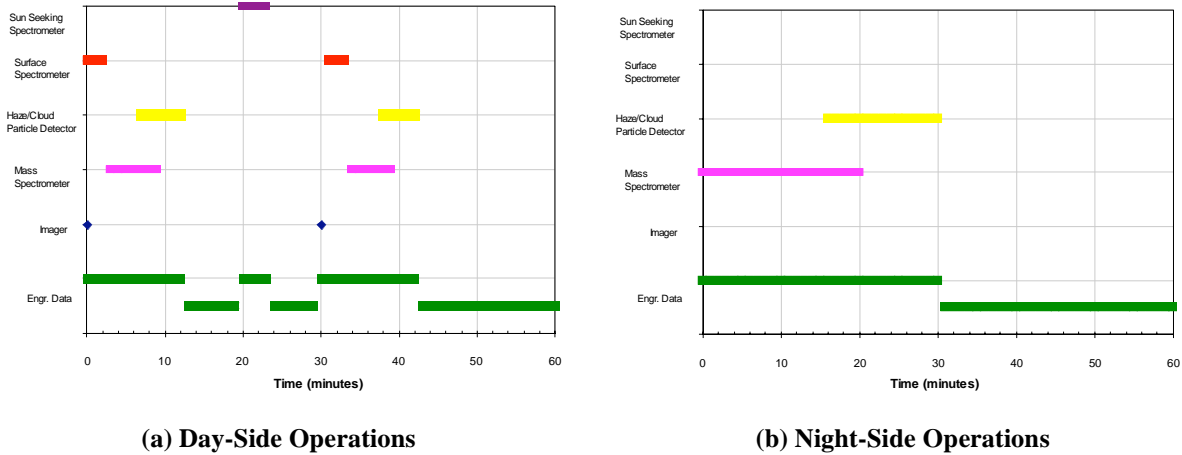


| (a) Day-Side Operations | (b) Night-Side Operations |

**Figure 2: Airship science instrument operational sequence.**

*2. Orbiter Data Collection and Return Strategy*

Orbiter operations are divided between operations while the airship is active and after the airship operational period is complete. While the airship is operational, the focus of the orbiter while overhead the airship is to serve as the data relay platform. During the periods when the orbiter is not over the airship, the emphasis is the orbiter science payload. The initial 4-months of orbiter operation focus on collecting data from the solar occultation, ultraviolet spectrometer, and visual and infrared mapping spectrometer instruments. The magnetometer boom is not deployed until after completion of the airship operational period since the boom deployment could pose additional mission risk. Use of the radar is limited to operational checkout periods while the airship is operational. The orbiter power is provided through four second generation multi-mission radioisotope thermoelectric generators (MMRTG) with a secondary battery system for load leveling. Since there is a significant amount of power required for receiving the airship data and transmitting the data to Earth, it is judged the radar operations should be limited until the additional power burden from airship communications is removed. After the airship operational period is complete, then the orbiter science instruments are balanced between the various operating scenarios.

## IV. Operating Environment of Titan

Operations of an aerial vehicle on Titan require a working knowledge of the atmosphere of Titan as well as providing large margins for the design process. Provided in Figure 1 is a nominal assessment of the pressure and temperature of the atmosphere of Titan. Specific parameters needed for performing design studies of aerial vehicles at Titan are provided in Table 4. The atmospheric density on Titan varies relatively uniformly from the average density at the surface as shown in Table 4 to about 3.5 $kg/m^3$ at the peak operational altitude of 10 km above the surface. All atmospheric properties were generated using the TitanGRAM atmosphere model.[15]

**Table 4: Comparison of Earth and Titan.**

| Parameter | Earth | Titan |
|---|---|---|
| Diameter | 12,756 km | 5150 km |
| Gravity | 980 $cm/s^2$ | 135 $cm/s^2$ |
| Average Surface Temperature | 288 K | 93 K |
| Average Surface Pressure | 1 bar | 1.5 bars |
| Average Surface Density | 1.24 $kg/m^3$ | 5.75 $kg/m^3$ |
| Average Surface Speed of Sound | 319 m/s | 181 m/s |
| Primary Atmospheric Constituents | $N_2$ 78%, $O_2$ 21% | $N_2$ 97% $CH_4$ 3% |

## V.  Comparison of Aerial Vehicles

One of the most alluring aspects of flying anything on Titan is that it is possible to design an aerial platform which is similar to what flies on Earth every day, thereby reducing inherent design risk.  It is reasonable to assume any of three types of powered aerial platforms could be flown on Titan: a helicopter, a fixed-wing airplane, or an airship. Detailed assessments of each of the platforms were performed as part of this study. The assessment began with the selected science payload and their intended operational sequence and data return strategy. Identification and selection of the necessary subsystems were performed as part of this study. Cursory assessments of an airplane, a helicopter, and an airship have been performed to determine if a closed mission is feasible. Based on the capabilities of the selected launch vehicle (Delta IV Heavy), the size and necessary performance of the Solar Electric Propulsion Module, and the Orbiter and its aerocapture system, the mass available for the aerial vehicle can be determined. It was found that a mass of up to 500 kg is available for the complete aerial vehicle. Meeting the desired lifetime of at least 90 days provides additional design constraints for the study.

### A.  Airplane

An airplane would use a propeller driven by an electric motor. An airplane has merit for flight on Titan given the high atmospheric density and low gravity. Due to the higher atmospheric density than Earth, the required propulsion power at even moderate speeds (>20 m/s) is excessive.[10] The need for reduced propulsion power resulted in an airplane with long, slender wings (high aspect ratio).  This configuration means multiple folds are needed in each wing for aeroshell packaging, thus increasing the deployment risk. Assessments of the propulsive power required for an airplane on Titan illustrate the excessive propulsive power which is required.[10] Other issues such as the propulsive power requirements and how that need is correlated to the power output available from projected future radioisotope thermoelectric generators aid in identifying the upper bound between airspeed and mass. An airplane also has limited capability regarding surface interaction capability either through repeated take-off and landings or deploying payloads. Based on the large propulsive power requirements and the limited surface interaction capability, the airplane was judged to not provide sufficient performance capabilities for further consideration.

### B.  Helicopter

Having the capability for repeated surface interactions provides a strong science incentive for considering helicopters or Vertical Take-Off and Landing (VTOL) type vehicles. Titan is ideally suited for a rotorcraft because of its thick atmosphere and low gravity. This study included a detailed assessment of a helicopter.[11]

The baseline helicopter considered was a double-blade helicopter with an ellipsoidal body 2.56 m long with a major cross-sectional diameter of 0.77 m. The tail length is 0.75 m. Each rotor has a radius of 1.6 m, allowing the helicopter to fit inside the aeroshell without the need to fold. The helicopter is equipped with a four-leg telescopic landing gear system that operates much like a piston so the helicopter can remain relatively level regardless of the local terrain slope.  A bladder is attached around the body, which is inflated during the initial deployment. The bladder will remain inflated throughout the mission, enabling the helicopter to land in liquid methane and still remain afloat. The induced drag from the landing gear and the bladder are minimal due to low flight speed.

Sizing the helicopter propulsion system and ensuring the total power needs (propulsion, subsystems, and science payload) are met was the primary design driver. A hybrid system was assessed which couples three second generation MMRTG's with a novel turbo-expander propulsion system. The turbo-expander propulsion system uses the waste heat from the MMRTG's to drive a generator which is then used to power an electric motor and thus drive the helicopter main propulsion system.[12] The helicopter was sized to meet a wide range of mission profiles with the most demanding profile being: 1) ascend to 1 km above ground level, 2) hover for 1 minute, 3) continue climbing to 10 km above ground level, 4) traverse up to 50 km of range, and 5) descend to the surface and land.  The helicopter also was to carry the same science payload as the two other aerial vehicles. Hover power (853 W) was the mission

**Table 5:  Helicopter subsystem mass distribution.**

| Subsystem | Mass (Includes 30% Contingency) - kg |
|---|---|
| Propulsion | 13.0 |
| Communications | 37.3 |
| Attitude Determination and Control | 31.1 |
| Command and Data Handling | 16.1 |
| Thermal | 14.0 |
| Electrical Power | 97.0 |
| Structures and Mechanisms | 69.9 |
| Flotation | 4.4 |
| **Sub-total** | **282.8** |
| Science Payload | 36.0 |
| **Total Mass** | **318.8** |

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parameter driving the sizing of the propulsion system. It was found the hover power equates to a maximum forward flight velocity of about 4.5 m/s. A nominal cruise velocity of 2.5 m/s was used. Subsystem mass distribution for the helicopter is provided in Table 5.

### C.  Airship

Preliminary analyses were performed for the three primary aerial vehicles. At the conclusion of that analysis, it was evident the choice was primarily between the helicopter and the airship. The detailed assessment of the helicopter was performed by a student design team at Georgia Tech,[11] while the detailed assessment of the airship was performed by the authors. The airship was sized for a similar mission to that of the helicopter (science payload and mission duration).  It was concluded the airship provided the lowest risk alternative to meeting the mission requirements and was thus selected as the baseline mission. In the interests of brevity, a summary level description of the airship is not provided here as a more detailed description follows.

### D. Baseline Aerial Vehicle Selection

Detailed assessments were performed for the aerial vehicles. The assessments results and how they influence the selection of the baseline vehicle are provided.  All three aerial vehicles can be sized to carry the baseline science payload. Both the airship and the helicopter have the ability to perform meaningful surface interactions. In addition, both the airship and the helicopter exhibit operating modes, which allow for recovery from system failures by either hovering (airship), or autorotating to the surface and waiting (helicopter). The final rationale for selecting the airship was the reduced complexity associated with the development and implementation of the airship over the helicopter. The baseline vehicle selected was the airship.

## VI.    Baseline Mission – Exploration via Autonomous Airship

### A. Airship Description

The baseline airship (seen in Figure 3) is a non-rigid design with a prolate spheroid shaped gasbag with helium as the lifting gas, an internal catenary and suspension system, two internal ballonets positioned fore and aft within the gasbag, an external gondola integrally attached to the bottom of the gasbag, a reinforced nose cap, and a four-fin tail attached to the aft of the gasbag.  The airship is powered by two (2) electrically-driven ducted propellers attached to the gondola via outrigger wings.  These propellers can be vectored in all three axes for accurate station-keeping and for compensation of wind direction when cruising.  The airship is powered by four (4) second generation Stirling-cycle radioisotope thermo-electric generators (SRGs) which are externally mounted to the gondola for thermal control purposes.  All science, electrical power subsystem (EPS), command and data subsystem
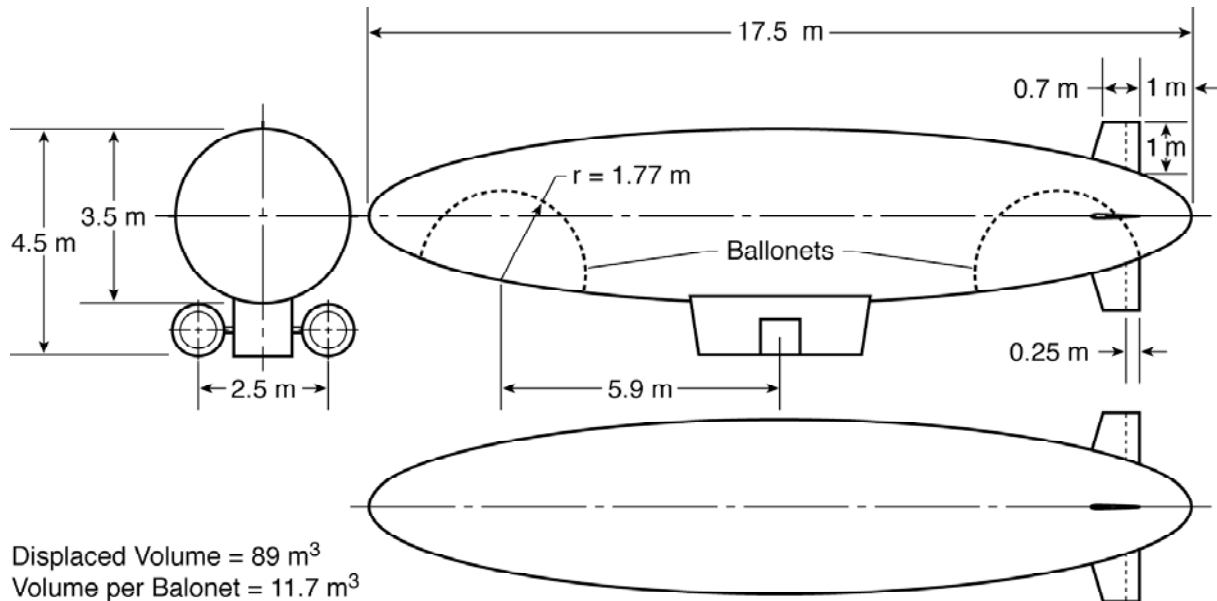


Displaced Volume = 89 m³
Volume per Balonet = 11.7 m³

**Figure 3: Airship 3-view drawing.**

(CDS), attitude control subsystem (ACS), and telecommunications (telecom) components are housed within the gondola, with the exception of some control surface actuators, the UHF antennas, and health monitoring sensors. Deployment occurs via extraction from the entry aeroshell, followed by a mid-air inflation of the gasbag.

## B. Airship Subsystems

The design study that was performed included assumptions regarding each subsystem element of the airship. The airship mass distribution is provided in Table 6.

**Table 6: Airship subsystem mass distribution.**

| Description | CBE Mass (kg) | Contingency (%) | Max. Expected Mass (kg) |
| --- | --- | --- | --- |
| CDS | 9.4 | 20.6% | 11.3 |
| ACS | 23.5 | 24.2% | 29.2 |
| Telecom | 17.5 | 24.3% | 21.8 |
| Thermal | 15.9 | 30.0% | 20.7 |
| Electrical Power | 64.9 | 30.0% | 84.4 |
| Inflation | 44.3 | 10.1% | 48.7 |
| Propulsion | 10.5 | 30.0% | 13.7 |
| Vertical Propulsion | 4.0 | 30.0% | 5.2 |
| Airship Hull | 50.0 | 48.4% | 75.6 |
| Airship Tail | 8.4 | 50.0% | 12.7 |
| Airship Gondola | 33.6 | 30.0% | 43.7 |
| Science | 23.1 | 23.5% | 28.5 |
| Science-SSP | 3.0 | 30.0% | 3.9 |
| **Total - Dry** | **309.0** | **29.2%** | **399.2** |
| Helium - Float at 5 km | 69.2 | 30.0% | 90.0 |
| **Total Float Mass - Wet** | **378.2** | **29.3%** | **489.2** |

### 1. Command and Data Subsystem

A block redundant Command and Data Subsystem (CDS) which includes the main processor and the flight software has been assumed. The CDS also includes the solid-state data recorder used to store the science and engineering data prior to relay to the orbiter. The airship has a significant amount of autonomy so development, implementation, and validation of the flight software imposes a key risk on the proposed mission implementation.[16] A block redundant Integrated Avionics Unit (IAU) employing miniaturized Multi-Chip Modules (MCM's) has been assumed. The CDS includes all cards packaged in a single chassis. Volatile DRAM storage and rad-tolerant field programmable gate arrays and ASIC's employed in the MCM's have been assumed. Data recording is based on assuming all data collected over a complete orbit of Titan about Saturn (15.9 days) is stored on-board. This ensures at least 2 opportunities to return the data to the orbiter. This data burden along with an assumed 400% data storage margin has led to the identification of a need for at least a 16 Gbits of data storage.

### 2. Attitude and Control Subsystem

Attitude determination and control of the airship is accomplished through a blend of legacy and advanced systems. Position, speed, and attitude are determined using flight proven systems and techniques. The primary navigation aid during periods when communications with the orbiter are possible is through ranging and Doppler from the orbiter. This terrestrially proven technique for in-flight position and speed determination (aka GPS) can be implemented using the UHF Transceiver on the airship and the orbiter. Early in the mission (the first 5 to 7 days), the accuracy of this technique will be insufficient as the ephemeris of the orbiter will have large uncertainties. As the ephemeris of the orbiter improves, then the knowledge provided by this technique will also increase. During periods when communications with the orbiter is not possible as well as early in the mission, legacy methods combining inertial measurements, direct altitude measurements with radar and pressure, temperature, and winds measurements through an air data system will be used. Existing technologies are sufficient for the needed accuracies such that no new capability is required. The primary control aspects provided by the ACS are through the propulsion subsystem and the tail mounted actuators. The tail-mounted actuators control the tail surfaces used for controlling the lateral direction of travel. Vertical control of the airship is provided through the ballonet system such that only venting and pressurizing the ballonets to achieve the desired vertical rate of travel is required.

### 3. Telecommunications Subsystem

All science and engineering data collected is processed and stored for later transmission to the orbiter. Use of omni-directional antennas reduces the control and pointing requirements on the airship thus simplifying the overall system. A mono-pole, whip style antenna located on the top of the gas bag has been assumed. Since it is uncertain how RF transparent the gasbag will be in the UHF frequency, and mounting the antenna on a deployable platform so it can see around the gasbag both provide significant uncertainty and mass penalties, it was judged using the monopole antenna was the optimum solution. A block redundant UHF telecom solution has been implemented with redundant transceivers. Other constraints for the relay telecom strategy include use of a 10 dB relay link margin as well as a 15 degree elevation mask.

### 4. Thermal Subsystem

Titan provides a unique and challenging thermal environment. Atmospheric temperatures are essentially at liquid nitrogen levels so that cryogenic design considerations dominate the solution space. Local heaters for the control surface actuators will suffice. All of the subsystems are mounted inside the gondola, which serves as a "Warm Electronics Box." The gondola will not be hermetically sealed so that atmospheric gases from Titan will penetrate into the gondola. Multi-layer insulation blankets line the inside surface of the gondola. Radioisotope heating units and strap-on electrical heaters provide local spot heating for all of the systems and elements requiring heating. The SRG's will be mounted in the gondola in such a way that their radiator fins will extend through the walls of the gondola directly into the atmosphere of Titan. A small radiator system will be used to provide a means of dumping the excess heat from the systems and the science instruments. This heat-pipe based system will operate with a surface temperature of about 40°C and an emissivity of 0.4 with some environmental back loading. The peak heat load required to be rejected is about 180 Watts without the propulsion electric motors. It is assumed that the radiator can reject about 160 Watts per square meter. This means that a radiator with a surface area of about 1.13 $m^2$ is required. This systems radiator is located on the lower surface of the gondola facing Titan. Mounting of the systems onto thermally conductive base plates provides a simple means of removing the heat from the components and moving it into the heat pipe system for eventual rejection to the environment of Titan.

### 5. Electrical Power Subsystem

A hybrid electrical power subsystem comprised of 4 SRG's and a single 12 A-hour Lithium-ion battery is used for the airship. One SRG provides a maximum of 95W at end-of-life (EOL) based on 10-years of decay and has a mass of 14 kg. System analysis indicates a maximum power level 470 W is needed, which would lead to a need for 5 SRG's. Using a low-level optimization, it is found that the peak power level is a short duration (about 1 hour) and lends itself to use of batteries for load leveling. The primary modes requiring batteries are during the vertical descent to the surface and during the science mode when contact with the orbiter is on-going. Duty cycle analysis has identified the total energy between battery charging is about 3.5 A-hours. Providing a 40% depth of discharge coupled with a 30% energy margin equates to a peak battery energy level of about 12 A-hours.

### 6. Airship Inflation Subsystem

The endurance of the airship is directly related to the amount of lifting gas lost by intentional venting (vertical/altitude control) and through unintentional diffusion through the gasbag both via seams and other protrusions and through the laminate itself. Estimates of the loss of lifting gas over a given time have been made for different gasbag materials.[13] These estimates are dependent on the particular gasbag material and its gas retention characteristics. The baseline gasbag and ballonet materials have been selected and the lifting gas reserve of 10.2 kg selected so the airship will stay fully inflated at 5 km for approximately 100 days. As leakage occurs without makeup, the gasbag volume will decrease causing the airship to seek a neutral point at a lower altitude. At the predicted leakage rate, the airship will slowly descend to the 1 km level within about 50 more days. The inflation subsystem uses a single large composite overwrapped toroidal tank for fully inflating the gasbag during the deployment phase. Once the gasbag is inflated, then the toroidal tank is isolated, vented, separated, and allowed to fall to the surface. Two small composite overwrapped pressure vessel tanks are used to provide the helium used for leakage makeup.

### 7. Propulsion Subsystem

The main component of the propulsion group is the propellers. The sizing of the propellers was based on basic propeller analysis momentum theory with an airship drag buildup. The propeller analysis was performed over a range of blade diameters (meaning the tip to tip length of the propeller, assuming a 2-bladed propeller), available powers, and densities (employing the density variations over the operating range) for a given maximum flight speed. The sum of the hull, tail, gondola, and miscellaneous drag is the total drag of the airship. This total drag was used to produce a total drag coefficient, which compared quite well to established ranges of this value for terrestrial airships.[13] Using the total computed drag for the airship at various altitudes, with the maximum drag occurring at the highest density (0 km altitude), it was possible to determine the thrust available. Given a maximum blade diameter

of 0.7 m, the power available could be varied until the thrust available equaled the thrust required.  Two design points were considered for propulsion sizing. Design point 1 is using a single propeller to drive the airship at a speed of 3 m/s. Design point 2 is using both propellers to drive the airship at a speed of 4 m/s.

*8. Vertical Propulsion*

Interacting with the surface, either by performing measurements within close proximity to the surface (a few hundred meters) or by depositing an SSP, is a desirable feature of the airship. It has been judged that landing or coming in close proximity to the surface is a critical event with the operational constraint of only performing these maneuvers when in contact with the orbiter. Operating anywhere between 1 to 5 km altitude is considered normal operations which can occur any time in the mission. Descent below 1 km is considered a critical event (descent but not operations at that altitude). A maximum descent rate of 25 meters per minute has been assumed. A fan system is used to inject atmosphere into the ballonets. Using the atmospheric properties of Titan, the drag on the hull during the vertical movement and the apparent mass of the local atmosphere, then 5 m$^3$ change in the ballonet volume is needed to reduce the altitude from 1 km to 0 km. It was found that a theoretical fan power of 30 W was sufficient to meet the desired descent rates with two fans (1 fan per ballonet, each at 30W) providing a redundant solution. Ducting and dampers are used to allow either fan to fill either ballonet (or both) thus providing full redundancy. The fans are operated at a constant speed, to reduce complexity, and are duty cycled to meet specific operating needs.

*9. Airship Envelope*

Using the mass and accommodation requirements of the science instruments, then the necessary subsystems can be sized. Once the subsystems have been sized and their mass defined, then the sizing of the gasbag, or envelope, can be performed. Different lifting gases were considered, but only two reasonable options were available based on terrestrial use and performance: hydrogen and helium.  While hydrogen has a slightly lower density than helium, and therefore has slightly better performance, its use was eliminated early in the design process due to operational liabilities associated with contamination of the science instruments' measurements.  Therefore, helium was selected as the lifting gas.

One essential parameter that should be mentioned about the gasbag is the differential pressure between the lifting gas within the gasbag and the Titan atmosphere.  Suggested values for most modern non-rigid terrestrial airships[13] show that a pressure difference of 125 Pa is sufficient, with a factor added to account for the maximum impinging velocity expected during flight (including wind gusts).  Including this factor assuming maximum wind gusts of 30 m/s gives a minimum pressure differential of 155 Pa.  Due to the cryogenic temperatures on Titan, as well as the higher atmospheric density, the materials chosen for the gasbag laminate will be able to withstand differential pressures in excess of 300 Pa.

A diameter to length (d/l) ratio of 0.20 was chosen based on separate theoretical and experimental work which pointed to this approximate value as producing the lowest total drag coefficient.[13] Gasbag mass was found by assuming an areal density of the laminate material used for the envelope material of 0.250 kg/m$^2$ over the hull surface area. The other major components of the Hull Group are the ballonets.  As discussed earlier, it is assumed there are two ballonets, positioned fore and aft, within the gasbag. The ballonets were assumed to be hemi-spherical in shape and to have material areal density 15% less than that of the gasbag (0.212 kg/m$^2$).

The Tail Group includes the tail surfaces and structure, as well as any rigging and support material.  For the tail sizing, the wetted area of the tail was taken to be a function of the total surface area of the hull/gasbag.  This relationship is based on the area relationship of the tail to the hull. The hull surface area is then multiplied by this ratio to obtain an estimate of the wetted tail area.  The planform area of the tail is then half of the wetted area, assuming the tail has flow on both sides.  This planform area is then multiplied by a historically-based value of areal density for the tail of 5.9 kg/m$^2$.[13]

The Gondola Group represents only the actual gondola structure. The attachment scheme to the hull is considered as part of the Hull Group and the internal components housed within the gondola are considered among the science instrument group and the internal subsystem components. For this study, the gondola design was not explored in detail.  However, an assumption was made for the gondola of a half-cylinder shape, approximately 0.75 m in diameter and 1.8 m in length (as described above).  This produced a total enclosed volume for the gondola of approximately 0.4 m$^3$. Allowing for ~75% internal volume margin (not including the SRGs, which are expected to be externally mounted), the total volume of the Titan Explorer Airship would need to be approximately 0.4 m$^3$.  In addition to volume, it was necessary to estimate the mass of the gondola structure.  Based on historical data[13], the typical terrestrial specific mass of 11 kg/m$^3$ was increased by a factor of 7 to a "density" of 77 kg/m$^3$ to account for the launch and entry loads typical terrestrial airships do not experience.

## C. Mission Description

Titan Explorer mission begins with a launch in 2018 using a Delta IV H launch vehicle. The 6-year cruise to Titan includes a single Earth gravity assist coupled with a Solar Electric low-thrust propulsion strategy. Arrival at Titan yields a direct entry and subsequent mid-air deployment of the airship while the orbiter uses aerocapture to put itself immediately into its intended orbit. Specific details and assumptions regarding the mission are provided below and in Table 7. Ensuring a "closed mission," or one where all aspects work together, including use of existing launch vehicles was an underlying theme to the study.

**Table 7. Titan Explorer mission assumptions.**

| No. | Assumption | Rationale |
|-----|------------|-----------|
| 1 | Launch in 2018 | Allows newer technologies to be developed. Allows full evaluation of Cassini-Huygens data. |
| 2 | Technology cutoff (TRL-6) in 2014 | Typical assumption – launch minus 4 years |
| 3 | No special planetary protection provisions | Consistent with current NASA policy. |
| 4 | Titan orbit insertion performed via aerocapture. | Reduces total launch mass |
| 5 | Low thrust solar electric propulsion to Titan | Reduces total launch mass. Eliminates need for large launch vehicle. Eliminates need for nuclear propulsion. |
| 6 | Single Earth Gravity Assist | Reduces total launch mass. Earth provides larger $\Delta V$ increment than Venus. |
| 7 | X-band as primary data return to Earth | Heritage. Provides lower performance bound. Ka-band or optical are enhancing. |
| 8 | Total radiation dose of 25 krads behind 100 mils of aluminum with an RDM of 2. | From JPL Team-X Evaluation of Titan Explorer |
| 9 | Entry Aeroshell | 3.75 m diameter, biconic shape with a 70-degree sphere cone forebody |

### 1. Interplanetary Cruise Phase

Transit from Earth to near Titan requires approximately a 6-year trip time (launch on 23 April 2018, Titan arrival on 17 March 2024). Cruise includes all operations from the end of launch to the start of the approach phase; defined as 75 days prior to the arrival of the entry system containing the airship at Titan. Most of the systems are dormant during the cruise to Titan. Science is limited in the cruise phase to periodic health checks and calibration activities for each of the science instruments. Operations are limited to flying the spacecraft stack and maintaining all elements at the desired level of readiness. Communications during cruise are performed through the orbiter truss mounted X-band high gain antenna (primary) or the medium gain antenna (backup).

Two significant events occur during cruise; Earth swingby and separation of the Solar Electric Propulsion Module (SEPM). The Earth swingby occurs about 22 months after launch. The Earth swingby occurs while the spacecraft is coasting to aid in accurate navigation to meet the current maximum acceptable probability of Earth impact to less than $10^{-6}$. After completion of the swingby, the ion engines are restarted and the mission continues.

As the spacecraft stack moves away from Earth (either prior to or after the Earth swingby), the amount of incident solar energy decreases so that the number of operating ion engines must be reduced to be commensurate with the available energy. A total of five ion-engines are used in the SEPM with a total xenon load of 1057 kg. Operation of the ion engines is reduced as the incident solar energy is reduced as the stack moves away from the Sun; initially as discrete engine operations, and finally modulated as a single engine. When the stack is at about 5.2 AU (about 17 months after the Earth swingby), the available solar energy level has diminished to the point where the power is sufficient to only power a single engine at 25% of its capacity so that it is no longer effective to continue operation of the ion engines. At that time, the SEPM is released from the spacecraft stack. During the remaining 30.5 months of the cruise phase (33 months to Titan, with the final 2.5 months being the approach phase), the spacecraft is coasting towards Titan. This approach phase is primarily focused on improving the navigated state and putting both the airship (in its aeroshell) and the orbiter (also in its own aeroshell) on the desired trajectories. Optical navigation (imaging Titan and Saturn), star trackers, and traditional RF techniques are used to improve the overall delivered knowledge state.

About 7 days prior to arrival, the airship in its aeroshell, is separated from the stack. After successful separation of the airship entry system, the orbiter system performs a preplanned maneuver, to revise its trajectory to no longer be on a direct entry trajectory and to delay the arrival of the orbiter so it can serve as the critical events relay platform for the airship entry system. At about 5 hours prior to the start of the aerocapture maneuver, the airship

entry system begins its entry into the atmosphere of Titan, corresponding to an orbiter to airship separation distance of 110,000 km. The UHF antenna mounted on the orbiter truss is used to receive the airship entry system critical events data. This data is collected and stored on-board the orbiter for eventual relay to Earth. After receiving the indication of a successful airship deployment and mission start, a tone is transmitted via the orbiter truss mounted antennas to Earth indicating successful airship deployment. After continuously transmitting the deployment tone for 10 minutes, the orbiter is rotated into its final inertial position for performing the aerocapture maneuver.

### 2. Airship Deployment

The airship entry system performs a direct, ballistic entry, into the atmosphere of Titan. A heritage approach blending the extensive Mars entry experience with the recent Huygens entry experience and the Cassini observational data provides a simple strategy for a robust entry solution.

At 15 minutes prior to atmospheric interface, the airship thermal control system shifts thermal management of the SRG's heat pipes from the truss mounted radiators to the aeroshell internally mounted phase change material heat sinks. The heat pipes going to the truss mounted radiators are isolated and severed, along with the cables to the truss mounted navigation and communication devices. Pyrotechnically actuated separation nuts are used to cut away the truss. When the airship entry system has reduced its speed to a local Mach number of about 1.1, a conical ribbon parachute is deployed using a mortar. When the system has descended to an altitude of about 15 km above the surface, the airship is extracted and the inflation begins (see Figure 4).

The heatshield retaining separation nuts are actuated, however the heat shield is not allowed to fall away. A lowering system is used to "lower" the integrated package containing the airship and all of its systems, the airship inflation system (including all compressed gas tanks), and the heatshield. This lowering system is attached at the tail of the airship envelope. When the lowering system has achieved a separation of at least 30 meters, then the inflation of the airship begins. The airship inflation continues until it is about 85% inflated. At that point, the ballistic coefficient for the parachute and backshell combination is about twice that of the airship, inflation system, and heatshield combination (including the buoyancy provided by the partially inflated airship). A line-mounted cutter cuts the lowering line at the tail of the airship. As the airship, inflation system, and heatshield combination falls away, the inflation process continues. At 20 seconds after cutting away from the backshell, the heat shield is
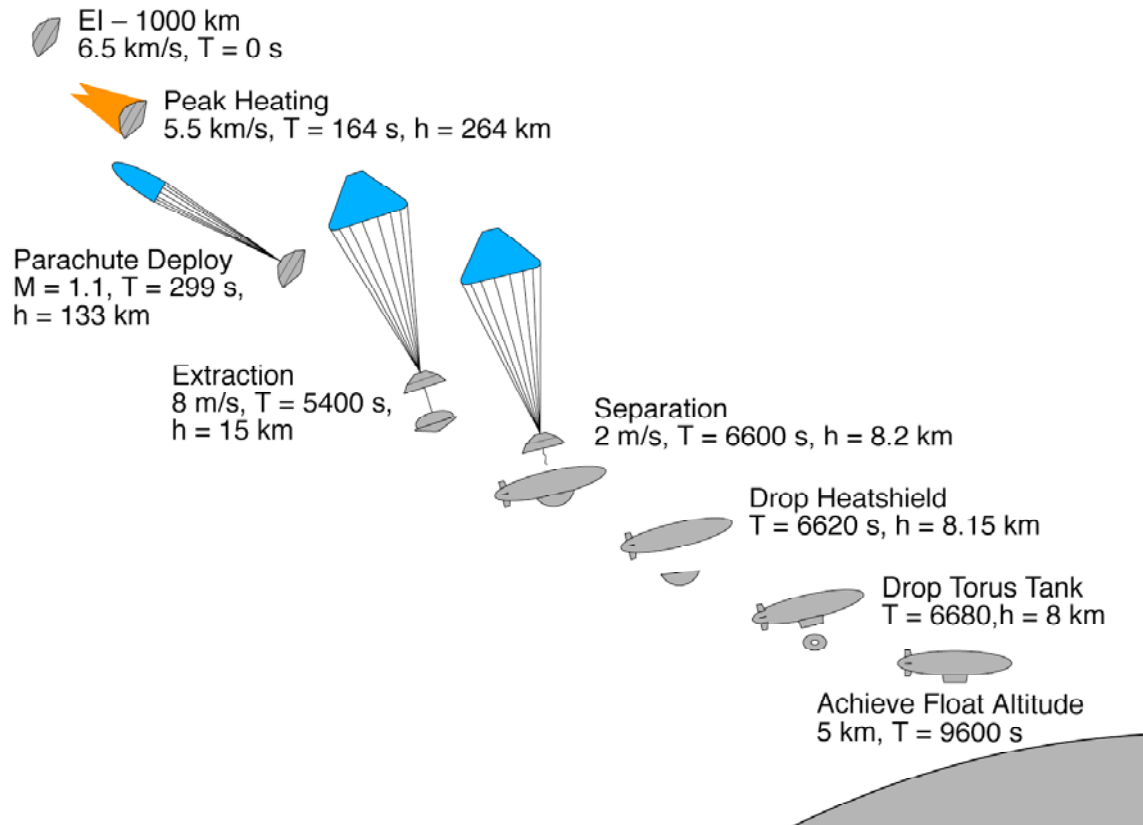


**Figure 4: Airship deployment and inflation sequence.**

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released from the airship and its inflation system. The inflation continues until the airship is fully inflated. At that point, the main inflation gas storage tank is dropped. Trajectory analysis has been performed to verify that none of these falling bodies contact each other during the nominal trajectory. With the heat shield and helium tanks cut away, the airship is free to continue with the rest of its deployment. At this point, the airship is fully inflated at an altitude of about 8 km. At this altitude, the airship is about 87% buoyant so it will continue to descend until it is 100% buoyant at the nominal 5 km float altitude. After the airship inflation is complete, the pyrotechnically actuated separation nuts retaining the propulsion pods are actuated allowing the two propulsion pods to lower and latch into place. At this point, the entry, descent, inflation sequence is complete and the system is considered ready to begin its initial checkouts and system verification testing.

*3. Airship Operations*

Airship operations are built around data collection and return with the perspective of correlating the data with a location. As noted above, there is a 14 orbit period where the airship and orbiter communicate between 35 to 75 minutes during each 5.2 hour orbit. After that, there is a nominal 5 day period (average) where the airship and orbiter cannot communicate. These two periods are used to define the airship operational architecture. Each of these categories is further divided into the time periods when the airship is on the Sun facing side of Titan and when the airship is on the side not facing the Sun. The baseline operational architecture consists of an intermittent data collection cycle, which is integrated with the relay data return as illustrated in Figure 2.

The baseline airship will navigate Titan nearly autonomously and will require robust and sophisticated navigational control. Upon deployment from the entry aeroshell and successful inflation, a certain period of the early phase of the mission will be spent exercising key airship systems. The general goal of the aerial flight segment from an operational perspective is to cover as much of the surface of Titan as possible (global survey) while stopping to concentrate on interesting areas. This approach will be very similar to current Mars rover exploration plans, but on a much larger scale. The airship will proceed along an assigned path, moving with the wind but employing its propellers to keep the path somewhat independent of the wind. This path will be uploaded to the airship on a periodic basis – more or less frequently depending on the current activity and its requirement for ground operations input. The strength of wind gusts could obviously affect the airship as it proceeds along its path, therefore, the assigned trajectory will have to be corrected in real-time by the on-board guidance, navigation, and control system using the propellers, control surfaces, and ballonets. It is expected there will also be autonomous obstacle avoidance capability within the navigation system such that the assigned altitude profile can be adjusted to account for larger than expected surface features.

There will be two methods for determining sites of scientific interest which will require the airship to make a dedicated survey either by hovering over the area (if possible, given the wind speed), circling about it, or initiating a ground interaction. Prior to the uploading of the assigned airship path, sites along the path can be designated as "areas of interest" that will require concentrated effort by the airship. It is expected in the first instance these areas have been discovered either by prior exploration (such as interesting sites previously discovered by Cassini, the Huygens probe, or Earth-based measurements) or by the Titan orbiter. In the second instance, the airship had discovered them on a previous pass over or near the area, and having been reviewed thoroughly by the science team on Earth, determined to be areas marked for future in-depth exploration. It is not expected the airship will be able to autonomously recognize areas of interest and therefore decide to concentrate on an area in real-time, although this level of autonomous technology is worth future investigation.

Flights between 1 to 5 km above the surface are considered "routine operations" and as such can occur regardless of the position of the orbiter. All flights below 1 km above the surface are considered critical events such that the airship must maintain continuous communication with the orbiter while the airship is either descending or ascending. Operations at the low altitude can occur after the orbiter passes overhead, however, a change in altitude will not be performed. Low altitude or surface operations will only occur during the 14 orbit period when communications between the orbiter and the airship is feasible. Prior to completing the 14 orbit period of communications, the airship will ascend back to the normal float range of 1 to 5 km.

Correlation of position with the science measurements is essential to increase the validity and fidelity of the data. If it is assumed that the airship uses only inertial data for propagating its state during the periods when it is not communicating with the orbiter means the IMU needs to propagate the state for a maximum of 6.6 days. Lateral position uncertainty throughout the extreme 6.6 day blackout period could be as high as plus or minus 48 km. Ground based corrections to the navigated position uncertainty can be performed since a direct comparison between propagated position (from the IMU) and the orbiter determined position can be made and back propagated to determine exactly where the airship has flown.

The crucial vertical channel is resolved through the use of direct surface altitude measurements. Coupling the vertical measured data with the propagated lateral position with the orbital radar altimetry data will result in a large degree of precision of where the science measurements were collected.

## VII.    Conclusions

An integrated assessment of a science mission to study Titan has been performed. Starting with a set of scientific goals and objectives, a set of observations has been defined. Further decomposition to a suite of science instruments followed by the details of each platform as well as the essential mission architecture has been defined.

High level mission requirements as characterized in the original NASA Research Announcement (NRA) were to focus on missions whose launch dates were after 2015 and were considered "Flagship" class missions (total mission cost in excess of $700 million FY2005). A blend of both existing (or near term) technologies and longer term developmental technologies has been assumed to provide a reasonable performance bound. Legacy systems provide the ability to define upper bounds on mass, power, volume, and performance which illustrate there are opportunities for significant improvement. A key assumption in this study was to only consider existing expendable launch vehicles (in terms of available launch energy and the physical integration constraints).

Various levels of maturity of the design exist within this study. Some new work was performed (primarily with the airship and the optional helicopter vehicles) while leveraging various other studies previously performed.[14] Results of the study indicate a combined mission including a long-lived orbiter and a short-lived in-situ aerial vehicle (airship or helicopter) can be implemented using existing launch vehicles coupled with either existing systems and components or systems currently under development with expected use dates in the 2012 type time frame. There are numerous opportunities for either reducing the system mass and power or increasing the overall system performance through a more aggressive infusion of newer technologies.

A preference for the airship based aerial vehicle is found in its reduced implementation complexity as well as its greater ability to accommodate the uncertainties of the environment of Titan.

The results of the study indicate an aerial exploration of Titan is feasible and requires minimal new technology. Being able to collect an extended, and potentially global, set of in-situ measurements of Titan will have many unanticipated changes in how we view our place in the universe.

## Acknowledgments

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