Dragonfly: A Rotorcraft Lander Concept for Scientific Exploration at Titan

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ABSTRACT

The major post-Cassini knowledge gap concerning Saturn's icy moon Titan is in the composition of its diverse surface, and in particular how far its rich organics may have ascended up the "ladder of life." The NASA New Frontiers 4 solicitation sought mission concepts addressing Titan's habitability and methane cycle. A team led by the Johns Hopkins University Applied Physics Laboratory (APL) proposed a revolutionary lander that uses rotors to land in Titan's thick atmosphere and low gravity and can repeatedly transit to new sites, multiplying the mission's science value from its capable instrument payload.

INTRODUCTION

Saturn's moon Titan is in many ways the most Earth-like body in the solar system.[1–3] This strange world is larger than the planet Mercury and has a thick nitrogen atmosphere laden with organic smog, which partly hides its surface from view. Since cold Titan is far from the Sun, on Titan methane plays the active role that water plays on Earth, serving as a condensable greenhouse gas, forming clouds and rain, and pooling on the surface as lakes and seas. Titan's carbon-rich surface is shaped not only by impact craters and by winds that sculpt drifts of aromatic organics into long linear dunes but also by methane rivers and possible eruptions of liquid water ("cryovolcanism").

While living things are ~70% water, and finding water has been a convenient initial focus for astrobiological investigations in the solar system, the chemical processes that conspire to lead to life rely on functions exerted by compounds of carbon, nitrogen, oxygen and hydrogen, with traces of sulfur and phosphorus (CHNOPS). In contrast to Europa (abundant in water, and perhaps sulfur), Titan is an "ocean world" that is rich in both carbon and nitrogen.[4,5] See Table 1 for data on Titan's environment.

FORMULATION OF THE DRAGONFLY CONCEPT

The NASA community announcement in January 2016 identifying Titan as a possible target for the fourth New Frontiers mission opened new possibilities in Titan exploration (Box 1). Although the exploration of Titan's seas had previously been considered, notably by the APL-led Titan Mare Explorer (TiME) Discovery concept,[6,7] the timing mandated by the announcement of opportunity precluded such a mission. Specifically, with launch specified prior to the end of 2025, Titan arrival would be in the mid-2030s, during northern winter. This means the seas, near Titan's north pole, are in darkness and direct-to-Earth (DTE) communication is impossible.[8] Even with the higher budget threshold of New Frontiers 4 ($850 million plus launch and operations costs) compared with Discovery (~$450 million

Table 1. Titan's Environment

Property	Surface Value[a]
Diameter	5150 km (larger than Mercury)
Surface gravity	1.35 m/s^2 (1/7 Earth)
Distance from Saturn	1.2 million km (20 Saturn radii)
Rotation period (Titan day or Tsol[b])	15.945 days (same as orbit period around Saturn)
Atmospheric pressure	1.47 bar (note: Earth surface pressure = 1.01 bar)
Atmospheric temperature	94 K
Atmospheric density	5.4 kg/m^3 (4× Earth sea level air)
Atmosphere composition	95% nitrogen, 5% methane, 0.1% hydrogen, many trace organics
Speed of sound	195 m/s
Atmospheric viscosity	6×10^{-6} Pa-s (~3× smaller than Earth air)
Obliquity	26° to Sun (equatorial plane is ~ Saturn ring plane)
Surface illumination	~1000× less than Earth (or ~1000× full moonlight) predominantly in red and near-IR light; visibility near surface ~10 km

[a] Atmospheric properties vary with altitude; surface values shown here.

[b] Tsol, Titan solar day.

plus radioisotope power source and launch costs), it would be challenging indeed to provide a relay spacecraft and a sea probe.

A lander with DTE communication would be possible at lower latitudes, however. The only detailed study of such a mission (see Box 2) was the 2007 *Titan Explorer NASA Flagship Mission Study*,[9,10] led by the Johns Hopkins University Applied Physics Laboratory (APL). This study advocated the science that could be obtained from three platforms, an orbiter, a hot-air (Montgolfière) balloon, and a lander. The lander (designed before Titan's seas had been discovered) was intended to be delivered to Titan's Belet sand sea, a large—and thus easily targeted—dune field expected to be free of rock and gully hazards. After the lander's parachute descent and landing on Pathfinder-like airbags (wherein if it landed on top of a dune, it would just roll down to the bottom), petals would unfold and science would begin, with cameras, a chemical analysis suite, a seismometer, and a meteorology package. Much of the science definition in the *Titan Explorer Study* was useful in formulating the Dragonfly proposal.

A scientific limitation of a single lander, however, is that it explores only a single location. This limitation can be mitigated slightly at "grab-bag" landing sites where geological processes have gathered samples from a range of areas (in Mars Pathfinder's case, a flood deposit of rocks; dune sands may similarly have material from a range of source locations). However, a lander with some kind of mobility, or augmented by some mobile element (e.g., a "fetch" rover), would help address the challenge of acquiring samples from sites more interesting than the landing point, a site that would be most likely selected for safety rather than for scientific interest.

The concept of a rotorcraft lander on Titan trickle-charging a battery for brief atmospheric flights by using the power from a radioisotope power source had been proposed some 17 years ago.[11,12] At that time, the vehicle was imagined to be a helicopter, a vehicle that is used on Earth for near-guaranteed access to a wide range of terrain, for personnel delivery, and for search and rescue. However, helicopters are mechanically complex (one

BOX 1. OCEAN WORLDS

Although the list of candidate New Frontiers missions described in the *2013 Planetary Science Decadal Survey* did not include a mission to Titan, the survey did recognize the scientific value of Titan exploration, advocating technology development toward a flagship mission. Further, the 2008 *New Opportunities in Solar System Exploration (NOSSE): An Evaluation of the New Frontiers Announcement of Opportunity* report advocated that New Frontiers missions should be responsive to scientific discoveries. In January 2016, NASA introduced an "Ocean Worlds" target (Titan and/or Enceladus) into the community notice regarding the upcoming New Frontiers 4 announcement of opportunity, the final version of which was released in December 2016. That announcement defines the overarching scientific objectives as follows:

> The Ocean Worlds mission theme is focused on the search for signs of extant life and/or characterizing the potential habitability of Titan and/or Enceladus.
>
> For Titan, the science objectives (listed without priority) of the Ocean Worlds mission theme are:
>
> - Understand the organic and methanogenic cycle on Titan, especially as it relates to prebiotic chemistry; and
> - Investigate the subsurface ocean and/or liquid reservoirs, particularly their evolution and possible interaction with the surface.

Figure 1. Dragonfly mission concept. After delivery from space in an aeroshell and parachute descent, the vehicle lands under rotor power and deploys a high-gain antenna for DTE communication. Powered by a radioisotope power supply that provides heat and trickle-charges a large battery, the vehicle can operate nearly indefinitely as a conventional lander but can also make periodic brief battery-powered rotor flights to new locations.

reason that this concept was considered only briefly in the *Flagship Study*).

However, technology developments in the last two decades, notably the revolution in availability of multi-rotor drones[a] made possible by modern compact sensors and autopilots as well as the development of sensing and control capabilities for autonomous landing and site evaluation for planetary landers, made a quadcopter or a similar vehicle a much more feasible prospect in 2016. In contrast to helicopter flight, multi-rotor flight with differential throttling effected purely electrically by motor speed control is mechanically simple and therefore lends itself to planetary application.

A brief evaluation using a parametric rotorcraft power model[13] indicated that a vehicle of representative size and power could in fact achieve unparalleled regional mobility on Titan, and the Dragonfly concept was born. Initially it was imagined that the vehicle might have a flotation ring, to permit landing on one of Titan's lakes, but a more conventional box-with-skids layout soon emerged once it was decided that operations on dry land would be the focus of the mission. A constraint in this application that is somewhat unusual for rotorcraft is the necessity to be packaged in a hypersonic aeroshell. The geometric trade of unblocked rotor disk area versus number of rotors[14] with such a constraint suggests that, in fact, four is optimal.

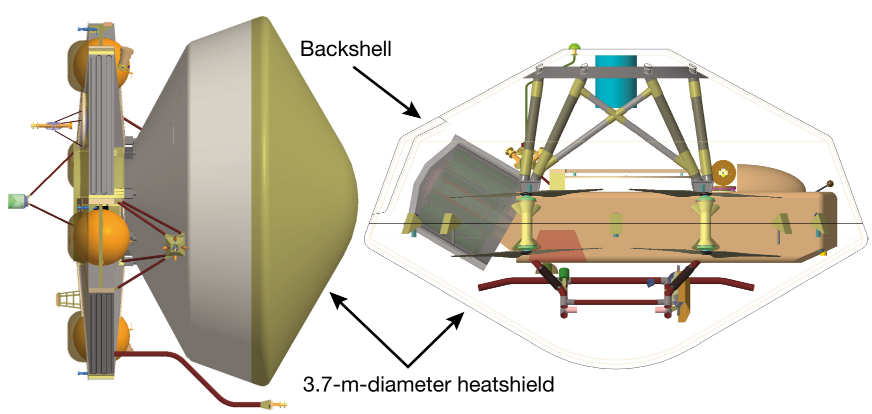

Figure 2. Although the challenges of delivering a vehicle into the Titan atmosphere are not the subject of this article, the design of the cruise stage and entry system demanded significant effort. The rotorcraft is launched "upside-down" with the stowed skids and the forward face of the aeroshell upward on the launch vehicle.

[a] It is interesting to recall that the first practical helicopter to fly in the United States, in 1924, was a multi-rotor vehicle, the "flying octopus" (see https://en.wikipedia.org/wiki/De_Bothezat_helicopter). Although this vehicle flew over 100 times with as many as four passengers and broke many records, the pilot workload to achieve control by differential thrust on four rotors each with variable pitch was formidable. Although the same capabilities were not achieved for another 20 years, the Army Air Service scrapped the project. It is also interesting to note that while hovering drones on Earth have been enabled by high-power-density battery technology, specifically the 21st-century emergence of lithium-ion and lithium-polymer cells, in Titan's low gravity and thick atmosphere, comparable vehicles (if kept warm) would not need such high power or energy densities.

BOX 2. PROMINENT POST-CASSINI MISSION STUDIES AND PROPOSALS

While many smaller studies are described in conference papers or similar (see Ref. 46 for a review), the following list identifies major efforts. The first suggestion of Titan helicopters (at least the first mention of which we are aware) falls into this former category, a passing mention of small fetch vehicles to return surface samples to a rather improbable 8-metric-ton nuclear-thermal reactor-powered spaceplane, described by Zubrin in a 1990 conference paper.[47]

- **1999 Prebiotic Material in the Outer Solar System Campaign Science Working Group (CSWG).** Various discipline-oriented CSWGs were a predecessor of the Planetary Science Decadal Survey, the first of which convened in 2003, before Cassini's arrival informed future priorities. Nonetheless, the CSWG recognized[48] the potential for aerial mobility at Titan and the importance of Titan's surface chemistry. The first thinking about heavier-than-air exploration, and rotorcraft in particular, took place in this period.
- **2006 TiPEx—Titan Prebiotic Explorer.**[49] TiPEx was a Jet Propulsion Laboratory (JPL) concept, not externally funded, for a Montgolfière (hot-air) balloon and orbiter. Surface chemistry was to be addressed by dropping a harpoon sampler to be winched back up to the balloon gondola. Earlier JPL studies had considered a more complex dirigible balloon (airship).
- **2007 Titan Explorer Flagship.** This APL-led NASA study[10,11] advocated a lander, Montgolfière, and aerocaptured orbiter to address the widest range of scientific disciplines and spatial scales. The lander would address surface chemistry, relieving the Montgolfière of the risks of near-surface operations and sampling. This was the first study to feature a NASA-appointed science definition team (SDT). The SDT assigned a higher scientific priority to the lander than to the Montgolfière—surface chemistry and internal structure were considered more important goals.
- **2009 Titan Saturn System Mission (TSSM).** This JPL-led study[50] built on Titan Explorer, but with a headquarters-mandated architecture including European Space Agency-provided *in situ* elements (a Montgolfière and a short-lived battery-powered lake lander), requiring Enceladus as well as Titan science, and prohibiting aerocapture. A related architecture was explored in a very preliminary way in the European-led TandEM (Titan and Enceladus Mission) proposal.[51]
- **2010 AVIATR.** This concept[52] was for an airplane at Titan, powered by Advanced Stirling Radioisotope Generators (ASRGs) to fly continuously to perform an aerial survey with DTE communication. Although stimulated by the 2010 Discovery solicitation, this idea proved incompatible with the Discovery budget.
- **2010 TiME (Titan Mare Explorer).** This APL–Lockheed Martin proposal[6,7] was selected for a Phase A study in the 2010 Discovery solicitation. It was a capsule that would float in Ligeia Mare, Titan's second-largest sea, using ASRGs for power and DTE communication and would perform (liquid) composition measurements, imaging and sonar surveys, and meteorological observations.

It is evident that Dragonfly responds to long-standing scientific priorities and ideas. Remarkably, the combination of long-term landed science and occasional aerial flight offers in a single platform most of the combined capabilities of both the lander and balloon elements of the 2007 *Flagship Study*.

Although there is a small aerodynamic penalty in the "over–under" quad octocopter layout (with a top and bottom pair of motors/rotors at each corner of the vehicle) compared with a "pure" quad, the octocopter configuration is more resilient, being able to tolerate the loss of at least one rotor or motor.

The architecture of the sample acquisition system, to be provided by Honeybee Robotics, was another major trade: a sampling arm like those used on Viking, Phoenix, or the Mars Science Laboratory, was considered, but it would be expensive and heavy and presented a single-point failure. Instead, two sample acquisition drills, one on each landing skid, with simple 1-degree-of-freedom actuators were selected. These provide a sample choice and redundancy. Titan's dense atmosphere permits the sample (whether sand, icy drill cuttings, or other material) to be conveyed pneumatically[15] by a blower—the material is sucked up through a hose and is extracted in a cyclone separator (much like in a Dyson vacuum cleaner) for delivery to the mass spectrometer instrument.

The scientific payload (Box 3) for Dragonfly is in many respects a (large) subset of that identified by a NASA-appointed science definition team for the 2007 *Flagship Study* lander, embracing geophysical, imaging, and meteorological studies, as well as the centerpiece science of surface chemistry. Novel elements include measurement of atmospheric hydrogen as a possible biomarker[16] and the capability of making rapid elemental composition measurements via neutron-activated gamma-ray methods[17] without requiring sample ingestion—a particularly powerful capability for a relocatable lander. Particular sites of interest deserving closer investigation with ingested samples include those where liquid water (e.g., from impact melt) has interacted with Titan's organic haze deposits to produce[18,19] pyrimidines (bases used to encode information in DNA) and amino acids, the building blocks of proteins. In addition to multiplying the surface chemistry science value by visiting multiple sites, Dragonfly's capabilities for meteorological measurements and imaging during flight are comparable with those of a balloon—the revolutionary single-element Dragonfly concept affordably fulfils most of the science objectives met by two of the elements (lander plus Montgolfière) in flagship architectures.

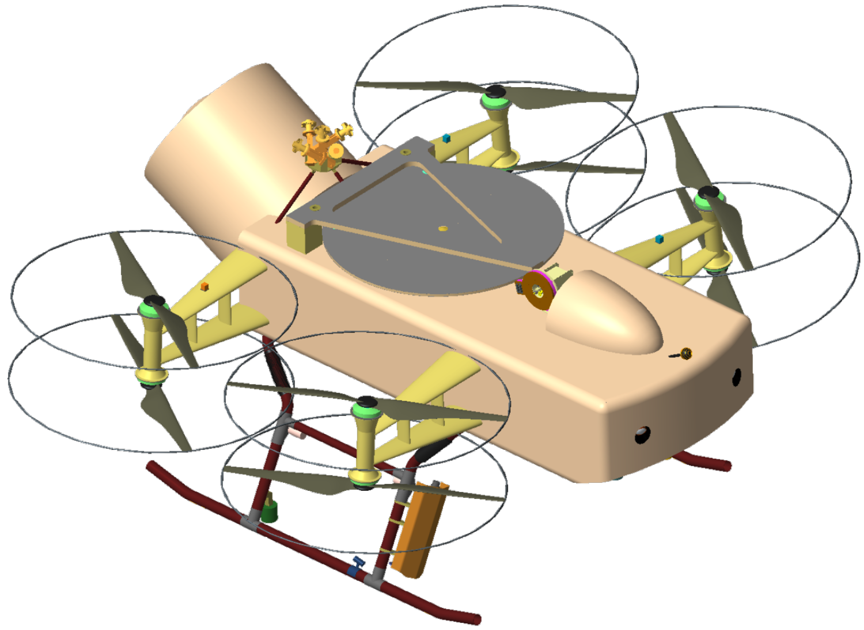

Figure 3. The Dragonfly configuration for atmospheric flight (with the gray circular HGA stowed flat). Note the aerodynamic fairing in front of the HGA gimbal. The cylinder at rear is the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). A sampling drill mechanism is visible in the nearside skid leg, and forward-looking cameras are recessed into the tan insulating foam forming the rounded nose of the vehicle. The rotor wing section and planform are designed for the Titan atmosphere.

ENERGY IS EVERYTHING

It was recognized, in the same study[12] that articulated the trickle-charged helicopter idea, that energy is the fundamental limitation in Titan surface exploration. In that environment, solar power is impracticable (sunlight at Titan's surface is ~100× weaker than at Earth, due to Titan's distance from the Sun, and is further diminished by a factor of ~10 by Titan's hazy atmosphere[20]), and the strong cooling provided by Titan's dense 94-K atmosphere requires sustained heat for thermal management.

The vehicle body, like the Huygens probe, has thick insulation around its main electronics box, and "waste" heat from the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) is tapped to maintain this interior (and most particularly, the battery) at benign temperatures. On the other hand, the sensitive gamma-ray detector of the DraGNS instrument (see Box 3) is mounted outside this warm box, exploiting the dense cold atmosphere to attain low operating temperatures without needing a mechanical cryocooler.

Missions with high-gain antennas (HGAs) empirically require about 5 mJ per bit per astronomical unit[21] to acquire and send science data to Earth [the linear distance dependence is an interestingly emergent "allometric" correlation (see also Ref. 22) that results from engineering efforts to defeat the inverse square law—spacecraft at greater distances tend to have larger antennas, for example]. A mission following on from Huygens should logically do better than Huygens. The Huygens probe returned about 100 MB of data (~3.5 h of an S-band link at 8 kbps, relayed to Earth by the Cassini orbiter[23]). To do, say, 100 times better, 10 GB, would therefore require at 10 AU about 0.5 GJ of energy (140,000 Wh, far beyond the capability of practical stored energy systems like primary batteries) and necessitates radioisotope power.

The free parameter in the system design is the mission duration. For the steady output from a radioisotope power source, the mission energy, and thus data return, scales directly with duration. One year of (say) 100 W output corresponds to 3 GJ of energy.

The New Frontiers 4 announcement of opportunity permits the use of up to three MMRTGs. Since these are relatively heavy, and the waste heat (some 2 kW) requires careful management (although some heat is in fact essential for this application), it was obvious that only a single unit should be used.

Slow degradation of the thermoelectric converter, in addition to the decay of the plutonium heat source, means the electrical power output at Titan is considerably lower than at launch, 9 years earlier. Furthermore, uncertainty in that degradation (known only from ground tests and from the ~5 years of operation of the MMRTG on Curiosity[24]) requires healthy margins on the power budget. An electrical power output of about 70 W from a single MMRTG is anticipated at Titan. While this is indeed low, it may be recalled that both Viking landers operated for years on this power level. The key is that landed operations are undemanding (no propulsion or attitude control) and flexible.

Although sample acquisition and chemical analysis are somewhat power-hungry activities, they require only a few hours of activity. Science activities that require continuous monitoring, namely meteorological and seismological measurements, although of low power, actually dominate the payload energy budget. Indeed, for these extended periods, the lander avionics are powered down and data acquisition is performed only by the instrument, to maximize the rate of recharge of the battery.

Except during polar summer or winter, operations of a lander on Titan with DTE communication are paced by the Titan diurnal cycle. A Titan solar day (Tsol) is 384 h long (16 Earth days). Seen from Titan, Earth in the sky is always within 6° of the Sun. Interaction with Earth, and logically any operations requiring real-time observation (such as atmospheric flight), occur during the day, and nighttime activities are generally minimal and power can be devoted to recharging the battery. Thus, a logical maximum size of the battery is that which completely captures MMRTG power during the Titan night, or 75*192 = 14 kWh. Such a battery—about a quarter of the size of the battery in a Tesla electric car—would be rather massive (140 kg), assuming a representative specific energy metric for space-qualified batteries of 100 Wh/kg. In practice, a smaller battery may be chosen, sacrificing some energy-harvesting efficiency for lower mass and cost. It should be emphasized that while the mission has been designed to function with the MMRTG, other comparable radioisotope power systems,[25] such as the Advanced Stirling Radioisotope Generator (ASRG) or an enhanced MMRTG with higher conversion efficiencies than the MMRTG, would permit an even higher data return or rate of flight.

ATMOSPHERIC FLIGHT PERFORMANCE AND AERODYNAMIC DESIGN

Titan's atmosphere is both denser (4.4×) and colder (94 K) than Earth's. The composition is predominantly (95%) nitrogen, and the low temperature means molecular viscosity is rather lower than for our air. The combination of higher density and lower viscosity means that an airfoil of given size and speed is operating at a Reynolds number that is several times higher than on Earth. To a first order, then, the ~1 m rotors of Dragonfly should resemble rotors of much-larger-scale systems on Earth—in fact, a blade section more typically used in terrestrial wind turbines has been adopted. Not only

BOX 3. DRAGONFLY SCIENCE PAYLOAD

The Dragonfly science payload includes the following instruments:

- **DraMS—Dragonfly Mass Spectrometer (Goddard Space Flight Center).** A central element of the payload is a highly capable mass spectrometer instrument, with front-end sample processing able to handle high-molecular-weight materials and samples of prebiotic interest. The system has elements from the highly successful SAM (Sample Analysis at Mars) instrument on Curiosity, which has pyrolysis and gas chromatographic analysis capabilities, and also draws on developments for the ExoMars/MOMA (Mars Organic Material Analyser).
- **DraGNS—Dragonfly Gamma-Ray and Neutron Spectrometer (APL/Goddard Space Flight Center).** This instrument allows the elemental composition of the ground immediately under the lander to be determined without requiring any sampling operations. Note that because Titan's thick and extended atmosphere shields the surface from cosmic rays that excite gamma-rays on Mars and airless bodies, the instrument includes a pulsed neutron generator to excite the gamma-ray signature, as also advocated for Venus missions. The abundances of carbon, nitrogen, hydrogen, and oxygen allow a rapid classification of the surface material (for example, ammonia-rich water ice, pure ice, and carbon-rich dune sands). This instrument also permits the detection of minor inorganic elements such as sodium or sulfur. This quick chemical reconnaissance at each new site can inform the science team as to which types of sampling (if any) and detailed chemical analysis should be performed.
- **DraGMet—Dragonfly Geophysics and Meteorology Package (APL).** This instrument is a suite of simple sensors with low-power data handling electronics. Atmospheric pressure and temperature are sensed with COTS sensors. Wind speed and direction are determined with thermal anemometers (similar to those flown on several Mars missions) placed outboard of each rotor hub, so that at least one senses wind upstream of the lander body, minimizing flow perturbations due to obstruction and by the thermal plume from the MMRTG. Methane abundance (humidity) is sensed by differential near-IR absorption, using components identified in the TiME Phase A study. Electrodes on the landing skids are used to sense electric fields (and in particular the AC field associated with the Schumann resonance, which probes the depth to Titan's interior liquid water ocean) as well as to measure the dielectric constant of the ground. The thermal properties of the ground are sensed with a heated temperature sensor to assess porosity and dampness. Finally, seismic instrumentation assesses regolith properties (e.g., via sensing drill noise) and searches for tectonic activity and possibly infers Titan's interior structure.
- **DragonCam—Dragonfly Camera Suite (Malin Space Science Systems).** A set of cameras, driven by a common electronics unit, provides for forward and downward imaging (landed and in flight), and a microscopic imager can examine surface material down to sand-grain scale. Panoramic cameras can survey sites in detail after landing: in many respects, the imaging system is similar to that on Mars landers, although the optical design takes the weaker illumination at Titan (known from Huygens data) into account. LED illuminators permit color imaging at night, and a UV source permits the detection of certain organics (notably polycyclic aromatic hydrocarbons) via fluorescence.
- **Engineering systems.** Data from the inertial measurement unit (IMU) may be used to recover an atmospheric density profile via the deceleration history during entry. IMU and other navigation data may provide constraints on winds during rotorcraft flight. Additionally, the radio link via Doppler and/or ranging measurements may shed light on Titan's rotation state, which, in turn, is influenced by its internal structure.

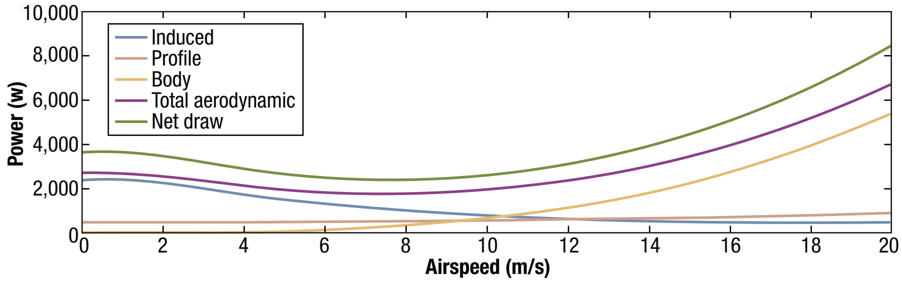

Figure 4. Rotorcraft power curve for a representative vehicle mass of 420 kg on Titan. The induced power required for rotor thrust falls toward higher speed, whereas the body drag increases quadratically and eventually dominates. These competing factors define the maximum endurance speed (the minimum in the curve ~8 m/s) and the maximum-range speed (where the tangent to the curve passes through the origin, corresponding to ~10 m/s). Titan's dense atmosphere and low gravity means that the flight power for a given mass is a factor of about 40 times lower than on Earth.

is this section aerodynamically efficient, it is also very tolerant of surface roughening (typically, in the case of wind turbines, due to insect impingement), making it a robust choice for Titan.

The low temperature also means that the speed of sound[26] in Titan's atmosphere is low (~194 m/s versus 340 m/s on Earth). This could be a factor for large or fast-rotating propellers in that severe performance loss occurs as the tip Mach number approaches unity. In practice, a tip Mach number of 0.4 is not a strong design factor.

An informal guide to determining the vehicle capability in early development was the specification that it should offer revolutionary science mobility to access a variety of geological terrains, being able to fly, in one hop, farther than any Mars rover has driven in a decade (i.e., about 40 km). Flight performance analysis[14] suggested that the maximum-range speed (Fig. 4) would be about 10 m/s, and that flight power for a representative 420-kg vehicle at this speed would be a little over 2 kW. A 30-kg battery at 100 Wh/kg could theoretically permit flight for 2 h and achieve some 60 km in range. In practice, battery performance would be heavily margined for safety and performance would be lower. Flight power scales roughly as mass^1.5, so a more massive vehicle would have lower endurance or would require a larger battery. Although the vehicle configuration is designed overall as a planetary lander with a somewhat boxy appearance, some streamlining is implemented (e.g., a rounded nose and fairings around the skid-leg drill mechanisms) to minimize aerodynamic drag in flight. For obvious reasons, the HGA is stowed during flight.

In addition to horizontal mobility, there is science value in achieving altitude. Of particular interest is the possibility of profiling the planetary boundary layer (PBL) via ascent to 500 m to 4 km altitude. The diurnal PBL thickness was measured during the Huygens descent to be ~300 m high,[27] although a possible feature[28] at ~3 km has been identified and attributed to a possible seasonal PBL,[29] and it is this quantity that apparently controls the spacing of dunes on Earth and Titan.[28] Although vertical ascent is possible, vertical descent is not (except at very low speeds, as for landing) since the vortex ring state, wherein the vehicle falls through its own downwash, creating an unstable condition, must be avoided. Descending vertically at very low speeds would also be very energy inefficient. Nominally, then, profiling flights[30,31] would be performed with normal forward motion, ascending or descending at about 20° to the horizontal. These flights could be performed during traverses to new locations, or if a local vertical profile with minimal horizontal displacement were desired, a spiral ascent and descent could be executed with return to the original landing site.

Titan's near-surface winds are predicted by global circulation models (GCMs) to be only 1–2 m/s maximum[31] (about the same as those measured by Doppler tracking of the Huygens probe), and, thus, the 10-m/s flight transit speed means that wind effects on range are minor.

SCIENCE MISSION PROFILE

Titan's thick, extended atmosphere in fact allows a rather wide corridor of entry flight-path angle (Huygens entered at –65°), making a rather wide annulus of target possibilities, depending on the direction of arrival. Aerothermodynamic considerations weakly favor arrival on Titan's trailing side (Titan is tidally locked to Saturn) to minimize the entry speed and, thus, heat loads and deceleration.

Arrival at Titan in the mid-2030s with DTE communication suggests a low-latitude landing site. This requirement means a similar location and season to the Huygens descent in 2005, so the wind profile and turbulence characteristics measured by the Huygens probe[32,33] are directly relevant. Furthermore, the sand seas[34] that girdle Titan's equator are both scientifically attractive and favorable in terms of terrain characteristics for landing safety—indeed, it was for these reasons that the 2007 *Flagship Study* identified these dune fields as the preferred initial target landing area.

The radar characteristics of Titan's dune fields[35] are such that there is relatively little small-scale roughness. Various methods to recover large-scale topography (altimetry, stereo imaging, and radarclinometry) suggest that Titan's dunes may be up to 150 m high with area-averaged

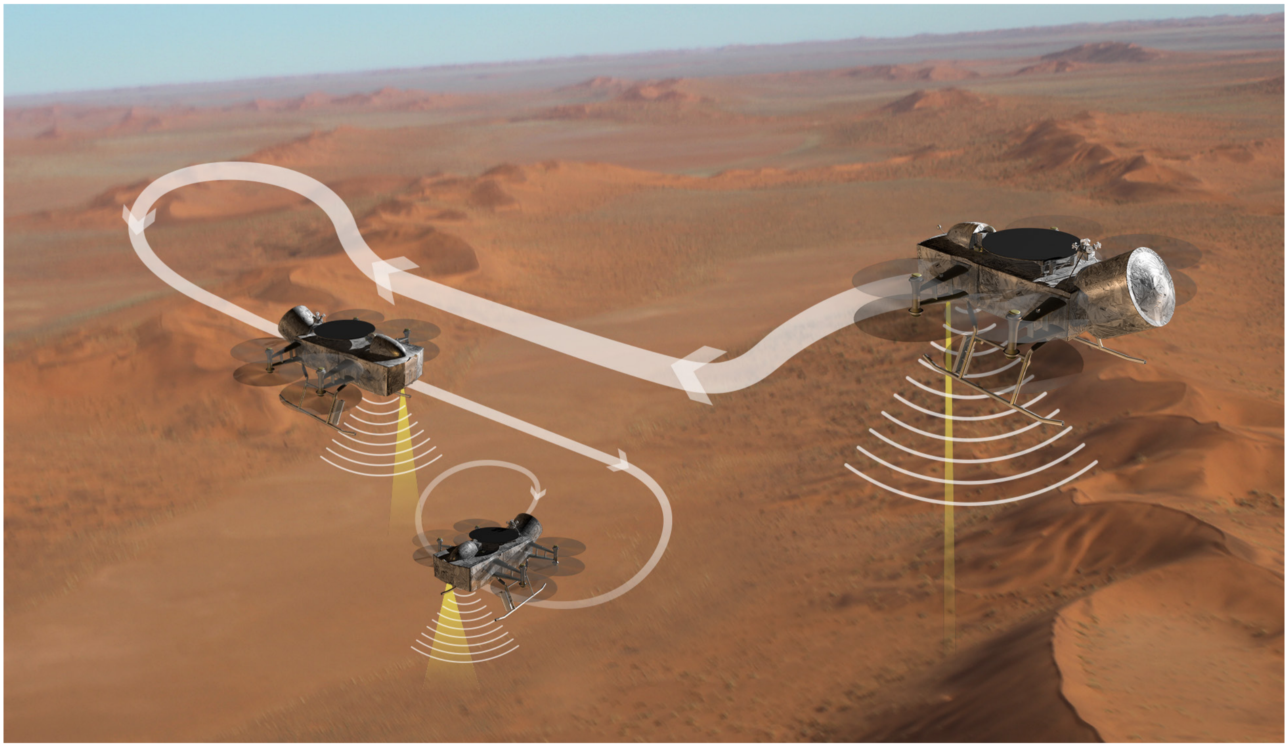

Figure 5. Initial descent. After release from the entry system and parachute, the vehicle can traverse many kilometers at low altitude using sensors to identify the safest landing site. The schematic is shown against an aerial image of the Namib sand sea, a geomorphological analog of the Titan landing site, with ~100-m-high dunes spaced by several kilometers.

slopes of about 5°.[36] Terrestrial analogs, for example the Namib sand sea in southern Africa,[37] have linear dunes of the same morphology and spacing (3–4 km) and height with flat inter-dune areas: analysis of digital elevation models [e.g., the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM), with 30-m postings] shows that at this scale some 50% of the area has a slope of 1° or less, and 95% has a slope less than 6°. For a vehicle able to tolerate modest slopes (e.g., 10°), there are certain to be ample locations that permit safe landing. In contrast to conventional planetary landers with rocket propulsion, which have limited divert capability, on Titan a rotorcraft lander on initial descent has sufficient endurance to scan a swath of many kilometers of terrain and then backtrack to the most favorable location.

Once safe landing on arrival is achieved, the rotorcraft mobility capabilities can be exercised progressively—for example, first making a brief hop for a few seconds within the immediate vicinity of the landing site where the terrain will be known from panoramic and/or descent imaging. Depending on the heterogeneity of the surface (e.g., patches of sand), a small displacement of a few meters or tens of meters may enable the sampling of different materials.

Then, flights of progressively increasing duration, range, and/or height can be made, returning to the original, known-safe, landing site. These flights can assess the performance of various sensors—for example, an initial hop may be made using inertial guidance alone, whereas later flights use optical navigation only after the quality of in-flight imaging and the abundance of suitable landmarks on Titan have been verified.

If the Titan terrain is as benign as the Namib analog suggests, safe landing zones can be more or less guaranteed between the dunes, and the full flight range of the vehicle can be exploited. However, a more conservative posture is as follows, based on a one-way flight range R (which itself will be a healthy margin beneath the actual vehicle capability):

1. A second landing zone (B) is identified by ground analysis of reconnaissance imaging, a distance R/3 or less away from the initial landing site A.
2. The vehicle makes a sortie over this zone using its sensors (lidar for terrain roughness, imaging, etc.) and returns to the original landing site (A).
3. Analysis on the ground of the sensor data confirms one or more safe sites within zone B (or if no satisfactory site is found, return to step 1).
4. A candidate third landing zone (C) is identified in reconnaissance imaging, a distance 2R/3 away from A.
5. The vehicle makes a sensing sortie over (C) but lands at (B).

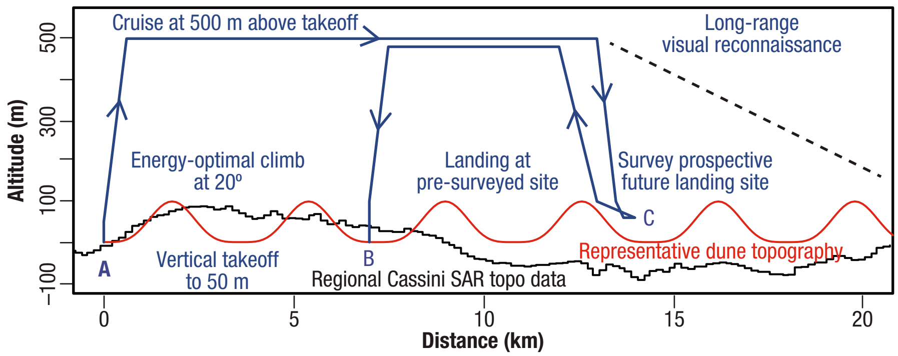

Figure 6. "Leapfrog" reconnaissance and survey strategy enables potential landing sites to be fully validated with sensor data and ground analysis before being committed to. Distance shown is example only—actual performance may be much better.

In this way, the mission need not commit to landing sites that have not first been assessed to be safe. This conservative approach, while taking longer to achieve a given multi-hop traverse range, enables the contemplation of much rougher terrains that may be associated with more appealing scientific targets (e.g., cryovolcanic features or impact melt sheets where liquid water may have interacted with organics on Titan).

At each new landing site, the HGA is unstowed and downlink begins. Priority data might include flight performance information and aerial imaging of the landing site to confirm its exact location in maps made from prior reconnaissance. A quick-look site assessment would use thermal measurements on the landing skids to estimate the surface texture (e.g., solid versus granular, damp versus dry); dielectric constant obtained by measuring the mutual impedance between electrodes on the skids would similarly constrain the physical character of the surface material. These measurements would take only seconds to minutes. Over a period of a few hours, the neutron-activated gamma-ray spectrometer would determine the bulk elemental composition of the landing site, allowing identification among a number of basic expected surface types (e.g., organic dune sand, solid water ice, and frozen ammonia-hydrate).

Armed with this information, and with imaging to characterize the geological setting, the science team on the ground might elect to acquire a surface sample with one or the other drills and analyze it with the mass spectrometer. Drilling and sample analysis are relatively energy-intensive tasks, which might be deferred into the Titan night when (unless the battery is large enough to capture the full MMRTG output) excess energy is available. Other nighttime scientific activities include seismological and meteorological monitoring and local (e.g., microscopic) imaging using LED illuminators as flown on Phoenix and Curiosity (e.g., Ref. 38). These illuminators would permit better color discrimination of Titan surface materials (since the daytime illumination, filtered by the thick atmospheric haze, is predominantly of red light) and could use UV illumination to help identify surface organic material via fluorescence,[39] which is common in the polycyclic aromatic hydrocarbons expected in the dune sands.

If a site proves to be of interest, the vehicle (better thought of as a relocatable lander than an aircraft) can remain at a given location for as long as desired, perhaps performing more extensive imaging studies with its panoramic cameras or sampling at different depths. It could also "shuffle" distances of a few meters to reposition the skids/drills or to obtain a different camera view. Observing the methane humidity over one or more Titan diurnal periods would inform the extent to which methane moisture is exchanged with the surface (an analysis analogous to that performed by Curiosity for water vapor on Mars[40]). Note that although Dragonfly lacks a robotic arm, it can nonetheless manipulate surface materials to understand their physical character. One example is that the seismometer can

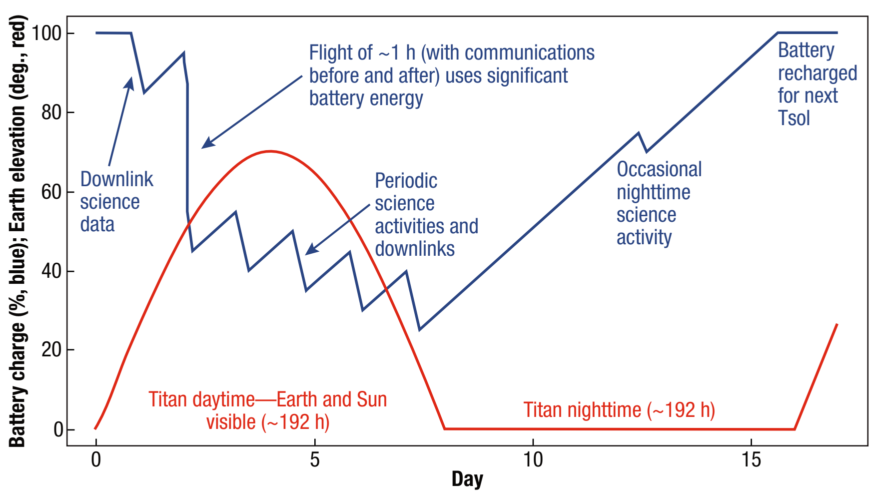

Figure 7. Energy management and communication concept of operations. MMRTG continuously recharges the battery, but downlink and especially flight demand significant energy. Activities can be paced to match MMRTG *in situ* capability while maintaining healthy margins on the battery state of charge.

observe the noise transmitted through the ground during drilling, diagnostic of the mechanical properties of the regolith and possibly indicating near-surface layering. Another example is that one or more rotors can be spun (at progressively higher speeds) to induce a known downwash on the surface material, and the speed at which sand grains begin to move (indicated either by imaging or electric field measurements) can thereby be determined. This "saltation threshold" is a key parameter in interpreting the large-scale morphology and orientation of Titan's dunes in global circulation models.[31,41] There are indications that, as on Earth, since large dunes take tens of thousands of years to form or reorient, the dune pattern carries a memory of past climate;[42] models suggest that astronomical changes (Croll–Milankovitch cycles, similar to those on Earth and Mars) may alter Titan's wind patterns and indeed the geographical distribution of its surface liquids. Decoding the dune pattern, however, requires good knowledge of the saltation threshold (estimated to be around 1 m/s,[43] but laboratory measurements[44] on Earth are limited in their capability to replicate Titan conditions, to say nothing of our ignorance of the exact sand composition and the possible role of triboelectric charging[45]).

At any given landing site, then, there is scope for rich scientific investigation in a number of disciplines. This scientific potential is multiplied by the dozens of possible landing sites that could be visited in a mission lasting a couple of years or more. The output from an MMRTG degrades slowly, and there are no major consumables on the vehicle, so the surface mission duration is not heavily constrained.

CONCLUSIONS

NASA is presently considering the Dragonfly concept, among many other proposals for missions to Venus, Titan, Enceladus, comets, and other targets. The authors hope it is selected in late 2017 for a Phase A study and ultimately for flight. Regardless of the outcome of the New Frontiers 4 solicitation, however, Dragonfly has introduced a revolutionary new paradigm in planetary exploration by demonstrating a detailed implementation proposal for unparalleled regional mobility. Having laid out this concept, the authors predict that henceforth it may be difficult to imagine a Titan lander mission that does not exploit this capability.

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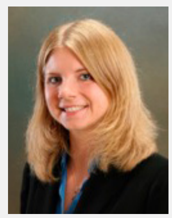

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