Optimizing Science Return from Titan Aerial Explorers

Ralph D. Lorenz[1],
Lunar and Planetary Lab, University of Arizona,
Tucson, AZ 85721-0092, USA
tel 520 621 5585 fax 520 621 4933
e: rlorenz@lpl.arizona.edu

This paper explores the scientific challenges of post-Cassini exploration of Titan, Saturn's giant, hazy moon. In particular, the scientific objectives are addressed, and the vehicle types that might be most appropriate are considered, paying particular attention to the energy required for mobility, for acquiring data, and downlinking it to Earth, and to the rate at which science data can be acquired. While many mission types are possible, a helicopter mission, flying only 10% of the time, may offer the best overall scientific return.

1. INTRODUCTION

Titan

Titan [1] 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 photchemical products form a thick haze which until recently has impeded remote sensing of the surface.

Titan's radius is 2575km 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: Titan's surface should be mostly of light materials – ice and organics.

The surface gravitational acceleration is 1.35 ms^{-2} at the surface, or about 1/7 that of Earth. The surface atmospheric pressure is 1.5 bar with a temperature of 94K and a density of 5.4 kgm^{-3} 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.

One particularly intriguing aspect of Titan is that methane, known since 1944 to be present in its atmosphere, is destroyed on short ($\sim 10^7$ 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, which is the dominant photochemical product of methane photolysis, are liquids at Titan's surface conditions, suggesting [2] Titan's landscape may feature lakes and seas of liquid hydrocarbons, as well as benthic, littoral and lacustrine geomorphologies like hydroblemes, tidal flats and cliffs.

This same photolysis yields a ubiquitous organic haze which obscured the surface from Voyager's cameras (at 0.3 to 0.65 micron wavelength) – see figure 1.

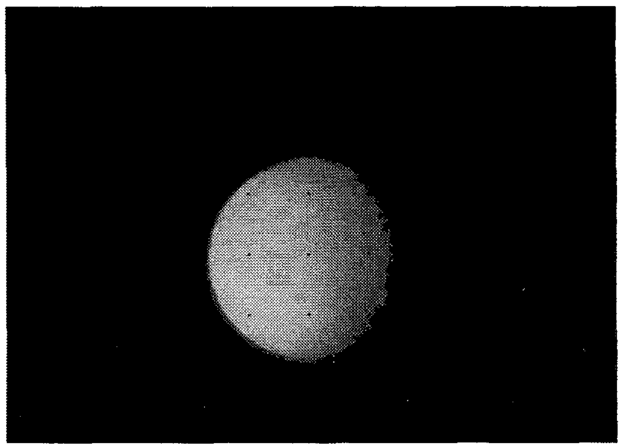

Figure 1. Titan as seen by Voyager – featureless apart from a seasonal difference between hemispheres in the haze albedo.

However, imaging at longer wavelengths [3] between near-infrared methane absorption bands with the Hubble Space Telescope (at 0.94 and 1.07 microns has shown that surface features are present and can be detected – Titan exhibits continental-scale variegation : most probably many features exist at smaller scales too.

More recently, groundbased adaptive optics and speckle techniques have rivalled HST's capabilities – especially at 2 microns. At these yet longer wavelengths, the haze optical depth is quite low.

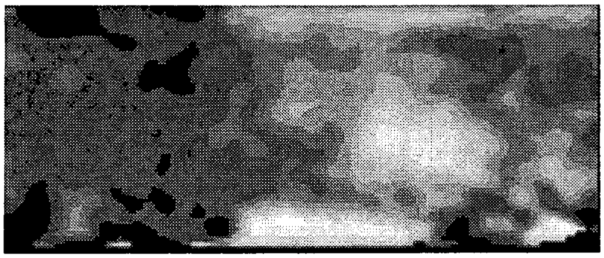

Figure 2. A crude map (~300km resolution) of Titan's surface reflectivity derived from Smith et al.'s [3] observations at 0.94 microns with the Hubble Space Telescope. The large bright region is on Titan's leading hemisphere : the antisaturn point is in the center of this map. The ESA Huygens probe will land to the upper left of the bright region.

The atmospheric photochemistry is something of a 'dead end' in that only nitriles and hydrocarbons are produced – oxygen-containing compounds (which include nearly all compounds of interest in prebiotic synthesis) have very low vapor pressures and so condense as solids and are locked on the surface in deep freeze. However, the nitriles may have been exposed to liquid water in isolated (but over the age of the solar system, extensive) surface and subsurface events like cryovolcanism and impact melting [4]. The interactions with liquid water (for thousands of years) almost certainly led to amino acids and other important molecules – an experiment that would be impossible to achieve in a terrestrial laboratory in an acceptable period.

Cassini

Most 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], 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 4m high gain antenna. Its scientific instruments are body-fixed The orbiter will deliver a 350kg European-built entry probe Huygens 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 [6]. 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 500m (about 3 times poorer than Magellan). Around 30% of the surface should be imaged this way.

An optical camera, the Imaging Science Subsystem (ISS) will make global maps at around 100m/pixel at 0.94 microns (although the scale of features that can be resolved will depend on the seasonally- and latitudinally-dependent haze opacity, as well as illumination and the contrast of the features themselves), and the Visual and Infrared Mapping Spectrometer will make coarser maps, but at several wavelengths (with lower haze opacity than at 0.94 microns), allowing perhaps some crude composition mapping.

Post-Cassini Objectives

The formidable instrumentation on Cassini will make Titan a much better-understood place than it is today, with many of the major questions about its origin and evolution (hopefully) answered. Its exotic (but perhaps strangely familiar) landscape will be unveiled – large features like seas and mountain ranges, crater fields and the like will be mapped out, and the camera on the Huygens probe will give us close-ups .

Titan's atmospheric photochemistry, and to a lesser extent its meteorology, will be much better-understood.

Yet new questions will certainly arise, many of which can be guessed today. A NASA-apponted Strategy Working Group suggested that a prioritized order for immediate post-Cassini exploration of Titan should be the Surface, Subsurface and atmosphere, with the aim of understanding

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.

As indicated above, the chemistry of the surface will probably be still largely a mystery, and is where the most far-reaching astrobiology issues lurk. The landscape is probably shaped by many processes which act on spatial scales too small to be resolved by Cassini's instrumentation, so wide-area high resolution imaging is likely to be a post-Cassini priority, both in its own right, and to identify sites where particularly interesting chemistry may have occurred.

Finally (for this paper – individual scientists will of course have their own favorite lists of post-Cassini questions) the subsurface of Titan will be a yawning gap in our knowledge. Titan's thick atmosphere forces all Cassini flybys to take place at altitudes around 1000km or higher – nearly half a planetary radius. This makes small-scale gravitational or magnetic anomalies – the traditional ways of probing the subsurface – impossible to detect. An apposite comparison may be drawn with Mars – thought of as magnetically weak, until measurements with high spatial resolution and sensitivity were made by the low-altitude periapsis passes of the Mars Global Surveyor.

2. MISSION CONCEPTS

Thus a future mission (or mission set) should provide for sampling and analyzing the surface materials. It should also feature high-resolution imaging, and probe the surface in globally-dispersed locations.

These objectives all imply a vehicle with global near-surface mobility. Even ignoring the crucial trafficability concerns on Titan, rovers so far have not even come close to global access : even the Lunokhods achieved only a few tens of kilometers, and that on very benign mare terrain.

Thus a near-surface aerial vehicle is indicated. While an orbiter might augment the science return by providing a communications relay, and itself carry novel instrumentation, I contend that (assuming Cassini performs as advertised) an orbiter cannot address the central questions itself [7].

Vehicle Concepts

Such a vehicle might be lighter-than-air (i.e. airship, balloon) or heavier-than-air (airplane, helicopter) or a hybrid. Since the mass that can be delivered to Titan by affordable and rapid means (specifically, say, a Delta III with a solid upper stage [8]) is 200kg or less, allowing for carrier spacecraft systems, entry thermal protection etc., a nominal mass for the Titan *in-situ* vehicle is taken as 100kg.

Flying perpetually would be simplest, suggesting a balloon or aeroplane, but these vehicles obviously are not ideal for surface sampling, a deficiency that might be addressed by expendable drop-sondes, if the required instrumentation is compact enough.

A balloon relies on the winds to carry it over interesting terrain. An altitude-controlled balloon or aerobot might have a chance of being able to control its destiny by moving vertically to find more favorable wind directions, although on Titan where the winds are predominately zonal (E-W [9]) achieving an arbitrary set of surface targets (especially if distributed over a range of latitudes) seems doubtful.

An airship travelling at a few tens of centimeters a second could cover global latitude ranges over a year or so (although will circumnavigate the globe several times in the zonal wind field). A given surface target could probably be achieved by reconnoitering from above, drifting E-W, then eight days later or so moving into position and descending to low altitude in the atmospheric boundary layer where the zonal winds will be attenuated. If equipped with enough thrust (or equivalently variable buoyancy) the vehicle could dock with the surface to acquire surface samples.

Surface access is easiest with a vertical take off heavier-than-air vehicle. However, such vehicles (helicopters, tilt-rotors and the like) require high power levels to fly. Thus a helicopter can easily pick a site to land, and fight gusts of wind much more easily than a bulky airship. However, it can only fly a small fraction of the time (about 10%, if a power source of about 100W is considered)

The airship and the helicopter are alike in the sense that they offer both surface and aerial access – only their defaults are different in that the helicopter if it fails (or requires a rest) must land, while the airship defaults to the sky.

Energy Cost : Sensing, Transmission and Locomotion

Energy is the sine qua non of activity. Even to passively acquire and record data requires some energy – usually electrical. Historical data, comparing data return with installed energy budgets[7] shows that while relay spacecraft, distance to Earth, downlink technology used, uncertainty about atmospheric absorption etc are all factors, to a zeroth order it takes 1 J (+/- an order of magnitude) of energy to acquire and downlink 1 bit of energy. For a worthwhile data return (~ 1 Gb) a mission energy budget of the order of 1GJ is therefore implied.

The energy required can be stored (e.g. as fuel, or primary batteries) or generated in-situ, by solar arrays. If mission duration is not constrained, a power (i.e. energy generation system) rather than an energy storage system, offers a larger energy budget. Although in some sense a stored energy system, a radioisotope generator has the functional capabilities of a power system.

Chemical stored energy devices typically provide only a few MJ/kg – making them essentially impracticable for such a large data return.

At Titan's distance from the sun (about 10 AU, so insolation at the top of Titan's atmosphere is about 15 W/m^2), and with the thick haze (which absorbs most of that), it would take 1 m^2 of solar array some millennia to generate this amount of energy.

This leaves nuclear energy – politically incorrect, but the physics is unavoidable. Small radioisotope sources presently under development using alkali metal thermionic conversion promise 70W or more, with a mass of about 15kg. Over 1 year, a 70W power source produces 2 GJ of energy.

But how is that energy allocated ? How much is devoted to actually acquiring the data, and how much to downlinking it. And how much might be devoted to mobility – a capability that is typically not required of planetary probes?

Let us consider data acquisition first. Considering the RADAR instrument presently flying on Cassini, this instrument uses a little under 80W, and at a range of 1000-1500 km can image a swath about 200km wide while travelling at 6km/s (the typical flyby speed) with pixels of about 300x500m. Thus the instrument can study about 9000 pixels/second, and data is typically compressed in some fashion to about 4 bits/pixel. Thus around 36 kbps is generated, with a reciprocal cost of 500 bits/joule.

Cassini's camera ISS has about 1 million pixels, each 6 microradians or so across. Thus at closest approach its pixel scale is 6 m/pixel. Assuming digitization at 10 bits/pixel, this instrument therefore generates 10^7 bits per frame. Exposure times of the order of seconds are probably appropriate (especially at the longer wavelengths where the solar flux is weak). This is commensurate with the pixel scale – at 6 km/s, the instrument footprint will traverse one frame in one second. The ISS power allocation is 60W, but much of this probably includes heating, power for filter wheels etc – probably 10W can be attributed to the guts of the imaging. Thus this instrument is capable of generating 10^7 bits/s at a cost of 10^6 bits/joule.

In all likelihood, contrasts of 10m scale cannot be resolved from orbit at CCD wavelengths due to the scattering properties of the haze (~100m is probably a more likely figure) but for the moment we will retain the present instrumental configuration for benchmarking.

It may be noted (as might be expected) that purely passive sensing has a far lower energy cost than active sensing. However, I will argue that this acquisition cost of data~ 10^{-2} to 10^{-6} J/bit is fairly trivial in either case. This is supported by the evaluation of downlink cost.

Using a 2m X-band antenna and the 34m DSN stations, 1 kbps could be achieved with around 20W of RF power [11], A gimballed or electronically-steerable 2m antenna can be envisaged inside a balloon envelope (a 100kg vehicle requires about 25 m^3 of volume and would be easily wide enough) and could be pointed at a beacon signal from Earth.) Ignoring pointing issues, the energy cost of this downlink mode is 50 bits/J. Thus to a first order, for a Titan mapping mission from orbit, the energy requirements of obtaining pixels on the surface and bits on the ground are equal for a radar mapper and an optical mapper. The same arguments are likely to be even more true for a near-surface vehicle which must expend power on propulsion as well as on communication : expanding the non-acquisition component of the energy budget implies that the data acquisition component must occupy a yet smaller fraction of the budget.

So what is the cost of traversing terrain? 'Free' cases such as passive balloons can be ignored (in the sense that these would probably drift E-W, and not be able to access arbitrary latitudes) as can orbiters. The energy cost of motion for controlled aerial vehicles is speed-dependent, of course.

To traverse 180 degrees of latitude in 1 year requires an average speed of 0.2 m/s – this may be considered the minimum powered travel speed (depending on altitude, the groundspeed of the vehicle may well be ~10 m/s, due to the zonal winds, but this does not affect the power requirement).

If the vehicle were to remain continuously airborne, it would need to travel at this average speed. On the other hand, if powered flight were to have a non-unity duty cycle, the powered flight speed would need to be higher. A survey of terrestrial vehicles [10] indicates that heavier-than-air flight requires a power (W) of $11m^{0.8}V^{0.9}$, with m the vehicle mass in kg and V the flight speed in m/s, whereas big, slow vehicles benefit from buoyant flight – airships require a flight power of $3m^{0.6}V^{1.85}$.

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On earth, a 100kg lighter-than-air vehicle would require a mere 2.5W to move at 0.2 m/s; an airplane would require 102 W. On Titan, increase propeller efficiency in the denser atmosphere might reduce these by a factor of 1-1.5; heavier-than-air vehicles also benefit by a factor of 7 due to Titan's lower gravity, although for this low flight speed.

At 1 m/s on Titan, both vehicle types would require 60 W or so. However, even on Titan, such a low flight speed requires very low wing loading for airplanes – a vehicle more like the Gossamer Albatross than a compact drone. It is difficult to conceive of a robust vehicle able to be delivered to Titan and yet have such a large area. Inflatables are an obvious idea, but then why not forget about the complications of aerodynamic lift and simply rely on buoyancy in the first place.

Above 1 m/s, airships become uncompetitive. At 10 m/s (roughly the equatorial rotation speed on Titan – an aircraft at this speed could stay 'stationary' at the sub-Earth or subsolar point) an airplane would require some 500W of propulsive power.

Thus per kilometer of travel, propulsive costs are minimized for aircraft by travelling fast, while for airships, by travelling slowly. A 0.2 m/s airship has a propulsive cost of about 10^4 J/km, while 1 m/s vehicles (the 'breakeven' between heavier-than-air and lighter-than-air) have a cost of around $6x10^4$ J/km.

From an altitude of 1km, around 1 km^2 of real estate is visible. If this territory is studied at a resolution of 10 m and a radiometric resolution of 10 bits/pixel, then travelling 1km generates 10^5 bits of data. From the considerations earlier, we see that this requires $2x10^3$ J to downlink. If the ground is studied with a 1m resolution, the downlink energy requirements are $2x10^5$ J/km – rather larger, in fact, than the propulsive energy requirements to traverse that distance.

This underscores that data selection and compression are perhaps more critical technology requirements than improvements in propulsion or aerodynamics.

It may be seen that even when the propulsive power is included, the mission energy requirements should still be far smaller in principle than the canonical 1 J/bit. Evidently engineering subystems dominate the energy requirements. There is much work to do to improve the power consumption of the nuts and bolts of spacecraft.

Since Titan's area is some 81 million km^2, it would take $8x10^{11}$ 10m pixels to cover it. A realistic mission, then cannot hope to cover it all. The trick is to cover the most interesting parts of the surface – unfettered mobility (i.e. not being at the complete mercy of winds) and the ability to interactively select both areas of study and the most interesting subset of data about them are key.

Accessing the surface is a prime scientific objective. The surface trafficability is highly uncertain, so rovers are not a good option. An airship, capable of maintaining sufficient negative thrust to acquire samples on the surface is one possibility. Surface access on difficult regions on Earth is typically achieved by helicopter.

While a somewhat fanciful concept at first, this option turns out to benefit substantially (more so than other concepts) from Titan's environment. The flight power for a given terrestrial helicopter to hover on Titan is no less than 38 times lower than on Earth (the gravity ratio, via the actuator disk equation introduces a factor of 7^1.5, or 19, while the thicker atmosphere brings another factor of 2 or so)

Nevertheless, the powers required are still high (~500W to hover – less in modest forward flight of several m/s) , but they are not unreasonable compared with other vehicle types on specific energy terms (~$5x10^4$ J/km), and because the helicopter (like the airship) can 'rest' for extended periods, a hopping strategy becomes attractive. The only penalty is that some kind of energy storage becomes necessary.

Some of the tradeoffs between different vehicle types are summarized in table 1.

Table 1 : Titan Aircraft Options

0.2 m/s airship	Workable 2W	
1 m/s airship	Workable 60W	
10 m/s airship		utterly impractical
0.2 m/s airplane		utterly impractical
1 m/s airplane		60W.requires very light structure
10 m/s airplane	allows continuous earth-view	requires several hundred W power (continuous)
1-10 m/s helicopter	good surface access	requires several hundred W power (intermittent)

Science Mission Considerations

The hopping strategy also introduces other aspects, that if not outright advantages, at least foster a natural mission profile.

First is that the survey science of the mission (imaging, subsurface sounding) conducted during the flight is likely to generate a much larger data volume than surface science (chemistry, and others below). The pointing requirements for direct-to-Earth downlink are quite strict, if that approach is used (e.g. the 1.8m X-band antenna has a beamwidth of 1.2 degrees) and much easier to achieve while on the surface than in flight. Thus while the vehicle is sitting on the surface charging its batteries, it can downlink its data.

Depending on the exact aerodynamic and propulsive performance of the helicopter, it can probably cover around 200km in 12 hours (enough to hop between likely targets and/or safe landing areas) using a stored energy of about 2.5 kW-hr. A technological challenge is to implement a battery system that can meet this capacity requirement for a reasonable mass (<30kg, say). Modern NiMH and Li-ion cells have the required specific mass, but careful attention to thermal design would be needed.

Among additional science objectives for a Titan explorer are measurements (yielding modest data volumes) of meteorological parameters, magnetic field, and seismic activity. It would be most useful for these to be made at a single surface location for several Titan orbits. The magnetic field of Titan may have some spatial variation (to be studied during the helicopter flight) but the sensed field will also be modulated by the changing distance to Saturn. This excitation may induce fields that are sensitive to the internal conductivity structure of Titan, revealing perhaps an ammonia-water mantle.

Seismic measurements clearly require surface contact for extended periods. In particular seismic activity might be strongly dependent on orbital position (via tidal effects).

Meteorological measurements made on the surface would complement those made in flight – a search for subtle meteorological effects (the pressure perturbations due to passing dust devil analogs, for example, and even the tide in the atmosphere which should modulate the surface pressure by about one tenth of a per cent during one orbit).

Titan's orbital period is 16 days and Titan is tidally locked to Saturn, so a surface station will be hidden from the Earth for about 9 days out of 16 – an ideal time for these long-term measurements and not ideal for imaging (since it is night). By flying to different longitudes, the orbital phase at which these measurement sequences are performed (with respect to the tidal maximum and minimum, or magnetic environment) can be varied through the mission so that all phases can be sampled.

Of course, when the vehicle is hidden from Earth, it cannot communicate directly, which is a problem (only avoidable by impracticably fast-flying aircraft which can exceed the planetary rotation speed) This is an argument that might favor the use of a relay satellite, in addition to the relaxation of pointing requirements on the antenna, the difficulty of accommodating a direct-to-Earth antenna, and the reduction in (aircraft) energy cost required for downlink.

A relay satellite would also permit downlink sessions every (terrestrial) day – this would also facilitate data selection by science teams on the ground – an early session could send jailbar or compressed imaging, with only the most interesting items selected therefrom for telemetry to Earth. This mode of operation has been used on the UoSAT earth observation images, as well as on the Galileo spacecraft.

3. Conclusions

The most pressing post-Cassini science questions – as far as they can be guessed at present – are impossible to address with an orbiter alone, although an orbiter may significantly augment the science return from a surface/near-surface element.

Global mobility is required to survey subsurface structure and near-surface travel is needed to study surface features with enough resolution to select candidates for in-situ chemical analysis. The specifications indicated in this paper, namely 1 Gb data return and 1 year mission duration are reasonable, but arbitrary. More detailed study is needed to understand the sensitivity of vehicle capability, design and cost to these and other boundary conditions.

Balloons, aerobots and landers each address only a subset of the principal scientific goals (although conceivably a combined set of vehicles might, although latitudinal traverse depends on meridional winds which are unknown at present, but probably too small)

Airplanes do not appear to be likely solutions – either too flimsy or too power hungry. Either way, surface access is difficult too.

An airship gets around these difficulties and represent an excellent solution where continuous flight is the nominal mode of operation : surface access is not trivial, however, and winds may hamper mobility. Innovative approaches such as tethers and/or drop-sondes might permit analyses of surface material, but these options require considerable further study.

A helicopter or tilt-rotor offers excellent precision landing capability, although has flight power too high for continuous flight. Nonetheless, a hop-rest mode of operation allows large distances to be covered in reasonable time, while also matching data acquistion rates with analysis and telemetry rates.

The reference concept outlined in this paper is therefore a 100kg rotorcraft, with a radioisotope power generation capability of about 70W. Both power and science data are buffered, by a ~ 3 kW-hr battery, and a several Gbit memory, respectively. Although a direct-to-earth link is conceivable, the data return capacity, frequent communication opportunities (and consequent leverage in data selection), and ease of accommodation on the aerial platform make the advantages in using a relay satellite all but overwhelming.

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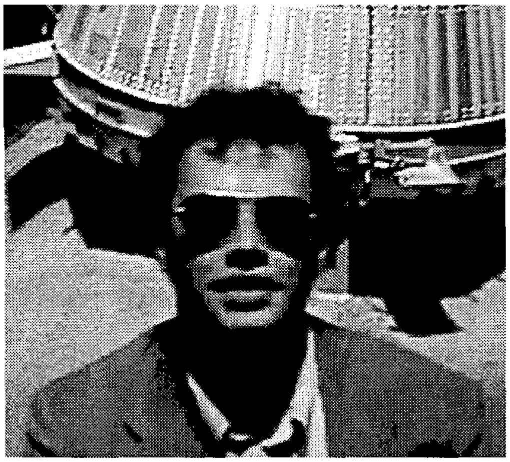

Ralph Lorenz is a Senior Research Associate in the Lunar and Planetary Lab at the University of Arizona. He has a B. Eng. in Aerospace Systems Engineering from the University of Southampton and a Ph.D. in Physics from the University of Kent, both in the UK. He worked for the European Space Agency at ESTEC, Noordwijk, The Netherlands on the payload of the Huygens probe (behind, above) destined for Titan. He is presently involved in NASA's smallest and largest planetary flight projects, DS-2 (as a science team member) and Cassini (as a member of the RADAR team and a co-Investigator on the Huygens Surface Science Package).