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ATMOSPHERIC FLIGHT FOR EXPLORATION OF TITAN

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by

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DEDICATION

I dedicate this thesis to my son Eric, who asked me “Daddy, can we fly a rocket ship to the Moon?” One day, I hope to be able to answer yes.

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ABSTRACT

This paper examines the possibility of exploration of Saturn’s moon Titan by a powered aircraft. The history of the scientific study of Titan is described, including the current knowledge of conditions within the atmosphere and on the surface. The advantages of an aircraft over a lander or an orbiter for a planetary science mission are discussed. A conceptual design for an aircraft capable of long-duration flight is presented.

INTRODUCTION

Atmospheric flight for extraterrestrial planetary exploration is not a new concept, but it is an idea that is mostly untested, compared to other types of missions such as remotely operated landers or rovers. Only two such missions have flown: the unmanned Soviet VEGA missions in 1985 which dropped separate balloons into the upper atmosphere of Venus.1 No heavier-than-atmosphere aircraft have flown on another planetary body, though a number of unmanned missions have been proposed for different destinations within the Solar System such as Venus and Mars. The successful flight of such an airplane would be a milestone in space exploration, much as the Wright brothers’ first flight signaled the beginning of the age of aviation. Saturn’s moon Titan is uniquely suited for exploration by air, due to its thick atmosphere, low gravity, and unique carbon chemistry. This paper will explain why an aerial mission would be most effective in exploring Titan, and will describe one possible design.

The remaining pages of the introduction will include a description of Titan and its atmosphere, and will describe some of the unanswered questions regarding the moon and the possibility that it may harbor life. A subsequent section will be devoted to explaining why an airplane is the best option for the exploration of Titan, the advantages and disadvantages such an approach compared to other mission proposals, and the challenges that must be overcome for successful flight. Finally, an autonomous unmanned aerial vehicle (UAV) design will be presented that will be capable of long-duration flight on Titan as the platform for a planetary science mission.

Description of Titan

After Jupiter’s moon Ganymede, Titan is the second-largest moon in the Solar System. It is the only planetary body other than Earth with a thick atmosphere composed primarily of nitrogen, and is also the only moon with a substantial atmosphere.[2] Titan was first discovered by Christiaan Huygens in 1655.[3] It was not until the late 20th century and the Voyager missions that close-up images of Titan were obtained. These showed a “fuzzy orange ball” and revealed nothing of the surface, but indicated the presence of methane in the atmosphere.[4]

Figure 1. Voyager image of Titan. Courtesy NASA/JPL-Caltech.

In the 1990s, scientists used the Hubble Space Telescope to observe Titan’s surface at narrow wavelengths between the methane absorption bands. Hubble was able to resolve much greater detail than Earth-based telescopes, due to the lack of distortion from Earth’s atmosphere. Infrared imaging at a wavelength of 1-2μm gave a clearer picture of the surface and showed that Titan is tidally locked to Saturn, with a rotational and orbital period of about 16 days.[5]

More recently, the Cassini mission has provided a continuous stream of data since entering orbit around the Saturn system in 2004, returning high-resolution images and synthetic aperture radar (SAR) measurements. Cassini released the Huygens lander, which parachuted onto the surface of Titan, providing scientists with the first images of the surface as well as key information about the temperature, composition, and dynamics of the atmosphere.[6]

In addition to direct imaging, Cassini data has been useful to refine precise measurements of the size, mass and orbits of Saturn and its moons, including Titan. According to recent calculations, the mass of Titan is $1.3452 \cdot 10^{23}$ kg, the radius 2575.5 km, and the average density 1.8798 g/cm^{-3}.[7] Based on these numbers, the calculated acceleration due to gravity is 1.3535 ms^{-2} at the surface, or about 13.8% of that on Earth.[8]

Atmosphere

At the beginning of the 20th century, not much was known about Titan's atmosphere, or indeed whether it had a substantial atmosphere at all. In 1907 (possibly 1908), astronomer José Comas Solá claimed to have observed limb-darkening, whereby the edge of the planetary disk reflects less light than the center, implying the presence of an atmosphere.[9] There is some dispute about the authenticity of his measurements.[10] It was not until 1944 that Titan was conclusively proved to possess an atmosphere, when Gerald Kuiper demonstrated the presence of substantial quantities of methane (CH_4) by spectroscopic observation of two corresponding absorption bands.[11] Following improvements in observational techniques, later measurements indicated the presence of even higher quantities of methane. In the 1970s, there were two competing models for Titan's atmosphere which attempted to explain the data. In the first (Caldwell), methane was the principal component of a cold, thin atmosphere: 90% CH_4 at 86K and 20 mbar. In the second model (Hunten), dissociation of ammonia (NH_3) produced large quantities of molecular nitrogen (N_2) which was the primary constituent gas, with smaller quantities of methane present. The Hunten model suggested a relatively high surface temperature and pressure of 200K at 20 bars.[12]

In 1981, Voyager 1 passed by Titan and showed that neither model was entirely correct. Ultraviolet and infrared measurements indicated that while methane was present the atmosphere was primarily composed of nitrogen (>90%), and a radio occultation experiment demonstrated that given such a composition the refraction of radio waves by the atmosphere was consistent with a pressure of about 1.44 bars, not 20. The atmosphere was also much colder than predicted by the Hunten model, being closer to 100K.[13]

In addition to nitrogen and methane, other more complex molecules have been found in the atmosphere. Hydrocarbons such as ethane and acetylene (C_2H_6 and C_2H_2 respectively) were detected from ground-based measurements in the 70s. The presence of these compounds hinted at photochemical reactions in the upper atmosphere. Through analysis of the Voyager data in the 80s, the presence of other nitrogen and carbon containing compounds was confirmed. These included propane (C_3H_8) and hydrogen cyanide (HCN), with trace quantities of benzene (C_6H_6), water (H_2O), carbon monoxide (CO) and carbon dioxide (CO_2).[14] The concentration of methane was observed to vary, from about 5% near the surface to about 1% in the upper atmosphere. The inert gas Argon was also found in variable quantities.[15]

According to the most current models, the hydrocarbons and nitrogen-carbon compounds are primarily formed by the dissociation of CH_4 and N_2 by ultraviolet light from the sun. Magnetospheric electrons and cosmic rays are also thought to play a role in breaking down the primary constituents. Once dissociated, the ions re-combine to form larger molecules. Also formed is molecular hydrogen (H_2), most of which ends up lost to space due to Titan's weak gravity. The heavier compounds tend to condense and eventually precipitate onto the surface.[16]

Like Earth, Titan has a very active climate, with clouds, wind, and rain. Since it is so much colder, methane on Titan takes the place of water in the hydrological cycle. The temperature and pressure on the surface and within the atmosphere are near the triple point of methane, where it can exist simultaneously as a gas, liquid, and solid. In changing from one state to another (e.g. condensation or evaporation), large amounts of energy may be released or absorbed, and as on Earth, this energy drives the atmosphere and produces weather effects.[17]

Due to the weather, atmospheric conditions vary based on latitude and time of day or season. However, a reasonably accurate vertical profile can be inferred from the available data (mostly from the Huygens probe), and will be important for planning future atmospheric missions. Figure 2 shows pressure and temperature by altitude.[18]

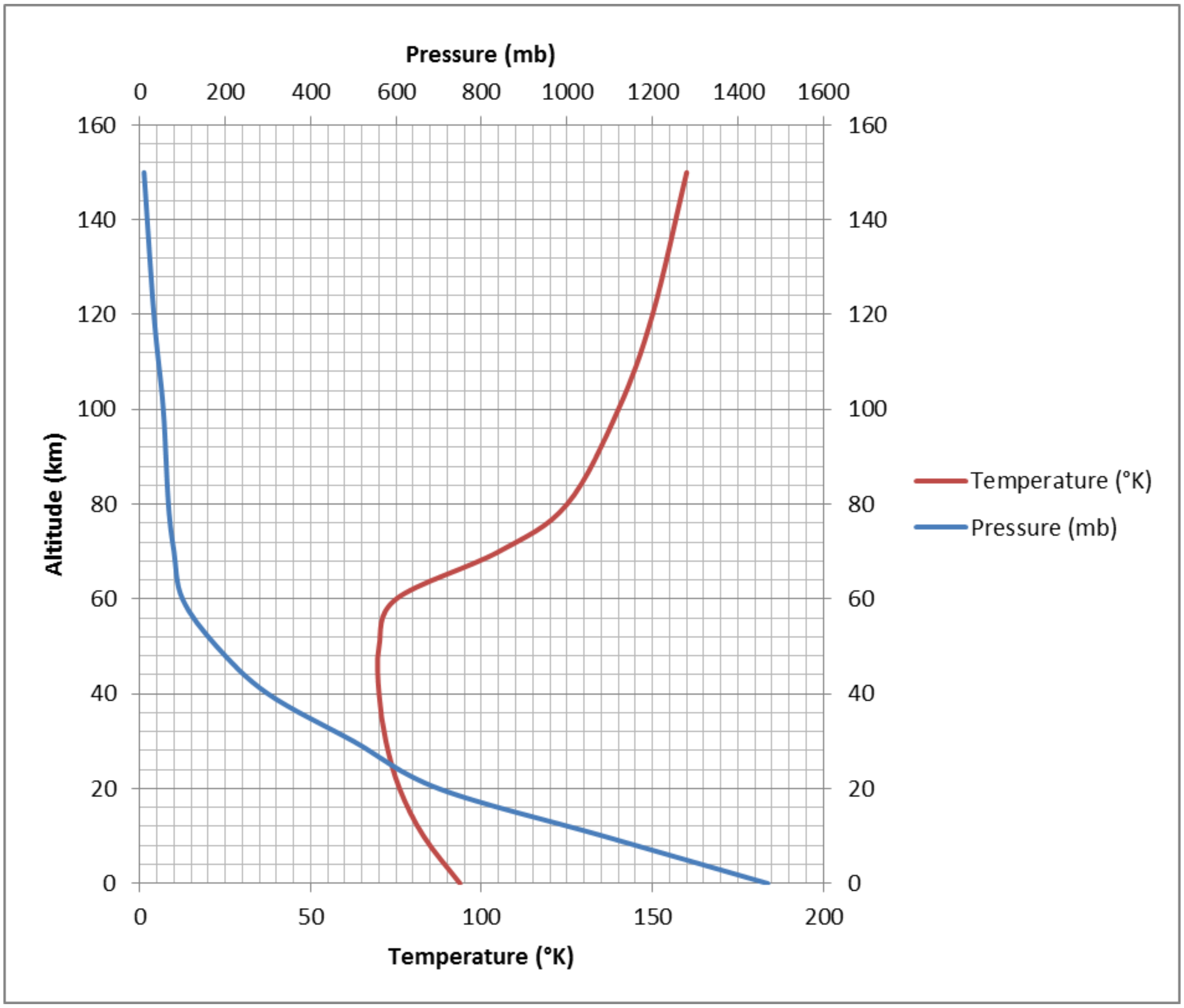


Figure 2. Pressure and temperature by altitude

Another important factor to consider for atmospheric missions is the horizontal wind speed at various altitudes. Near Titan's surface, winds are minimal. Above about 10 km, winds are generally prograde, meaning they blow in the same direction as the moon rotates. At around 32 km, winds exceed the speed of rotation ("super-rotation"). This is also the case above 80 km. However, between 70 and 80 km, an unusual layer of calm air separates the super-rotating layers.[19]

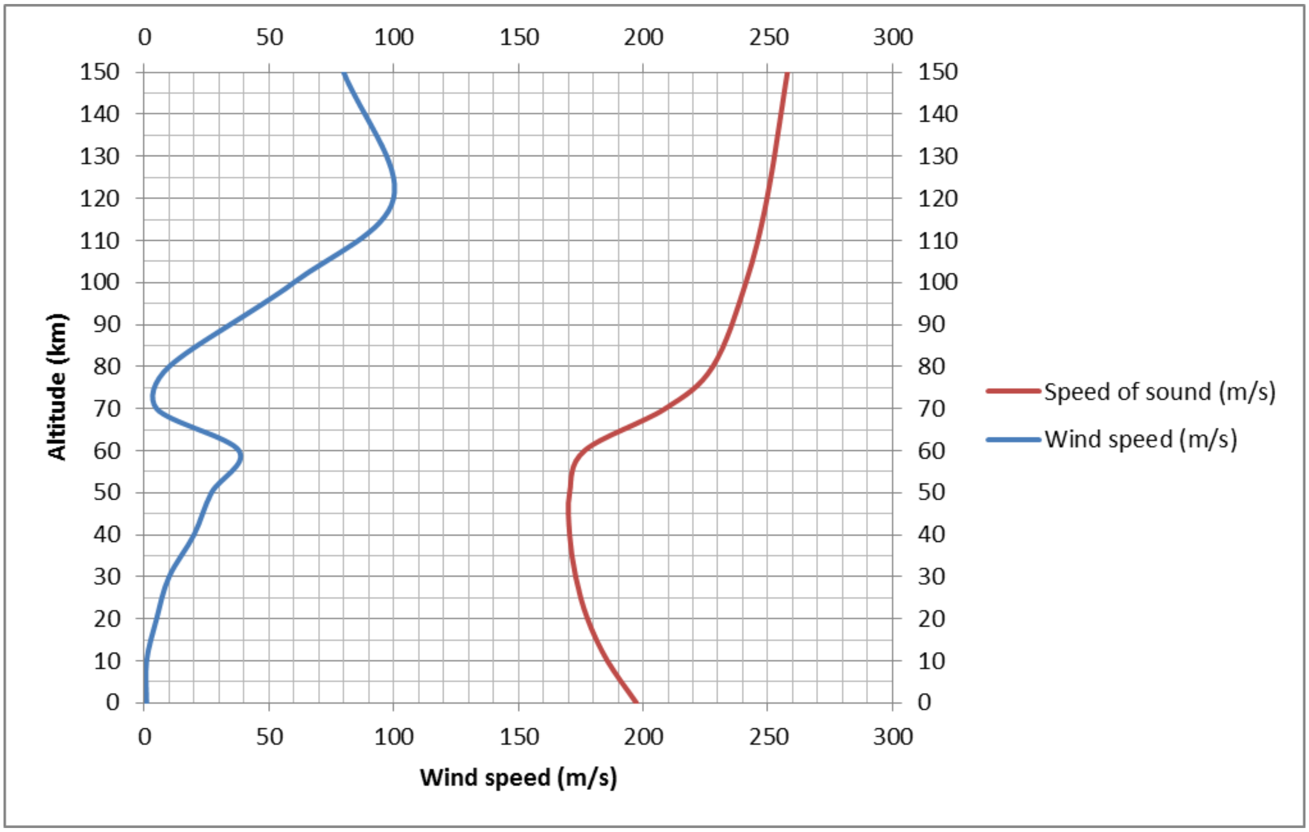


Figure 3. Wind speed and speed of sound by altitude

Figure 3 shows a graph of wind speed by altitude.[20] It also includes a calculated estimate of the speed of sound by altitude, relying on the ideal gas approximation. At the surface, it is about 197 m/s.[21]

Surface

Due to the haze in Titan's atmosphere, direct imaging of the surface at optical wavelengths was not possible until the Huygens landing. Also with the Cassini-Huygens mission, the Cassini orbiter obtained the first SAR imagery of Titan, but covering only about 25% of the surface, with many large gaps. Previously, in the 1980s, some scientists had thought the surface of Titan was covered by oceans of liquid hydrocarbons such as ethane. Hubble images in the 1990s showed variations in albedo (reflection coefficient) over large areas of the surface, which cast doubt on the ocean theory. However, seasonal or small permanent hydrocarbon lakes are still likely to exist, and the consensus based on Huygens imagery is that fluvial activity is responsible for substantial erosion and sedimentation on Titan's surface.[22] Huygens also demonstrated that the surface of Titan is primarily water ice, frozen as hard as rock at 94K.

In addition to atmospheric processes, Titan's surface is also subject to the action of tectonics and potentially cryovolcanism. These can be reasonably inferred from the lack of old, defined craters, indicating recent surface activity. While SAR data indicates Titan's surface is rough in many places, there are only relatively small variations in elevation, with the highest known peaks reaching only about 2 km. A recent theory suggests that Titan's tectonics result from cooling and contraction of a subsurface ocean of liquid water and ammonia, which causes the water ice surface to fold and crack.[23] However, while it is intriguing, the existence of such an ocean has not been proven. If it does exist, it conceivably could harbor life based on carbon chemistry similar to that on Earth.[24]

Unanswered Questions

There are a number of unanswered questions regarding Titan and its history, which are likely to make future exploration scientifically profitable. In addition to further understanding regarding the formation, geology, and chemistry of the moon, the most intriguing questions relate to whether Titan could currently harbor life, or whether it may be similar to a primordial Earth.

One uncertainty is the source of the methane in the atmosphere. Because it is constantly being broken down by the action of sunlight and other energetic processes, it would eventually disappear unless it is being replenished from some other source. Current estimates indicate that the lifetime of CH_4 in Titan's atmosphere is between 10 and 30 million years. There are several theories about the source of the methane. It could conceivably be stored under the surface in the form of methane hydrates, or could be produced by the reaction of water with certain minerals. Alternately, it is possible that most of the methane arrived via a comet that collided with the surface.[25] Another theory suggests that the methane is produced by the metabolism of some unusual organism, but this is deemed unlikely due to the ratio of Carbon-12 to Carbon-13, which does not suggest biological activity, at least for the production of methane.

Could some type of life exist on Titan? For life as we know it (or at least typically imagine it), to exist three things are required: water, organic chemistry, and energy. Titan is abundant with the first two, but is lacking in the third, on the surface at least, due to its distance from the Sun. While the sunlight reaching Titan's surface is hundreds of times brighter than the full moon on Earth, it is still orders of magnitude dimmer than daylight on Earth.[26] Another problem is that on the surface, the water is all frozen. If the hypothesized subsurface ocean did exist, it could conceivably satisfy all three conditions, even if somewhat extreme by Earth standards: a temperature of 260-300K, pressure of 5 Kbar, and a pH of 11.5 or higher.[27] Another possibility is that there are warm areas near the surface where liquid water could persist. These could be caused by cryovolcanism from the ocean or in areas subject to impacts from comets or other space debris.[28] On Earth there are cold-loving microorganisms known as psychrophiles which can survive frozen in ice at temperatures as low as 253K.[29]

The most immediate unknown regarding Titan is the surface itself. Much of it has never been imaged at any detail. Cassini continues to map parts of the surface using radar, but coverage is still spotty. The next section will examine the possibilities for future missions to get a better look at the surface of Titan.

THE NEXT STEP FOR TITAN EXPLORATION

Some of the history of the exploration of Titan was presented in the previous section. This chapter will describe the options for further exploration, with a view toward showing why an aerial mission would be the most effective and scientifically productive option. Only robotic space missions will be considered, since a human-crewed mission to the outer planets (or indeed, any other planet) is unlikely in the near future.

Types of Missions

There are relatively few classes of robotic space missions intended for planetary exploration. Historically, they can be divided into the following general categories: flyby, orbiter, lander, and aircraft, though this is not a list of every conceivable type. Some hybrid missions may consist of multiple vehicles that perform two or more separate but related missions. An example is Cassini-Huygens, in which the Cassini spacecraft orbits Saturn, while also performing repeated flybys of Titan and the other moons of Saturn, and the Huygens craft is deployed to the surface of the target. There are other possible missions, such as a sample return, but such missions generally function within the framework of one of the listed types. Some examples and advantages and disadvantages of each type are described in detail below, with comparisons of their capability to acquire useful information about an individual target.

Flyby

Probably the most successful examples of planetary flyby spacecraft are the Voyager probes, which were originally intended for exploring Jupiter, Saturn, and the moons of both planets, but have since had their missions extended decades longer than originally planned.[30] In the typical flyby mission, the spacecraft will visit a series of targets, or a particular target on the way to another destination. Due to the distances and relative velocities involved, the spacecraft usually will not remain near any given target for long. In terms of remote sensing capability, this means that the spatial and temporal resolution of any sensor data is likely to be low. The advantage is that the spacecraft can cover vast areas and great distances, and this was what made the Voyager missions successful. With respect to Titan, even the relatively small amount of data returned showed that it was an interesting place, and deserving of further exploration.

Orbiter

The primary purpose of an orbiter is of course to enter orbit around the target. The specific orbit depends on the individual mission's goals. For example, many communications satellites are placed in a geostationary Earth orbit in order to provide continuous coverage of a given area of the planet. This permits a ground station to keep its antennas aimed at the satellite without active tracking.[31] However, for mapping other planets, an orbit that covers as much of the surface as possible is ideal. Mars Global Surveyor is a good example of such an orbiter: it used successive aerobraking maneuvers to alter its initial capture orbit to a near-circular polar orbit with a period of about two hours. This orbit also had the benefit of being sun-synchronous, so that the angle of illumination of the local terrain remained constant, and allowed coverage of the entire planet's surface every seven days. In addition to capturing images at visible wavelengths, Mars Global Surveyor also collected thermal and magnetic data as well as laser altimetry information.[32]

So, compared to a flyby craft an orbiter would be capable of remote sensing with higher spatial and temporal resolution, and given the correct orbit, complete coverage of a target's surface. There is one major limitation to attempting this on Titan, however: the photochemical haze in Titan’s upper atmosphere blocks and scatters much of the visible light reflected from the surface. A Titan orbiter mission would need to focus on other wavelengths such as infrared, or use active remote sensing methods such as radar which are not significantly attenuated by the atmosphere.

Lander

The history of space exploration includes many successful examples of spacecraft landed on other celestial bodies, such as Surveyor 1 on the Moon, the Viking landers on Mars, and Huygens on Titan itself. The most successful landers are the rovers that are capable of semi-autonomous operation, such as the Mars Exploration Rovers *Spirit* and *Opportunity*, the latter of which has traveled more than 30 km across the surface of Mars.[33]

The greatest advantage of a lander is that it is in contact with its target’s surface, allowing direct examination of the composition, and permitting image capture at very high spatial resolution. The primary disadvantage of a lander is that the observational area is small, though a rover with substantial mobility will be able to extend its area of observation. A lander or rover is likely to be most useful where an interesting feature on the surface has been identified and the lander can accurately be delivered to that particular location.

Aircraft

As mentioned in the introduction, the Soviet VEGA balloons to Venus were the only aircraft that have flown on a planetary body other than Earth. Each VEGA balloon was about 3.5 meters in diameter, and carried a 6.9 kg science package, with sensors to detect temperature, pressure, wind speed, light level, and cloud density. They were deployed at an altitude of 50 km and functioned successfully for about two days, relaying data back to Earth at a rate of 2 kbps.[34]

While the VEGA missions produced only a moderate amount of scientifically useful information, they inspired a number of subsequent balloon designs for Venus, Mars, and Titan, but none have yet made it into space.

In addition to buoyant flight, numerous powered lift producing aircraft have been proposed. In 1978, NASA commissioned the Ad Hoc Mars Airplane Science Working Group to assess the utility of an unmanned airplane for the exploration of Mars. The Working Group created a concept design propelled by a hydrazine powered piston engine, which was theoretically capable of sustained flight for up to 25 hours while carrying a 40 kg payload.[35] They considered three different capabilities of the aircraft: collecting samples, deploying instrumentation, and aerial surveying. Sample collection was determined to be the most difficult option, since the airplane would have to take off and land. However, the airplane had great advantages for the other two operational modes, since its altitude and range permitted access to areas of the surface that would be very difficult to access from the ground or from orbit. This would allow the aircraft to deploy packages such as a small lander to areas otherwise inaccessible.[36] The Working Group recognized that the most important advantage of the airplane was for visual imaging. Compared to an orbiter, the airplane could capture images at much higher spatial resolution, but could also travel much farther than any rover, and could be directed to revisit interesting targets. Another benefit of aerial imagery is the ability to capture oblique images, which are more valuable for two reasons: they are easier for humans to accurately interpret, and they provide direct information about the topography.[37]

Some of these advantages will apply to a balloon as well as an airplane, but each platform has its own set of problems. While a balloon could potentially capture images at the same angles and resolution as an airplane, it would be at the mercy of the winds, and would not be able to revisit interesting areas. But a balloon could potentially remain aloft for months or years, with little or no expenditure of energy. An airplane must produce enough thrust to generate lift to keep it in the air, and this requires substantial amounts of power. In the case of the original Mars airplane design, its endurance was limited by the requirement that it carry its entire fuel supply. Mars is made more challenging by the thin atmosphere, requiring that an airplane fly at transonic speeds (>0.6 Mach at 1.5 km) just to stay in the air.[38] The atmosphere is much more favorable on Titan and Venus, and a design proposed in 2002 by Landis et al. relied on solar panels which would provide sufficient power to keep the craft airborne continuously on the sunlit side of Venus.[39] Unfortunately solar power would not be feasible for Titan, since it is ten times farther from the sun that Earth. At the surface, daytime illumination is several hundred times brighter than a moonlit night on Earth, which is plenty of light to see by but still thousands of times less than a sunny day here on the blue planet.[40] On the other hand, thanks to Titan's dense atmosphere and very low gravity, far less power is required to lift an equal mass. In this case, a radioisotope based power source could permit long-term operation on the icy moon.

Summary

Why fly on Titan? The short answer is that it has an atmosphere: obviously an atmosphere is required for flight, and Titan's is particularly suited for that. Also, the same atmosphere limits the ability to acquire clear images of the surface from orbit. If it could fly indefinitely, an airplane on Titan could map a substantial portion of the surface at high resolution, and it could locate interesting areas for exploration by future lander or rover missions more effectively than a balloon. An ideal mission would also include an orbiter with the primary purpose of relaying communications from the aircraft back to Earth, and also providing a reference for navigation. Such an airplane mission could not be expected to answer every scientific question about the moon, but it would pave the way for later visits, and is therefore the next logical step in the exploration of Titan.

FLYING ON TITAN

The most challenging aspect of flying on Titan is getting off of Earth. Any design must account for a large number of factors. These include limitations on size and mass imposed by the launch vehicle and the specific transfer orbit to reach Saturn. A realistic mission will also be faced with cost constraints, so it isn't always possible to buy a ride on the biggest rocket available. Therefore, because the aircraft design will depend on the overall mission, both must be considered together. While the last chapter focused on showing why an airplane is the best option for the next mission to Titan, this chapter will demonstrate with a conceptual design that building such an airplane and getting it there is entirely feasible with current technology.

The Design Process

Aircraft design is the process of creating a flying machine to meet given specifications and/or to pioneer innovative ideas and technology. It is both an art and a science.[41] It is also an iterative process, in which there are a large number of variables which themselves depend on other variables. Therefore, a design refinement that modifies one variable could affect other variables which may then require a change to the original variable. It is the specific performance requirements of the mission that constrain the important variables enough to make the design process possible. Thus, the most critical aspect of the design process is to correctly define the requirements.[42]

In the case of the Titan Flyer,[43] some of the goals that an aircraft could best satisfy were given in the last chapter. It will need to be able to fly high enough to view large areas of the surface, and to travel at a reasonable speed in order to explore new areas. Since it will be unpiloted, it must also be aerodynamically stable and have an automatic control system capable of handling weather events or other unpredictable atmospheric effects. It should also be able to stay in the air as long as possible, perhaps indefinitely. As mentioned previously it will require a long-lasting source of power, such as a radioisotope generator which runs on the decay heat of an unstable isotope. While capable of producing useful energy for decades, the limitation is that the instantaneous power output is relatively low. It must also carry a useful science payload. Given these design points, an aircraft optimized for gliding at moderate altitude with minimum required propulsive power would be likely to succeed at this mission.

The ideal capabilities are tempered by the practical limitations of spaceflight. In general, that means that the physical size and mass are restricted by the choice of launch vehicle. Short of building a bigger rocket, a designer must work with what is available. For an airplane, a critical dimension is the wingspan, since large aircraft tend to be more efficient that small ones. In order to fit a reasonably sized airplane into a typical payload fairing, most designs call for folding the wings and/or empennage at one or more points.[44] The following subsections will describe the choice of design features.

Flight regime

While it is easy to say that it is not difficult to fly on Titan due to the dense atmosphere and low gravity, it still presents a number of problems. Chief among these is that the density creates substantial resistance, requiring an aircraft to fly slowly in order to conserve energy. At 10 km, this is less of a problem than near the surface. It is also a good altitude from which to capture images of the surface, so it was assumed as a starting point. Next, 5 meters/second (18 km/h) was chosen as the target cruising velocity. At this speed an aircraft could circumnavigate Titan in about 38 days.[45]

Aerodynamics

Even though the atmosphere of Titan is so different from Earth, it is possible to accurately simulate the aerodynamics thanks to the concept of flow similarity. Given identical similarity parameters, the lift, drag, and moment coefficients are the same for a given body, or a geometrically similar one. This is why wind tunnels can successfully model the flow on scaled prototypes.[46] In this case the most important similarity parameter is the Reynolds number (Re). The Mach number is almost zero at 5 m/s.[47] At the target velocity and altitude, the Reynolds number is calculated as 9.2×10^{6}, which is a relatively high value.[48]

The NACA 4412 cambered airfoil was chosen for the wings, and symmetric NACA 0012 airfoils for the tail. These are older designs but will perform well at higher Reynolds numbers, and are thick enough to permit internal reinforcement where necessary. A wingspan of 6 meters was chosen. The body measures 4 meters from nose to tail. The tail is conventional.

Structure

Because the temperature on Titan is extremely cold, conventional materials are likely to fail under load. A cryogenic composite material would probably be necessary, but an actual test of such material is outside of the scope of the conceptual design. The structural material should be relatively strong and thick.

The wings are designed with one fold each, in order to permit the 6m wingspan to fit within a 4m aeroshell.

Power and Propulsion

Because of the lack of sunlight, a nuclear power source is the only realistic option for a long-lasting energy supply. One type, radioisotope thermoelectric generators, has a long history of operation in space, including on the Voyager missions. These devices produce electricity by the flow of decay heat from a radioactive isotope, typically Plutonium-238. Due to limited supplies of Pu_{238}, NASA has developed the Advanced Stirling Radioisotope Generator (ASRG), which is capable of producing 140 W_e in a 21 kg package while using only one quarter of the amount of Plutonium.[49] Unfortunately, the United States no longer produces Pu_{238}, and in recent years NASA has been forced to purchase it from Russia. According to Senate testimony by the American Geophysical Union, unless production is restarted immediately, future planetary science missions will be delayed or become prohibitively expensive.[50]

For the purposes of this conceptual design, it is assumed that sufficient quantities of Pu_{238} will be available in the near future, and this airplane will use an ASRG for electrical and propulsive power.

Instead of solely generating electric power, an ASRG could be adapted to output mechanical power directly to a propeller. This was considered and initially seemed attractive, but the idea was rejected in favor of using the electrical output to drive a motor, which would then drive a propeller. The advantage of using a motor is that it is easier to throttle, and when not operating at peak power, excess energy may be stored in batteries. A 200W motor could be run at 50% or less power for normal operation, and up to 100% power, by drawing from batteries, when climbing or maneuvering. 10 kg of Lithium Ion batteries should provide 0.8 kWh of reserve energy.[51]

The specific propeller design was not considered here, but as with the aircraft itself, the operating speed will probably be low due to the density of the atmosphere. The motor is assumed to have an efficiency of 0.8, and a reasonable assumption for propeller efficiency is 0.85, which results in an overall efficiency of 0.68. So each 100 W_e input, the aircraft produces 68 W shaft power (W_s).

Science Package

The science package chosen is the ARES payload, which was designed for a Mars airplane but suitable for Titan exploration as well. It includes two cameras, a mass spectrometer, a point spectrometer, and a magnetometer. It masses about 10 kg and requires 30W of electrical power.

Control and Communications

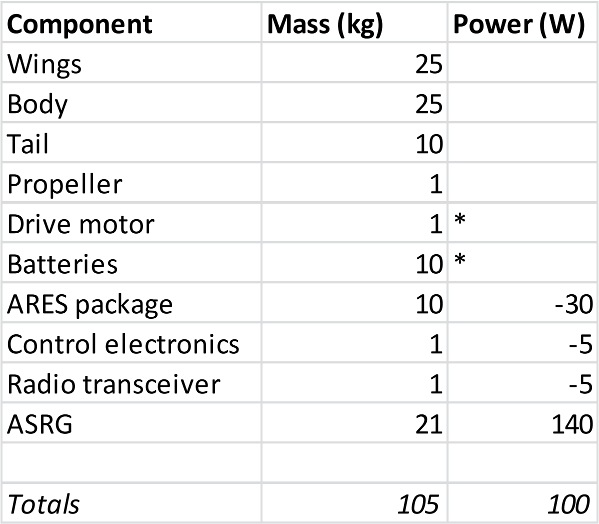
Specifics of control electronics were not considered, however there are several important problems that must be solved. The greatest challenge is for the airplane to be able to calculate its own position in order to plot a successful flight path to accomplish the science mission. Obviously, there is no GPS on Titan, and much of the surface has not been mapped. Titan also lacks a magnetic field. In order to navigate, the control system must be able to integrate inertial data with known references such as the relative position of Saturn or a signal from a source in a predictable orbit, such as an actual orbiter craft.

Because data transmissions direct to Earth would be limited in terms of data rates, the airplane would ideally be equipped with a high-gain antenna in order to upload recorded data to an orbiter specifically designed for relaying such data back to Earth.

Summary of Characteristics

Figure 4 provides a summary of the mass and power characteristics for the conceptual design aircraft. There is a margin of 100 W for driving the propeller and/or charging the batteries, depending on the power required to maintain flight at a given velocity. Power required is detailed in the following section (Design Performance Simulation).

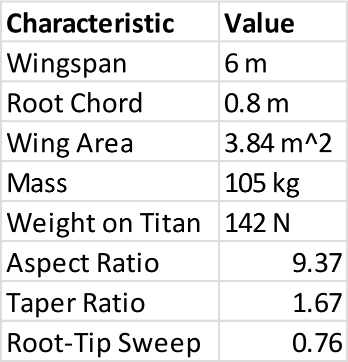
The estimated overall mass of the airplane is reasonable because it is similar to that of the ARES platform.[52]



Component	**Mass (kg)**	**Power (W)**
Wings	25	
Body	25	
Tail	10	
Propeller	1	
Drive motor	1	*
Batteries	10	*
ARES package	10	-30
Control electronics	1	-5
Radio transceiver	1	-5
ASRG	21	140
Totals	*105*	*100*

Figure 4. Component parameters

Figure 5 shows the general aerodynamic characteristics. The aspect ratio is moderately high, with a slight taper ratio and sweep. With a mass of 105 kg, the aircraft has an effective weight of about 142 N when operating on Titan. This is substantially less than its weight on Earth, and therefore the analysis must account for the difference.



Characteristic	Value
Wingspan	6 m
Root Chord	0.8 m
Wing Area	3.84 m^2
Mass	105 kg
Weight on Titan	142 N
Aspect Ratio	9.37
Taper Ratio	1.67
Root-Tip Sweep	0.76

Figure 5. Aircraft parameters

Design Performance Simulation

Initial design and analysis was performed with the open-source software XFLR5.[53] It is based on XFOIL, which is a Computational Fluid Dynamics (CFD) program originally created by Mark Drela in 1986. XFOIL permits the design and simulation of individual airfoils at a range of flight conditions.[54] XFLR5 takes it one step farther and allows a designer to simulate an entire aircraft. The following pages will present detailed performance data for the selected design under conditions similar to those in Titan’s atmosphere. The significance of each graph will be explained.

Airfoil

Figure 6 shows the profile of the NACA 4412 airfoil, used for the wings. It is a cambered airfoil, which means that it is asymmetric and designed to increase the maximum lift coefficient while reducing the stall speed.

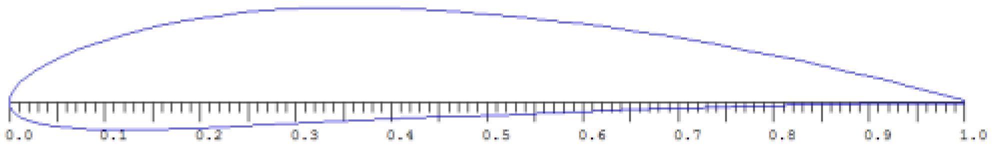


Figure 6. NACA 4412 airfoil

The wing airfoil was tested in simulation at Reynolds numbers from Re = 500,000 to 19,500,000, which corresponds with operation in Titan's atmosphere at 10 km and velocities of 1 m/s to 20 m/s. Figure 7 shows the lift coefficient plotted against drag coefficient for this range of Re. The light blue line at the bottom is the first plot at Re = 500,000 and each successive line above indicates an increase of 1,000,000.

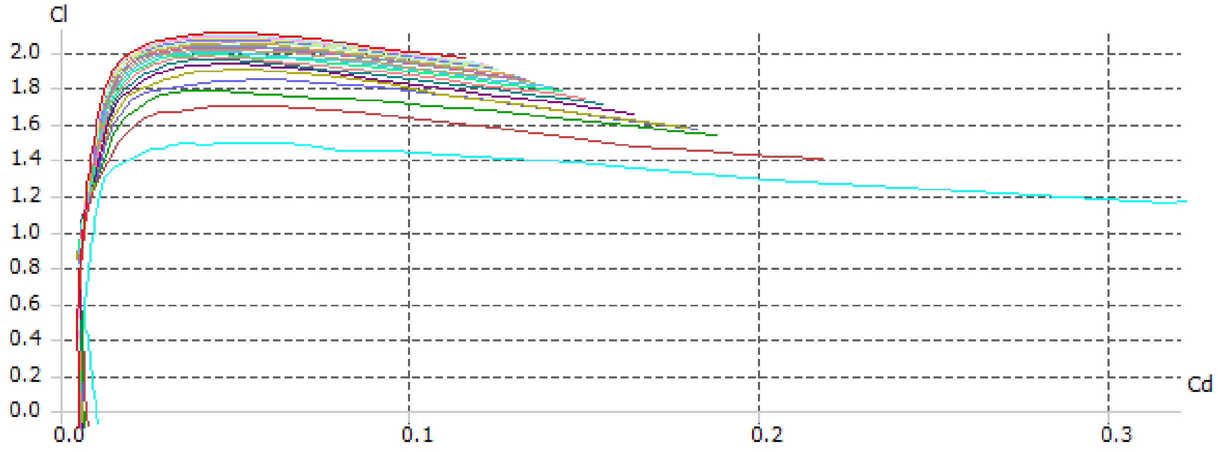


Figure 7. Airfoil Cl vs. Cd

Figure 8 shows a plot of lift coefficient versus angle of attack (α) at the same range of Reynolds numbers. The stall angle for each particular mode is indicated by the peak of the graph, where the lift begins to decrease as the angle of attack is further increased. At higher Reynolds numbers, it is shown that the stall angle increases.

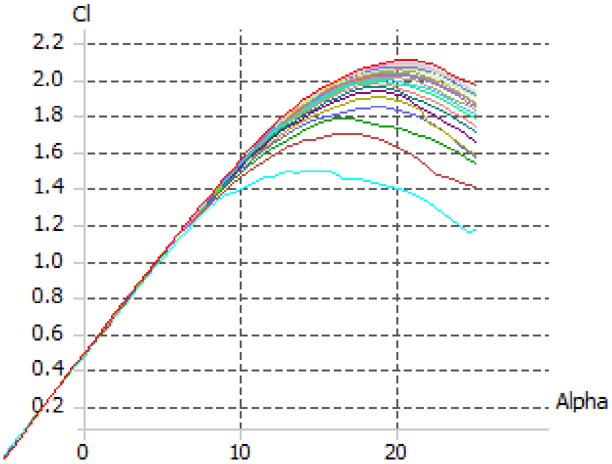


Figure 8. Airfoil Cl vs. angle of attack

Another important characteristic of an airfoil is the lift to drag ratio (“L over D”). An airfoil is most efficient when operating at the highest lift and lowest drag. Figure 9 shows the lift to drag ratio plotted against α.

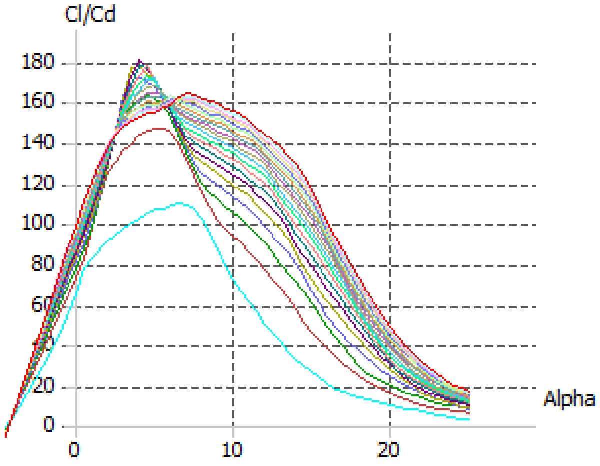


Figure 9. Airfoil Cl/Cd ratio vs. angle of attack

As the angle of attack is varied, the coefficient of moment also changes. It signifies the torque produced on the airfoil by the force of the air flow. Figure 10 shows the coefficient of moment versus α. Because the airfoil is cambered, it experiences a negative moment, which acts to twist the leading edge of the airfoil down. For symmetrical airfoils, generally the opposite is true.

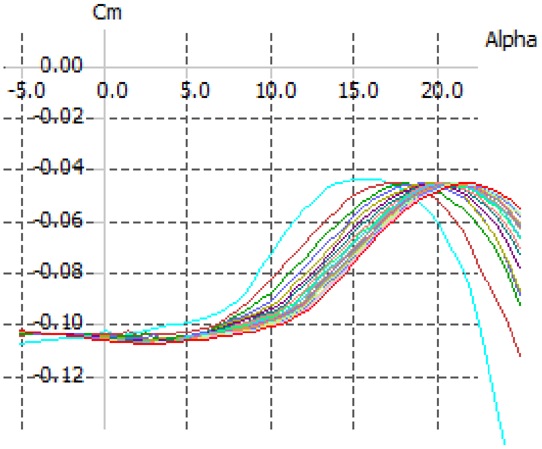


Figure 10. Airfoil Cm vs. angle of attack

Analysis of the moment is important for stability, and airplanes require some type of stabilizer in order to counteract it. On a typical airplane this is the horizontal stabilizer located on the tail.

Wing

The airfoil shape is used to construct a wing section, which is symmetrical about the origin of the Y axis. The wings are designed with a slight upward bend known as dihedral, which acts to provide roll stability. The wings are also swept slightly to enhance the dihedral effect and have a moderate taper ratio. Figure 11 presents a 3-view of the wing section.

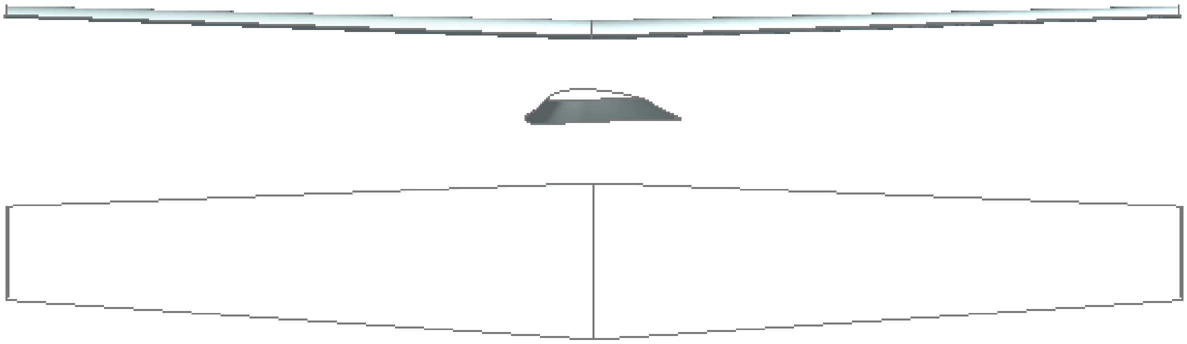


Figure 11. Wing 3-view

This wing arrangement is relatively conventional for an airplane designed to operate at subsonic speeds.

Airplane

The overall airplane design must satisfy a few requirements. It must have sufficient volume to contain the required components and have the necessary structural strength. It also needs to have a center of gravity towards near the front in order to remain stable. The tail is also necessary to provide sufficient force to counteract the moment on the wings.

The configuration selected to fulfill these requirements is shown in Figure 12. As with the wings by themselves, the overall design is also relatively conventional. It is similar to some types of sailplanes, but with shortened wings and an enlarged tail. The horizontal and vertical stabilizers use a symmetric NACA 0012 airfoil. The propeller is not shown, and there are no landing gear because the aircraft is not designed for intentional landing. Also, the control surfaces are not modeled but are assumed to function conventionally.

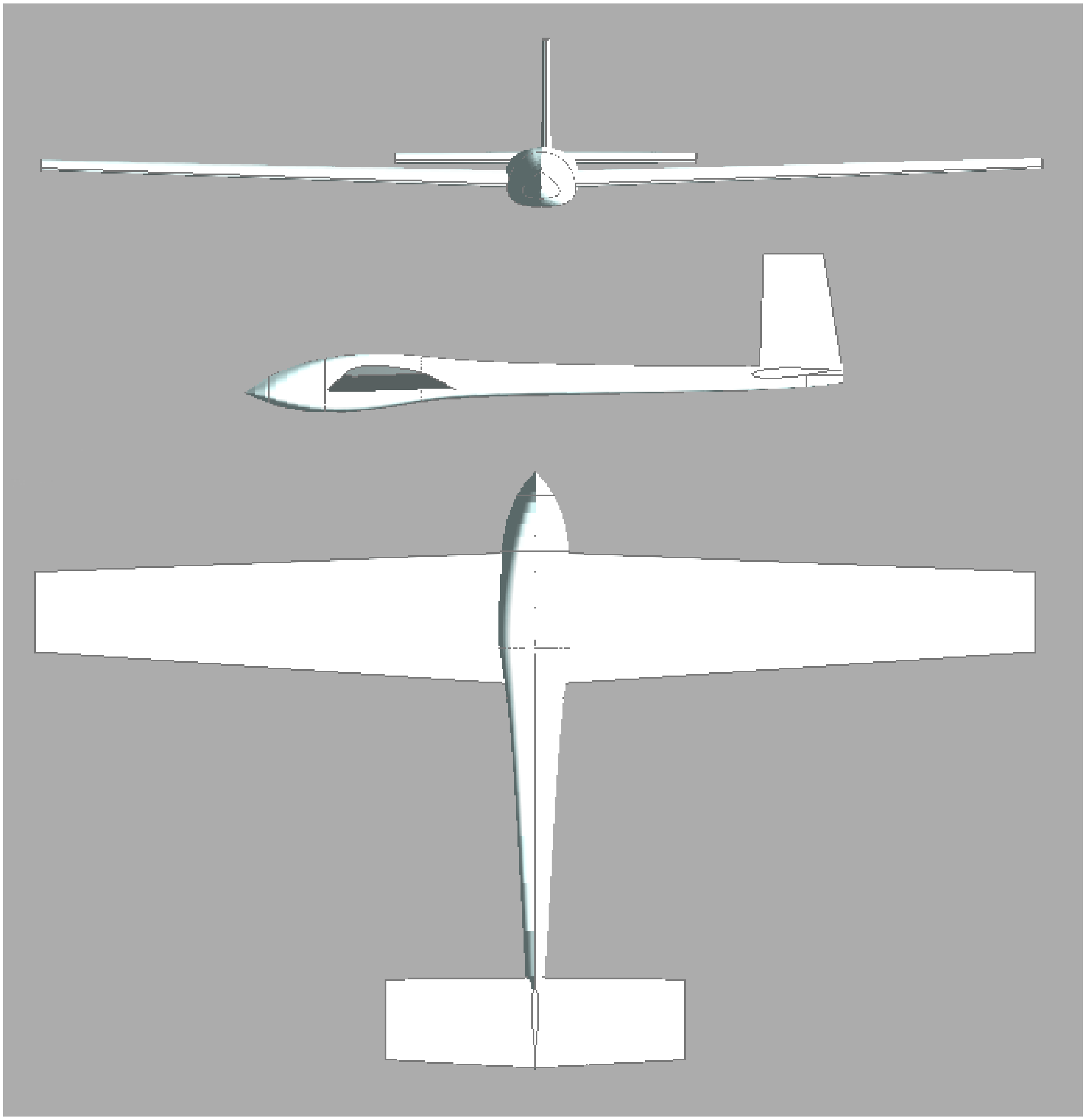


Figure 12. 3-view of completed aircraft

When all the elements are combined in an aircraft, the performance parameters can vary widely from those of the airfoil or lone wing section. Just as with the airfoil itself, the aircraft can fly most efficiently when the lift to drag ratio is at its highest. Figure 13 plots L/D for a range of α from -2.0° to 12.0° for two separate conditions: fixed lift (142 N, purple line) and fixed velocity (5 m/s). For both situations, L/D peaks around 3.0°. At this angle of attack, the airplane could probably glide for a very long distance in Titan's atmosphere.

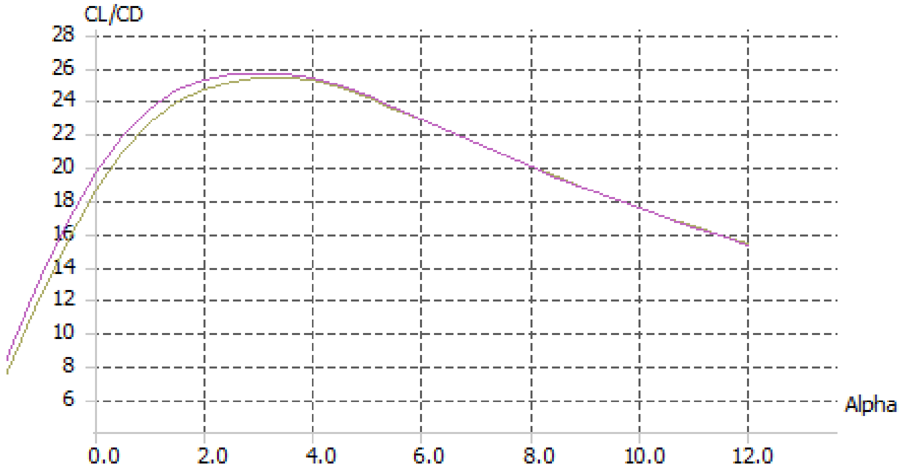


Figure 13. Airplane lift over drag vs. angle of attack

Figure 14 illustrates the coefficient of moment versus α. In this graph it can be seen that the moment has a negative slope, which is critical for most types of aircraft. It shows that when the airplane is at a negative angle of attack (nose down), the pressure of the airflow acts to push the nose up. At a positive α, the opposite is true. Therefore any change is damped. If the aircraft were not properly balanced and the slope of the moment graph was positive then any change in α, such as from control inputs, would act to push α farther in the same direction. This would amplify even the smallest change and make the aircraft very difficult to control.

As indicated by the graph, the airplane could probably be flown with little control input except trim as necessary to maintain altitude.

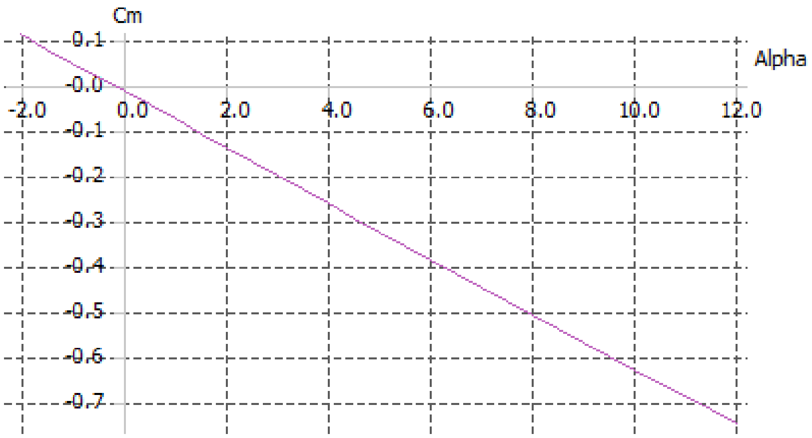


Figure 14. Airplane coefficient of pitching moment vs. angle of attack

On Titan, the airplane will do more than simply glide. It is important to ensure that there is sufficient power to maintain altitude and to perform any additional maneuvers that are necessary. Figure 15 shows a graph of power required versus velocity.

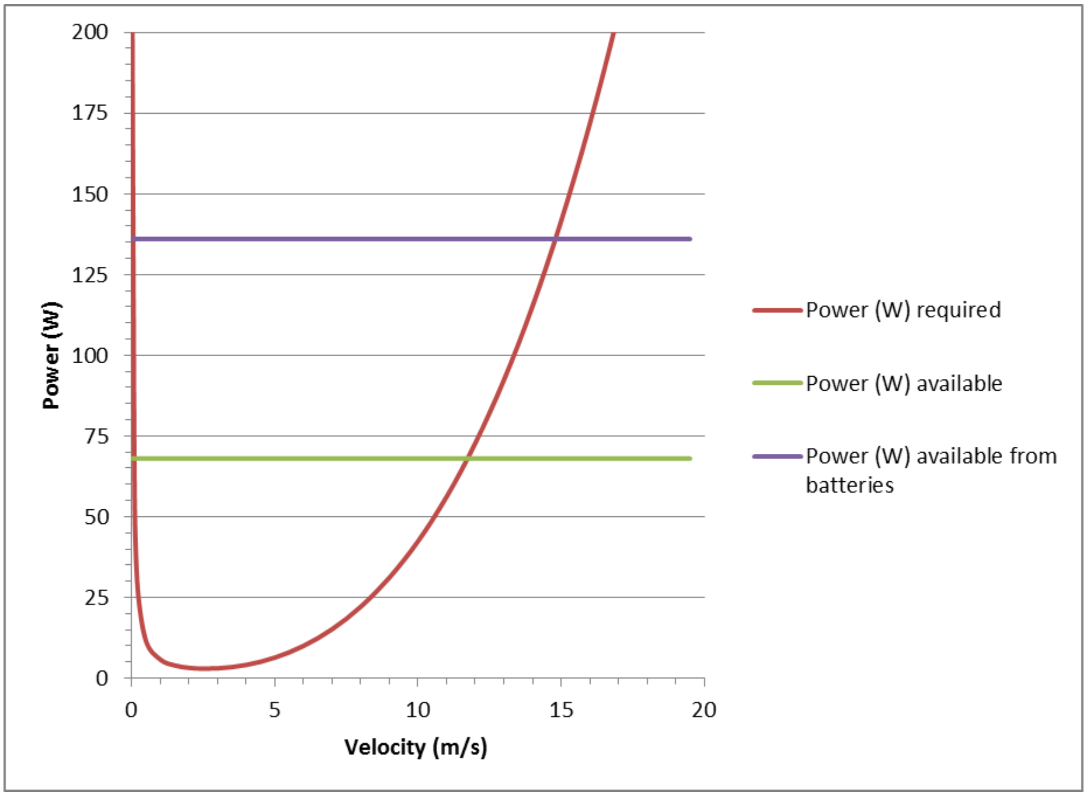


Figure 15. Power required vs. velocity

The power required (shaft power, P_s) for level flight is determined from velocity and a number of factors related to the environment such as atmospheric density (ρ) and computed from the aircraft analysis such as zero-lift drag coefficient (C_{D0}), weight and wingspan.[55] The graph shows that for the given aircraft design, very little power is actually required to fly on Titan. The necessary power is at a minimum around 2.5 m/s, where just under 3 W is necessary to maintain altitude. That is a relatively slow speed, and in order to fly faster, the necessary power increases quickly. Using all the available electrical power from the ASRG (100W), the drive motor can produce 68 W shaft power, which is only able to pull the aircraft at about 11.5 m/s. Drawing stored power from the batteries could increase this slightly to just under 15 m/s.

So, even though flying on Titan is easy, flying fast is difficult. A different design could be optimized for flight at a higher velocity, and additional nuclear power supply could be added. Alternately, the airplane could fly at a higher altitude where the atmosphere is thinner, but this would reduce the spatial resolution of captured images. For the given mission, the analysis shows that this design should perform well.

Limitations of the analysis

The computer analysis has its limitations. First the XFOIL algorithms produce more accurate results at lower Reynolds numbers, and this aircraft is intended for operation at higher numbers.[56] Also, the Vortex-Lattice Method used by XFLR5 for simulating flow around the entire aircraft is an old method, and there probably are better computational models. Commercial CFD software would provide a more accurate and more expensive result. Regardless of what the computer shows, it is important to validate the results through accurate testing in the real world, in a wind tunnel or in actual flight. For the ARES craft, NASA was able to build a half-scale model and test it at high altitude on Earth in order to simulate the atmosphere of Mars.[57] It may be somewhat more difficult to find an approximation of Titan's atmosphere on Earth.

Getting There

Along with the airplane itself, it is necessary to consider the other aspects of the mission that would place it on Titan.

Additional requirements

An orbiter should travel to Titan with the airplane. It is necessary for the two reasons mentioned previously. First, to relay science data from the airplane to Earth. Second, to provide navigational assistance to the airplane. The airplane would also need to be placed in an aeroshell which would act as a heat shield for decelerating in Titan's atmosphere.

Rocket

Because the airplane is sized to fit within a 4 meter payload fairing (relatively large), it requires a relatively large rocket. An Atlas V 400 series rocket could satisfy this requirement, but probably would be expensive.[58] Minimizing the mass, and also choosing an optimized transfer orbit could help reduce the expense.

Orbit

Saturn is a long way off at 10 astronomical units away from the Sun. In order to get a spacecraft there with minimum propellant, many past missions have used gravity assist maneuvers to alter the trajectory of the spacecraft. This was the case with both Voyager missions, as well as Cassini-Huygens. Cassini was large enough, at almost 6000 kg, that existing rockets could not send it directly to Saturn, so it made gravity assist flybys of Venus, Earth and

Jupiter in order to increase its orbital energy enough to reach Saturn. Even then it still took seven years to arrive.[59]

This airplane, a small orbiter, and an upper stage with sufficient propellant to decelerate upon reaching Saturn should not mass nearly as much as Cassini. Therefore, a direct transfer orbit should be possible, without requiring any gravity assists. This would involve one burn to leave Earth orbit, and one to slow down before Saturn orbit insertion.

Orbit calculation software can be used to find a path optimized for total delta-V, using the patched-conic approximation. Using one such program, an orbit was found that would take a spacecraft to Saturn orbit in six years with a total delta-V of 15.54 km/s.[60] This is detailed in Figure 16.

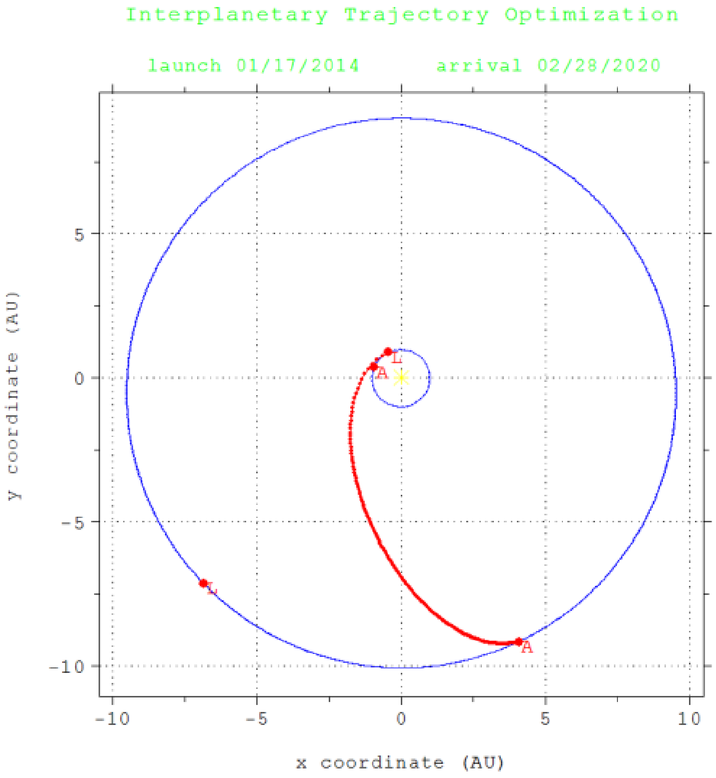


Figure 16. Optimized transfer orbit

From Saturn, Titan orbit is very close and would require little maneuvering on the part of the spacecraft.

Deploying the airplane

Once it arrives at Titan, the orbiter and aircraft must separate, with the orbiter entering a stable orbit outside of the atmosphere. The airplane, packaged in its aeroshell, will encounter Titan's atmosphere and decelerate at several Gs. Once it has slowed substantially, a parachute will be deployed. The parachute should be either a hemisflo or ringsail type, as opposed to the disc-gap-band parachute used with Huygens.[61] The aeroshell will be released, and the wings will unfold and the parachute will be cut loose at about 20 km above the surface. The aircraft will descend to its operating altitude of 10 km.

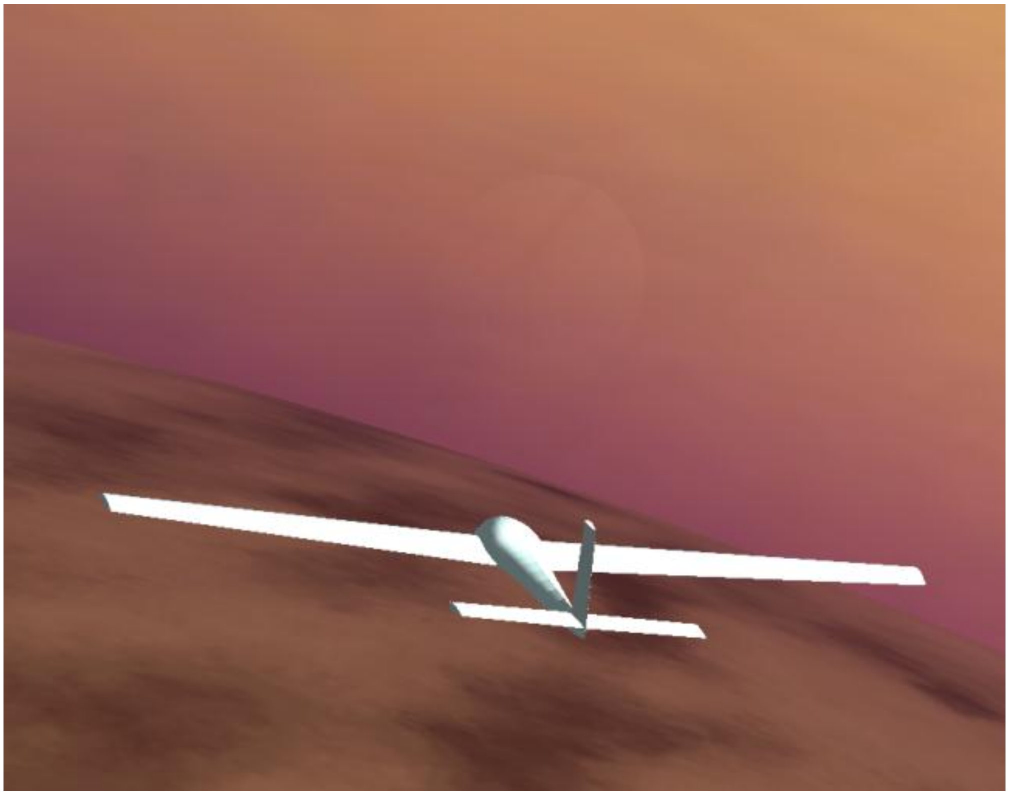


Figure 17. Concept airplane flies over Titan, with Saturn faintly visible. Credit: author.

Now What?

Once flying on Titan, the sky is the limit. Unlike the ARES airplane with its mission measured in hours, with its nuclear power source the Titan Flyer is capable of flying indefinitely. It could potentially map the entire surface of Titan and provide data about global atmospheric circulation. The engineering data could be just as useful. Concepts that are proven could be refined and used for flight in other locations such as Venus, or even the gas giants themselves.

CONCLUSIONS

This thesis paper has advanced three related points, hopefully with some success for each. These points come from a position that assumes space exploration is useful not only for pure scientific knowledge, but something that we *must* do, as humans. Far from being a waste of money, our short history of space exploration has provided incalculable benefits of technology and inspiration.

Point one: Titan is an interesting place and worthy of further exploration. In chapter one, a summary of the current scientific understanding of Titan showed that it is a unique place, and in some ways resembles a young Earth. There is still much that is not known about Titan, and theorizing can only go so far. To find out more of this moon's secrets, it is necessary to actually go there.

Point two: The next step for the study of Titan should be exploration by air. This is the case because Titan has a dense atmosphere which blocks the view of the surface from orbit but also provides an excellent medium for powered flight. This allows a close up view of the surface, but gives the ability to explore on regional or even planetary scales. For this purpose, an airplane also has a number of advantages over a buoyant aircraft such as a balloon.

Point three: A relatively simple design concept is capable of accomplishing this mission. From a simple set of requirements, it is possible to create a design that will successfully fly on Titan, and be capable of long term operation. A realistic design concept that satisfies requirements of the science mission was presented, and could be built with current technology. A single aircraft such as the one presented could potentially survive years flying above Titan's frozen surface, returning incredible amounts of valuable data.

If such a mission was successful, it would not be an end in and of itself but just another step in the exploration of Titan, and the Solar System. It is hoped that these steps will eventually lead us to the stars.

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[18] Data collected from multiple sources. See: Roe, 1. Griffith, 18. Lebreton "Results from the Huygens probe on Titan," 155.

[19] Lebreton, Jean-Pierre, et al. "Results from the Huygens probe on Titan," 156-158.

[20] Data from Lebreton "Results from the Huygens probe on Titan," 157 and Tomasko, M. G. et al. "Rain, winds, and haze during the Huygens probe's descent to Titan's surface." *Nature* 438, no. 7069 (December 8, 2005): 770.

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[43] This is used as a generic title, rather than a unique name, much like “Mars Flyer”. See Wilson, “The Wright Path to a Mars Flyer”, 41.

[44] Example: Wilson, “The Wright Path to a Mars Flyer”, 43. Also see Landis, et al. “Atmospheric Flight on Venus,” 6.

[45] The circumference at that altitude is $2\pi(r+10\text{km}) = 16182$ km, at 18 km/h this is 902.5 h or 37.6 days.

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[47] See Fig. 3, $M = 0.027$

[48] See equation 1.35, Anderson, *Fundamentals of Aerodynamics*, 38. For Titan atmosphere at 10 km, $\rho=3.638$ kg/m^3, $\mu=1.978\times10^{-6}$ m^2/s (assuming pure N_2).

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