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NAVIGATION OF AERIAL PLATFORMS ON TITAN

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Future missions to Saturn's giant atmosphere-shrouded moon Titan may involve aerial platforms such as airships or helicopters. A significant challenge is the navigation of such vehicles, both in terms of global position determination and path planning in the zonal wind field, and for local stationkeeping to acquire organic surface samples of astrobiological interest. This paper overviews the Titan environment and the likely science goals and mission scenarios for post-Cassini missions, and examines the various methods (astronavigation, complicated by the hazy atmosphere, but possible at selected wavelengths; dead-reckoning, doppler navigation using an orbiter, expendable beacons, etc.)

INTRODUCTION

Future missions to explore Saturn's giant moon Titan [1,2,3] after the approaching Cassini-Huygens mission may involve mobile aerial platforms such as airships or helicopters. Such vehicles can exploit Titan's unique aeronautical environment (thick atmosphere, low gravity) to explore on global scales, yet still access surface material to search for prebiotic compounds. The question then arises how these vehicles might determine their location on Titan, a body with an optically-thick atmosphere, no intrinsic magnetic field, and no GPS constellation. This paper gives some initial considerations to the problem of navigation on Titan.

Titan's atmosphere is not completely opaque. Despite the bland, featureless appearance of Titan's haze from the Voyager 1 cameras at wavelengths of 640nm and lower, near-infrared wavelengths between methane absorption bands are rather more transparent - maps have been made of Titan's surface from earth using HST and groundbased telescopes at wavelengths of 0.94, 1.07, 1.28, 1.58 and 2 microns (figure 1). The optical depth of the organic haze in Titan's atmosphere progressively decreases at longer wavelengths, from several at green and yellow wavelengths to around 1 at 0.94 microns to perhaps 0.2 at 2 microns.

This clearly heterogenous surface is likely to demand detailed in-situ investigation at multiple locations. Cassini will map a large fraction (but not all) of Titan with optical and radar instruments at resolutions of typically a few hundred meters. Such resolution is unlikely to be adequate (just as it is inadequate on Mars) to identify lander-scale sites at which surface sampling should take place (in particular to examine surface ices at locations where transient exposures of liquid water may have interacted with surface organics). Thus a mobile platform (capable of performing a local high-resolution survey from beneath Titan's obscuring haze, before committing to a sampling site) is favored over one or more landers for a future mission. Early studies for such missions are underway.

The navigation problem on Titan may be considered in two parts. First, there is the global-scale navigation problem – where is the vehicle on this map? As will be discussed in this paper, this problem can be addressed by a combination of astronavigation, possibly augmented by navigation information from a communications orbiter.

The second part of the problem is for navigation or station-keeping around target sites of interest, to perform detailed close-up surveys to select landing or sampling sites (these may not be the same thing – sample acquisition systems may be deployable from an airship that avoid the need to actually land). Additionally, it may be desirable to monitor some sites for activity (e.g. observe the tide at a shoreline) and thus some sort of loitering capability is needed.

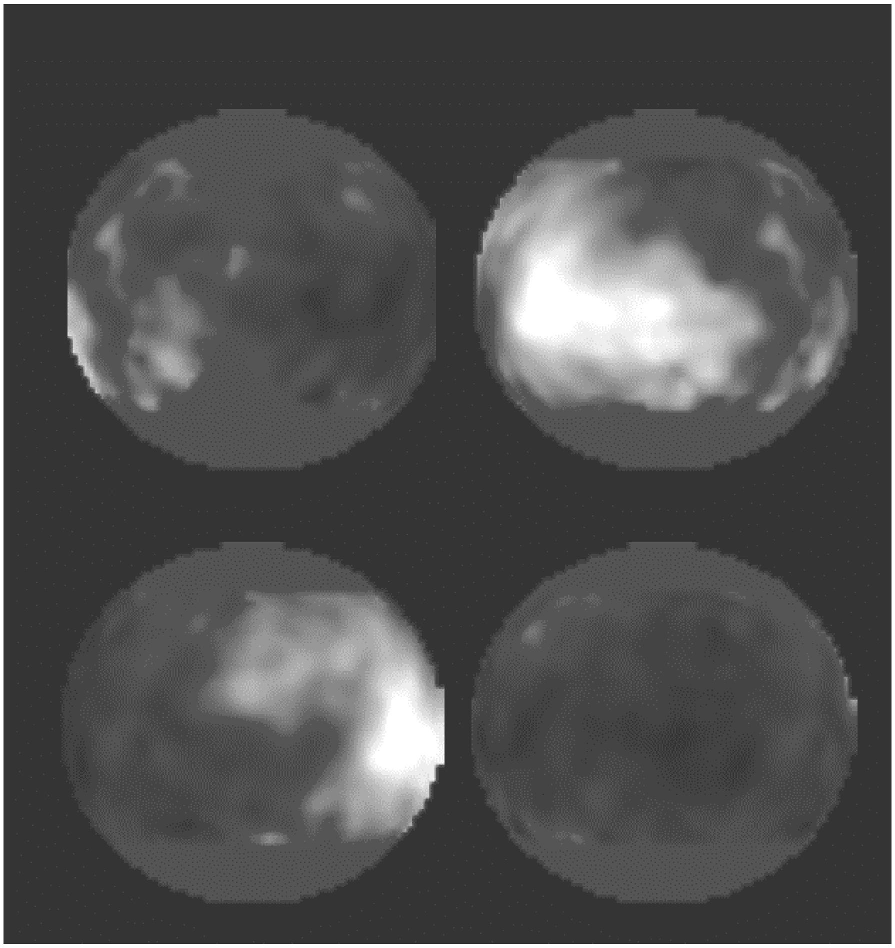

Fig 1 :Map of Titan projected onto a globe seen from 4 longitudes. Map at 940nm wavelength was made in 1994 using observations from the Hubble Space Telescope.

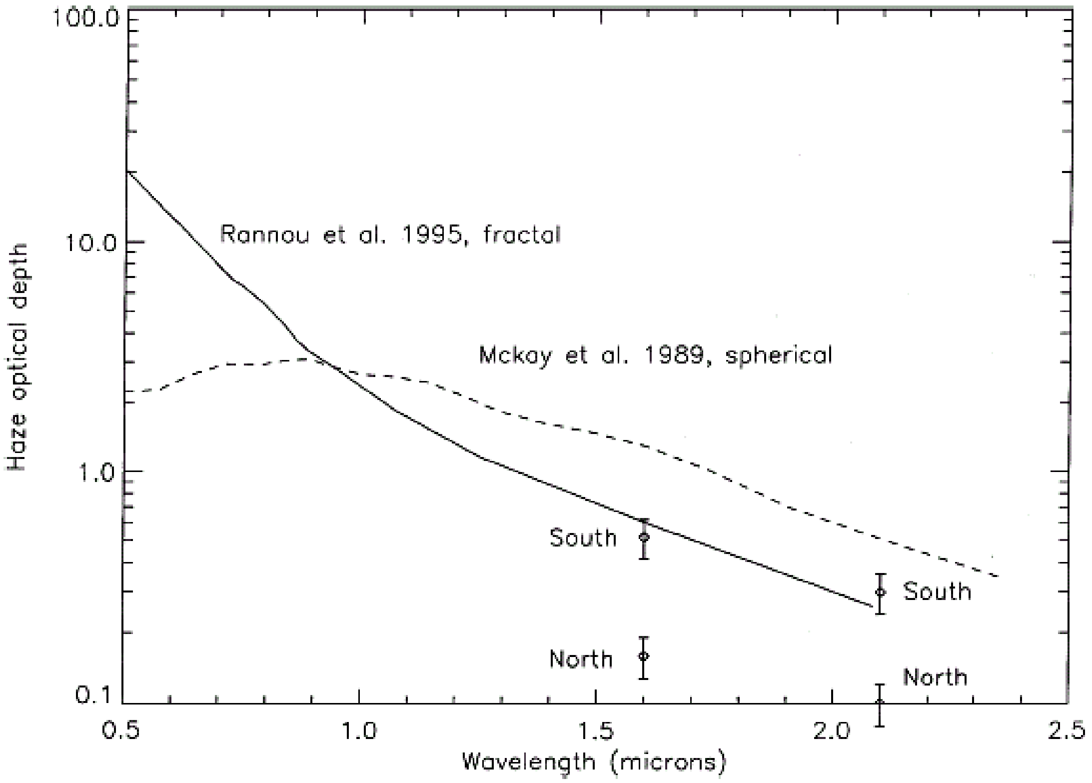

Figure 2. The optical depth of Titan's haze layer (from [4]) – the curves show two microphysical models tuned to observations of Titan's disk-integrated brightness : the datapoints are for two separate hemispheres observed with speckle imaging by Gibbard et al (1999). The optical depth is dramatically lower at 2 microns – low enough to permit observation of bright sources in the sky. Note that the two hemispheres have different optical depth, and that these depths change seasonally – in 2010 the situation will be reversed from that shown here.

ASTRONAVIGATION

The first and most obvious position reference is the sun. Titan rotates synchrously in its 15.945 day orbit around Saturn, so the 'day' on Titan is some two weeks long. For a given location on Titan, the sun position throughout the day can constrain latitude and longitude. Imaging of the sun the horizon was performed [5] by Pathfinder to refine its location.

A second reference source is Saturn itself. Because of the synchronous rotation, Saturn hangs in the sky over one point on Saturn's surface. Titan's orbit is somewhat eccentric (e=0.029), so Saturn grows and shrinks slightly. More importantly there is a libration, with the subsaturn point oscillating in longitude by +/- 3 degrees during an orbit.

As seen from Titan, Saturn will exhibit phases like the Earth's moon. If an imaging system can resolve Saturn (which is some six degrees across) by observing in the near-IR where the haze is more transparent, the phase of Saturn gives directional information when the sun is invisible.

Additional directional information is given by the shadow of the rings, which will fall on Saturn's southern hemisphere. The larger satellites of Saturn might be detectable, being several magnitudes brighter than the brightest stars. Rhea in this sense is the most promising, being the largest satellite other than Titan, as well as relatively distant from Saturn (at elongation it would be 25 degrees from Saturn.)

Note that in Titan's thick atmosphere, refraction is somewhat (x4) stronger than on Earth – an astronomical source 20 degrees above the horizon will appear about 95 arcseconds higher up. Given the scattering issues, this is unlikely to be significant.

Close to equinox around 2024, Saturn eclipses of the Sun will occur. In principle these offer opportunities for quite precise navigation information. At Titan's orbital speed around Saturn, a timing of eclipse onset with a precision of 1s indicates a longitude precision of 0.1 degree. The sun subtends only 1/20 of a degree, so the penumbra is small. Some modelling effort would be required, however, to understand the refractive effects of Saturn's atmosphere on the eclipse lightcurve.

Unfiltered wideband imaging can at least yield the solar position to within a degree. 940nm imaging with a 5 or 10nm-wide filter should produce rather better images, using an ordinary CCD detector: other detector technologies could be used at longer wavelengths where the haze scattering is even less. Incorporation of a polarizing filter would eliminate singly-scattered light to enhance the contrast even more. (Although discussed here purely in a navigational context, sky imaging on Titan is likely to be scientifically fascinating [3] – haloes or methane rainbows might be observable.)

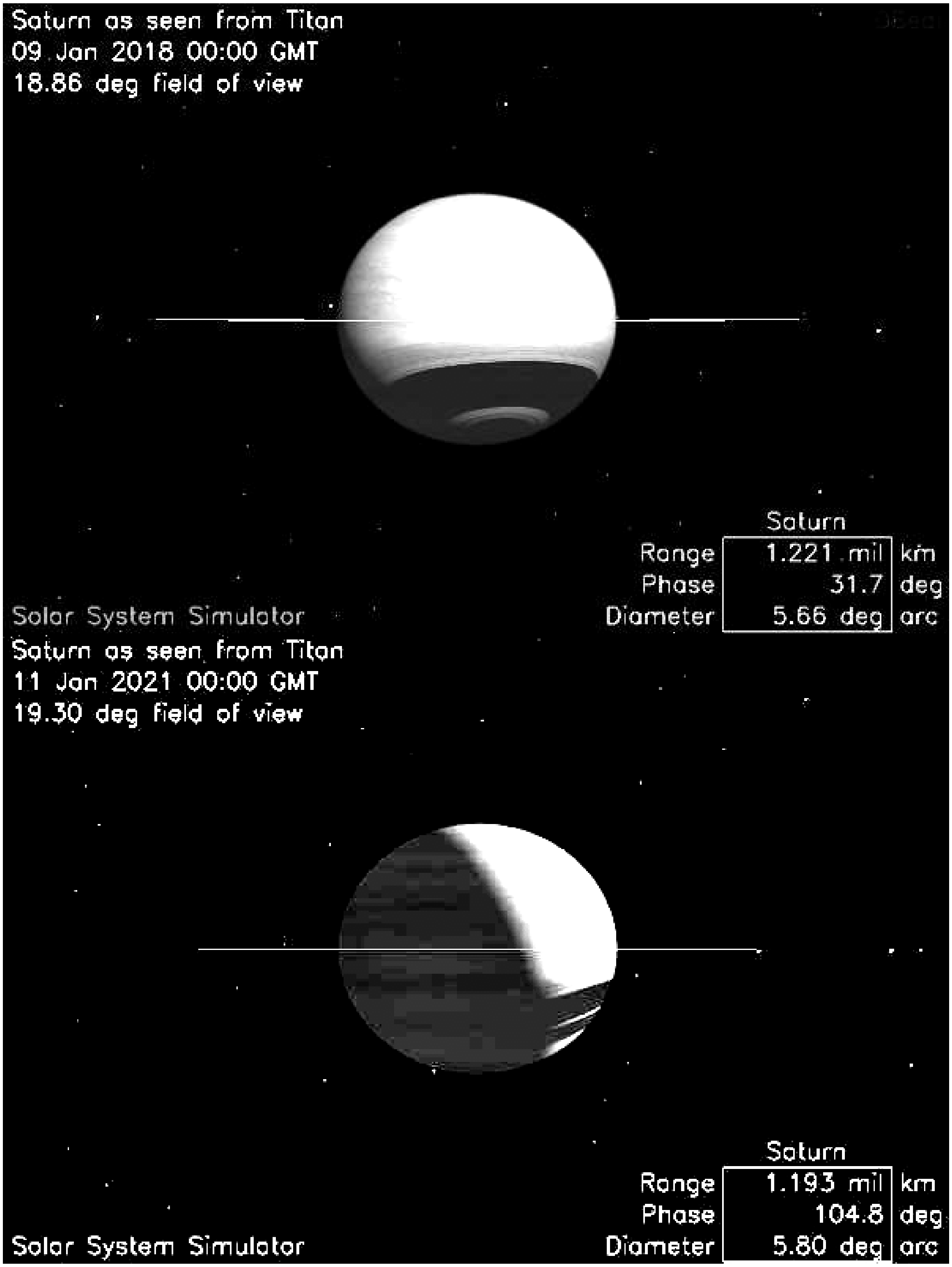

Figure 3. View of Saturn from Titan (ignoring atmospheric effects) generated by Dave Seal's Solar System Simulator (see http://space.jpl.nasa.gov) Saturn displays phases as seen from Titan. During the likely 2015-2022 timeframe of a Titan follow-on mission, during northern summer, the rings will cast an appreciable shadow on Saturn.

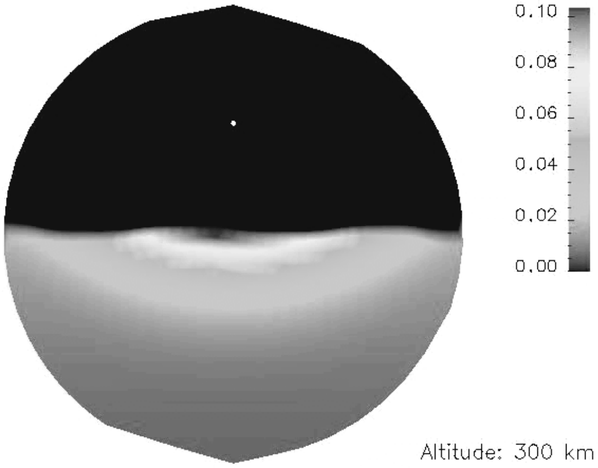

Figure 4a. Simulations by Bjorn Grieger of the Max-Planck Institut fur Aeronomie in Katlenburg-Lindau, Germany (associated with the Huygens DISR instrument) see http://www.linmpi.mpg.de/~grieger/huygens/egs01/ Simulations are for wideband imaging 0.6-1micron, and are therefore representative of about the worst possible imaging that can be done – the scattered component would be much less at 2 microns. Image represents a hemispheric view, looking towards the horizon. At high altitude, the white dot is the unattenuated sun at an altitude of 45 degrees; below is the reflection of the sun from Titan's haze.

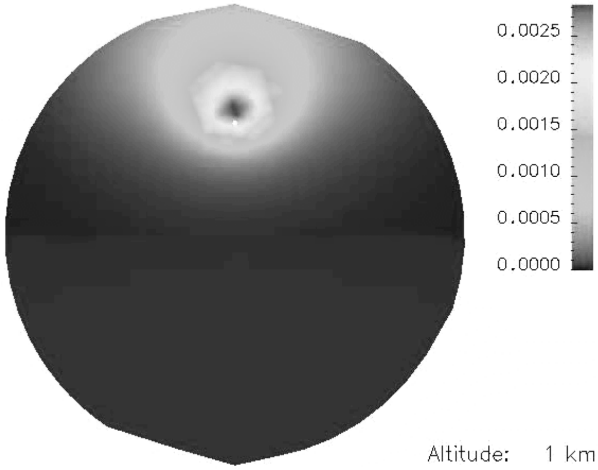

Figure 3b. View from the surface. Note that the fluxes are now considerably lower (but this is still orders of magnitude brighter than full moonlight on Earth). Note that the centroid of the aureole is slightly displaced from the solar position, but this is calibratable. Even with this kind of wideband all-sky camera data, azimuth or time of transit (and thus longitude) and solar elevation (from which latitude can be derived) are easily determined.

SATELLITE NAVIGATION

Although a navigation satellite constellation is unlikely to be available, a single orbiter for data relay and remote observation is a probable adjunct to the near-surface platform. TRANSIT-style doppler navigation may therefore provide some position information - the time of zero doppler shift indicating the coordinate orthogonal to the orbital plane (i.e. latitude, for a polar orbiting satellite) and the shape of the doppler curve indicating the cross-track distance.

A Titan orbiter is far from ideal for such a measurement, since for adequate lifetime the spacecraft must be at an altitude of some 1200km (half a Titan radius). The sea-level air density on Titan is 4 times that of Earth, and in Titan's low gravity, the atmospheric scale height is around 4 times larger, thus the air density falls off very gradually with altitude, forcing the high orbit of a Titan satellite. To put the issue in perspective, the parachute of the ESA Huygens probe to be delivered by Cassini in 2005 is deployed at an altitude of 170km, an altitude that is 'in orbit' at Earth.

The high altitude and low gravity mean that Titan orbital velocities are somewhat lower than for Earth (and thus the doppler shift on the received radio signal is lower) – see figure 4. Furthermore, since the altitude is so high, the shape of the doppler curve is a much poorer discriminator of the miss distance of the satellite groundtrack from the Titan platform (expressed in the figure as a delta-longitude $\Delta\phi$, assuming the platform at the equator and the satellite in a polar orbit).

One advantage of Titan is that the high altitudes mean that a much larger range of $\Delta\phi$ is available, as the orbiter is above the horizon even when it is further away. This is important as it means a larger fraction of orbital passes are available – since the Titan orbital period is around 4 hours long. The slow nature of the passes should also allow Doppler measurements to be made with rather more precision – longer integration times are possible, and the low doppler-rate simplifies signal acquisition and lock. An orbiter pass on Titan lasts about one hour – much longer than on Earth. For the $\Delta\phi=20^o$ pass on Earth, the satellite is only above the horizon for about 5 minutes. The more overhead passes are longer.

More analysis needs to be done to optimize the orbit for both navigation and communication purposes. It may be (depending on the latitude range of desired or permitted targets for the Titan platform, and on the scientific observations if any to be made from the orbiter) that a low-inclination orbit would be preferable.

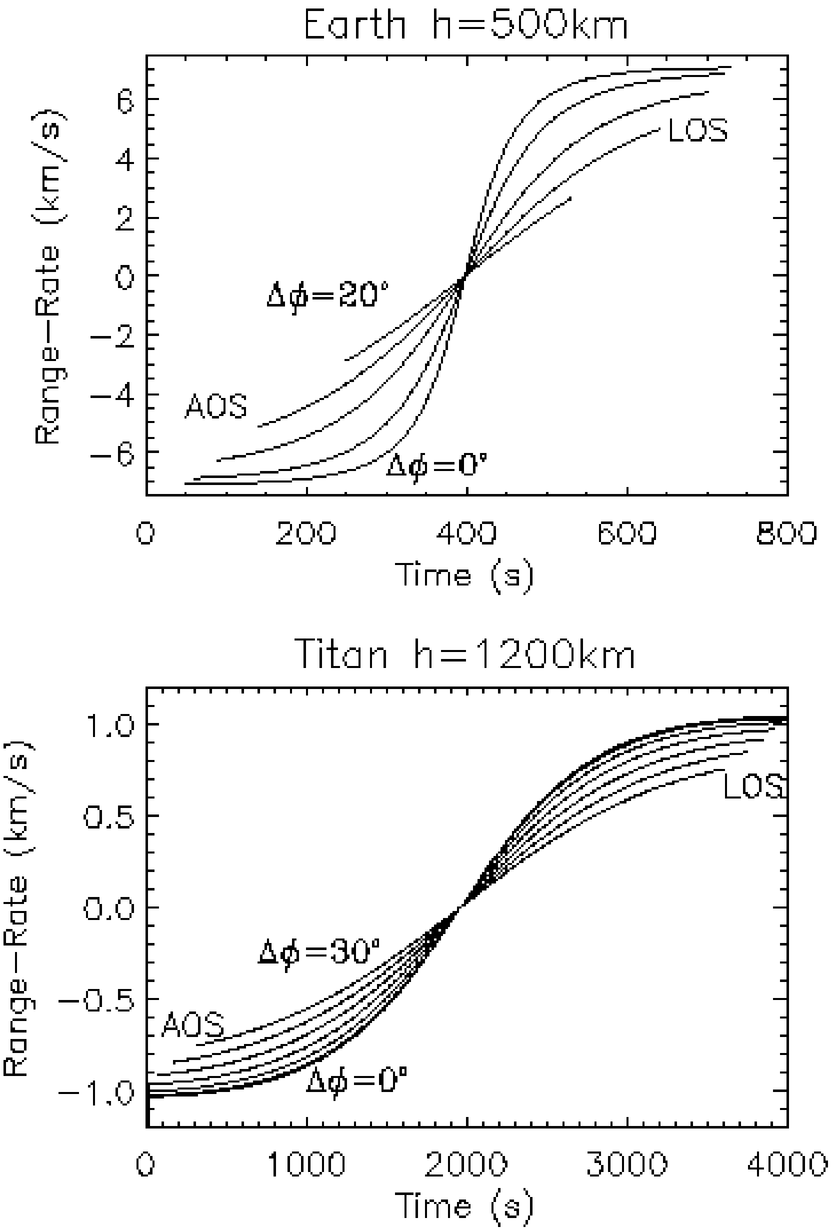

Figure 5. Range-rate of a satellite as a function of time : range rate is zero at closest approach. The doppler shifts are almost a factor of 7 times smaller than for Earth. The high altitude also means that curves for different miss distances have shapes that are much more similar to each other (the Δϕ values above assume the Titan platform on the equator at some longitude ϕ, and the orbiter crosses the equator due northwards at longitude ϕ+Δϕ.) Nevertheless, useful constraints can still be determined.

TERRAIN COMPARISON

From an altitude of a few kilometers, the view obtained by an aerial vehicle will be very different from that obtained by Cassini. Furthermore, since Cassini's imaging coverage will be incomplete (and made under varying conditions of illumination and resolution) terrain-matching will be a challenge, certainly beyond the likely capabilities of on-board computation.

However, it is likely that scientific analysis on the ground can identify major features such as shorelines, mountains, impact craters etc. that can determine the vehicle's position. How useful this is for path planning will depend on the latency of the communications link.

LOCAL NAVIGATION

Separate from the determination of latitude and longitude, local surveys, stationkeeping and landing will require position determination and control relative to surface features with a precision of a few meters. Since environmental accelerations are likely to be gentle (since windspeeds near the surface will be small) 'dead reckoning' via inertial measurements is unlikely to be sufficiently sensitive and precise.

Here autonomous terrain comparison is a likely candidate : optical flow is an active area of research in the Unmanned Aerial Vehicle (UAV) community and this technology is improving rapidly. For Titan application, it may be that such a system would benefit from dedicated illumination to minimize environmental effects. Another technique would be to deploy high-contrast markers onto the surface to act as reference points.

For local navigation on kilometer scales it may be necessary to drop beacons or transponders onto the surface to act as references. A transponder has the advantage of offering range information, and in principle of requiring a lower steady-state power, since only the receiver need be on continuously. If packages are to be dropped onto the surface, it might make sense to instrument these – in particular seismometers would benefit from intimate contact with the surface.

ALTITUDE MEASUREMENT

Radio altimeters can be designed with robust performance characteristics, and the units flying on the Huygens probe should provide altitude reference from over 25km down to the surface.

For near-surface operations, such as surface sample acquisition, it is likely that better altitude referencing may be required. For operations with a range of a few to a hundred meters, optical devices using structured light, laser rangefinders etc. are likely candidates.

Laser rangefinders are now compact and inexpensive, being incorporated in modern binoculars.

Acoustic altimetry is another possible technique – acoustic rangefinders are widely used for 0.3-10m ranges for mobile robotics applications and weigh a few grams. The Huygens probe carries an acoustic sounder, with an estimated surface detection range of 300m.

All of these techniques could be use multiple beams. The radar, and particularly the sonar technique, might be augmented with a doppler measurement capability to record over-ground velocity. A radar sounder at longer wavelength than the Huygens unit would be an attractive payload element – as well as altitude and surface topography/roughness information (the latter, derived from radar or sonar or both, may be particularly useful for evaluating landing sites) it could perform subsurface sounding, to determine the depth of hydrocarbon lakes and the possible presence of near-surface melt.

Pressure sensors could also perform an altimetric function (although note that the pressure scale height on Titan is rather larger than on Earth owing to the low gravity) although meteorological changes, including an atmospheric tide, would suggest that pressure sensing would not be ideal as the prime altimeter.

CONCLUSIONS

Navigation on Titan is far from trivial, especially given our substantial ignorance of that body, a situation that should be partially remedied by the arrival of Cassini and Huygens. However, the combination of various available and emerging methods should permit adequate navigation capability to permit a platform to move to, loiter around, and make contact with, designated locations on Titan.

The various navigation methods also in themselves permit a number of interesting scientific investigations.

ACKNOWLEDGEMENT

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