GETTING THE TELEMETRY HOME: HOW DO YOU GET DATA BACK FROM TITAN?

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ABSTRACT:

Exploration of Titan is one of the primary objectives of the Cassini/Huygens mission Saturn due to launch in 1997. Limited data will be provided by Huygens as it descends to the surface via parachute and by Cassini as it orbits Saturn and occasionally passes near Titan. Interest in Titan is high because of its planet-class size, dense atmosphere, and the possibility of continents and seas. Already, there are discussions for a follow-on mission to Titan. There are several proposed designs such as balloons and boats to explore Titan's ethane seas. In all cases, reliable data links back to Earth are absolutely essential. However, simply increasing the power has its limits due to constraints on launch weights. There are a number of possible options for getting data back from Titan. These alternatives, and their effect on the mission profile are discussed.

KEY WORDS

Cassini, Climate, GPS, Huygens, Meteorology, NAVSTAR, Oceanography, Saturn, Telemetry, Titan, Transit

WHY TITAN?

Titan is the most interesting satellite in the solar system from a number of perspectives. It is the largest moon of Saturn; although it is a satellite, it is laraer than the planets Mercury and Pluto. It has a dense atmosphere with a surface pressure about 1.5 times that of the Earth. Most intriguing is the possibility that Titan may possess large lakes or seas of cryogenic hydrocarbons such as ethane and methane [Lunine, et. al., 1983; Lunine, 1992; Lunine, 1993]. Recent narrow band imagery of the surface of Titan reveals a very non-uniform surface that may include lakes [Hubble Space Telescope Institute and University of Arizona, 1996]. Given some proof that Titan possesses large bodies of fluid cryogenic hydrocarbons, it could be considered a gigantic analog model of the Earth's climate system complete with land masses, moderately thick atmosphere, and large bodies of liquid. By studying the climate of Titan. we could gain further understanding of the processes and mechanisms that shape the Earth's climate. A comparison of physical parameters for both Titan and Earth is given below.

Table 1: COMPARISON OF PHYSICAL PROPERTIES OF TITAN AND EARTH

PROPERTY:	TITAN	EARTH
Surface radius	2575 +/- 0.5 km	6378 km (equatorial
Mass	1.346 x 10^{23} kg (2.2% of M_{Earth})	5.974 x 10^{24} kg
Surface Gravity	1.345 m/s^2	9.806 m/s^2
Mean density	1,881 kg/m^3	5,517 kg/m^3
Solar Flux	15.2 W/m^2 (~ 1.1% of Earth)	1,370 W/m^2
Distance from Sun	1.42 x 10^9 km (Saturn's distance)	149.6 x 10^6 km
Distance from Saturn	1.226 x 10^6 km (20.3 R_{Saturn})	-
Orbital period	15.95 d (around Saturn)	365.24 d (around Sun)
Rotational period	15.95 d	1 d
Surface temperature (ave.)	94 K	290 K
Atmospheric composition	Nitrogen (76-99%), Methane (0.2-21%), Argon (0-21%)	Nitrogen (78 %), 0xygen (21%), Argon (1%)
Surface pressure	1496 +/- 20 mbar	1013 mb
Sea/Lake composition	Ethane, Methane, Other organics	Water, Halides
Sea density	400-700 kg/m^3	~ 1,035 kg/m^3

[Banaskiewicz, 1993; Lebreton, 1992; Lorenz, 1993: Lunine, 1983; Srokosz, M., et. al., 1992; Zarnecki, et. al., 1992]

The Cassini/Huygens mission is due to be launched October 1997, with arrival at Saturn during June 2004. The Cassini orbiter (built by NASA) will then study Saturn and its moons. The Huygens probe (built by ESA) will enter the atmosphere of Titan during September 2004, take measurements of various atmospheric parameters during the hours long descent phase, and land a telemetered instrument package on the surface by use of a parachute [Lebreton, op. cit.]. The possibility of hydrocarbon lakes or seas has been given sufficient credence to where the surface science package for Huygens has been designed for operations in cryogenic liquids (Zamecki, et. al., op. cit.]. The expected lifetime of the probe after landing is on the order of minutes [Lebreton, op. cit.]. The Cassini orbiter will continue to provide limited aperiodic data on Titan during its multi-year mission around Saturn. Despite the data that will emerge from these efforts, is certain that Huygens and Cassini will raise many more questions that will require further exploration.

FUTURE MISSIONS

If Titan turns out to be as interesting as expected, there will be an impetus to conduct fully global exploration of the surface, seas, and atmosphere. For example, on Earth one must explore the tropics, the temperate zones, and the poles in order to build any sort of realistic understanding of atmospheric and oceanic circulation. Future Titan exploration has been discussed extensively by Lorenz [1994]. Among the various ideas are small “boats” with expendable probes for the exploration of Titan’s seas [Mitchell, 1994] and balloon-borne instruments [Lorenz and Nock, 1996] for global exploration of the surface and lower atmosphere of Titan. (It should be noted that land “rovers” are not currently being considered for the exploration of Titan. This is due to current models predicting that the surface of Titan will be covered with organic sludge [Lunine, op. cit.; Lorenz, op. cit.] that would be impassible to small vehicles.) In all cases, the surface exploration payload would probably be on the order of tens of kilograms. This would mean that the power source would be limited, creating problems with communicating data back to Earth.

With respect to cryogenic operations of explorers, the various weapons and space programs have built a large amount of knowledge in the field due to the use of cryogenic propellants and operations in space. However, this would have to be melded with modifications of current meteorological and oceanographic instruments. Huygens is a good example of some of the adaptations and their potential. It should be noted that cryogenic conditions could be an aid in the field of power management. The temperatures are low enough that high temperature superconducting materials could be used, thereby drastically lowering power consumption and wastage.

Reliability is a major concern. Missions to the outer planets are not only expensive from a launch vehicle point of view, but also due to the expense of a long cruise to the objective. The Cassini/Huygens mission will take about seven years to reach Saturn even with the use of gravity boosts from Venus, Earth, and Jupiter. Any follow-up exploratory missions will need to be able to operate on site for years if continuous coverage of Titan is to be attempted. This will require the use of redundant and fault tolerant systems as well as multiple “rovers” equipped with at least some AI programming for autonomous operations.

GETTING THE DATA BACK: Radio Propagation

The bottom line of any space mission is the data returned to the scientists and engineers. Succinctly, the equation that describes some of the physical limits of this data flow is the familiar link equation:

$$P_r = P_t + G_t + G_r - FSL - L_o \qquad \text{Eq. (1-1)}$$

where:

P_r	is the power received in dBW
P_t	is the power transmitted in dBW
G_t	is the gain of the transmit antenna in dB
G_r	is the gain of the receive antenna in dB
FSL	is the Free Space path Loss in dB
L_o	represents other losses such as cable losses, polarization mismatch, etc., in dB.

One of the physical limits of any space mission is the power system. This translates directly into a limit on the amount of data that can be forwarded via the telemetry systern. At the current time, power available on deep space missions is on the order of tens of watts.

The free space path loss is determined by the operating frequency and the distance traversed as:

$$FSL[dB] = 20\log f\,(MHz) + 20\log R(km) + 32.4 \qquad \text{Eq. (1.2)}$$

where:

FSL	is the Free Space path Loss in dB
f	is the radio frequency in MHz
R	is the distance in kilometers

Given a range of potential operating frequencies in S, X, and Ka bands and the extrema of the Earth-Titan distance, the free space path loss is as follows:

Table 2: FREE SPACE PATH LOSS FOR TITAN-EARTH LINK

Frequency (in MHz)	Maximum distance (in 10^9 km)	Minimum distance (in 10^9 km)	Maximum loss (in dB)	Minimum loss (in dB)
2000	1.659	1.499	282.8	281.9
8000	1.659	1.499	294.9	294.0
10000	1.659	1.499	296.8	295.9
30000	1.659	1.499	306.3	305.5

(Minimum distance occurs when Saturn is at perihelion and the Earth is at aphelion and both are on the same side of the Sun. Maximum distance occurs when both Saturn and Earth are at aphelion and are on opposite sides of the Sun.)

As can be seen above, the difference between the maximum and minimum free space loss due to orbital position is about 0.9 dB or about a factor of about 1.2 in linear terms. More "harmful" is the geometric spreading loss difference between 2 GHz and 30 GHz - a factor of about 23.5 dB.

To some extent, the geometric spreading loss difference between high and low frequencies can be offset by the aperture size. From the formula:

$$G[dB] = 10\log\left(4\pi A\frac{\eta}{\lambda^2}\right) \qquad \text{Eq. (1.3)}$$

where:

G is the gain in dB
A is the area of the antenna aperture
η is the aperture efficiency
λ is the wavelength of the signal

one gets the following data (assuming 100% efficiency):

Table 3: GAIN AS A FUNCTION OF FREQUENCY AND ANTENNA RADIUS

	Antenna Radius		
Frequency (MHz)	1 m	2 m	5 m
2000	32.44	38.46	46.42
8000	44.48	50.50	58.46
10000	46.42	52.44	60.40
30000	55.96	61.98	69.94
Gain (dB)			

One can see that higher frequencies will give a higher gain for a fixed antenna size and that larger antennas give higher gains for a given frequency. This works for both the spacecraft transmit and ground receive antennas.

The final component of the link equation is the losses due to less than perfect efficiency in the system, such as polarization mismatch, line losses, and other effects. These are minimized by careful attention to the engineering details such as reducing receiver noise, using high quality connectors, and other methods.

One of these other losses is atmospheric absorption. This is particularly acute above 20 GHz and is a major problem near the molecular oxygen and the water vapor absorption frequencies (~ 60 GHz and ~ 22 GHz, respectively). A potential solution to this and rain attenuation is to use orbiting antennas to receive the data which would be relayed to the ground. This is not currently feasible or cost effective compared to the Deep Space Network (DSN) in the radio regime. However, when the TDRS (Tracking and Data Relay Satellite) H, I, and J satellites are launched starting 1999 [JPL, 1996], this could possibly support very low data rate experiments at Ka-band. Once orbiting or lunar radio telescopes go online, they could provide an edge over reception through the atmosphere on Earth at Ka and higher frequencies.

GETTING THE DATA BACK: Direct Link vice Relays

There are two types of data forwarding to consider - direct links from the surface of Titan to Earth and relays from Titan’s surface to an orbiter which forwards the data to Earth.

Direct Propagation From The Surface

For the case of telemetry propagated directly from the surface of Titan, power will be severely limited. Radioisotope Thermal Generators (RTGs) are probably the only reasonable choice for a surface power system since batteries alone would have too short a mission lifetime. Solar cells would be grossly inefficient given the distance from the Sun plus the very optically thick atmosphere of Titan.

In the case of data from an undersea probe, acoustic links to a surface boat may be most advantageous. These expendable probes would have lifetimes on the order of minutes and could be powered by batteries. This was previously covered by Mitchell [1994].

Given the use of an RTG for a boat or flyer, the size of the generator will govern the communications practices of the mission. For constant communications, the RTG scales with the required power. If only aperiodic data dumps are needed, the RTG can be somewhat smaller by accumulating “excess” power in a rechargeable battery and using this excess during communications sessions. The size of the power system then becomes a function of the RTG output, the storage capacity of the battery, and the communications requirements.

Note that for this type of mission, a drawback is that every surface craft will require at least this minimum power system mass to communicate directly to the Earth. This translates into either a larger launch vehicle or a longer cruise time for the mission.

Any sort of mobile probe such as a rover, balloon, or boat will be in constant motion in six degrees of freedom (x, y, z, roll, pitch, and yaw). With so many degrees of freedom and the chance for rapid motion within many of them, some care must be taken that the proper polarization for the transmit/receive unit is used. Circular polarization and helical antennas are likely choices. In addition, circular polarization of the telemetry results in nullifying the effects of Faraday rotation.

Orbiting Data Relay

An alternative to direct propagation from the surface of Titan is to have the surface and atmospheric probes relay their data back to a Titan orbiter which would then relay the data to Earth. This has the advantage that each surface probe would need a much lower power to propagate a signal from Titan to orbit. The difference in free space path loss is about 135 dB for an orbiter at 300 km vice propagation directly to Earth, a “savings” of almost 150 dB. The relay orbiter would be equipped with a heavy duty power supply to send the data all the way back to Earth.

One advantage of this approach is that the mass of an individual probe is reduced since less power is required to get the data to an orbiting relay. This could translate into more surface probes for a given launch.

Another advantage of a Titan orbiter is its possible use as a navigational aid for surface probes. Mitchell [1996] discusses the importance of "geo" location of a surface probe to provenience its data. Without proper location readings, the value of data is greatly diminished. (For example, it is interesting to note that surface winds or sea current is 3 km/hr. It is much more useful to get this data and the place where it occurred so that it can be compared to other data from different regions or times.) The optimum way to do geolocation is via a satellite navigation system similar to TRANSIT or GPS/NAVSTAR. The TRANSIT type of system requires only one spacecraft but takes several minutes to give relatively low accuracy geolocation data. A NAVSTAR type system takes on the order of seconds to provide locations to within meters; however, this is at the cost of the need for at least four orbiters.

With respect to polarization and antenna type, circular polarization is probably the best choice. A small, low gain antenna could be enough to get the telemetry from the surface to the Titan orbiter.

As in the direct propagation case, power would likely be in the form of RTGs on the surface/atmospheric craft. However, the need to only get the data to orbit vice all the way back to Earth makes the power requirements orders of magnitude lower. This would lower the mass for the power system for each craft, resulting in more surface explorers for a given launch mass.

An interesting aspect of using an orbiting relay satellite(s) is that the relay could rely upon solar cells rather than RTG power. JPL has current plans [Penzo, 1996] for the use of large, efficient solar cell arrays for outer planet missions. Drawbacks of the use of such an array include size (remember that the solar flux is about 15 W/m at Titan vice 1370 W/m at Earth's distance), gravitational torques due to Titan and Saturn. and aerodynamic drag on large array in orbit around Titan. In any case, the size of the power generator can be made smaller by the use of storage batteries for times of peak consumption.

A clever variation of the orbiting relay approach was put forth by Lorenz and Nock [op. cit.]. They propose using the Cassini Saturn orbiter for a relay back to Earth. Recall that Cassini will act as a relay for data from the Huygens Titan probe. Using Cassini would require aperiodic data tranfers when the Saturn orbiter was within range of the surface probe. This would cut the cost for an orbiting relay, but increase the cost for RTGs since higher powers would likely be required for the surface craft to contact Cassini. This power would be related to the maximum distance for data relay. Another potential problem is that by the time a follow-on mission to Titan arrived, it is likely that a substantial part of the lifetime of the Cassini orbiter would be over.

In the early 21 st century, it could prove advantageous to use optical (laser) communications from the Titan orbiting relay back to Earth. Lasers Using methodology from Lambert and Casey [1995], the gain of a gaussian laser transmitter (“antenna”) for a given wavelength and aperture size is as follows:

Table 4: GAIN AS A FUNCTION OF WAVELENGTH AND OPTICAL TRANSMITTER RADIUS (Gaussian illumination)

	Optical Transmitter Radius		
Wavelength (manometers)	0.5 m	1.0 m	1.5 m
500	119	122	125
1000	113	116	119
1500	109	113	115
Gain (dB			

(Note that the gain for a uniformly illuminated aperture is 3 dB less.)

The mass of a laser telemetry system is comparable to that of an RF system and will become increasingly lower in the near future. The laser system also requires less power than an RF system for a given bit rate [Ibid.]. The reduction in power translates into a further reduction in mass. In theory, the use of a laser link from Titan orbit to the Earth would lower the mass of the system, resulting in either more instruments delivered to Titan, the use of a smaller (cheaper) launch vehicle, or a shorter cruise time to Titan.

The receiver could be any given telescope in orbit around the Earth, such as the Hubble Space Telescope and its successors. The advantage of an orbiting telescope is the lack of atmospheric absorption and distortion of the signal. Ground based telescopes with adaptive optics and artificial “guide star” capability could also be used as laser receivers, possibly more economically than space based ones.

The use of laser links for deep space missions was conceptually proven by using the Galileo probe’s camera to receive laser pulses from Earth based transmitters at distances of up to six million kilometers [Ibid.] The remarkable thing about this test is that Galileo was not built to use optical data links nor was the emitter built specifically for this test.

The Europeans and Japanese are planning to launch data relay satellites in the 1998 timeframe that will be equipped with the capability to use laser crosslinks to low orbiting spacecraft such as SPOT-4 [Faup, Planche, and Nielsen, 1996; Jono, Nakagawa. Suzuki, and Yamamoto, 1996]. This will provide practical experience with tracking and transmission challenges and could lay the groundwork for later missions.

SUMMARY AND IMPLICATIONS:

Initial plans for the exploration of Titan are being executed. If Titan is as interesting as current models and data indicate, follow-ups to the Cassini/Huygens mission will become a reality. One of the key systems for such a mission is the telemetry system, which in turn depends on power.

There are a number of possibilities for such systems. After comparing direct transmission from Titan's surface to the Earth vice relay of telemetry through a Titan orbiter, the relay concept holds many advantages: power flux at the Earth (which translates into bit rate), power required for surface explorers, and the capability to do data proveniencing. Investigation of transmission modes indicate that radio links from Titan's surface to the orbiting relay and laser links from the relay to Earth would be the most advantageous. All these technologies are mature and should be cost effective in the early 21st century.

Although the whole concept of large scale exploration of Titan may sound esoteric, it could provide a very large gain in our knowledge of Earth's climate. This gain could directly translate in lives and money saved through better climate and weather forecasts.

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