Spatially Resolved Observations of an Upcoming Titan Occultation

Project Description

RESEARCH PLAN

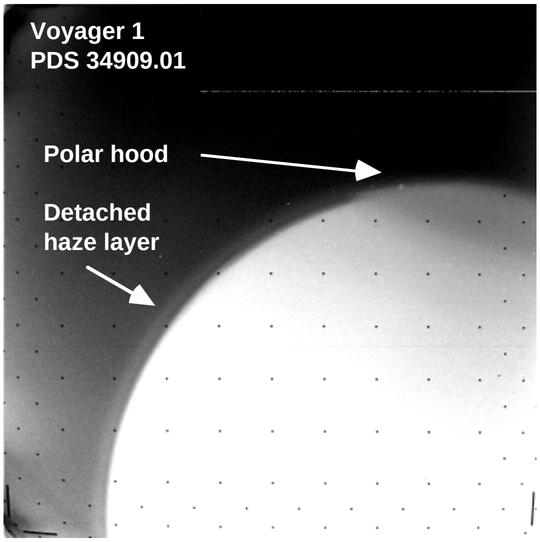
1. BACKGROUND AND PROJECT OBJECTIVES

In 1989 Titan briefly moved in front of 28 Sgr, a 6th magnitude star, an event that was observed from over 20 telescopes in Europe and Asia. The resulting data set (a collection of lightcurves of the disappearing and reappearing star) has proven to be a watershed event in our understanding of Titan's vertical temperature profiles, zonal wind fields and haze distributions. We request time on the AEOS 3.67-m telescope as part of a similar campaign to observe a stellar occultation predicted for 20 December 2001 (UT).

Titan's atmosphere is predominantly nitrogen with traces of methane and other hydrocarbons and aerosols. Titan's surface pressure is only 50% larger than that of the Earth's, but Titan's lower surface gravity results in a much more extended (and ten times more massive) atmospheric column. Because methane and aerosols dominate the opacity of Titan's atmosphere in visible and near IR wavelengths, Voyager's vidicon cameras (operating at 0.6 µm or shorter) were unable to see below Titan's stratosphere (or roughly 150 km). During its 1981 flyby, Voyager did image an asymmetrical distribution of aerosols at higher altitudes (Fig. 1), and this asymmetry has been seen to change radically on a 16-year timescale (Fig. 2). One the the difficult questions to address is where the hazes are formed and how they are transported. Stellar occultations are one of the only techniques that can probe Titan's upper atmosphere, where the haze particles are initially formed by the UV photolysis of hydrocarbons in a nitrogen environment.

Fig. 1

A Voyager 1 image of Titan showing a detached haze layer at 300-350 km and a north polar hood of dark haze particles. The north pole would have appeared bright at longer wavelengths (e.g., 890 - 950 nm) because of the wavelength-dependent single scattering albedos of the haze particles.



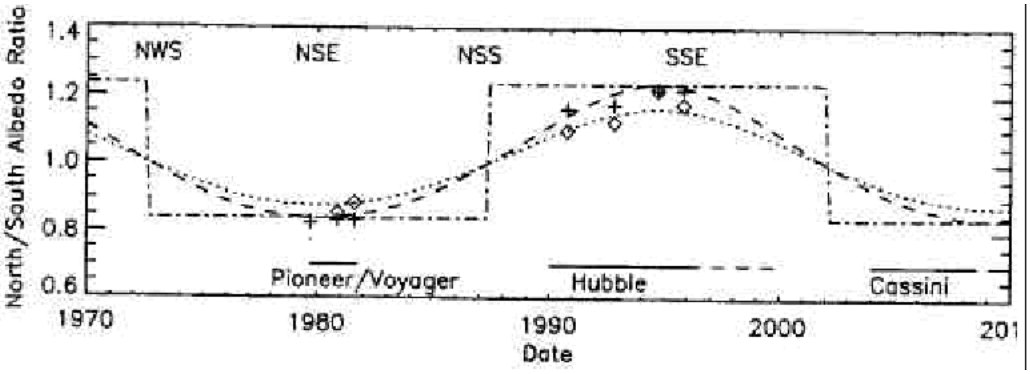


Fig. 2 (From Lorenz et al. 1997.) A sinusoidal fit to Titan's rapidly changing N/S albedo ratio. The ratio refers to visible albedos. The concentration of haze is reversed during the HST measurements of the mid-1990s relative to the Voyager images of the early 1980s. The mechanism for the haze reversal is unknown.

Stellar occultations are uniquely valuable in their ability to probe the refractive and absorptive properties of Titan's atmosphere near the microbar level, around 300 - 600 km. This range contains the transition region from eddy- to diffusion-dominated mixing and is critical in understanding the transport of energy, momentum, trace species and aerosols in Titan's atmosphere. Few other groundbased techniques can resolve this altitude band. Several Cassini instruments are planning stellar and/or solar occultation experiments after the Saturn system encounter in December 2004. The observations we propose here complement the planned Cassini experiments in two ways. First, Titan's atmosphere varies quickly, with noticable differences on yearly timescales (observed in HST images). Second, this groundbased occultation probes altitudes that are lower than the regions probed by Cassini's Ultraviolet Spectrometer (e.g., Fig. 23 of Esposito et al. 2001), which will measure temperatures via the N_2 scale height.

The 1989 occultation was a success in large part because many chords traced by the star behind Titan's atmosphere were observed (Fig. 3).

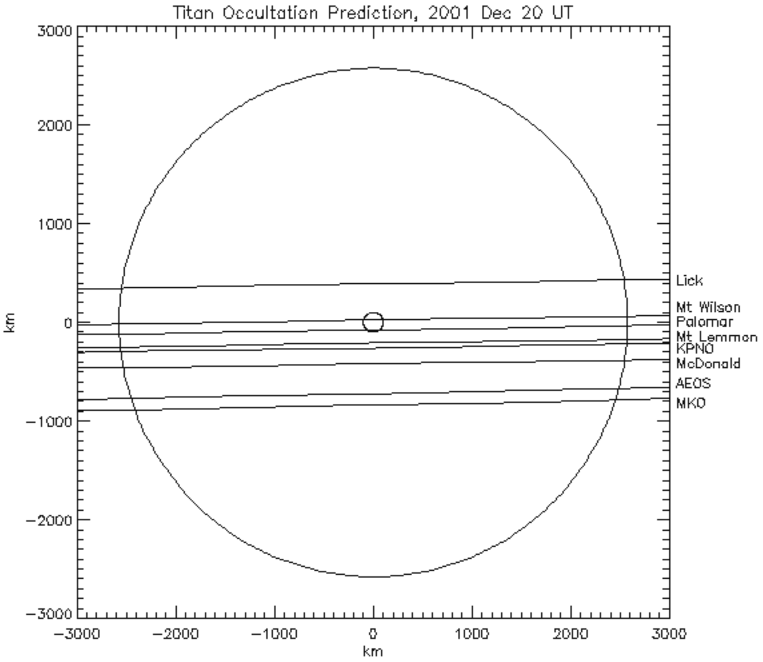


Fig. 3

The groundtracks of the upcoming 20 DEC 2001 Titan occultation for various observatories, all of which will probe the atmosphere at µbar levels. Mt Wilson and Palomar nominally intercept the central flash region, which potentially probes mbar levels as well. The AEOS telescope provides a valuable chord in between McDonald Observatory and Mauna Kea observatories. More significantly, the AEOS system is the only one that has the potential of observing the event with adaptive optics at wavelengths below 1 µm. Since refraction by N_2 and extinction by hazes are both wavelength dependent, this single 0.9 µm data set provides a crucial comparison to 1.7µm or 2.3µm data sets that will be obtained from other sites.

A multitude of groundstations is helpful in sampling different parts of Titan's shadow (particularly the central flash region)) and also in acquiring lightcurves at different wavelengths. Observations at visible *and* IR wavelengths can separate the otherwise correlated contributions due to extinction and differential refraction (see Section 2.1). For this reason the AEOS system is a key part of a campaign that involves proposed observations from Keck, IRTF, Lowell, Palomar, Lick and McDonald Observatories. The AEOS telescope is the only CCD-wavelength adaptive optics system that can acquire this event.

In summary, the upcoming stellar occultation will provide information regarding Titan's vertical temperature, pressure and density profiles, the distribution of hazes at high altitudes, and the latitudinal variation in zonal winds. The Titan occultation campaign objectives are to:

- Measure the vertical temperature profile from 300-600 km at 10-km resolution.
- Measure a power spectrum of the vertical termperature profile, which in turn constrains the presence of gravity waves in Titan's upper atmosphere.
- Measure the asymmetrical morning vs. evening temperature profiles separately from the star's immersion and emersion lightcurves.
- Measure Titan's oblateness and, in turn, constrain zonal wind speeds.
- Measure the separate extinction and differential refraction lightcurves (in conjunction with NIR observations from other sites).

We describe these goals in detail in Section 2, and observing strategies for achieving them in Section 3.

2. SCIENTIFIC GOALS: DETAILED DISCUSSION

2.1 AN ASIDE: STELLAR OCCULTATION OVERVIEW

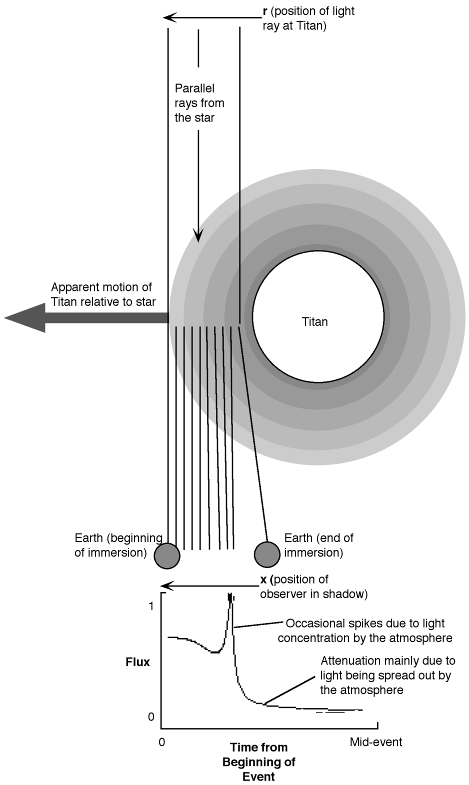


Fig. 4

Differential refraction of starlight during a stellar occultation by an atmosphere. Starlight that is originally parallel impinges on a spherical atmosphere from the top of the page, is refracted by the atmosphere, and is captured by our telescope, situated on the Earth, near the bottom of the figure. In an isothermal atmosphere (not shown), the flux decreases smoothly and monotonically. In Titan's case, it is more likely that density differences in its non-isothermal atmosphere will change the bending angle and introduce spikes in the lightcurve.

The variation in a star's flux during a stellar occultation is a very sensitive measure of the refractivity of the atmosphere, shown schematically in Figure 4. The starlight gets bent by refraction as it passes through the atmosphere. For an isothermal atmosphere, the angle by which the starlight is deflected increases exponentially. As evenly-spaced distances in the planet's atmosphere (Δr) get mapped to wider and wider distances in the plane of the observer (Δx), the observed stellar flux decreases by the ratio $\Delta r/\Delta x$. Local variations in density can slow the exponential increase in the bending angle, leading to the "spikes" seen in occultations by Mars, Titan, Triton, and all the giant planets. If the rays actually converge, then we have a local focusing of starlight, and the flux can exceed the pre-occultation upper baseline.

The differential refraction also causes the image of the star to "stall" at a radius somewhat below half light. As shown in Fig. 8, as the observer proceeds closer to the center of the body's shadow, the observed rays nevertheless come from a narrow region in the planetary or satellite atmosphere. If the observations are not precisely central, the observer sees the image of the star "creep" around the limb of the body. As we describe below, the position of the star's image is related to the oblateness of the body.

The spikes caused by temperature fluctuations are seen in occultations of Titan and all four of the giant planets. The height of the spikes depends on the atmospheric structure, the data rate, and the angular size of the star. In Fig. 5, we see examples of stellar occultations by Titan (left) and Uranus (right).

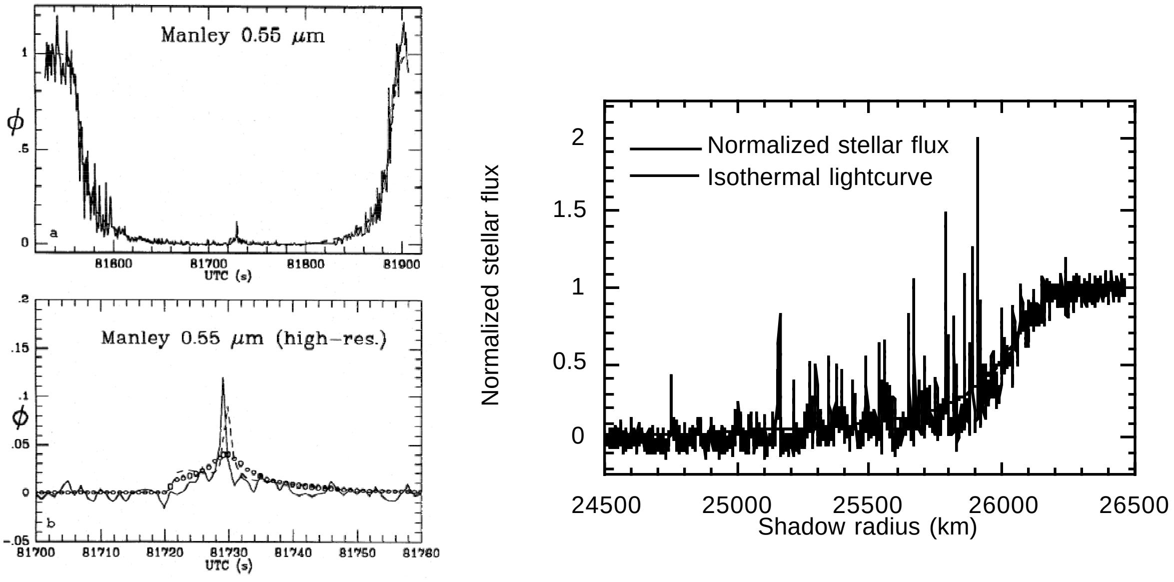


Fig 5. Left: Occultation of 28 Sgr by Titan, observed from Manley Observatory in the UK, from Hubbard et al. 1993 (their Fig. 8). Right: Occultation of U34 by Uranus, observed from IRTF (emersion only). Also plotted are the best-fit isothermal lightcurve (Baum and Code 1953). The spikes are real, and are caused by small-scale fluctuations in the density and temperature of the atmosphere.

2.2 GOAL 1: VERTICALLY RESOVED TEMPERATURE PROFILES

Atmospheric temperature profiles are critical for understanding the energy balance in giant planets (e.g., Atreya et al. 1986), interpreting thermal emission to derive abundances of minor species (e.g., Hanal et al. 1992), and studying dynamics (e.g. Andrews et al. 1987). In each of these key areas, temperature gradients are nearly as important as the temperatures themselves, and vertically-resolved measurements of temperature are needed. Occultations of stars by solar system objects provide the highest spatial resolution possible from ground-based or Earth-orbiting observatories. The decrease in stellar flux due to differential refraction of the starlight as it passes through a planetary atmsosphere allows us to measure temperature as a function of altitude near the 0.1 to 100 microbar level. The theoretical limit is the Fresnel scale, which is ~1.4 km in this case. For 28 Sgr, the angular diameter of the occulted star limited the spatial resolution to 20 km; this star is much fainter, and should have a diameter which is equivalent to 1 km at Titan. For this event, we will be limited by signal-to-noise ratio and data rate to a 1-4 exposures a second, corresponding to a resolution of 4-18 km. In contrast, direct imaging at AEOS with a FWHM of 0.05" gives a spatial resolution of only 300 km.

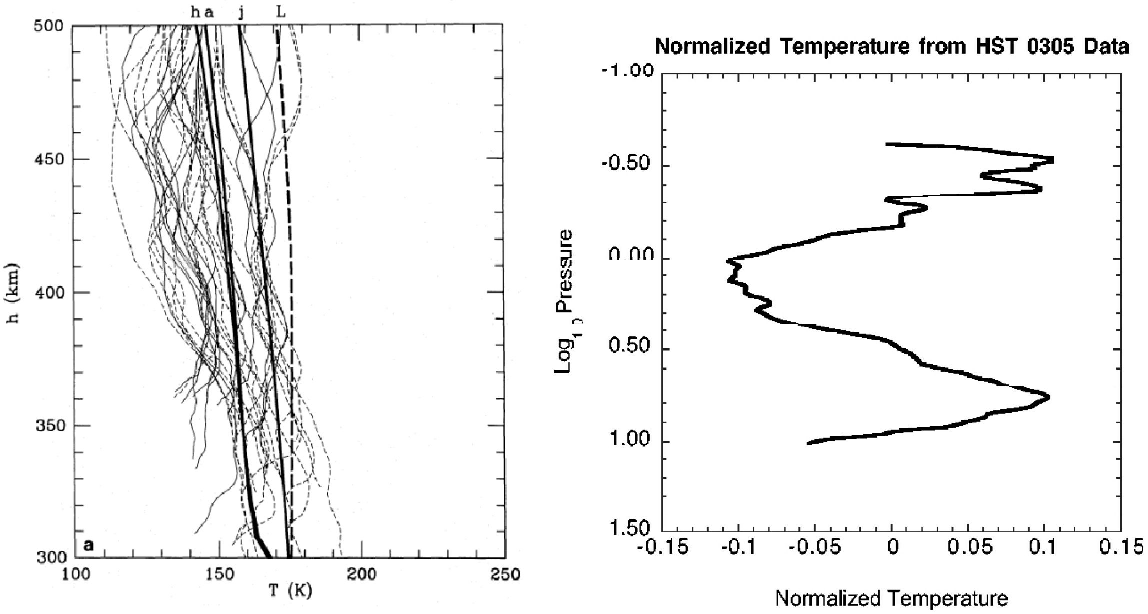


Fig. 6. Left: Normalized temperature vs. altitude from xx ligthcurves from the occultation of 28 Sgr by Titan (Hubbard et al. 1993). Right: temperature vs. pressure (in microbar) for one occulation of GSC 5249-01240 observed by the HST (Foust 1999). The original caption from Hubbard for the left panel is "*Comparison of model atmospheres (heavy curves) and inversions for temperature vs. altitude above Titan's solid surface at r = 2575 km (lighter curves), assuming a loss-free atmosphere with no horizontal scattering. The solid curves are from chords which primarily sampled the northern hemisphere of Titan, while dashed curves are from chords which primarily sampled the southern hemisphere.*"

2.3 GOAL 2: POWER SPECTRA AS AN INDICATION OF WAVE ACTIVITY.

The interaction of gravity waves, with small vertical scales (1-100 km) are important factors in the large-scale dynamics, energetics, and mixing in the Earth's upper atmosphere, and presumably, the upper atmosphere of Titan as well. Stellar occultations are the only ground-based observational technique that can detect temperature, pressure, and density fluctuations at sufficiently fine vertical resolutions, often matching or bettering the resolution available from in-situ probes. Furthermore, occultations probe the region of the homopause, which marks the transition from molecular to eddy diffusion. The latter process is caused by the small-scale dynamics in question. Recent analysis of the power spectra of the vertical variation of temperatures in the atmospheres of Titan (Sicardy et al. 1999), Saturn (Foust 1999), and Jupiter (Young et al. 1998) show a striking resemblance to spectra of gravity waves in the Earth's stratosphere and mesosphere.

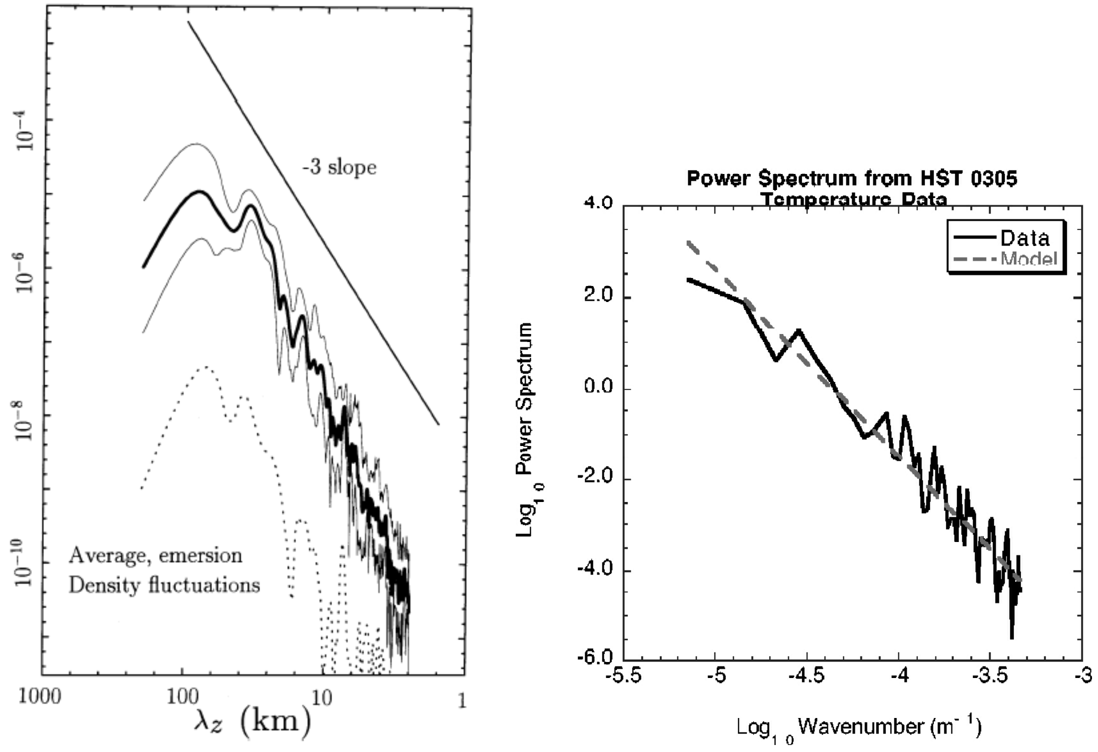


Fig. 7 Left: Normalized temperature vs. pressure (in microbar) for one occulation of GSC 5249-01240 observed by the HST. Right: Power spectra from temperature data. The log base 10 of the power spectrum of the normalized temperature (in meters/cycle) is plotted against the log base 10 of wavenumber (in units of inverse meters). The solid line represents the data, while the dashed line is the best fit to a power-law. Both figures are from Foust (1999).

2.4 GOAL 3: VARIATION OF TEMPERATURE WITH TIME OF DAY OR WITH LATITUDE

The temperatures at the altitudes probed by the stellar occultation are controlled by a variety of terms, including cooling in IR bands of hydrocarbons, heating by solar UV absorption, and adiabatic heating or cooling due to vertical winds (Yelle 1991, Muller-Wodarg et al 2000). These heating and cooling rates should depend on latitude, longitude, and local time of day. Each observed lightcurve will probe a pre-dusk sunlit limb during ingress and a pre-dawn shadowed limb during egress. The combined observations from this and other planned sites will measure temperatures at latitudes ranging from 9° North to –20° South.

2.5 GOAL 4: SHAPE OF TITAN'S UPPER ATMOSPHERE

The zonal winds on Titan are important for understanding the dynamics and temperatures in Titan's upper atmosphere, and may prove useful the Huygens entry probe trajectory. Zonal winds alter the shape of isopotential surfaces, and occultations have produced zonal wind estimates on several atmospheres (e.g., Baron et al. 1983, Hubbard et al. 1993).

The AOES observations *alone* will be able to measure the shape of Titan's upper atmosphere at high southern latitudes. As described above, one side effect of the refraction of the starlight through Titan's atmosphere is that the stellar image "stalls" at an altitude of ~300 km. Fig 8 shows the effect on the paths of the stellar images, represented by thick lines. Note that the stellar images first probe the atmosphere vertically, and then move essentially horizontally. At any given time, the line connecting the image of the star (on the thick lines) and the position of the observer (on the thin lines in Fig. 8) is perpendicular to surfaces of constant density in Titan's atmosphere. Therefore, the rate at which the stellar image observed from AEOS creeps around Titan's south pole will depend on the shape of Titan's atmosphere for latitudes in the range -20° to -90° at ~300 km. This observation depends critically on our ability to spatially resolve Titan and the stellar image. Without adaptive optics, one can only record the integrated Titan + stellar flux, and all spatial information is lost.

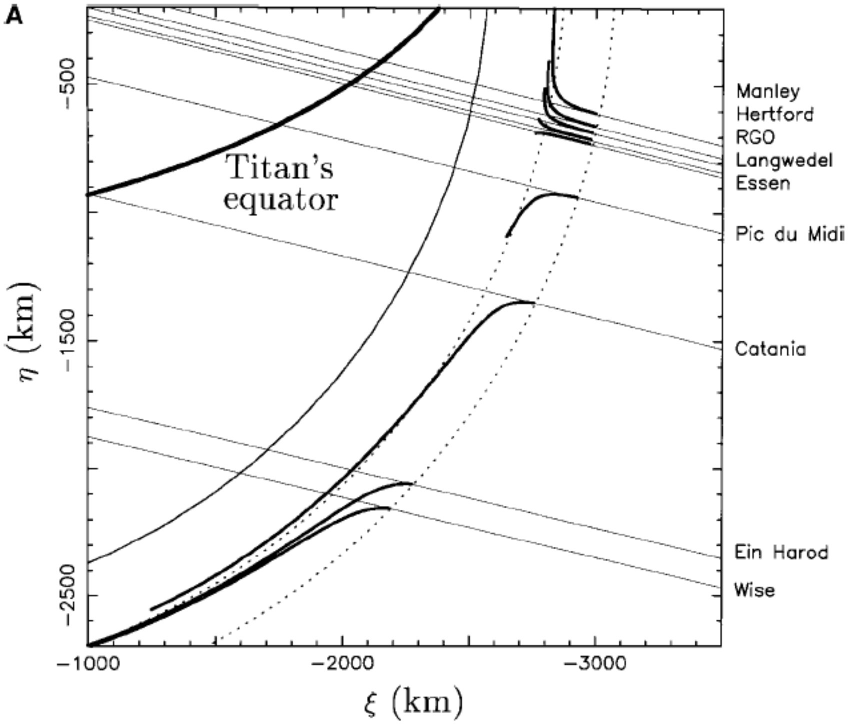


Fig. 8.

Closeup views of ten tracks from the ingress of the 28 Sgr occultation by Titan (Sicardy *et al.* 1999). The thin lines are the tracks followed by the observers in Titan's shadow (analogous to the straight tracks in our Fig. 3). The dotted circles show the 300- and 500-km altitude levels, between which the most significant data are recorded. The thick curves are the tracks actually followed by the stellar images along the limb, between these two limits.

Additionally, in conjunction with other observatories, we will be able to measure the shape of Titan's upper atmosphere at equatorial and low southern latitudes. As seen in Fig. 3, various sites will probe Titan's atmosphere at latitudes ranging from 9° North to 20° South, measuring altitudes with an accuracy of a few km.

2.6 GOAL 5: HAZE PROPERTIES

The hazes in Titan's atmosphere are important for understanding the chemistry of the atmosphere and for interpreting images of Titan's shrouded surface. When occultations by hazy atmospheres are observed at only one wavelength, it is difficult to distinguish the separate effects of absorption and differential refraction. The other observations of Titan in this campaign will be observing at near-IR wavelengths (many at 2.3 mm). At these wavelengths, the line-of-sight optical depth of the Titan hazes at the occultation altitudes are small, while at visible wavelengths, the tangential optical depth at 300 km from the 28 Sgr occultation ranged in latitude from ~0.1 to 1 (Hubbard *et al.* 1993). Observation at visible wavelength therefore complement observations at IR wavelengths to eliminate the refraction/extinction ambiguity.

3. OBSERVING STRATEGY: NEED FOR AEOS

Without AO imaging, the upcoming Titan occultation will not provide any useful stellar photometry. By resolving the occulting object (such as Titan, Uranus, Neptune, etc.) into spatial elements that are 50 - 200 times smaller than the non-AO PSF, the AEOS system opens up otherwise challenging events in which the star is 4 - 6 magnitudes fainter than the object which occults it. In addition, the path of the star's image, if it can be resolved, provides a sensitive constraint on the oblateness of the atmosphere (Fig. 8). The AEOS system is therefore necessary for this occultation observation, and it enables an additional experiment that would not be possible without the AO spatial resolution.

The rest of this section addresses three concerns having to do with (a) the relative brightnesses of the star and Titan, (b) the signal-to-noise ratio at the desired 1-Hz frame rate, and (c) the spatial resolution required to obtain useful results by watching the star's image migrate along the limb during imeersion and emersion.

3.1 SOLVING THE STAR/TITAN CONTRAST PROBLEM

The 1989 28 Sgr occultation was propitious in two respects: the star's shadow cast by Titan crossed over many observatories in Europe and Asia, and the star itself was particularly bright (~6th magnitude). The star which Titan will occult on December 20, 2001 (2MASS star name 0435215+200905) also traverses many observatories (Fig. 3), but it is much fainter, with B, V, and R magnitudes of 14.5, 13.8, and 12.4 respectively. Since Titan’s Vmag = 8.04, or about 7.5 per sq. arcsec, it is clear that there will be a contrast problem between the star and Titan on the order of 6 magnitudes in R, or a factor of 200 in flux. Fortunately there are two strategies that will bring the contrast ratio close to 1:1.

Titan's disk subtends 0.87" on December 20, 2001. The AEOS system should resolve this disk into 238 resolution elements, assuming 0.05" seeing with the AO system. This represents a major improvement, since each element now has a Vmag of 14, or 5.9 magnitudes fainter than that of Titan's integrated disk. The AO system alone could potentially improve the contrast ratio of the star to Titan's surface elements to 1:1.

If, however, the AO system can only achieve 0.1" seeing (as Titan is close to the limit of the AO system), then Titan's disk is resolved into only 60 elements, each of which is about 4 times brighter than the star. To further improve the contrast, we plan to observe Titan in a methane band at 0.89 µm. Titan's spectrum is dominated by methane absorption features (Fig. 9), such that Titan's geometric albedo is 0.08 at 0.89µm, much lower than 0.31 or 0.28 (Titan's albedo at 0.83 µm or 0.94 µm respectively).

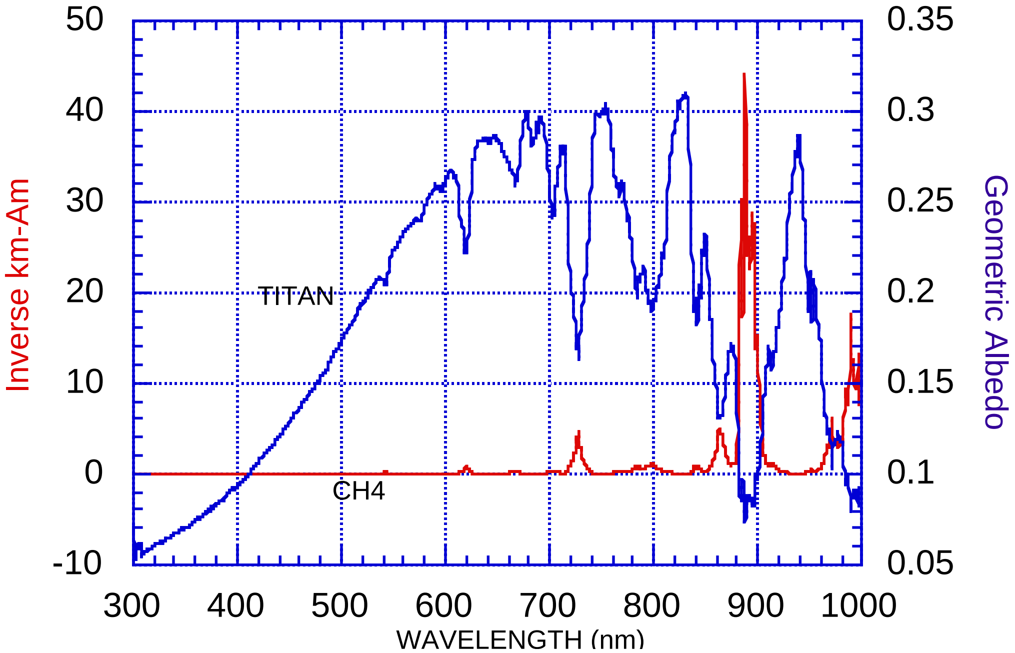


Fig. 9
This double-Y plot compares Titan’s spectrum (in units of geometric albedo) and the absorption coefficient of methane (km-Am^{-1}). This overlay (based on data from Karkoschka 1994) shows that even a small CH_4 absorption feature (e.g., the one at 719 nm) results on a major feature in Titan’s spectrum. The 890 nm feature is the strongest shortward of 1 µm.

In addition to beating down Titan's brightness by a factor of 3.5, observing at 0.89 µm has the advantage that the occulted star (Rmag = 12.4) is redder than the sun. Compare 12.4 to 13.8, the magnitude of a 0.1" element on Titan at 0.89 µm, and it is apparent that the star will be at least 3.5 times brighter than the adjacent pixels of Titan's limb.

3.2 TIME RESOLUTION AND THE PHOTOMETRIC SIGNAL-TO-NOISE RATIO

The usual challenge in occultation observations is to balance the photometric SNR requirements with short exposures times, since time resolution translates into vertical resolution of the reconstructed atmosphere. The star traverses Titan's atmosphere at a rate of 19 vertical km per second, or one scale height every 2.5 seconds. A SNR of 60 is typically sufficient to invert a stellar lightcurve into vertical temperature, density and pressure profiles – what SNR can we achieve with one-second exposures on a 12.4 magnitude star?

The AMOS manual (p. 29) states "For short integration times, i.e., less than one second, the visible imager can detect targets as dim as Mv = +16." At Rmag = 12.4, the occultation star is 27 times brighter than a 16th magnitude object. In the photon shot noise limited case, the star's SNR ratio would be sqrt(27) = 5.2 times better than a 16th mag object's, or 27 times better in a read noise limited situation. Read noise is 14 e-/pixel for the AO/vis sensor on the 3.6-m telescope (Snodgrass, personal communication). We make the following assumptions to estimate the number of electrons generated by a 12.4-mag. star per second.

The AMOS manual states that the quantum efficiency of the AO/vis detector is 45%. We have to guess the throughput of the system; ten percent is typical for non-AO systems, but the NIRSPEC spectrometer on Keck looses an additional factor of 100 in AO mode. We will assume that the system thorughput in AO mode is 45% of 0.1, 0.035, or 0.01. A 12.4-magnitude star's flux is 9.12e-15 erg/cm^2/s/Å in a Johnson I filter, and the number of erg/photon is 2.21e-12 at 9000Å. With no filter in place (i.e., integrating over the instrument's entire 3000 Å range), this stellar flux translates to a signal of 5895, 2036, or 589 electrons per second (for assumed throughputs of 0.1, 0.035, or 0.01 respectively), or signal-to-noise ratios of 242, 143, or 76. If we use a 300Å filter centered at 8900Å to help reduce Titan's brightness, then the signal-to-noise ratios are 76, 43, and 21 instead.

It is not clear whether our target SNR of 60 can be achieved with a 300Å methane filter in place. We therefore request 2 partial nights for trial runs 1 and 8 days before 20 Dec. to evaluate the AO-enhanced SNR of Titan and the occultation star (or equivalent) with and without methane filters (which we will provide).

3.3 STELLAR ASTROMETRY DURING IMMERSION/EMERSION

The nominal oblateness reported by Hubbard et al. (1993) from the 1989 occultation will lead to a small difference in the star's position - about 30 km - between the circular and oblate cases. Centroiding of the star to 30km (a tenth of a pixel) is a realistic goal, given the tens of images resulting from ingress and egress. The standard procedure is to perform a least squares fit for Titan and the star simultaneously, using pre-event images of each as templates, and the star's brightness and ∆RA,∆DEC offsets relative to Titan as three unknown parameters.

3.3 SUMMARY: OBSERVING SCHEDULE

For the trial run, we request 3 + 3 hours of observing time to assess the SNR of the occultation star (or equivalent 12.4 magnitude star with a nearby AO source) with and without a methane filter and to test the AO system's performance using Titan as the source. Since this event happens soon after sunset, we want to be prepared to begin data acquisiton with AO as soon as possible. For the occultation itself, we request 4 hours of observing time in the evening, including a nearby solar standard (TBD), and observations of Titan with 30 min pre- and post-event cushions. The occultation occurs at 5:20 UT on 20 December 2001. The length of the occultation is about 310 seconds, given the star's shadow velocity across the Earth of 19.3 km/sec.

OBJ	**DATE**	**UT**	**RA**	**DEC**	**ALT**	**MAG**	**NOTES**
Titan	13 Dec 01	5:20	4h38m	+20°14'	30°	8.0	Same Titan-Saturn separation as 20 Dec.[1]
Star	13-19 Dec	flexible	TBD	TBD	TBD	12.4	SNR filter test on a 12.4-mag star[2]
HR 1341	20 Dec 01	4:20	4h20m	+21°46'	30°	5.38	A0 standard for photometry
Occ Pair	20 Dec 01	4:30	4h35m	+20°09'	29°	8.0	Separate pre-event imaging
HR 1341	20 Dec 01	4:40	4h20m	+21°46'	31°	5.38	A0 standard for photometry
Occ Pair	20 Dec 01	4:50	4h35m	+20°09'	31°	8.0	Occultation run (1 hour)
HR 1341	20 Dec 01	6:00	4h20m	+21°46'	51°	5.38	A0 standard for photometry
Std Star	20 Dec 01	6:30	TBD	TBD	TBS	>6	Solar analogue standard for photometry
Occ Pair	20 Dec 01	7:00	4h35m	+20°09'	61°	8.0	Separate post-event imaging

[1] Opposite Saturncentric quadrature for Titan (Titan orbit = ~16 days) (3 hours).

[2] Use AO target star brighter than 6-mag with nearby (20 arcsec) 12.4-mag star (3 hours).

4. WORK PLAN AND SCHEDULE

The path from occultation observations to published papers consists of both data reduction and a substantial modeling effort. In this observing proposal we request support for data reduction only. PI (E.Young) and Co-I (L. Young) are both expected to spend 1-mo on this effort. Individual tasks in this occultation-specific reduction include:

- Check time-stamp of observations. (1 person-week)
- Model atmospheric extinction from photometry of AO star. (1 person-week)
- Extract separate Titan and star images from post-event imaging. (2 person-weeks)
- Perform nonlinear least squares fit to solve for star's position and brightness and associated uncertainties. (4 person-weeks)
- Make reduced data available to collaborators and submit this data set to NASA PDS. (1 person-week)

5. DATA MANAGEMENT AND OUTREACH

Occultation projects are often large collaborations between observers and atmospheric modelers (see, for example, author lists for Hubbard et al. 1993 and Sicardy et al. 2000). One of us (Leslie Young) is coodinating an observing campaign for this occultation at over 7 telescopes in Hawaii and the western US (Fig. 3). She is maintaining a web site to coordinate observing efforts: **<http://www.boulder.swri.edu/~layoung/occl/occl.html>**. We plan to submit the raw and reduced observations to NASA's Planetary Data System (PDS).

MANAGEMENT PLAN

This proposed observing project is part of a larger observing campaign. PI (E. Young) will manage the details of this observing run, under direction from Co-I and campaign coordinator L. Young. This unusual management set-up is meant to ensure that the AEOS system occultation lightcurves will be fit into the entire modeling effort.

The PI is responsible for the data reduction of the AEOS observations. Co-I L. Young is responsible for incorporating the AEOS lightcurves into a comprehensive modeling effort. The timescale for the data reduction effort is nominally 3 months. We will submit a final report one year after the occultation date.