GLOBAL EXPLORATION OF TITAN'S CLIMATE: OFF THE SHELF TECHNOLOGY AND METHODS AS AN ENABLER

B. J. Mitchell
The Johns Hopkins University/Applied Physics Laboratory

ABSTRACT:

Recent narrow band imagery of the surface of Titan reveals a very non-uniform surface. While there are no global oceans of liquid ethane/methane as once conjectured, the imagery does suggest the possibility of seas or lakes of liquid ethane, methane, and other organic materials. If these exist, Titan 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. Reuse of existing technology and methods may be a way to speed development and lower costs for the global study of Titan. Surprisingly, one of the key technologies could be a Transit or Global Positioning System (GPS) descendant for use in tracking probes wandering the surface of Titan.

KEY WORDS

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

BACKGROUND:

The study of Earth' s climate is one of the most challenging and important fields of scientific endeavor. Yet, a quick survey of current high interest topics such as the El Nino - Southern Oscillation (ENSO) (Cane, 1992) and global change (sometimes known as "global warming") shows that there is little scientific agreement on climate factors (Schneider, 1992). Further, our understanding of short term weather patterns is based on our knowledge of climate. This in turn directly affects lives and economic activity around the globe.

A field that has developed within the past three decades is the field of comparative climatology. One of the outgrowths of the observations performed by such missions as Mariner, Pioneer, Magellan, Viking, and Voyager (Beatty and Chaikin [ed.], 1990) is the ability to compare the climate of Earth to the climates of Venus, Mars, Jupiter, Saturn, Titan, Uranus, and Neptune. The power of such studies lies in the fact that the physical equations that describe the physics of atmospheres and oceans are the same no matter which planet is being studied. The difference between planetary climates lies in the varying boundary conditions such as local solar flux, atmospheric constituents, rotation rate, etc.

While there have been many advances in our understanding of planetary atmospheres as a result of the various exploratory missions, there has been very little similar gain in the field of oceanography for a simple reason, there are no other oceans in the solar system besides those on Earth. However, Titan (the largest moon of Saturn) may have lake or sea sized bodies of liquid ethane, methane, and other constituents (Lunine, 1993; Dermott and Sagan, 1995). Thus, exploration of any lakes on Titan may offer the best opportunity to advance our understanding of Earth's oceans[1] in the same way that studying other planetary atmospheres has advanced our understanding of our own atmosphere.

CLIMATOLOGY PRIMER:

Climatology can be looked at in terms of studying structure, dynamics, and thermodynamics of a climate system. All of these involve boundary conditions - limits on the parameters of interest. Many types of telemetered instruments have been devised to study these parameters. These three things all interact in complex ways to produce the environment that we see around us.

Structure is simply the physical divisions that exist in nature such as the location of the continents and oceans. It also includes less visible systems such as the various atmospheric and oceanic layers. All of these are defined in a consistent manner with respect to the various physical boundary conditions and other parts of the climate framework.

Dynamics includes movement of air and water and their interactions with the land. The movement of large air masses and ocean currents are the driving forces of Earth's

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[1] Note that in this paper, the term oceanography is used to describe the study of large bodies of liquid from small lakes up to large oceans. Strictly speaking, the study of lakes is known as limnology. However Gibbs (1977) points out that one of the major difference between oceanography and limnology is that the boundary conditions differ - oceans are large enough to ignore the effects of land in many cases, whereas lakes are more subject to the effects of surrounding terrain. However, both must obey the same fluid dynamic and thermodynamic laws.

weather. These are physically bounded by the balance of forces defined by the Navier-Stokes equation (the fluid dynamics equivalent of Newton's laws).

Thermodynamics includes measurement and predictions of quantities such as temperature, pressure, density, relative humidity, and chemical constituents.

In the field of climatology, there is much agreement about what are some of the major climate factors: atmospheric structure, greenhouse gases, currents such as the Gulf Stream, basic equations such as the Navier-Stokes equation, etc. However, there is considerably less agreement how these factors interact and what the time dependent results will be. An example of this is the effect of greenhouse gases such as carbon dioxide and methane on climate. There is no universal agreement that the rise in concentration of these gases will result in a considerably warmer climate (Washington, 1992).

TITAN PRIMER:

Titan is the most interesting satellite in the solar system from a climatology perspective. It is the largest moon of Saturn; although it is a satellite, it is larger 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, 1993). A comparison of physical parameters for both Titan and Earth is given below.

With a dense atmosphere and the possibility of large bodies of liquid, Titan may provide a useful analog comparison model for Earth climate studies. Of particular interest would be any large bodies of liquid. This would present the first chance to do comparative oceanography and could lead to gains in our understanding of our own hydrosphere.

To this end, 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 and land a telemetered instrument package on the surface by use of a parachute (Lebreton, 1992). 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 (Zarnecki, et. al., 1992). Among the oceanographic data to be gathered are: acoustic properties and depth of the ocean, ocean wave properties, ocean density, permittivity, thermal properties, response to impact, and ocean constituents. The expected lifetime of the probe after landing is on the order of minutes (Lebreton, 1992). In addition,

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%), Oxygen (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)

various atmospheric parameters will be measured during the descent phase of Huygens including wind speeds and direction, atmospheric composition, lightning detection, and surface imagery (Ibid.).

The Cassini Saturn orbiter will provide climatological data on Saturn and Titan. Huygens may provide the very first exo-oceanographic data. This could provide enormous amounts of unique data of use in studying Earth's climate, particularly contributions from the hydrosphere. However, it is certain that Huygens and Cassini will raise many more questions that will require further exploration.

FUTURE MISSIONS - INSTRUMENTATION:

If Titan is found to be a useful model for comparative climatology studies, it will be necessary to conduct global exploration. 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 surveyed by Lorenz (1994) and various authors. The good news is that lighter than air or low power consumption aircraft may be ideal for covering large volumes of land and atmosphere. The lower gravity and thicker atmosphere should make these vehicles lightweight and capable of long endurance. The instruments required would essentially be modifications of current remote sensing, meteorological, and oceanographic instruments. Two major modifications required would be 1) the ability to operate in a cryogenic environment and 2) the need for increased reliability due to the expense and long lead time to field replacements.

With respect to cryogenic operations, 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 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".

As mentioned before, there is already much known about operating probes in hostile atmospheric environments. Missions such as Viking on Mars show that it is possible to operate meteorological instruments in a forbidding environment for years at a time. However, there is no experience at operating oceanographic probes in anything other than Earth conditions. An adaptation of a standard oceanographic probe for measuring sea temperature as a function of depth has already been proposed for operations at Titan (Mitchell, 1994). Various types of current meters, composition sensors, and other standard oceanographic instruments would need to be adapted as well.

FUTURE MISSIONS - TELEMETRY:

One key part of any planetary mission that often is taken for granted by the investigative community is communications with the probe and its instruments. When this fails, the mission is at least thrown into chaos and may fail completely with a resulting monetary loss of hundreds of millions of dollars and inestimable scientific data.

The telemetry portion of a climatological study of Titan would be a key ingredient to mission success. The data signal itself could follow any of the current telemetry standards such as that put forth by the Consultative Committee for Space Data Systems (known simply as CCSDS). Use of such a standard that allows adaptive allocation of data bandwidth would be advantageous from a power and spectrum management point of view.

Radio operating frequency is also a concern since this affects both structures and power systems. From the formula:

$$G\,[dB] = 10\log\left(4\pi A \frac{\eta}{\lambda^2}\right) \qquad \text{Eq. (1)}$$

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 can see that higher frequencies will give a higher gain for a fixed antenna size.

Also of concern is the free space path loss:

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

where:

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

Notice that higher frequencies result in greater losses due to physical spreading.

As can be seen above, there are propagation trade-offs between antenna gain and FSL. Longer wavelengths (lower frequencies) result in lower free space path loss; however, these require a larger dish size in order to obtain a given gain vice a higher frequency (shorter wavelength) radiowave. In addition, the type of antenna is a factor - do you use a relatively high powered isotropic antenna or a directional parabolic dish in order to lower power requirements? For Earth - space links, a plethora of combinations have been tried with most current solutions involving parabolic dishes in the S, X, and K bands. However, for mobile users (such as the various soon to be launched satellite cellular phone systems like IRIDIUM (Motorola, 1990)) the use of low gain quasi-omni directional antennas is needed for ease of use. In the case of mobile instruments on Titan, for the sake of simplicity it is likely that similar antennas and frequencies would be used.

The case of telemetry from submerged oceanographic probes is a bit more problematic. On Earth, telemetry is relayed either acoustically or via a cable (Baker, 1981); radio is not used because of the electromagnetic properties of water. On Titan, the use of cables or wires carrying telemetry to a surface relay is prohibited due to cryogenic conditions making such connections likely to break. Acoustic links have been proposed; these could use CCSDS formatted digital data. In addition, the telemetry links themselves could provide useful data about the liquid in which they operate (Mitchell, op. cit.). Also, since any bodies of liquid on Titan are likely to be dielectric at S band radio frequencies (Ulamec, et. al., 1992; Lorenz, 1992) it may be possible to use radio links to carry telemetry and telecommand data to/from the surface and submerged probe.

One other telemetry concern is how to actually get the data back to Earth. Requiring all surface probes to carry sufficient equipment to communicate directly with Earth would add a large burden on a mission involving tens of mini-probes. The optimal solution would be to provide data relay from low powered surface probes to one or more higher powered orbiting relays that would in turn send the information back to Earth. The use of orbiting relays would have another possible key benefit that will be examined in the next section.

FUTURE MISSIONS - GEOLOCATION:

All the data in a world is of little use if one does not know from whence it came. In other words, geolocation is a key ingredient to the success of any planetary mission. In the case of detailed Earth bound geolocation, a very large variety of method have been used, ranging from compass and sextant to Global Positioning System (GPS). For other planets, there has been no requirement for ultra-precise geopositioning up to this point. This will become critical as locations must be determined with accuracies well under a kilometer.

For exploration of Titan, a coordinate system would need to be defined from scratch. This will probably be based on the position of a major terrain feature for longitude and on the rotational equator for latitude. Various methods are possible; there are two major classes - ground based emitters such as Omega and Loran, and space based emitters similar to Transit and Navstar GPS. (A very good comparison of the various methods is found in Logsdon, 1992.)

Ground based emitters like Omega and Loran send out a radio signal from which the positional fix is determined. In the case of Omega, this determination is via phase difference of arrival of multiple VLF signals from various emitters around the globe. (VLF is used due to the need to cover the globe with a small number of emitters.) In order to replicate such a system on Titan, multiple VLF emitters would have to be deployed around Titan's surface. This could be a problem due to transmit antenna size and mass and probable hostile surface conditions such as hydrocarbon sludge (Lunine, 1992). The use of higher frequency signals with smaller antenna would result in a reduced area of coverage for each emitter, thereby requiring more fixed surface stations.

The Transit system operates by transmitting two continuous tones so that a receiver on the ground sees a doppler shift within the signals as the satellite passes through the field of view. By combining this data with knowledge of the satellite's orbit and the exact time (Transit provides this data in a broadcast), one can obtain a positional fix. Obtaining this fix can take ten to fifteen minutes on Earth.

Navstar GPS operates by sending out ephemeris and time information that is received by the user on two frequencies (to compensate for ionospheric effects). Four or more satellites must be in view in order to provide latitude, longitude, altitude, and their time derivatives. The end result is near instantaneous and highly accurate (anywhere from 1 - 100 meters, depending on type of receiver and instantaneous satellite constellation geometry) positional fixes.

Orbital systems similar to Transit and GPS are a better choice for Titan navigation and geopositioning than ground based systems like Omega. One reason is that a satellite system would not be exposed to hostile ground conditions. Another key reason is that the satellite navigation function could be added to the same spacecraft bus that would act as a relay of data from Titan to Earth. (These same satellites would probably have some remote sensing capability as well, in order to provide information to the Titan ground segment for purposes of "targeting".) Choosing which form would be largely a function of expense and accuracy requirements.

The area covered per satellite can be determined from a variation of Black's (1991) work on Earth orbital coverage:

$$c = \operatorname{acos}\left(\frac{\cos(e)}{1+\frac{h}{R}}\right) - e \qquad \text{Eq. (1.3)}$$

where:

- c is the half angle of the viewing cone
- e is the required elevation angle of the satellite as seen from the ground. Most practical systems require 5 to 10 degrees elevation angle
- h is the altitude of the satellite (in kilometers)
- R is the equatorial radius of Titan (2575 km)

From this, coverage area is derived.

$$\text{Area} = 0.5\,(1 - \cos(c)) \qquad \text{Eq. (1.4)}$$

where:

- Area is the area covered by the satellite in steradians
- c is the half angle of the viewing cone

Finally, the resulting circle diameter of the viewing cone is:

$$r_g = 2 \times 2575 \times c \text{ (radians)} \qquad \text{Eq. (1.5)}$$

where:

- r_g is the circle diameter in kilometers.
- c is the half angle of the viewing cone converted to radians.

This explicitly shows that higher altitudes require fewer satellites to cover all of Titan. Conversely, for a given number of satellites, the higher the constellation orbit, the more satellites in view at all times.

In comparing a Transit type system versus a Navstar system, one must also determine how often a positional fix is required. A small number of Transit type satellites could be used to provide quasi-periodic positional coverage for the surface rovers with the trade-off that it could take tens of minutes to compute the position. With a GPS (or Titan Positioning System - TPS) constellation, more satellites than in the Transit-type constellation would be required, but very accurate, continuous, quick position and velocity fixes could be computed. In either case, an accurate satellite ephemeris would be required. (This would be complicated by the very large perturbation effect of Saturn on any Titan orbiter.)

The choice of system type is dependent on the needs for accuracy, velocity determination, coverage, and expense. A Navstar-TPS system would provide superior positional accuracy and velocity determination of probes (a key factor with atmospheric or oceanic drift type craft for use in analyzing currents.) Such a system would be required for position accuracies on the order of meters. However, to provide the requisite four plus visible spacecraft for true three dimensional position fixes, a relatively large number of satellites would be required. A Transit type system could operate with but a single spacecraft in a polar orbit about Titan but would provide only quasi-periodic, low accuracy coverage (of the order of hundreds or thousands of meters) for position determination.

SUMMARY AND IMPLICATIONS:

With the distinct possibility that Titan possess hydrocarbon seas in addition to a moderately thick atmosphere and land masses, Titan emerges as a gigantic analog laboratory for climatological studies of relevance to Earth. The Huygens/Cassini mission will provide many initial answers but will raise many more questions, especially if the presence of hydrocarbon seas is confirmed. This could lead to a concerted effort to study Titan in detail for the purposes of furthering our understanding of the climate processes at work on Titan. In turn, this work could lead to new insights on Earth's climate. Much of what is currently used in the fields of instrumentation and telemetering should be readily adaptable for use on Titan. A somewhat surprising result of planning a coherent approach to exploring Titan is that one of the key technologies will be geopositioning for instrument package location and through them, mapping of features and currents. 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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