A Survey of Titan Balloon Concepts and Technology Status

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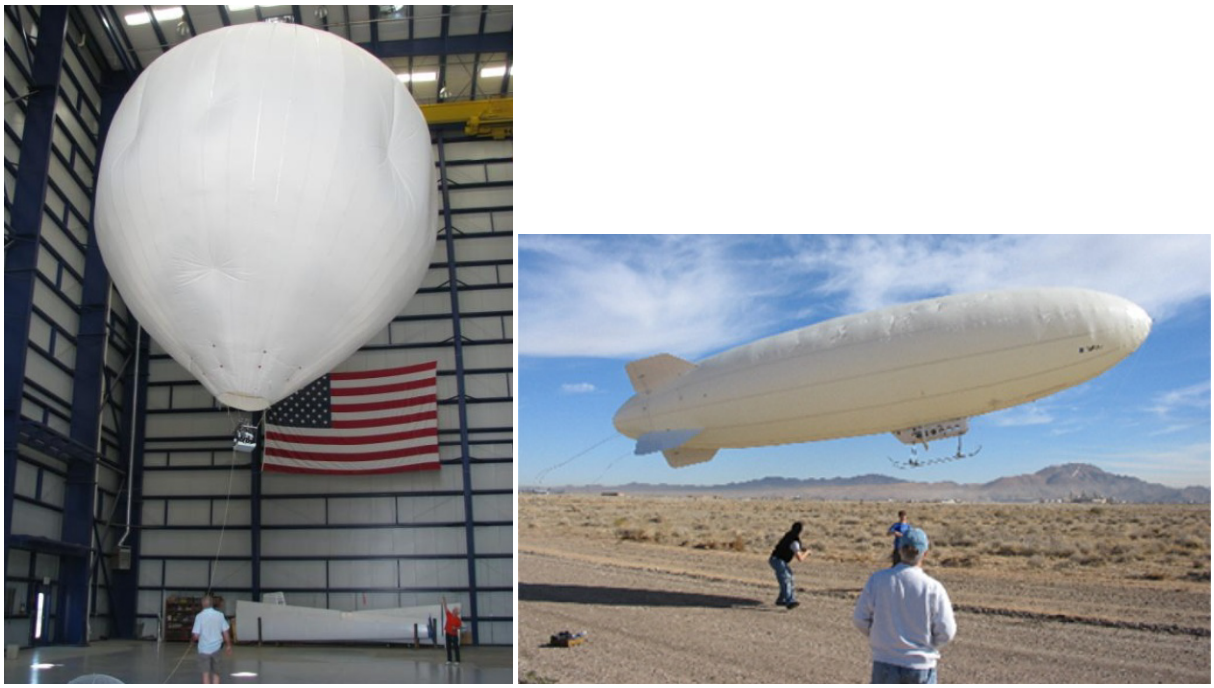
Abstract

This paper surveys the options for, and technology status of, balloon vehicles to explore Saturn's moon Titan. A significant amount of Titan balloon concept thinking and technology development has been performed in recent years, particularly following the spectacular results from the descent and landing of the Huygens probe and remote sensing observations by the Cassini spacecraft. There is widespread recognition that a balloon vehicle on the next Titan mission could provide an outstanding and unmatched capability for *in situ* exploration on a global scale. The rich variety of revealed science targets has combined with a highly favorable Titan flight environment to yield a wide diversity of proposed balloon concepts. The paper presents a conceptual framework for thinking about balloon vehicle design choices and uses it to analyze various Titan options. The result is a list of recommended Titan balloon vehicle concepts that could perform a variety of science missions, along with their projected performance metrics. Recent technology developments for these balloon concepts are discussed to provide context for an assessment of outstanding risk areas and technological maturity. The paper concludes with suggestions for technology investments needed to achieve flight readiness.

Introduction

Suggestions for the use of balloons to explore Titan date at least to the mid-1970s.[1,2] Improved understanding of Titan in the wake of the 1980 Voyager 1 flyby resulted in additional and refined thinking,[3,4] but it was the Cassini-Huygens mission that arrived at Saturn in 2004 that spurred an outpouring of Titan balloon concept and technology development. Recent review articles by Lorenz[5] and Dorrington[6] discuss this history and provide a large number of references. The results from Cassini-Huygens revealed Titan to be a complex and fascinating world with diverse topographical features and a methane-based hydrological cycle. The motivation to return to Titan for further exploration only intensified in the wake of these results, with increasingly widespread recognition that a buoyant vehicle could provide an outstanding and unmatched means of *in situ* exploration on a global scale (e.g., Ref. 7). The Huygens probe also measured low winds speeds (< 1-2 m/s) and excellent visibility below a 10 km altitude. These two key results cemented Titan's status as an extremely well-suited flight environment for buoyant vehicles, complementing the previously known favorable aspects of dense, high molecular weight atmospheric gas, very small diurnal temperature variations and low gravity.

A remarkable feature of the work done on Titan balloons in the past decade and a half is the tremendous diversity of proposed balloon concepts. This diversity parallels that of actually flown balloons on Earth over the past two and a half centuries consisting of light gas and hot air balloons in a wide variety of shapes, sizes and control features. Two recent Titan examples from JPL are shown in Fig. 1. The balloon design space is multi-dimensional and especially prone to



(a) (b)

Fig. 1: Examples of Titan balloon concepts: (a) 9 m diameter hot air prototype during room temperature testing. (b) 11 m long motorized blimp utilized as a technology testbed.

hybridization, including the fundamental provision of buoyancy itself given the development of Rozier balloons that combine light gas and hot air characteristics. Balloon vehicle concepts therefore resist simple categorizations and it can be difficult to evaluate and compare competing concepts for an application like Titan exploration given the large number of possible combinations of features.

One purpose of this paper is to present a conceptual framework for thinking about the balloon design space in an attempt to facilitate the ongoing discussions and analyses of Titan balloon vehicles by the community at large. A second purpose is to describe an analysis of which balloon vehicle concepts make sense for different science objectives, using the conceptual framework as an organizing principle. The result is a rather small set of preferred balloon options distilled down from the large universe of possible choices. These recommended options necessarily contain an element of subjectivity, but an attempt is made to clearly articulate the assumptions and preferences that underlie the analysis. The third purpose is to summarize the technological maturity and outstanding risk areas for each of the recommended concepts, drawing upon the progress reported in the recent literature. The paper will conclude with suggestions for future investigations that could address these outstanding risks and bring the balloon concepts to flight readiness for a Titan mission.

Assumptions

This analysis of Titan balloon concepts aligns itself with current mission thinking by adopting three key assumptions:

1. The balloon vehicle is a major element of the exploration architecture and not a small auxiliary payload on an otherwise conventional lander or probe mission.
2. The balloon flight duration would be measured in months and not hours or days. Long duration would be essential for exploiting the advantages of a mobile platform that could visit many places, and it is probably needed to justify the large expense of conducting a Titan balloon mission.
3. The balloon would fly below the haze layer so that an onboard camera could acquire a large number of ground images. This would require a flight altitude below approximately 10 kilometers, based on the Huygens results, an altitude that also provides the ancillary benefit of being warm enough to avoid the potential complications of methane ice accumulating on the balloon.

This last assumption reflects current mission thinking about the proposed science priorities for a Titan balloon (e.g. Ref. 7) and deliberately excludes, for this analysis, examination of options for exploring the upper atmosphere.

There are a number of important consequences resulting from these assumptions. First, there would be no alternative to radioisotope-generated electrical power for a long duration mission at Titan. A few tens of Watts of continuous power would be needed to operate the onboard electronics alone, and additional energy for thermal heaters would be required to keep the payload sufficiently warm in the 85-94 K Titan cryogenic environment. Solar power would be impractical below the Titan clouds and haze given the incident flux of only ~0.3 W/m^2 and the consequent need for large (and heavy) solar arrays in the size range of many hundreds of square meters. The best primary batteries based on lithium chemistry would be similarly impractical: even a large 50 kg lithium battery can provide only 8 W of continuous power over a 3 month period.

A great advantage of using a radioisotope device is that the waste heat could be used to keep the balloon payload warm, thereby eliminating the electrical power otherwise needed to run heaters. However, a radioisotope power source is a relatively large and massive device. The projected specifications for the Advanced Stirling Radioisotope Generator (ASRG) are a 32 kg mass and an output of 140 W electric and 360 W thermal. Different mission studies have concluded that either one or two ASRGs would be required to provide enough power for the balloon depending on the details of the telecommunication system, instrumentation and science data return. The net result is that either 32 or 64 kg of ASRGs must be carried by the balloon, which basically would preclude the kinds of small balloons with few kilogram payloads often flown at Earth. This suggests that a complete Titan balloon payload would be on the order of 100-200 kg once the ASRG is added to the structure, thermal control, avionics and instrument masses. This paper assumes a payload in this size range.

There is relatively little change in atmospheric properties between the surface and 10 km: the temperature decreases from 94 to 85 K, the pressure from 1.5 to 1.0 atmosphere, and the density from 5.4 to 3.9 kg/m^3. This modest variation simplifies the design of balloons intended to traverse the entire altitude range, an advantage incorporated into the study.

Balloon Design Conceptual Framework

Despite the foregoing assumptions, the Titan balloon design space remains large. One way to organize the analysis of options is to create a conceptual framework that looks at the balloon from two distinct but related perspectives:

1. Functional requirements: what the balloon has to do to accomplish the scientific mission.
2. Design choices: the hardware and software features selected for the vehicle so that it could perform the required functions.

In the proposed approach, the functional requirements are specified first and the design choices follow as a result. Typically, many different vehicle designs can satisfy any particular specification of functional requirements; however, there are usually clear advantages for one design over another.

Figure 2 presents a graphical depiction of the major elements of functional requirements for a Titan balloon. Figure 3 presents a similar graphical depiction for the design choices. In each case, one element is seen as most fundamental and is therefore placed at the center of the diagram. The flight environment is central to the functional choices: fundamentally one must define where the vehicle has to fly and identify the atmospheric properties for that environment. Similarly, the choice of buoyancy provision is central to the balloon design space and informs all other design choices to a greater or lesser extent.

As described in the previous section, current mission thinking is overwhelming focused on balloons that could fly below the clouds and clearly see Titan's surface. This choice is reflected in the description inside the environment circle in Fig. 2. In the proposed conceptual framework, the remaining functional requirements are grouped into four categories as shown in Fig.2:

1. The mass of payload (cargo) that must be carried by the balloon. The focus here is on the larger payloads commensurate with heavy radioisotope power sources.
2. The flight duration. The emphasis is on long duration, notionally 3 months or longer.
3. Trajectory control: either none, vertical only, horizontal only or full vertical and horizontal control.
4. The degree to which the vehicle would interact with the surface: none, close approach for observation, persistent landing or sample acquisition that could be accomplished with either a touch-and-go or persistent landing paradigm.

The lifetime category is sub-divided into three time durations: the minimum of 3 (Earth) months, an intermediate duration of 3-12 months, and a very long duration of a year or longer. The intermediate category duration approximately corresponds to the time required for a balloon to circumnavigate Titan at near-equatorial latitudes. Shorter durations would therefore result in regional explorations, while longer ones would allow for extended global coverage.

Trajectory control includes a subtlety that is not immediately apparent from the simple graphical depiction in Fig. 2. The amount of control required must also be specified, both in terms of navigational accuracy (allowable deviation from the target) and the timeliness with which that accuracy is achieved. For example, it is necessary to specify not only that a particular location must be visited and with what allowable position error, but also whether the location must be reached in a day or a year or somewhere in between. The continuum of possibilities is well-illustrated in a recent study[8] that quantified the timescales on which different Titan geographical locations could be reached by balloons using different amounts of trajectory control. A key conclusion is that Titan's gentle winds in the lower atmosphere would enable relatively small amounts of control to drastically reduce the time required to overfly a particular location. Nevertheless, many balloon mission concepts have been proposed (e.g. Refs. 7 and 9) that feature no trajectory control at all on the premise that there is enough diversity and density of science targets that a wind-driven balloon would naturally fly over a sufficient number.

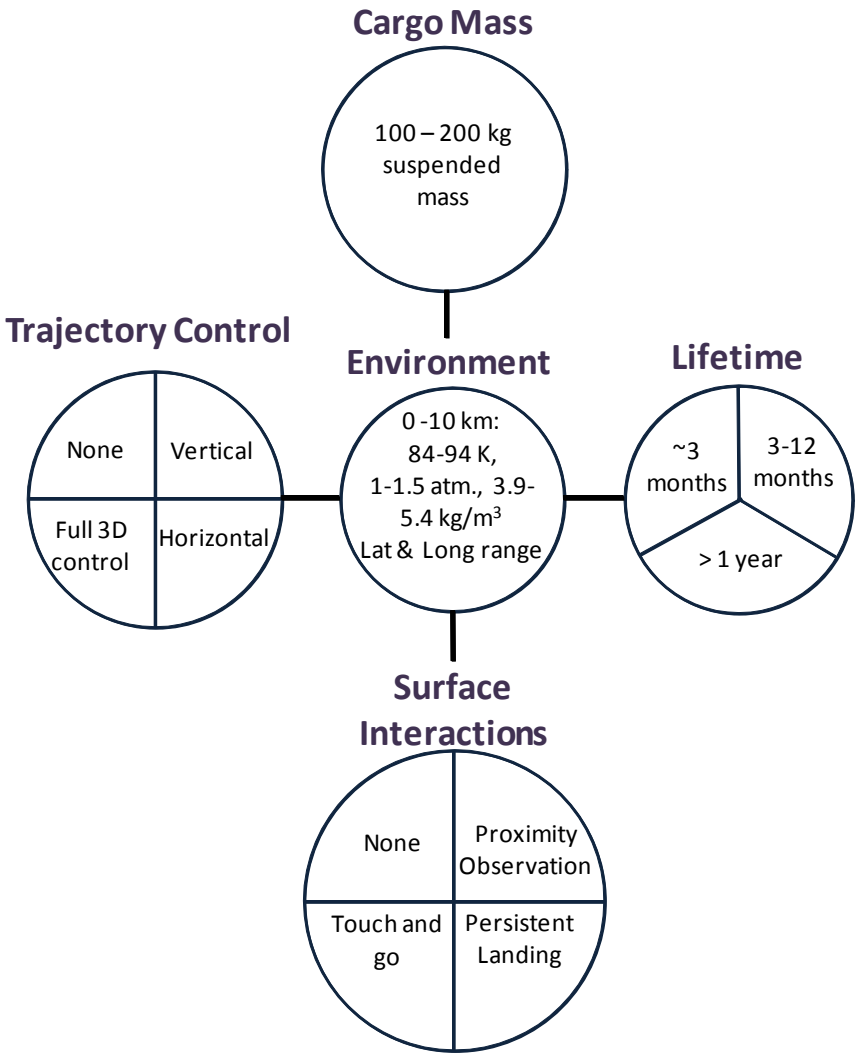


Fig. 2: Functional Requirements Parameter Space

Surface interaction functionality is arguably a subset of trajectory control. However, the high importance of this functionality for Titan exploration motivates giving it a separate category. Certainly some capability for trajectory control is a necessary prerequisite so that the vehicle could approach and safely operate on or near the surface. Three levels of surface interaction are identified:

1. Proximity observation, in which the balloon would come close to the surface for observations (within hundreds of meters) but would not contact it.
2. Touch and go, in which some part of the balloon gondola, or a tethered device lowered from it, would come briefly into contact with the surface.
3. Persistent landing, in which the balloon gondola would actually land on the surface for a prolonged period of time (minutes to days).

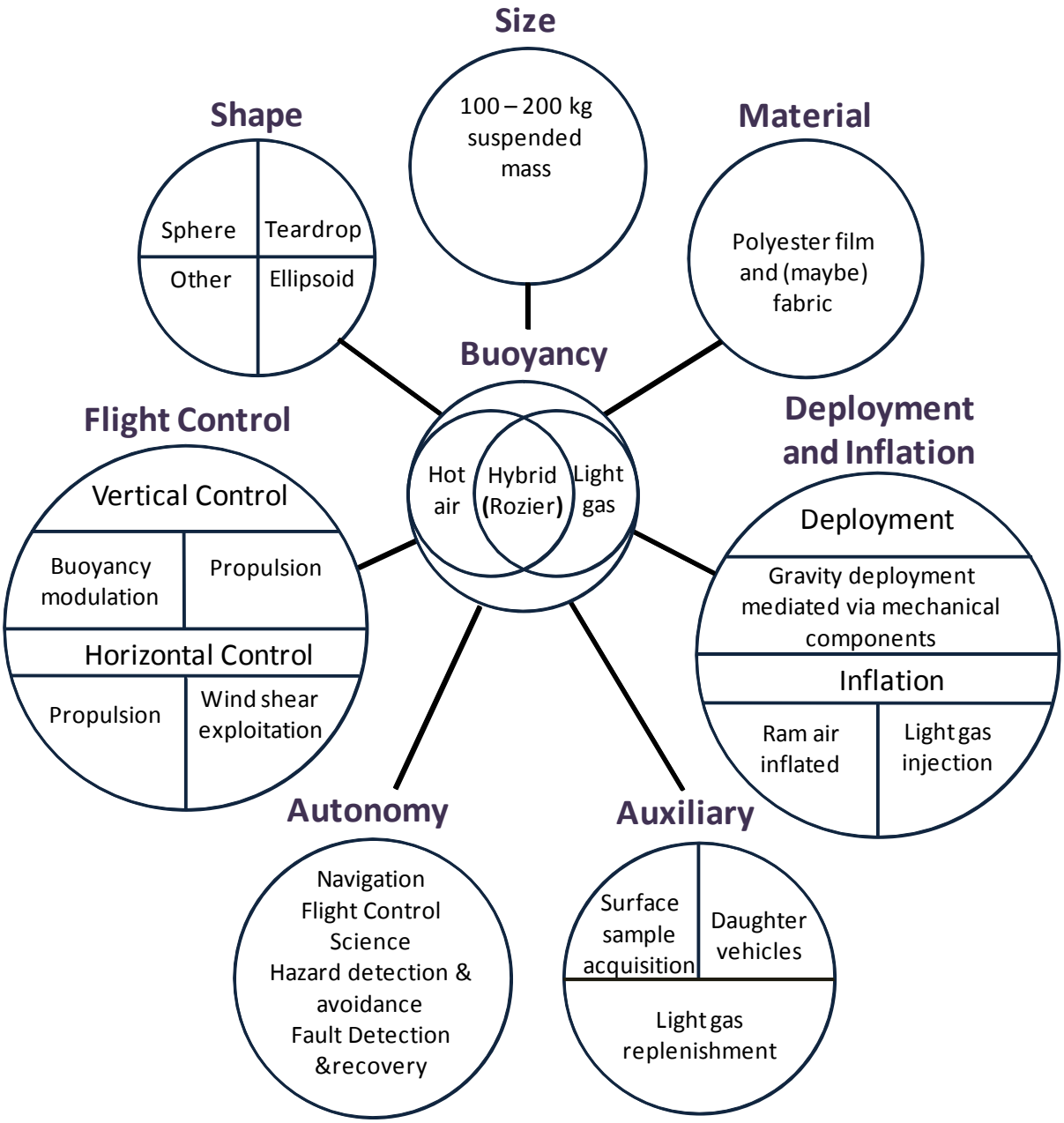


Fig. 3: Design Choices Parameter Space

Surface sample acquisition is a key functionality of interest for a Titan balloon concept, and that would be possible in both the touch and go and persistent landing options. Highly accurate trajectory control would be required if samples are to be acquired from specific locations of small, meter-scale lateral extent. At the other extreme, much more limited trajectory control would be required if it is acceptable to acquire any kind of sample from a large area many kilometers across.

There are typically a large number of possible Titan balloon designs that could satisfy any given set of functional requirements. The design choices in this framework are grouped into

eight categories as summarized in Fig. 3. Each category is discussed below in the context of Titan balloon designs.

1. **Buoyancy:** Lift is provided by the hydrostatic force of the atmosphere acting on the lower density gas contained inside the balloon. This lower density can be achieved either by using a lower molecular weight gas inside the balloon or by heating ambient atmosphere to reduce its density. The first kind is known as a light gas balloon, the second a hot air or Montgolfiere balloon. Both options would be feasible at Titan in addition to a combination light gas and hot air hybrid concept known as a Rozier balloon.

   Hydrogen and helium balloons provide the largest buoyancy per unit volume (~3.5 – 5 kg/m^3 at this altitude range) but are sensitive to small pinhole leaks in the envelope over the multi-month mission timescales. Hydrogen is slightly better than helium, providing 8% more buoyancy per unit volume, but both require comparable allocations of storage tank mass. Hot air balloons could only be implemented at Titan for multi-month missions by using the waste heat from a radioisotope power source to raise the temperature of the ambient atmosphere inside the balloon. Although there are some uncertainties in existing thermodynamic performance models of Titan hot air balloons, analysis indicates that approximately 1 – 2 kW of thermal energy would be required to float a double-walled balloon with the kind of 100-200 kg payload mass under consideration here (e.g., Refs. 7 and 9). The two-wall construction would provide for an insulating layer of gas between the walls, thereby reducing the heat leak to the environment and improving buoyancy generation per unit heat input. This design is highly tolerant of pinhole leaks in the envelope, but is larger by order of magnitude in balloon volume given the much reduced buoyancy per unit volume achievable with a hot air balloon compared to a light gas balloon.

   The mass required for this larger hot air balloon size is generally offset (and more) by the fact that light gas balloons also require a comparatively heavy gas storage system to carry the helium or hydrogen until the moment of inflation at Titan. Rozier balloons tend to combine the deficiencies of both types (pinhole sensitivity and low volumetric efficiency) but can mitigate the risks associated with thermodynamic performance uncertainties of pure hot air balloons if those risks cannot be otherwise retired.
2. **Shape:** The key factor in shape selection is whether or not the balloon is internally pressurized. The natural or "teardrop" shape typically used on Earth for unpressurized (also known as zero pressure) balloons would also be the default choice for Titan. Both zero pressure light gas balloons and hot air balloons fall into this category, with hot air balloons being non-pressurized by definition because they are continuously vented to the atmosphere. In contrast, pressurized balloons, often referred to as "superpressure" balloons, employ spherical or ellipsoidal shapes to most efficiently withstand the structural loads on the balloon material. Streamlined ellipsoids are typically used for propelled balloons to minimize drag (e.g., blimps), while spheres are used for un-propelled balloons to minimize the balloon mass. Other lifting-body type shapes under development on Earth (e.g., Ref: 10) are also possible, although the low flight speeds achievable at Titan tend to greatly diminish their utility.
3. **Size:** The balloon size is determined by the suspended mass and the volumetric efficiency of the buoyancy method. Light gas balloons are on the order of 50 m^3 for a 150 kg payload, while hot air balloons are an order of magnitude larger, ~500 m^3.
4. **Material:** Most of the work done to date suggests that polyester-based films or polyester film plus fabric laminates are the best choice for the balloon material for the cryogenic

environment.[7,9,11] These polyester materials have been shown to avoid catastrophic structural failure due to brittleness at these cold temperatures, but are prone to development of pinhole defects with repeated flexing over time.[11] This material can be used for both light gas and hot air balloons with an areal density of approximately 100 g/m^2 for pressurized balloons and 50 g/m^2 for unpressurized balloons that have a much reduced strength requirement. The resulting total balloon mass corresponding to the sizes listed above are ~6 kg for pressurized balloons and ~16 kg for unpressurized single-walled balloons. Both are small compared to the 100-200 kg payload masses, indicating that material areal density is not a strong design driver. However, double-walled hot air balloons would have a mass of 2 x 16 = 32 kg, large enough to warrant more attention to optimizing the balloon material mass.

5. **Deployment and Inflation:** A distinguishing characteristic of all planetary balloons is that they must transition from a compact, stored configuration inside the spacecraft to a fully inflated and free-flying configuration upon arrival at the destination. This process is generally divided into two main phases: deployment, which takes the balloon from a folded condition inside the spacecraft to an unfolded configuration outside the spacecraft; and inflation, which puts buoyancy gas inside the deployed balloon.

   Deployment and inflation could occur in the atmosphere during a parachute-assisted descent upon arrival, or it could occur on the surface after landing the spacecraft. Aerial deployment and inflation is generally favored to avoid contact of balloon material with rocks or other surface dangers. The only example of a planetary balloon, the Soviet VEGA mission at Venus, employed aerial deployment and inflation.[12] In aerial deployment, gravity is typically the motive force used to unfold the balloon and remove it from the spacecraft, mediated through mechanical components like tethers, connectors, actuators, brakes and energy dissipaters (e.g., ripstitch).

   Inflation is fundamentally different for hot air and light gas balloons. Hot air balloons are filled with atmospheric gas via ram-air inflation through an open port at the bottom of the balloon. Light gas balloons inject hydrogen or helium from a storage tank through a pipe into the balloon. Once inflation is complete, any connections to the spacecraft must be severed (parachutes, tethers, gas feed pipes) to enable to the balloon to float away on its mission. A severed light gas feed pipe must be sealed with a valve to prevent subsequent gas loss from the balloon.

6. **Flight Control:** The simplest balloons do not use flight control but instead travel with the prevailing wind at an altitude determined by the interplay of buoyancy, wind and changing thermal conditions. There are two options for adding control: using propulsion and modulating the buoyancy.

   Propulsion can be achieved with motor-driven propellers aligned in either the horizontal or vertical directions. This approach is simple and direct, but would require a significant amount of power on a power-constrained (140 – 280 W) Titan mission. One study estimated that 55 W of motor power could generate a 0.85 m/s flight speed with a typical Titan hot air balloon.[13]

   Buoyancy modulation takes different forms for the two kinds of balloons. Hot air balloons are modulated by opening and closing a valve that sits at the apex of the balloon. When open, warm air vents to the outside, buoyancy decreases and the balloon descends. Conversely, when the valve is closed, the internal temperature rises, buoyancy increases and the balloon ascends. This control method requires only a little power to actuate the valve and can be repeated as many times as is needed. Light gas zero pressure balloons achieve altitude

control through gas venting and ballast drops. This technique has been used reliably for centuries on Earth, but suffers from the problem that buoyancy gas and ballast are finite resources and hence place a limit on flight duration. Under favorable circumstances, however, the consumption rate of ballast and buoyancy gas can be so low as to support long duration flight. For example, Earth flights over Antarctica have lasted for up to six weeks due to the favorable environment afforded by continuous sunlight during summer solstice.[14] The diurnal temperature variation at Titan is expected to be even lower (more favorable) than that, suggesting that longer flights of perhaps three to six months would be achievable.

Light gas superpressure balloons are essentially constant buoyancy devices designed to fly at a fixed atmospheric density, which at Titan would correspond closely to a fixed altitude. Therefore, superpressure balloons are not amenable to buoyancy modulation techniques.

An important possibility is the use of altitude control to effect a limited form of lateral control through exploitation of the circumstance that different wind velocities exist at different altitudes (vertical wind shear). The basic idea is to move the balloon to an altitude where favorable lateral winds exist that would move the vehicle towards a desired target. Preliminary analyses indicate that this technique could provide substantial coverage improvements at Titan as compared to completely uncontrolled balloons.[8] A different wind shear exploitation strategy is to hang an aerodynamic control structure a large distance under the balloon and create a net lateral force on it due to the wind velocity difference between the balloon and control structure altitudes.[15] However, the Titan winds are very small in the lower atmosphere (≤ 10 km), suggesting that this technique may be most applicable in the upper atmosphere where the wind and wind shear are much larger.

7. **Autonomy:** Any amount of flight control would require some level of onboard vehicle autonomy because the round trip light time of 138 to 168 minutes (depending on the time of year) would preclude meaningful teleoperation (joystick control) of Titan vehicles by operators on Earth. There are a number of capabilities within this domain and for each there is a range of performance parameters possible from minimal autonomy to extensive.
    a. Localization: This is the ability of the vehicle to figure out its location on Titan. Typically one divides the issue into global location (latitude and longitude) and a local position relative to a surface feature ("100 meters southwest of that hill"). A key challenge is that Titan balloons must navigate without a global positioning system, which on Earth has become ubiquitous and greatly simplified the navigation problems faced by aircraft and other types of vehicles. The performance metric is the error on the position knowledge.
    b. Flight Control: This is essentially an autopilot, the onboard smarts to operate the vehicle control mechanisms so as to direct the vehicle to fly in the desired direction and arrive at the desired location. The performance metric here is the deviation from the desired trajectory or position.
    c. Science: This is the ability of the onboard computer to acquire and process science data with reduced or minimal input from scientists back on Earth. This ranges from easy implementation, with standardized sensor operation scripts, to difficult implementation, with an autonomous science capability in which the onboard system chooses what data to collect and when, and the degree to which data is processed or summarized prior to transmission back to Earth.

d. Hazard detection and avoidance: This is the ability to detect hazards around the vehicle and direct the flight control system to avoid them. This is particularly important in any kind of close approach or landing on the surface where large rocks or other topography could pose a crash hazard.
e. Fault detection and recovery. This is the self-monitoring of the vehicle to detect and mitigate onboard component failures.

8. **Auxiliary:** This topic is a collection of auxiliary capabilities that could be designed into a Titan balloon vehicle to provide additional functionality.
    a. Surface sample acquisition: This is the mechanism and control system for a device that could acquire surface samples and bring them into the vehicle for analysis. It would include acquisition, transfer, and sample preparation capabilities. It also would include cleaning of the sample handling train to prevent cross-contamination if multiple samples are to be acquired with the same hardware.
    b. Daughter vehicles: The main Titan balloon vehicle could serve as a carrier for one or more small daughter vehicles that could be detached during the mission. The possibilities include aircraft, gliders, drop sondes, boats, ground rovers and landers. Without a nuclear power source, each of these possibilities would be restricted to some kind of chemical battery and hence short term operation. In principle, an aircraft, boat or rover could be re-mated with the parent vehicle for recharging of its batteries and reuse.
    c. Light gas replenishment: The Titan atmosphere contains methane at a roughly 3% concentration level. This methane could be chemically processed to produce new hydrogen buoyancy gas that could be injected into a light gas balloon to compensate for gas loss through pinhole defects. Depending on the balance of loss rate and production rate, such chemical processing could perhaps extend the lifetime of light gas balloon indefinitely, albeit at the cost of the mass and power required for the processing device.

Titan Balloon Options and Technological Status

Despite the multitude of possible design combinations described in the conceptual framework, it will now be argued that the Titan balloon concept space can be well-characterized by identifying just five distinct options that span the range from simple to complex. Table 1 summarizes the five options resulting from this argument in which each successive option adds another significant functional capability that could dramatically enhance the mission. Figure 4 schematically depicts the five options on a notional plot of technological maturity versus functional capability. In each case, a recommendation is made for the balloon design that is deemed most suitable, along with outstanding technological risk areas and an alternate, or fallback, balloon option. Certainly there are detailed variations possible within each of these five options, but as depicted they serve as useful mileposts that highlight the key classes of potential Titan balloon missions.

Option 1 would be the simplest balloon mission at Titan, one that results from choosing the least ambitious set of functional requirements from Table 1 of the framework. This would be a wind-driven, uncontrolled balloon that would remain aloft at a near constant altitude for a 3 month flight. At an average speed of 1 m/s, such a balloon would traverse almost 8,000 km of

Table 1: Summary of Five Main Titan Balloon Options

Option	Functional Requirements				Description	Recommended Balloon Design	Risk Areas	Alternative Balloon Design
	Altitude	Lifetime	Trajectory Control	Surface Interactions				
1	10 km, near constant	3 months	None	None	Simplest wind-blown balloon for higher altitude regional reconnaissance.	Light gas superpressure balloon.	Leak rate through pinhole defects.	Hot air balloon operated at constant altitude.
2	1-10 km	3-12 months	Vertical only	None	Altitude controlled balloon but no close surface approach. Wind-blown.	Hot air balloon with altitude control system.	Hot air thermodynamic behavior predictions and margins.	Light gas zero pressure balloon with venting and ballasting.
3	1-10 km	3-12 months	Vertical and horizontal	None	Altitude controlled balloon but no close surface approach. With horizontal control to enable coarse targeting.	Hot air balloon with propeller propulsion.	Achievable flight speeds. Robust functioning and accuracy of the autopilot and navigation system.	Hot air balloon with wind shear control system.
4	0-10 km	3-12 months	Vertical and horizontal	Touch and go at a coarse scale	Altitude controlled balloon with surface approach and sampling at a coarse scale. With horizontal control to enable coarse targeting.	Hot air balloon with propeller propulsion, hazard detection system and surface sample acquisition system.	As in 3. plus: autonomy required for safe ground approach; reliable "touch and go" sample acquisition and processing system.	Motorized blimp with hazard detection and surface sample acquisition system. Also with H_2 replenishment.
5	0-10 km	3-12 months	Vertical and horizontal	Persistent landing at a fine scale	Altitude controlled balloon with surface approach and sampling at a fine scale. With sophissticated horizontal control to enable fine targeting.	Motorized blimp with hazard detection and surface sample acquisition system. Also with H_2 replenishment.	Deployment and inflation of blimp. Ability to produce sufficient H_2 makeup gas. Autonomy required for safe and accurate ground approach and landing. Ability to safely persist on surface.	Hot air balloon with propeller propulsion, hazard detection system and surface sample acquisition system.

the surface, presumably sufficient to overfly a wide variety of terrains, albeit without the ability to linger over any one of them or otherwise perform a close inspection of, or interact with, the surface. Such a mission would be suited to aerial reconnaissance of the surface and meteorological investigations of the atmosphere. Two recent mission proposals featured a balloon of this type: a helium superpressure balloon was proposed for the Titan Aerial Explorer (TAE) mission in 2010 [9] (Fig. 5); and a RTG-Montgolfiere balloon was proposed for the TSSM mission in 2008 [7] (Fig. 6).

These two different proposed concepts illustrate that either a light gas or a hot air balloon could perform an Option 1 mission. Many hundreds of uncontrolled helium superpressure balloons have flown at constant altitude at the Earth, with flight durations of months typical when flying at higher altitudes so as to be above inclement weather.[16] The two identical Soviet VEGA balloons at Venus also were helium superpressure balloons and bear a resemblance to what a Titan version would look like (Fig. 7). A great advantage of Titan compared to the Earth is that the cold temperature would reduce the diffusion rate of gas through the balloon material almost to zero. Also, the negligible diurnal temperature variations in the lower Titan atmosphere would greatly reduce the amount of internal pressurization required for superpressure balloons

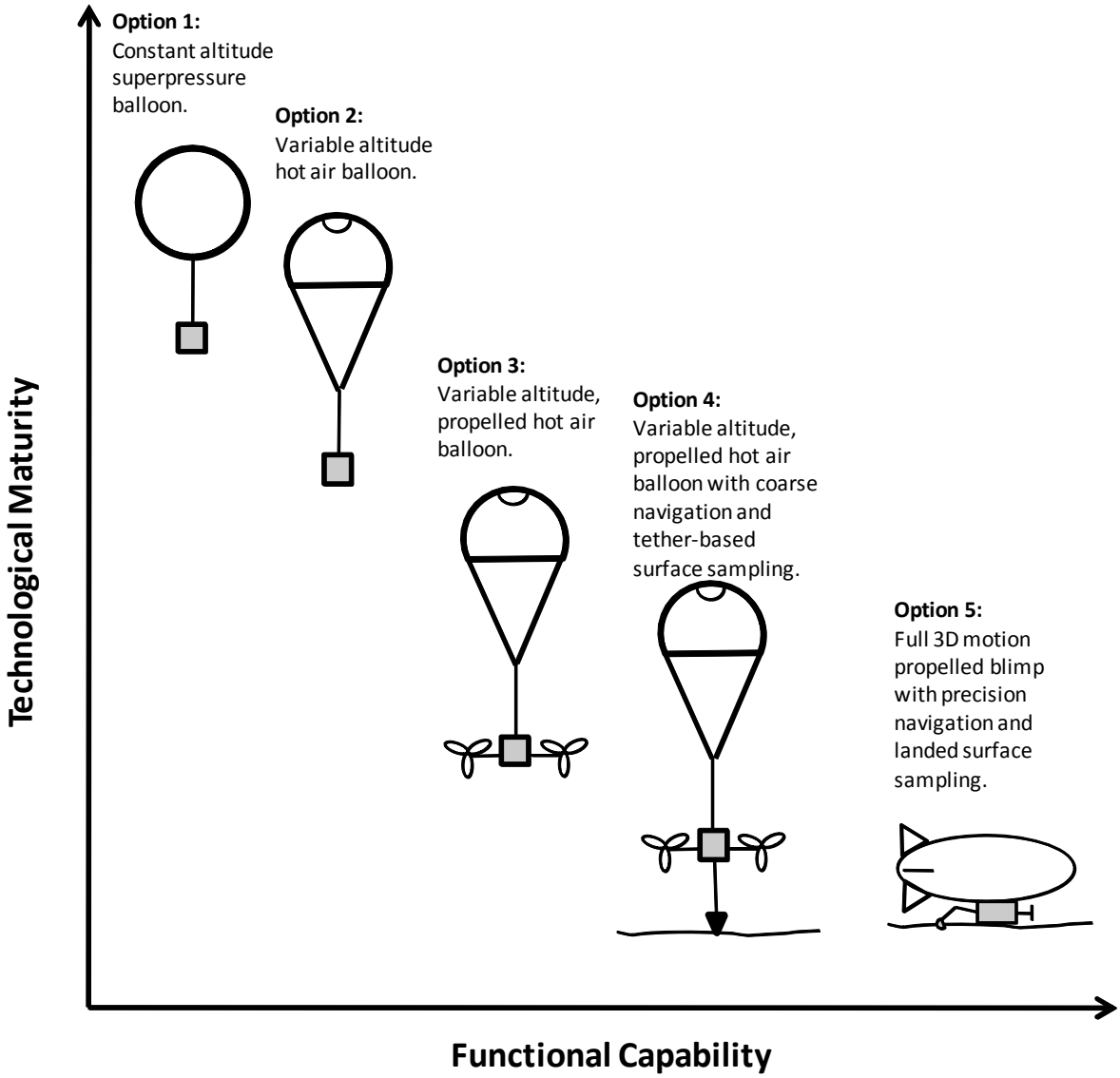


Fig. 4: Schematic depiction of the five Titan balloon options as a function of technological maturity and functional capability.

and the rate of gas venting and ballasting required for zero pressure balloons. These facts strongly suggest that such balloons could support multi-month missions at Titan. However, the achievable lifetime for a Titan light gas balloon remains an unanswered question at the present time given the absence of test data and the complications posed by the cryogenic environment and having to deploy and inflate the balloon after a multi-year trip to Titan in a stored configuration. Calculations indicate that a 50 m^3 spherical helium balloon at Titan could fly for 6 months without ballasting even with approximately 10 pinhole defects of size 10 microns in diameter each. Testing is required to ascertain whether an actual balloon is better or worse than this.

The TSSM mission concept proposed a hot air balloon primarily because of concern over the lifetime uncertainty of a light gas balloon and the need to be confident in delivering a 6-12

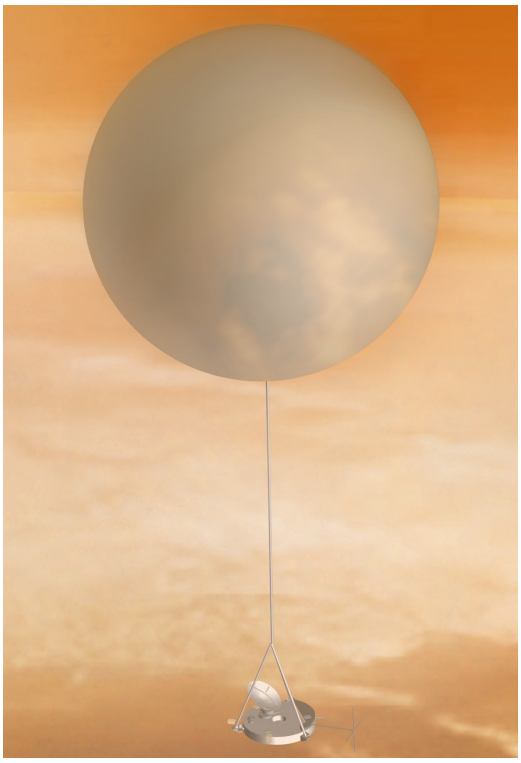


Fig. 5: Artist's Concept of TAE Balloon (Ref. 9)

Fig. 6: Artist's Concept of TSSM Balloon (Ref. 7)

month mission.[7] The inherent altitude profiling capability of hot air balloons was not utilized in the TSSM mission design; instead, the balloon was to be controlled only to the extent that the 10 km flight altitude was maintained at all times. In principle, there is no difference between a hot air balloon operated to stay at a constant altitude and one that varies in altitude in a controlled fashion. The apex valve opening must be continuously adjusted with a feedback control loop to modulate the buoyancy and move to and maintain the desired altitude. Differences would only arise if the balloon operates sufficiently close to the ground that there would be a need to add hazard detection and avoidance autonomy to prevent inadvertent ground contact. As such, a hot air balloon is very well suited to satisfying the functional requirements of Option 2 from Table 1 in which altitude profiling is added to the basic capabilities of the most primitive balloon option. Altitude profiling allows for a much more extensive characterization of the atmosphere, as has traditionally been done with descent probes like Huygens and Pioneer-Venus. The great advantage of using a balloon is that repeated profiles would be possible: there is no practical limit to the number of profiles that a hot air balloon could do at Titan. A light gas, zero pressure balloon could also perform altitude profiling, but the consumption of ballast limits the number of profiles possible, making it a less attractive choice.

The outstanding risk area for a Titan hot air balloon is accurate prediction of the thermodynamic behavior of the balloon under all flight conditions. This is a particular concern for transient stress cases such as the initial inflation of the balloon in which the atmospheric gas must be heated up before the balloon reaches the ground. Recent analysis and computational fluid dynamics simulations are helping to quantify the expected behavior,[17] but further work is required to quantify error margins and validate the models.

The next step up on balloon mission sophistication would be to add horizontal control so that large scale surface features could be targeted for overflight (Option 3). The need for this

functionality touches on an ongoing debate within the exploration community: namely, is Titan interesting enough everywhere so that it would not matter where you fly or that you could not stay in one place? Or is there sufficient value in being able to target and perhaps loiter at specific places to justify the added balloon vehicle cost and complexity? The current analysis cannot answer such a question, but it can describe the kind of vehicle needed to provide the targeting and loitering capability.

Fig. 7: Test Model of the VEGA balloon. A Titan superpressure balloon would also be a sphere, but larger (4.5 vs 3.4 m) and made with polyester material. The white color, however, would be similar.

The conceptual framework identified two options for providing horizontal control: propulsion via propellers or wind shear exploitation. Propellers are the simplest approach and the one recommended here. Wind shear exploitation would avoid the mechanical complexity of adding propellers to the balloon and the power needed to run them, but is challenged by the problem of navigating a poorly understood Titan wind field, one that would have to be mapped in real time as the balloon flies there. Either approach almost certainly could be made to work, but on the presumption that sufficient electrical power would be available, the choice of using propellers offers the most straightforward and robust approach. Note that, in principle, the electric motor and drive train could be electrically heated to avoid the complications of cryogenic temperature operation. The analysis of Elfes *et al.*[8] indicates that even small wind-relative flight speeds of tens of centimeters per second could enable overflight of particular surface features in short time scales. The outstanding risk areas for this vehicle are quantification of the achievable wind-relative flight speeds and the robustness and accuracy of the autopilot and autonomous navigation system needed to direct the balloon to its target. The navigation accuracy requirements are deliberately minimized in Option 3 by targeting only large areas many kilometers across. The slow flight over the Titan surface also would afford more time for human ground controllers to help direct the balloon, providing another relaxation on the amount of onboard autonomy required.

A key limitation of both Option 2 and Option 3 is that the balloon would not approach the surface. This constraint is depicted here as enforcing a minimum altitude of 1 km, although the actual limit could be higher or lower than that depending on the topography that must be avoided along the flight path. The overwhelming motivation to fly at lower altitudes than 1 km is to touch the surface and acquire samples that could be analyzed. This functionality would still require horizontal control so that the desired target could be reached. However, there is a large difference in vehicle design depending on the size of the surface target from which the sample is to be acquired. Two limiting cases are considered here: in Option 4, the sample could be taken from anywhere within a large area many kilometers across, similar to the overflight requirement in Option 3. This could be a relatively homogenous area like a lake or dune field, or an inhomogeneous area from which it would be okay to get any sample as long as one could

document exactly where the sample came from. Conversely, in Option 5, the sample is to be taken from a very small surface feature or object, like a rock perhaps 1 m across. The requirements for vehicle control, navigation and autonomy are very much more challenging in Option 5 as compared to Option 4, and this leads to fundamentally different vehicle designs.

The balloon vehicle for Option 4 could be the same propelled hot air balloon in Option 3 with added features for sample acquisition, accurate altitude control near the surface, and hazard detection and avoidance. Touch and go sampling would suffice here given the lack of fine targeting of surface objects, and this would afford the possibility of not even having to land the vehicle but instead to use a tethered-assisted collection device from low altitude. Very early proof of concept testing has demonstrated the essential viability of this approach from altitudes up to ~70 m.[18] Nevertheless, substantial development work remains to be done before a reliable system would be available, along with the associated requirements for sample processing and cross-contamination control for repeated sampling. The other additional risk area for this vehicle would be the autonomy system itself for safe ground approach. Terrestrial hot air balloons routinely fly near and land safely on the ground with human pilots, albeit with proportionally more thermal power available that any kind of Titan balloon. However, given that the Titan winds are going to be very low near the surface, and typically much lower than is experienced on Earth, it is plausible that an automatic pilot could be developed with sufficient performance.

Option 5 represents the complex end of the design spectrum for a Titan balloon. Recommended here is a light gas motorized blimp (Fig. 8) with all the features required for a mission that wants to acquire a surface sample from a small, 1 meter scale target like a rock: propulsion for full 3D control, streamlined shape to maximize wind-relative flight speed, sophisticated autopilot, autonomous navigation and feature recognition to find and land near the target, landing system to safely persist on the surface long enough (minutes to hours) to acquire the sample, and a fault detection and recovery system to help the vehicle survive anomalies in the more risky near surface environment. Motorized blimps themselves have a century-old history on Earth. Autonomous blimps have recently seen significant technology development,[11,19,20,21,22] but much work remains to be done to achieve the overall vehicle performance required for a mission like Option 5. Two additional risk areas are associated with motorized blimps: first, the aerial deployment and inflation of an elongated blimp-like shape; second, gas leakage out of the blimp envelope. The gas leakage risk for a blimp is worse than for a simple light gas balloon because a blimp would require internal ballonets to accommodate altitude changes, and those ballonets would endure much more material flexing than a pressurized balloon with an attendant increased risk of pinhole formation. Longer duration missions approaching a year or more would almost certainly be required to justify the added expense of an Option 5 blimp, likely driving a requirement for a buoyancy gas replenishment system. Encouraging early work has been done on developing a system to replace lost buoyancy gas with hydrogen extracted from atmospheric methane,[23] but more work must be done to achieve flight readiness for a Titan mission.

Collectively, Options 1 to 5 span not only the complexity space for Titan balloons but also the technological readiness state. The simple superpressure balloon of Option 1 is well understood and implementable in the near term. The one key risk area of leak rate could be readily addressed with cryogenic testing of prototypes. Furthermore, the threat to lifetime could be almost certainly mitigated by modest ballasting for missions up to a few months in duration. The hot air balloon of Option 2 requires further work to bound the uncertainty of the thermodynamic performance predictions, but even this risk could be largely mitigated in the near term with generous design margins in the form of larger balloons providing more than necessary buoyancy.

Fig. 8: Artist's concept of motorized Titan blimp (Option 5 example vehicle).

There is an appreciable drop off in technological readiness for any of the propelled balloons in Options 3, 4 and 5. Each step adds one or more significant new risk areas for propulsion, autonomy and sample acquisition technologies. Although the history of terrestrial balloons and the limited Titan-specific work to date are strongly suggestive that the engineering challenges can be met, enough work remains to be done to pose substantial uncertainty in estimating the ultimate technical performance achievable. This uncertainty complicates efforts to design future missions because the additional cost and risk of more sophisticated balloon technologies cannot be reliably quantified. It is plausible that even moderate investments in Titan balloon technology could provide substantial improvement in the ability to estimate cost and risk in more advanced mission concepts.

Conclusions

This paper has presented a conceptual framework for analyzing Titan balloon vehicles, dividing the problem into two parts: the functional requirements of the balloon and the design choices available to synthesize a vehicle to meet them. Five balloon options have been described that span the design spectrum from simple to complex. Light gas (hydrogen or helium) balloons are recommended at the ends of the spectrum, with a superpressure balloon at the simple end and a motorized blimp at the complex end. The middle three options would utilize a hot air, or Montgolfiere, balloon with increasing levels of sophistication as requirements for horizontal control and surface sampling are added to the basic variable altitude flight capability. All five options have benefitted from recent research but only the simplest light gas and hot air balloons (Options 1 and 2) are arguably close enough to maturity to support reliable Titan mission designs in the near term.

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