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Post-Cassini Exploration of Titan: Science Rationale and Mission Concepts

RALPH D. LORENZ
Lunar and Planetary Lab, University of Arizona, Tucson, AZ 85721-0092, USA.

The likely scientific questions posed by Titan after the upcoming Cassini mission, and the engineering issues associated with the platforms required for these investigations, are reviewed. Landers and balloons satisfy a limited set of scientific objectives; aeroplanes seem largely impractical due to high power requirements or structural challenges. Airships and helicopters appear to be quite feasible, given several advantageous aspects of Titan's environment, and would satisfy the broadest range of scientific objectives.

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1. Introduction

Titan [1,2] is and will remain even a decade from now an object with particularly exciting scientific problems, some of which can be scoped even prior to the commencement and completion of the Cassini mission. In particular, high-resolution imaging, subsurface sounding and the prebiotic chemistry of water-exposed organics will be a focus of any future mission. Titan is also an exotic environment which challenges the exploration vehicle designer – the dense atmosphere, low gravity and the likely presence of widespread surface liquids force a plethora of vehicle options to be considered.

Presented in this paper are the most pressing scientific issues likely to remain after (and be stimulated by) the findings of the Cassini mission. Discussion follows on some of the mission options that may be the most appropriate for addressing these questions, noting previous mission studies. Finally, two of the more promising of these concepts are explored in more detail, and identify those technologies where technical development in the next several years might be best directed.

1.1 Titan

Titan is the largest satellite of Saturn, and unique in the solar system in that it is the only satellite with a substantial atmosphere. This atmosphere is both interesting, in that it is the only significant nitrogen atmosphere in the solar system other than that of Earth and also is host to extensive organic photochemistry, and frustrating in that these photochemical products form a thick haze (fig. 1) which until recently has impeded remote sensing of the surface.

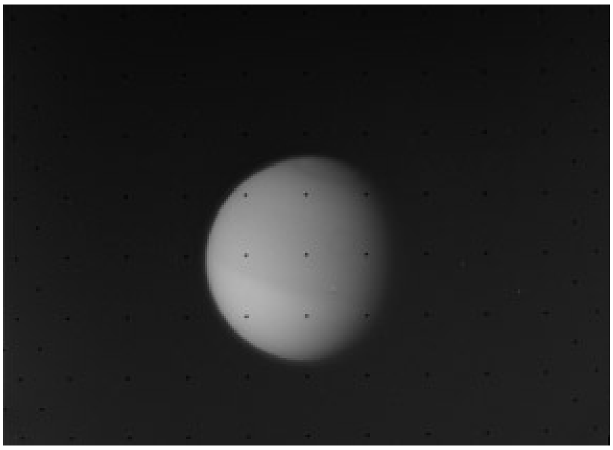

Fig. 1 Voyager Image of Titan (in blue light) showing the near-featureless haze layers. The northern hemisphere (at spring equinox in 1981) has a slightly higher haze abundance and hence is darker.

Titan's radius is 2575 km, fractionally smaller than Ganymede, and intermediate between that of Mars and the Moon. Its density has been determined at 1880 kg/m^3 – suggesting a roughly 50:50 mix of rock and ice. Titan is large enough that the energy of accretion should have softened and melted the outer layers of ice, allowing the rock component to settle into the interior forming a rocky core.

The surface gravitational acceleration is roughly $\frac{1}{7}$ of the Earth's. The surface atmospheric pressure is 1.5 bar, and the temperature of the atmosphere just above the surface is 94 K. The atmospheric density near the surface is therefore around 4 times that of the Earth. The composition is predominantly molecular nitrogen, with a few per cent methane, an undetermined amount (less than a few per cent) of argon, and traces of many organic compounds. The environmental parameters relevant to vehicle design are summarized in the Appendix.

The low gravity causes the atmospheric scale height to be large – around 40 km, or 5 times that of Earth. Thus the pressure and density of the atmosphere fall off very slowly with altitude – unity optical depth of the haze is reached at visible wavelengths at about 100 km altitude, and the Huygens probe deploys its parachute at an altitude of 170km – an altitude that might be considered 'space' on Earth: see fig. 2.

One particularly intriguing aspect of Titan is that methane, known since 1944 to be present in its atmosphere, is destroyed on short (~10^7 year) timescales by solar ultraviolet radiation. This implies that its presence in the atmosphere is buffered by resupply and/or a surface reservoir. Both methane and ethane, the latter being the dominant photochemical product of methane photolysis [3], are liquids at Titan's surface conditions – making a surface at least partially covered with hydrocarbon liquids a likely scenario [4]. Thus Titan's landscape may have been modified by marine, lacustrine or fluvial processes, like the Earth.

1.2 Cassini

All the above aspects of Titan have been known since soon after the encounter with Voyager 1 in 1981. The most obvious scientific questions stimulated by those findings were related to atmospheric photochemistry and the gross nature of the hidden surface. The Cassini mission was designed to address these questions, as well as many other aspects of the phenomenologically rich Saturnian system, replete with icy satellites, the archetypical ring system, a magnetosphere and two atmospheres.

The Cassini mission is described elsewhere in detail [5,6], but in brief it features a formidably-instrumented Saturn orbiter spacecraft – at over 4 tons launch mass, the largest interplanetary spacecraft constructed in the West. This vehicle is powered by 3 radioisotope thermoelectric generators and a 4 m high gain antenna. Its scientific instruments are body-fixed (scan platforms which would have dramatically enhanced the flexibility of the mission were deleted in a cost-cutting exercise in 1992). The orbiter will deliver a 350 kg European-built entry probe named Huygens [7] to Titan's atmosphere, through which it will make a 2.25 hour descent down to the surface. After the probe delivery, Cassini will orbit Saturn for another 3.5 years, making around 43 further flybys of Titan (whose gravity it uses to modify its orbit.)

With Titan's thick hazy atmosphere in mind, Cassini was equipped with a radar instrument [8]. As well as generating global coarse emissivity and reflectance maps of Titan's hidden surface, this instrument will make altimetric profiles across parts of the surface, and near closest approach will use synthetic aperture radar to image strips of the surface with resolutions as low as 500 m (about 3 times poorer than Magellan). Around 25% of the surface should be imaged this way.

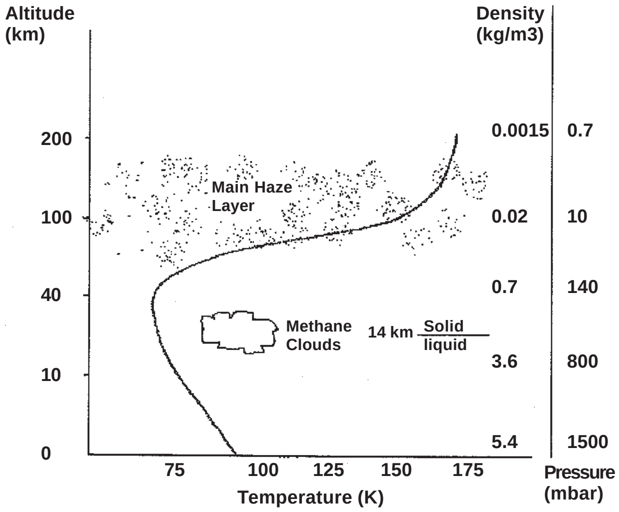

Fig. 2 Schematic of Titan's atmosphere: The line shows the temperature profile: the scale on the right shows pressure and density at each altitude. NB the altitude scale is non-linear.

Modelling of light propagation in Titan's hazy atmosphere in the early 1990s suggested that at some wavelengths, light might reach – albeit diffusely – the surface. The haze has an orange colour, and at near-infrared wavelengths is quite reflective. Further, since the haze particles are less than a micron in size ('diameter' is perhaps a poor term, since the particles are fractal aggregates rather than spheres) the optical depth of the haze drops significantly above half a micron. In between bands at which the atmospheric methane absorbs radiation, the total optical depth of the atmosphere becomes quite small. Groundbased spectroscopy [9] confirmed that the surface could be sensed (and that Titan's surface shows longitudinal variations in reflectivity) and in 1994 the Hubble Space Telescope created a map of Titan's surface [10], showing several dark spots and a large bright region (fig. 3). Recent advances in ground-based imaging (speckle imaging [11], and adaptive optics [12]) have made similar observations at 1.6 and 2 micron wavelength. The inferred reflectivity of the dark spots is incidentally <0.05 [11] , suggesting that these areas may well be lakes of liquid hydrocarbons.

Cassini carries a CCD camera [6] (able to image

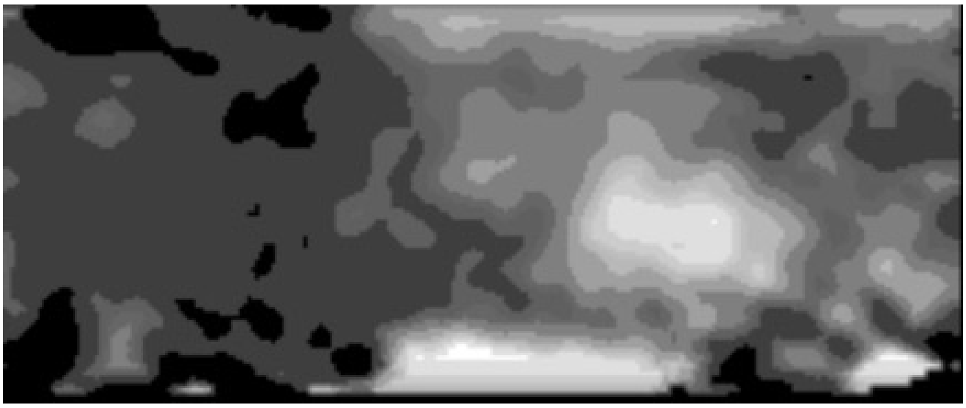

Fig. 3 Map of Titan's surface, derived from HST images at 0.94 microns. The large bright feature and several of the darker regions have been confirmed by other HST observations as well as new ground-based techniques. The dark regions are almost certainly covered in liquid hydrocarbons.

up to 1 micron – a rather longer wavelength than Voyager's vidicon camera) which should be able to image the surface in the 0.94 micron window at which the HST map was made. In principle, at closest approach (1000 km) the Cassini Imaging Science Subsystem (ISS) has a pixel scale of 6 m; however, the scattering due to the haze is likely to limit the practical resolution to perhaps 100 m or poorer, depending on the contrast in the scene and the phase angle of the observation. The Visual and Infrared Mapping Spectrometer will be able to image the surface in several windows at longer wavelengths (where the atmosphere is more transparent still) but at lower resolutions - down to 500 m.

The Composite Infrared Spectrometer (CIRS) will make detailed chemical abundance measurements throughout the atmosphere, constraining the photochemical processes at work there. Upper atmospheric chemistry – valuable for determining the energy deposition mechanisms that drive the photochemistry, and the escape processes that will have modified the inventory throughout time, will be constrained by the above instruments, and by sun and stellar occultations observed by the Ultraviolet Imaging Spectrometer and the direct measurement of species with the Ion and Neutral Mass Spectrometer.

On the Huygens probe, a Descent Imager/Spectral Radiometer will profile the haze properties with altitude, and will image the surface (albeit only a tiny portion of it) at resolutions of better than a metre. A gas chromatograph/mass spectrometer will make direct measurements of an even broader range of chemical species in the atmosphere at various altitudes, and using an aerosol collector and pyrolyzer will determine the composition of the ubiquitous haze. It will furthermore measure the isotopic ratios of several species (notably argon) which will provide valuable constraints on the initial volatile inventory and outgassing history of Titan.

Thus Cassini will reveal much of Titan's surface in detail comparable with the Magellan maps of Venus, or slightly poorer than Viking orbiter imagery of the surface of Mars. The details of atmospheric chemistry, and the formation and evolution of Titan – the two questions that received most attention in the wake of the Voyager encounters (which left geologists with little to discuss) will be amply tackled by Cassini's formidable array of instrumention.

1.3 Post-Cassini Questions

It is a canon of planetary science that a mission generates more questions than it answers, and Cassini may not be an exception – it is likely that Cassini's optical and radar images will be highly evocative, showing a world that while enormously different from our own, has some strange familiarity that begs closer inspection. Further, in the years since Cassini's inception, interest in the origin and evolution of life has been stimulated by the ALH84001 meteorite and the aggressive program of Mars exploration underway in NASA, and more recently ESA and the UK too. The key role of liquid water has long been noted in prebiotic chemistry [13], yet Titan is far too cold for liquid water to persist anywhere near its surface [14].

The low temperature causes the – initially exciting – organic photochemistry in the atmosphere to be an evolutionary dead end, producing only hydrocarbons and nitriles. Biological molecules contain oxygen as well as carbon, but the vapour pressure of oxygen-bearing molecules (even the simplest ones like water or CO_2) is so low that they condense out as trace solids in the haze at extremely small mixing ratios.

Thompson and Sagan [15] realized that the most exciting chemistry would occur on those sporadic instances where liquid water could act – albeit in a transient fashion – upon the organic haze that had sedimented onto the surface. Liquid water, and water-ammonia (ammonia acts as an antifreeze – the eutectic composition of 30% ammonia in water has a melting point of only 176 K) could be introduced onto the surface either as a cryovolcanic eruption, or as a result of crustal melting following an impact cratering event. While an ice crust would form immediately on a body of aqueous liquid emplaced onto the surface, it could take some thousands of years for a large body to freeze solid. These timescales are long enough that (a) significant hydrolysis of the nitriles to form amino acids could occur and (b) they are longer than laboratory investigation on Earth practicably allows. Thus a key issue is how complicated did the organics on Titan get before they froze solid: fig. 4 sets the scene for this question.

High-resolution imaging, while exciting in its own right for characterizing Titan's exotic landforms and the processes that shape them, will be essential to determine those sites where effort should be expended to sample and analyze surface material. While Cassini data at 100-500 m resolution may well identify candidate regions, it is probably not good enough to be certain of putting a lander on a site where it can drill or melt the surface ice to investigate its composition (just as Viking orbital imagery is not adequate for Mars sample site identification, but needs Mars Global Surveyor data at higher spatial resolution).

Another aspect of great interest, that will not be addressed closely by Cassini, is the subsurface, which may in fact be where the greatest fraction of the organic inventory of Titan resides [16]. Conventionally the subsurface of a planet can be probed in several ways – seismically (which obviously requires intimate contact with the surface), using subsurface sounding radar, and measuring magnetic and gravitational fields. Generally the latter two are performed on planetary bodies from orbit. On Titan, however, this is not possible, as the distended atmosphere makes orbits with altitudes of less than 1200 km or so unviable – atmospheric drag causes the satellite to re-enter within weeks. Yet 1200 km is half of a Titan radius, so the short wavelength components of any sensed fields are negligible – Titan resembles a point source and no details can be resolved gravitationally or magnetically. Thus these measurements require some kind of aerial or surface platform. There is a remarkable recent analogous situation for Mars – early measurements showed that it lacked a large intrinsic magnetic field, but it was only when measurements were made with more sensitivity and spatial resolution (read 'lower altitude' for both of these) that remarkable structures of remnant magnetization were found [17].

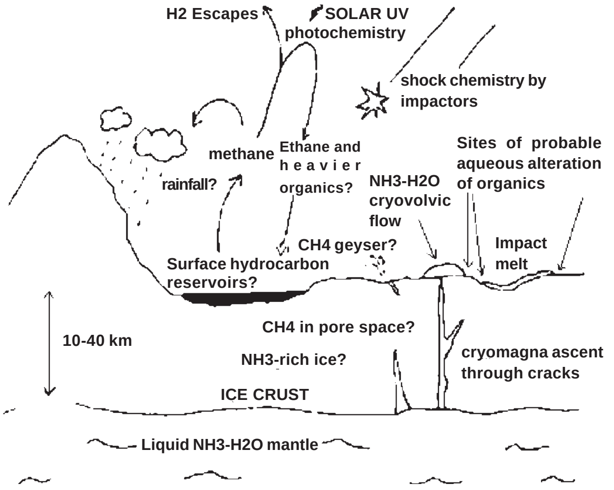

Fig. 4 Schematic of the dominant processes affecting the volatile inventory on Titan and the formation of prebiotic molecules.

Similarly subsurface sounding by radar can be performed from orbit (and indeed was done so on Apollo 17 [18], and is planned for both Europa and Mars). However, the orbital altitude there was a tiny fraction of the planetary radius, such that the time delay of an echo corresponds most closely to depth (i.e. a more or less 'flat earth' approximation applies). In Titan orbit, the curvature of the surface makes surface clutter a much more dominant contribution for a given echo delay, making it very difficult (to say nothing of the drop in signal to noise forced by the higher altitude) to extract any subsurface echo.

The above considerations are underscored in the report of the NASA-appointed Campaign Strategy Working Group for Prebiotic Chemistry in the Outer Solar System which was charged with developing scientific objectives and technology requirements for future missions to Titan and Europa. Their report [19], which guides the Solar System Exploration Subcommittee (SSES) and ultimately future NASA policy, states (my italics)

'the following *prioritized order* for immediate post-Cassini /Huygens exploration of Titan: *Surface, subsurface, and atmosphere*. With this in mind, our suggested priorities are to understand the following aspects of Titan:

(1) Distribution and composition of organics;

(2) Organic chemical processes, their chemical context and energy sources;

(3) Prebiological or protobiological chemistry;

(4) Geological and geophysical processes and evolution;

(5) Atmospheric dynamics and meteorology;

(6) Seasonal variations and interactions of the atmosphere and surface.

Thus while an orbiter may be useful for some of the more parochial scientific questions post-Cassini, the most pressing post-Cassini questions require access of the surface material in two or more locations, and the ability to perform sensing over wide areas of the surface using sounding or field measurement techniques from modest (<100 km) or low altitudes.

1.4 Why Now?

A legitimate question is ‘Why think about this now?’, years before Cassini has even arrived.

Applying reductio ad absurdum, one might retort that spaceflight would never have happened had thought not been given to what can or should be done in the future. Less facetiously, there are three principal reasons.

First, to capitalize on Cassini’s findings. Public interest in Titan will be very high after the first revelations of the surface, and thus support for the development of a future mission (particularly during its more expensive development and integration phases) will be strong. Were initial design efforts and technology studies to begin only after the Cassini tour began, support and interest may have waned before the higher-spending development phase is encountered, risking descope or cancellation.

Second, the outer solar system cannot be accessed with the same convenience or impulsiveness as Mars (i.e. a decision to suspend Mars exploration can be quickly reversed, and the results of a new initiative can be seen on timescales nearly commensurate with those of the election of politicians, offering them the hope of a useful public relations ‘payback’.) Titan trip times are in general long and mission opportunities infrequent (especially if Earth flyby trajectories are prohibited for political reasons associated with the use of radioactives). To add technology development and preliminary design phases to the critical path would push the mission back another several years, into the latter half of the 2010-2020 decade. (An admittedly null justification for Titan is that most aspects of these vehicles – especially heavier-than-air ones – is that they are largely insensitive to the present unknowns about Titan. While an efficient and robust design of passive buoyancy control of an aerobot [20] cannot be achieved given the present uncertainties in Titan’s tropospheric composition and temperature structure, nor can a balloon trajectory be confidently predicted given our near-complete ignorance of the winds on Titan, the detailed design and technology development for heavier-than-air vehicles can begin with the knowledge at hand.)

The third reason is geometric. Titan has an obliquity slightly higher than the Earth, with the result that large regions of the body are shrouded in polar night for nearly a decade at a time. At equinox (equivalently, the ring plane crossings seen from Earth) in 1995 and 2010, the sun is at the equator and the whole surface is illuminated. By 2015, the sun will be at 15 deg north and the southern polar regions will be in darkness. It is possible that a mission could simply ignore those regions, but I would contend we do not yet know Titan’s geography well enough to be sure that areas of great interest will not be there. A secondary consideration is that Saturn, whose orbit is appreciably eccentric - is at aphelion in 2019: the illumination available for imaging drops by about 10% from 2010 to 2019.

A related but perhaps more significant issue is that the haze in Titan’s atmosphere follows a seasonal cycle, with the spring hemisphere being darkest (more haze) near equinox (fig. 1 and fig. 5). Recent theoretical modelling [21], and observations with HST [22], indicate that the haze evolution is not gradual, decaying away, but rather the haze seems to suddenly ‘slosh’ from the spring hemisphere into the autumn one as the sun crosses the equator, and then only a gradual change for the next 10 years. Cassini will be arriving in a fairly quiescent period. It would be most desirable indeed to observe these changes in the 2010-2015 time frame to extend the time baseline of the Cassini observations, and capture the period when seasonal change is most rapid.

2. Previous Designs and Engineering Considerations

Titan’s exotic environment has prompted a number of imaginative ideas, and the present study is hardly the first. Entry probes were considered as early as 1973 [23]. A 1976 Martin-Marietta study considered penetrators, sounding rockets and balloons, as well as rather fanciful Viking-style landers [24]. A subsequent (post-Voyager) Science Applications International Corp study [25,26], guided by the same sci-

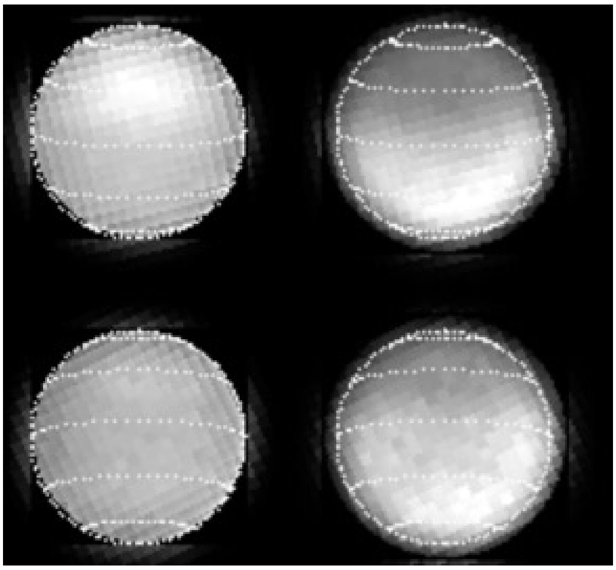

Fig. 5 Images from HST at blue (439 nm, left) and near-IR (889 nm, right) wavelengths, taken in 1994 (top) and 1997 (bottom). The north-south haze asymmetry in 1994 is similar, but reversed, from that seen two seasons earlier (fig. 1) but has all but disappeared only three years (one half season) later. The asymmetry is reversed in the near-IR, which also shows substantial year-to-year changes.

ence objectives that shaped Cassini, devoted particular attention to balloons and dirigibles as well as entry probes.

It is interesting to correlate these studies with their scientific setting with regard to Titan, and the political climate of solar system exploration at large. That Marietta (builders of the Viking landers) should advocate Viking-style landers is not surprising, and both that study and the SAIC one consider penetrators, a technology long advocated for Mars (and only presently underway). Both of these studies assume large delivery masses – using shuttle or Titan launches with high-energy liquid (or nuclear-electric) upper stages, a proposition that would be untenably expensive in the present epoch.

Since the Cassini development began, some other Titan concepts have been considered: in the early 1990's, when the prevailing paradigm of Titan's surface was a global hydrocarbon ocean [4] submarines [27] and expendable depth probes [28] were considered, although not in great detail.

With the (rather more interesting) expectation of a variegated solid/liquid surface, and the focussed objective of performing an inventory and analysis of surface and subsurface organics described above, new mission concepts need to be explored. Before particular concepts are described and evaluated, some engineering considerations are reviewed in the following subsections.

2.1 Power

Whatever vehicle architecture is chosen, to a first (or at least zeroth) order, data return may be related to the energy available. While distance to the Earth, antenna gain, use of relay orbiters etc. are all crucial factors, it takes 1 joule of energy (give or take an order of magnitude) to acquire and downlink 1 bit of information: see fig. 6. Thus we first consider the energy sources that might be applied to a future Titan explorer.

It may be noted that as a body is explored, the incremental information content (i.e. scientific value) of a bit of information falls, unless it is the result of a particularly novel measurement. Thus, after the Cassini mission a Titan explorer probably needs to return of the order of gigabits of information to be worthwhile. It follows that a mission requires of the order of 10^9 joules of energy – either stored or generated.

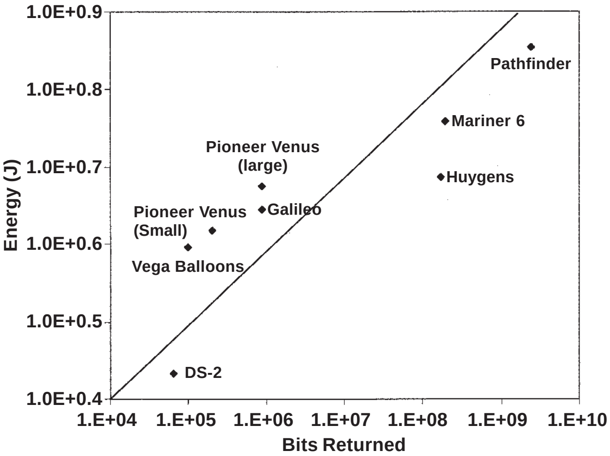

Fig. 6 Data return volume for planetary missions plotted against mission energy budget, data from A. Wilson, Solar System Log, Janes (1987) and other sources. The line shows a 1 J/bit relationship, which appears to be a good zeroth-order metric.

Batteries are not suitable for anything other than a short-duration lander mission. With state-of-the-art Lithium Thionyl Chloride cells at typically 100-400 W-hr/kg, a 10^9 J energy storage system would weigh 600-2400 kg: clearly absurd. It may be further noted that battery performance, even on comparatively warm Mars, is compromised by the low temperatures.

The same considerations apply for other chemical energy storage (e.g. monopropellant fuels for a mechanical engine to drive a propeller, or fuel cells). At the risk of considerable complexity, the mass requirements can be reduced by a factor of around 5 – not enough to justify the additional complexity.

One recurring idea (known to this author in the Marietta study [24] but perhaps originated earlier than that) is that the methane in Titan's atmosphere could be burned (in an oxidant brought from Earth) to produce power, or warm lifting gas in a hot air balloon. This idea, sadly, is bogus, in that a stoichometric combustion requires two molecules of oxygen (i.e. 32 atomic mass units, a.m.u.) to burn one of methane (16 a.m.u.) Thus, immediately it is seen that it is half as efficient to bring the oxidiser to Titan as to carry fuel on Earth, or equivalently only 50% better than bringing both fuel and oxidiser.

An important consideration for chemical energy storage is that at Titan's surface temperatures, the combustion products CO_2 and water (or water from fuel cells), would freeze, posing difficult exhaust blockage problems. Monopropellant hydrazine might do rather better with N_2 and H_2 exhaust, but some NH_3 would be present due to incomplete decomposition, and this would also freeze out.

Solar power is similarly difficult. At 9.5 AU from the sun, only 1.1% of the terrestrial solar constant is available. Worse yet, in Titan's lower atmosphere, only the red and near-IR wavelengths of sunlight penetrate through the haze : the total solar power density on the surface is a tenth [28] of that incident on the top of the atmosphere. Worse yet, almost all of that is at wavelengths longer than the work function of the most efficient photovoltaic semiconductors (i.e. a single photon does not have enough energy to promote an electron to the conduction band) like Gallium Arsenide, so conversion efficiency will not be as high as the state-of-the-art might suggest.

Realistically, the daily-averaged solar power available near Titan's surface is 0.25 W/m^2 times whatever conversion efficiency (15% ?) can be achieved given the weak red illumination. Thus a 5 m^2 array would take centuries to generate a GJ of energy.

Radioisotope power, while politically problematic, is therefore the only viable energy source for a Titan mission. This does not, however, imply the bulky RTGs used to date. Improvements in thermoelectric conversion efficiency suggest a 75 W electrical (600 W thermal assuming a 12% conversion efficiency, compared with the 5% typical of current devices) isotope source using the alkali metal thermoelectric conversion or 'AMTEC' principle weighing 15 kg should be available by 2005 [29]. For Titan aerial vehicles, yet higher powers might be available from the same isotope power source using thermal-mechanical energy conversion (using a Stirling cycle, for example) with conversion efficiencies of up to 30%. Since no other present applications are known to be under active development for such devices, the concepts discussed in the rest of this paper will assume the AMTEC thermoelectric device.

It may be noted that the thick cold atmosphere will be very effective at maintaining the cold end of the energy converter at a low temperature. The cold junction temperature will depend on the heat flow through the converter and the effective conductivity between the cold junction and the ambient infinite heatsink at 94 K. Most RTGs are cooled only radiatively, so the 'cold' junction is in fact quite warm (e.g. even in 1 bar atmosphere, the Ulysses RTGs were 'hot to the touch', according to one anecdotal report). On Titan, the 5.4 kgm^{-3} atmosphere should effectively quench the cold junction temperature: the thermoelectric conversion efficiency scales directly with the thermodynamic (Carnot) efficiency $(T_{hot}-T_{cold})/T_{hot}$. Thus performance calculations of a converter (thermoelectric or otherwise) should explicitly consider the cold junction temperature.

2.2 Communications

A JPL study [30] showed that using an omnidirectional S-band link from the Titan platform (i.e. imposing no attitude stability constraints) with an orbiter would allow contacts several times per day (important for maximizing the utility of the downlink by allowing interactive data selection by the science teams on the ground) could permit a data return of 2 Gb in 30 days.

An alternative [31] is to downlink data to Earth directly. With an omnidirectional link, this is possible, but only just (using the 34 m Deep Space Network stations, a downlink rate of about 5-10 bps might be possible – somewhat poorer than the current data return rate from Galileo). Use of the more sensitive 70 m stations would enable a factor ~4-10 improvement in these numbers, but would probably be prohibitively expensive to encumber for a mission of many months in duration.

A high gain antenna for direct-to-Earth communication would allow much higher data return – a 1.8 m antenna at X-band would permit 1 kbps downlink with a reasonable RF output power (25 W) to a 34 m DSN station, but would require pointing to better than 1.2 degrees, which is probably difficult to achieve on an aerial platform. Accommodation of such a large dish antenna on an aerial platform might impose severe aerodynamic penalties. However, use of a terrestrial signal as a beacon, and flat phased-array electronically-steerable antennas might ameliorate both of these difficulties.

Equivalent beamwidths (i.e. gain) can be achieved using a smaller antenna by moving to Ka band (32 GHz) bringing antenna diameter down by a factor of three or four. Unfortunately attenuation in Titan's atmosphere at this wavelength has not been evaluated, so there is some uncertainty in the viability of this option. Further, the manufacturing tolerances on such short wavelength dishes would be tight, making the equipment relatively expensive.

One option that would be worth exploring – if very accurate pointing is possible, as from a platform on Titan's surface - is optical communication. Although the haze will introduce some scattering, the absorption opacity in the methane windows is fairly low. In particular, the 1.04 micron window is coincident with the wavelength of light emitted by Nd:YAG laser materials (used, for example, in the Mars Orbiting Laser Altimeter MOLA on the Mars Global Surveyor). Longer wavelength lasers yet are under development and could take advantage of the yet lower haze opacity at longer wavelengths. If this method could be proved viable, it may be cheaper to set up a network of optical telemetry stations on the Earth than use the overcommitted DSN or construct a relay spacecraft, although the pointing accuracy would have to be high.

In summary, although it adds significant complexity and expense, an orbiting relay may be the most efficient way of conducting communications, both for the link budget reasons discussed above, and because in principle it would permit regular (~once/day) contact. A workable alternative, subject to accommodation issues and pointing ability, is to use a high-gain X-band antenna mounted on the vehicle. Ka band and optical techniques require further study.

2.3 Delivered Mass

In the 2008 to 2010 timeframe, Jupiter gravity assists are not available. Earth swingbys are ruled out owing to the use of radioisotope power supplies. A Delta III with a solid upper stage could deliver ~200 kg on a direct trajectory on a type 1 transfer [30]. Venus flyby trajectories are possible, adding somewhat to flight time, but allowing perhaps 400 kg delivered mass to the Saturnian system.

Much larger delivered masses (~1000 kg) are possible using Solar Electric Propulsion, although at much higher cost and risk.

These are delivered masses to the Saturnian system. Unlike Cassini, a Titan-dedicated mission could enter Titan's atmosphere directly from its interplanetary arrival trajectory. An orbiter could be aerocaptured by ballute.

For the purpose of the present study, which does not consider costing issues quantitatively, the direct delivery will be assumed, and thus vehicle masses of the order of 50-100 kg are considered, allowing for entry protection and a possible orbiter. While these masses are indeed small compared with Viking and even Pathfinder, in the context of modern highly-integrated systems such as DS-2 and Beagle-2, highly capable instrumentation and its support systems should be achievable.

2.4 Thermal

Titan's thick, cold atmosphere poses a more difficult challenge in some respects than does the cold of space. First, multilayer insulation does not perform well, since the interlayer gap is filled by gas, so foams or dewars must be used to provide insulation.

That said, it is easier to have electronics work while very cold than while hot – the microcontroller on the DS-2 Mars microprobes, for example, operated satisfactorily at temperatures below 200 K. However, sample handling and energy storage systems at least will probably need to be kept well above the ambient temperature.

The thermal regime provides another motivation for retaining radioisotope power in that the thermal output of the device can be used to keep the electronics and systems warm.

2.5 Entry and Descent

Delivery to Titan's surface or lower atmosphere, while a formidable engineering challenge, is from a purely physical point of view quite straightforward. Titan's large scale height makes it the easiest atmosphere in the solar system into which to enter – even vertical entry is possible (if not optimal) for conventional thermal protection materials, in contrast to the grazing entries required for the terrestrial and giant planets.

The packaging and deployment issues associated with balloons, airships or aircraft are certainly nontrivial, but are likely to be amenable to skilled engineering design.

3. Instrumentation Applications

Some of the likely instrumentation has been alluded to earlier. Indicated here are specifically what measurements might most usefully be made.

3.1 Surface Chemical Composition

It may be that novel instrumentation may be more appropriate for the organic and prebiotic chemical assays that will need to be made than the gas chromatograph traditionally used for planetary exploration. There is considerable activity and progress in this area, for which advances are expected and sought in connection with the search for life on Mars and Europa. Chemical-specific electrodes, fluorescence techniques, Raman spectroscopy and others are possible candidates. All, however, will require some kind of sample acquisition system (except perhaps the Raman technique, which could conceivably be performed in a non-contact mode). Ideally, a system would be able to sample a few (~10) cm down, to investigate near-surface composition gradients.

3.2 Magnetometry

A small magnetometer would be a worthwhile payload element: Cassini will be unable to resolve small-scale anomalies because of the high altitude of its flybys. Measurements of the magnetic field on Titan over several Titan orbits will be of considerable interest in that these will probe the deep interior - this technique recently indicated the existence of a conductive layer in the interior of Callisto [32]. Since Titan's orbit is somewhat eccentric, the strength of Saturn's field varies over the course of one orbit (16 days), although the excitation is not as large as for the Galilean satellites, bathed in Jupiter's strong and inclined field. The induced fields and currents within the deep interior of Titan will depend on the conductivity profile of the crust and mantle, and in particular the presence of a molten layer.

A simple fluxgate magnetometer – such as have been used on spacecraft for attitude determination – would be adequate for this measurement, and would weigh about 0.1 kg.

3.3 Meteorological Sensing

Although Titan's weather is expected in general to be fairly quiescent (as a result of the thick atmosphere and great distance from the sun) there are known to be time-variable cloud phenomena [33] – almost certainly associated with tropospheric methane, and possibly with methane rainfall. Monitoring temperature, pressure and methane humidity will be valuable. Methane humidity may be measured with a simple absorption cell – possibly, but not necessarily, using a tunable diode laser. Speed of sound measurements can also be easily accommodated on a vehicle, and if the temperature is known, methane abundance can be inferred.

Simple pressure and temperature measurements would be taken as a matter of course. Resource requirements for such sensors are very modest.

3.4 Subsurface Radar Sounding

Detecting conducting layers – notably water-ammonia cryomagmas beneath the surface would be important in constraining the thermal evolution of Titan, and identifying areas where recent cryovolcanism has occurred, and in turn where aqueous/organic chemistry may have occurred.

One caveat Is that Titan's subsurface may be somewhat radar-absorbing, due to ammonia in the ice itself [34]. Even in this pathological case, a simple sounder would return very worthwhile data in that it could measure the depth profile of any hydrocarbon lakes and seas, thus constraining the volatile inventory on Titan.

3.5 Imaging

Side-looking imaging from an aerial platform in many respects offers a more intuitive 'airplane window' perspective on geomorphological structures than the nadir-viewing typically offered by satellite imaging. Also, since there will be relatively little topographical information returned on Titan from Cassini (a few radar altimetry tracks and perhaps a few stereo imaging observations at optical wavelengths – at uncertain resolution owing to the scattering by the haze) side-looking imaging will give much novel geomorphological information.

As well as geomorphology for geomorphology's sake, the imaging will provide new insights into Titan's meteorology, revealing clouds and rain, as well as wind effects on liquid surfaces (waves and froth). Many physical processes that occur on spatial scales too small to be resolved from Cassini observations, including tides, aeolian transport etc. will also be open to study.

Finally, high resolution imaging will be important for identifying the very localized targets for chemical analysis.

3.6 Other Measurements

Other measurements are obviously possible. Considering the subsurface in particular, some kind of seismic sensing would be of great interest, given the tidal excitation of Titan's crust and interior. Some kind of gravity gradiometer (such as are used for terrestrial gravity surveys by aircraft) would be of interest – and indeed is probably the only way of detecting gravity anomalies given the thick atmosphere.

4. Vehicle Concepts

A variety of platform options are presented in fig. 7.

A key (and at present unresolved) question is how at many surface locations must in-situ sampling be performed. If only one or two, then individual landers may be able to meet the objectives, although wide-survey imaging and field measurements will not be accomplished. Further, the landers must have a targeting precision as good as the knowledge of the target location (which I have argued is not adequate to identify surface landing sites, although this issue could be tackled by making the lander mobile.

Unless all the targets are within a few km (at most) of each other, rovers are unlikely to offer adequate range to visit them all.

Since the fundamental engineering uncertainty at present is the trafficability of the surface, aerial concepts are in fact the most conservative. However, their capabilities with regard to the primary objective of sampling the surface narrow down the options – aeroplanes specifically are challenged in this regard. One possibility is that if the required surface analysis instrumentation can be made small enough, expendable drop-sondes could be released from the platform to investigate the surface. If relatively few sites are to be investigated, this is a potentially attractive option. However, since such sondes would almost certainly need to melt some of the surface material in order to analyze it, small sondes are unlikely to be adequate.

Passive balloons and/or aerobots (balloons with altitude control) could perform surveys, although probably only over very restrictive latitude ranges [35] since the meridional winds are weak.

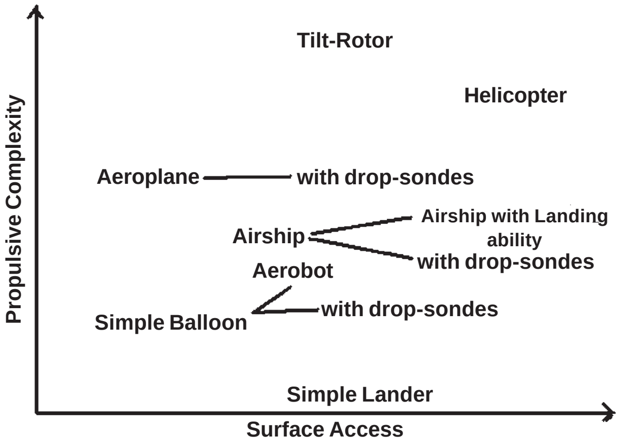

Fig. 7 Crude overview of possible aerial vehicle types.

Propelled aerial vehicles are likely then to be the only ones able to perform global survey and allow the precision delivery of surface sampling instrumentation. Propulsion for such vehicles is likely to be the main driver on power requirements.

The power for various flight vehicles can be estimated from formulae developed in a separate study [36]. These powers are derived from regression of statistics of a wide range of terrestrial vehicles, and fold in factors such as propulsion efficiency not considered in previous studies [24,35].

Propeller-driven aeroplanes (typical of terrestrial remotely-piloted vehicles and light and transport aircraft) have a flight power of 10.9 $(g/g_e)\ m^{0.9}\ V^{0.8}$ where m is the mass in kg and V is the flight speed in m/s, g is the acceleration due to gravity, with subscript e denoting the value for Earth. It may be noted that Titan aircraft gain a factor of 7 from the reduced gravity. A 100 kg vehicle flying at 10 m/s would need a power (W) of about 600 W – requiring ambitious energy conversion. Flying at 1 m/s would reduce the power to around 60 W, a level that could be (just) sustained continuously by an AMTEC converter. However, such a low flight speed would require a very large wing area, making the required structure resemble that of human-powered aircraft like the Gossamer Albatross. It seems difficult to envisage such a vehicle being deployed reliably on Titan.

For continuous flight, lighter than air options offer clear power savings (and propulsion can be applied with a non-unity duty cycle, without fear of surface contact). Propulsive power for airships is given by $1.5m^{0.6}\ V^{1.85}\ (\rho/\rho_e)^{0.33}$ – note that a more dense atmosphere is harder to push through (although for a fixed total vehicle mass, the payload mass fraction will be much higher in a denser atmosphere since the lifting gas and envelope masses can be smaller). As might be expected, the speed dependence is stronger, but the mass dependence weaker. Again for a 100 kg vehicle at 10 m/s, the power is impractical ~ 2.5 kW, although at 1 m/s, the power is a very manageable 40 W.

A 100 kg airship would require a lifting gas volume of around 25 m^3, and hence about 15 kg of helium lifting gas (less for hydrogen). Again, this is a quite reasonable number. Detailed design would be needed to evaluate envelope mass and lifting gas diffusion rate. It may be noted that a large high gain antenna could be installed within the envelope, so aerodynamic penalties with this option would be avoided.

Helicopter forward flight speed is difficult to consider, but power can be estimated from that needed to hover. Realistic vehicles typically have installed powers of about twice the ideal (‘actuator disk’) hover power of $(mg)^{1.5}/(2\rho A)^{0.5}$, where A is the rotor disk area. This latter property, again for practical structures on terrestrial crewed and model helicopters, scales as $m^{0.8}$, such that terrestrial helicopters have powers of about 100 $m^{1.1}$ W. Taking a 100 kg terrestrial helicopter to Titan gains a factor of $7^{1.5}$ from the reduced gravity, and 2 from the higher density, giving a remarkable factor of 38 reduction in required power. Thus a 100 kg Titan helicopter – even without special effort to reduce power by having longer rotor blades – would require about 450 W to hover. In steady forward flight, the power will be somewhat less. Maximum forward speed for a given power is difficult to estimate, but similarity arguments suggest [36] that several metres per second can be expected for this power and mass combination.

As for the 10 m/s aeroplane, this value is too high for continuous use: unlike the aeroplane, however, the helicopter can easily land. Furthermore an efficient planetary mission will generate data (from imaging of new areas for example) at a rate comparable with that at which it can transfer that data to Earth.

Thus an efficient design will not try too hard to

TABLE 1: *Exploration Vehicle Concepts.*

Concept	Meteorology	Surface Coverage	Surface Access	Tech Risk	Programmatic Appeal	Technology Required	
Simple Balloon	+	-	--	+	+		Cheap. Confined to a single line of latitude?
Aerobot	+	-	+	-	+		as above.
Airship	+	+	+	-	++	Navigation, Landing, Stationkeeping	active altitude and near-surface position control
Airplane	+	++	-	-	+	Navigation, Structure or Power Source	good survey platform, but generates data faster than it can download.
Helicopter	+	+	++	-	++	Navigation, Landing, Energy Storage	ideal for main science objectives.
Tilt Rotor	+	++	++	--	++	Navigation, Landing	better cruise performance than helicopter, but more complex.
Simple Landers	-	--	++	++	-	Precision Landing	Cheap. Important to land in the right place. Does not address survey objectives.
Gliding Lander	+	-	++	-	+	Precision Landing, deployment mechanics	simple lander, but with gliding parachute allows brief survey.
Rover	-	-	++	-	-		Surface Trafficability unknown. Limited range

‘Stationkeeping’ denotes near-surface position control – gust compensation, buoyancy management etc.

cover area rapidly (i.e. the average speed will be low). However, a vehicle with a very low airspeed will not easily traverse to targets of particular scientific interest, identified in Cassini data for example. The solution is a vehicle that can fly at modest speed, but spends substantial periods unpowered – on the ground. Thus the helicopter is the favoured mission concept.

4.1 Mission Concept 1 – Titan Helicopter

Scientifically, the ability to land and take off to other sites is essential for the goal of measuring the detailed composition of surface materials – and it is on the surface that the most interesting organic compounds will have been formed.

Spending extended periods on the ground is also scientifically attractive for other disciplines. It would allow seismic observations – the tide excited by Saturn's gravity and Titan's eccentric orbit is likely to stimulate crustal activity. Additionally, a fixed location from which meteorological changes will be useful – there are diurnal insolation variations, perhaps with small temperature effects, as well as pressure perturbations due to passing weather systems and the atmospheric tide. A fixed observation point from which the effects of the changing magnetic field in which Titan is bathed allows magnetotelluric sounding of the interior. The novelty of these measurements promises a rich scientific return, yet the mass, power and data requirements of all of these instruments are very modest.

The diurnal cycle indicates perhaps the most appropriate period for the vehicle to spend on the surface – night. During that time (roughly 8 terrestrial days) the vehicle can store energy for its daytime flight, as well as download (if an orbiting relay is present) the large volume of data acquired during the previous flight and landing and subsequent chemical analysis. Data acquisition during this period will be modest (it is dark) – limited to the geophysical and meteorological monitoring mentioned above.

A fixed-wing aircraft poses significant uncertainties with regard to its ability to land and take off safely on a surface of unknown roughness (and indeed, stickiness). A helicopter (or tilt-rotor aircraft), while fanciful at first sight, may be the most prudent engineering solution.

Thus, while 0.45 kW should be available for peak loads, the cruise flight power will actually be much less – the energy required to fly for 12 hours, for example, will be of the order of 3 kW-hr , or 11 MJ, although since ~50 W will be available from the AMTEC source this reduces the stored energy requirements to perhaps 2.5 kW-hr, an amount easily replenished during the ~8 day Titan night.

At 6 m/s, a 12 hour flight will cover some 200 km, a range that should allow a new safe landing site (the 'staging area') to be reached. 2.5 kW-hr is quite a significant energy-storage requirement, requiring 50 kg of NiCd batteries at 50 Whr/kg. However, battery technology is improving all the time, and NiMH and Li-ion technologies can perform 2-3 times better, making a manageable 20-30 kg battery mass. Thermal design needs to be careful to keep the batteries at their required operating temperatures, or low-temperature battery technology needs to be developed.

During the flight, ground-penetrating radar would generate a profile of subsurface topography (notably the bed of any hydrocarbon lakes or seas) and detect any near-surface intrusions of water-ammonia cryomagma. Simple and compact instrumentation would also monitor spatial variations in methane abundance due to meteorological process or release at the surface.

At an altitude of 5 km, this 200 km flight uncovers some 2000 square km of new territory. Imaged at 1 m resolution and 8 bits/pixel, this generates about 16 Gbit of data. Although probably only a fraction of this can be telemetered back over the subsequent 16 days, the downlink is stepwise, allowing transmission of 'thumbnail' or 'jailbar' previews to the ground first. Science teams on the ground would then select the most interesting subset of the data for subsequent complete downlink. This approach is already used on the Galileo mission, and has been also used for Earth-imaging from the University of Surrey UoSAT series – both limited downlink-situations.

The first priority will be the identification of the next target for surface sampling (in the latter part of the flight data, close to the landing site). The staging area will have been chosen from existing data as a safe landing zone, and the vehicle may spend a couple of days here recharging while the target data is downlinked. Once the nearby (few km away) target has been designated by the science teams, the vehicle can take off and traverse there.

After more close-up imaging, the vehicle would perform in-situ analysis of the surface material as night falls, and the cycle would begin again.

4.2 Mission Concept 2 – Titan Airship Explorer

This concept would feature an airship delivered to Titan's lower atmosphere. It would drift westwards in the zonal winds, while slowly traversing north-south under its own propulsion.

The vehicle will slowly (quite slowly, since the low temperature at Titan makes diffusion of air into the envelope, and of lifting gas out of it, slow) lose buoyancy. This can be compensated to a limited extent by topping up the envelope from a pressurized reservoir. The lost buoyancy can also be compensated by the release of ballast.

Taking ballast from the Earth to Titan is clearly a wasteful proposition, unless the ballast serves a useful purpose. One obvious idea is to have instrumented ballast, namely dropzondes, although whether the rate at which ballast needs to be released corresponds exactly with when scientifically the most interesting targets are encountered is at best uncertain. One reasonable scenario is that one or two dropzondes are employed in a 'contingency' investigation at the start of the mission, and the rest are retained until a wide-area survey mission is complete.

Since re-encounter of targets can be more-or-less predicted – the vehicle needs only to move to the correct latitude and it will eventually drift over the target. By then descending into the atmospheric boundary layer (where windspeeds are low) it can loiter in proximity to the target, conducting further investigations with higher spatial resolution, and/or deploy more drop zondes. If the vehicle has a large buoyancy control range, it could perhaps land.

4.3 Mission Concept 3 – Gliding Lander

This concept largely sacrifices the survey objectives (or leaves them to a lighter-than-air platform *without* surface access capability). The landers would be deployed at about 200 km altitude (a slightly higher altitude than Huygens – a lower mass/area ratio is assumed) and would deploy a parawing. With a modest 5:1 glide ratio, they could traverse to their designated landing sites over several hours, covering over 1000 km (the exact value depends on the strength of the zonal winds and the flight direction – downwind obviously allows the longest traverse).

This traverse would allow some limited imaging and magnetic survey before landing at the designated site. After landing, the vehicle could perform surface sampling, local imaging and seismic/magnetic/meteorological monitoring.

Such a (limited) mission – which would essentially only be worthwhile if it could be accurately targeted – could perhaps be performed using primary battery power, although this will limit both the mission duration and total data return.

4.4 Technology Development Needs

The concepts and considerations outlined above point out a number of technological areas where development could particularly facilitate (or enable) a Titan mission. These include

(1) Instrumentation. Compact, low-power radar sounder. Compact prebiotic chemical analysis and sample acquisition/handling/melting. Evaluation of the capabilities of ~1 kg dropzondes.

(2) Power. High-efficiency thermoelectric or thermodynamic energy conversion, taking the peculiarities/advantages of the Titan environment into account. Energy storage technologies (also taking environmental issues, notably temperature, into account) need to be identified.

(3) Communication. Integration of direct-to-Earth downlink capabilities with an aerial vehicle – evaluation of aerodynamic penalties associated with large high-gain antennas, pointing performance requirements corresponding to various gust loading scenarios. Ka-band and optical communication have not been evaluated in detail, but offer superior performance.

(4) Control – autonomous landing, inertial navigation.

(5) Aeronautical/Structural – detailed aerodynamic design, noting the Reynolds number regime and packaging/deployment issues. Optimization of wing or rotor design. Evaluation of lifetime-limiting factors (diffusion through envelope for lighter-than-air vehicles).

(6) Environmental – Adhesion of low-temperature organics : landing gear design and thrust margin. Thermal insulation performance in wind/flight conditions.

(7) Mission – Direct delivery scenarios, trading flight time against arrival declination (low declination allows lower entry speeds and hence lower heat loads)

5. Conclusions

The mission concepts outlined above are only three members of an infinite set of possibilities. They have been guided by the present author's ideas of the most important scientific issues, together with an engineering assessment of what is likely to be achievable, and an aesthetic desire for 'efficiency' – to match the mission's data-gathering profile with the rate at which it can be downlinked and assimilated by the scientific community to optimize the rest of the mission. Clearly a wider technical and scientific review of these concepts (or variants of them) is appropriate: it is hoped that this paper will stimulate such discussion. It may even be that a combination of vehicles would offer the best overall science return.

Technological development needs have been identified, and several vehicle types and mission concepts evaluated.

Orbiters do not usefully address post-Cassini objectives, but do facilitate communication with Earth from mobile platforms, both in terms of contact during Titan night and increasing total data return without imposing accurate pointing on the mobile vehicle. Nonetheless, particularly for vehicles with landing capability, direct-to-Earth communication is possible using a high-gain antenna.

A helicopter mission uniquely benefits from Titan's environment and offers substantial appeal – from a technological perspective, as well as to the public at-large. It furthermore addresses the broadest range of scientific objectives.

An airship, particularly with good buoyancy control and/or a set of deployable probes for surface investigations, is a possible although weaker alternative. Aeroplanes appear essentially impractical. Balloons and landers are quite feasible, but address a much narrower set of science objectives.

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A. Appendix: Titan Aircraft Environment Specification

A.1 Gravity

Titan's surface gravity is 1.35 ms^{-2}. This value may be assumed constant throughout the troposphere (0-40 km) although it falls off significantly at higher altitudes according to the inverse square law: Titan's surface radius is 2575 km.

A.2 Composition

Titan's atmosphere is dominantly nitrogen, with a small quantity of methane (around 1.7% at high altitudes, possibly increasing in the lower troposphere to several per cent). Argon may be present at a level of a few (<5) per cent, although it has not been detected. Hydrogen, and many hydrocarbons are present at trace levels. For parameters such as viscosity and speed of sound, a pure nitrogen composition can be assumed with only modest error.

A.3 Density

I use a six-term polynomial fit to the tabulated Lellouch-Hunten [7] Titan atmosphere model developed for the design of the entry system of the ESA Huygens probe. Specifically, the density $\rho(h)$ in kgm^{-3} for the full 0-1000 km altitude range can be specified as

$$\log_{10}(\rho)=A+Bh+Ch^2+Dh^3+Eh^4+Fh^5$$

with A=0.778687, B=-0.029026, C=7.3195e-5, D=-1.12923e-7, E=7.81597e-11, F=-1.98452e-14, with h the altitude in km. While suitable for entry studies at high altitude, this polynomial is not an ideal fit for the lowest couple of scale heights of the atmosphere.

For the 0-40 km altitude range of interest for this study, the following polynomial is more accurate: A = 0.72065, B = -0.0128873, C = -0.0003254, D = 2.50104e-6, E = 6.43518e-5, F = 0.

NB at these modest pressures and low temperatures, there are deviations from the ideal gas law of several per cent. These non-idealities are not considered further, since measurement uncertainties and spatio-temporal variations of that order also occur.

A.4 Temperature

The temperature structure may similarly be specified by a polynomial. Nominally, in the lowest few km of the atmosphere, $T(h)=T_0-1.15h$, with T_0 the surface temperature. The canonical value for T_0 at the equator is 94 K, but extreme models allow a range of 90-99 K. In any case, some small (~2 K) latitudinal and seasonal variation is likely. Above 100 km or so, in Titan's stratosphere, the temperature is around 170 K.

A.5 Speed of Sound

The speed of sound depends on molecular mass and ratio of specific heats as well as temperature (and, indeed, the speed of sound is to be measured on Huygens for this very reason). But assuming a nitrogen composition, the speed of sound at the surface is roughly 200 m/s, or about 55% of that at the Earth's surface. Mach number for a given flight speed is correspondingly higher on Titan.

A.6 Viscosity

Although not traditionally used directly in vehicle design, the atmospheric viscosity μ is important in that it controls flow over surfaces. These effects are parameterized through the Reynolds' number $Re=\rho v l/\mu$ with v the flight speed and l a reference length (e.g. wing chord)

It may be noted that the low temperature, and hence low viscosity, is useful in that it increases the Reynolds number for a given vehicle compared with terrestrial conditions (in the same way that cryogenic wind tunnels are used to increase the test Reynolds number) – thus ameliorating some of the adverse low-*Re* effects encountered with small vehicles such as low lift-to-drag ratio.

The viscosity of nitrogen (and thus, to a good approximation, Titan's atmosphere) is roughly $1.718\text{e-}5 + [5.1\text{e-}8 * (T-273)]$ Pa s, with T in K as above. Thus, the viscosity is roughly half that of the Earth's atmosphere.

A.7 Icing

The possibility of icing exists in Titan's atmosphere, in that certain altitude regions are below the freezing point of the condensable atmospheric constituent, methane. Specifically, above 14 km altitude, according to the nominal temperature profile, a nitrogen-methane gas mixture can be in thermodynamic equilibrium with a solid nitrogen-methane solid phase (ice or snow). Clouds at this altitude should, therefore, be clouds of ice crystals.

As on Earth, however, crystallization may be kinetically inhibited, and supercooled liquid droplets may be present. If these impact upon a flight vehicle, the surface of the vehicle will nucleate crystallization and the droplet will freeze in place – this is the mechanism of icing on terrestrial aircraft. The author of the present paper and others made a brief study for Huygens, and it was concluded that while some icing may occur, the effects on a free-falling probe will be minimal. As on terrestrial aircraft, however, ice build-up can disrupt airflow on lift-generating surfaces and degrade the lift-to-drag ratio, perhaps catastrophically.

A further uncertainty exists in that droplet nucleation itself may be strongly inhibited, and thus the atmosphere may be supersaturated with vapour.

The substantial uncertainties in all these effects argue that altitudes above about 10 km be avoided.

A.8 Winds

The dominant circulation on Titan, as on Venus, is zonal, with speeds of up to 100 m/s at high altitudes (200 km). The direction appears to be prograde, although the observations indicating (or rather, confirming, since this direction was always expected) prograde rotation are generally, but not universally, accepted.

Substantial variations must occur with altitude and latitude: winds probably peak at around 60 degrees latitude, and decrease at lower and higher latitudes. Winds decrease at lower altitudes to a low (but uncertain) speed near the surface. A ballpark value of about 10 m/s at 10 km altitude may be assumed, but the envelope of possible winds is 0-20 m/s.

Meridional (N-S) and vertical winds, on a planetary scale are very small (mm/s) although in conjunction with (sporadic i.e. low-probability) weather systems could be higher.

As for near-surface winds, planetary momentum balance requires that the average wind be zero, but the typical wind speed is of course not. A couple of physical scale speeds can be derived [37], specifically one relating the rotation rate and the Ekman depth (i.e. the transfer of momentum by eddy viscosity), and a speed related to the transport of heat around the planet. These scale speeds correspond to surface wind stresses, not necessarily to physical speed of air at a given altitude: however such speeds will scale linearly with them.

For the Earth the speeds are 0.2-0.3 m/s, while for Mars 0.8-1.6 m/s. Both Venus and Titan have speeds of 0.003-0.01 m/s - or a factor 30-100 slower than on Earth (as might be expected 10 times further from the sun).

Wind speeds on Earth within a few metres of the ground are typically ~5 m/s, although highly skewed distributions exist, and are usually described by a Weibull distribution of the form

$$P_{(>v)} = \exp\left(-[v / c]^k\right) \qquad \text{(A1)}$$

with P the probability of winds exceeding a speed v; c and k are a scale speed and a shape parameter respectively. For many terrestrial locations c ~4-10 m/s and $1.2<k<2$. Even in relatively windy locations (selected for their wind energy potential) winds exceed 10-15 m/s only for about 10% of the time.

Similar fits to Martian wind speeds measured by the Viking landers [38] yield in fact quite similar numbers, although the tail of the distribution is slightly longer (k is lower, owing to the violent dust storms). However, it should be borne in mind that these measurements were taken at an altitude of 1.6 m, compared with the 10 m that is normal for terrestrial wind measurements. Scaling by the logarithmic profile in typical atmospheric boundary layers suggests that the corresponding 10 m speeds for Mars are probably a factor of ~2-3 higher, more or less commensurate with the relative scale speed indicated above. Thus we may have some better-than-order-of-magnitude confidence in the relative wind speed estimated in this way.

It seems, therefore scaling the typical Earth speed by the relative Titan scale speed that near-surface windspeeds on Titan are likely to be under 0.2 m/s, and perhaps well under 0.1 m/s.

A.9 Weather

There have been indications from HST observations, and ground-based spectroscopy, that large-scale ‘clouds’ exist. Their optical depth is uncertain; they last at least for several tens of hours, but cover (as far as the sparse observations to date indicate) at most a few per cent of Titan’s disk.

Methane rainfall may occur, but is not well-constrained.

The hazard due to lightning was determined for Huygens (~2 hr descent) to be small. Depending on the duration of the aircraft mission, this hazard (and that due to triboelectric charging of the aircraft) might have to be re-evaluated.

A.10 Insolation

Although details (like multiple scattering from fractal particles) are a subject of much ongoing work, to a first order the insolation environment is well-understood. Insolation at the top of Titan’s atmosphere varies between about 16.8 $\mathrm{Wm^{-2}}$ at perihelion (June 2003) to 13.6 $\mathrm{Wm^{-2}}$ at Aphelion (about 15 years later). Virtually all blue light is absorbed by the stratospheric haze. Selected red and near-IR wavebands are absorbed by methane in the atmosphere

To a first order the resultant downwelling flux near the surface (i.e. that available to a near-surface aircraft) is triangular, zero at about 0.4 microns, reaching a maximum at 0.6-0.7 microns, and falling off again. The total flux is about 10% of the flux incident on the top of the atmosphere. A significant fraction of the flux at selected near-IR wavelengths does reach the surface (useful, perhaps, for sensing the sun), but the power content is very low since the solar flux is small.

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