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Occultation observations of Titan with Cassini VIMS

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1.

2. Stellar occultations

The basic observation strategy adopted for Titan stellar occultations was the same as that employed for ring stellar occultations. Prior to the beginning of the occultation, VIMS obtained a 16 X 4 high-resolution image cube of the region around the target star, in which the pixel containing the star was identified using onboard software. The VIMS IR scanning mirror was then set to this pixel location and a continuous series of IR spectra was obtained in OCCULTATION mode. In this mode, the pointing remains fixed and the IR channel records a spectrum every 20, 40 or 80 msec, depending on the stellar brightness. Every 64 samples, the data are briefly interrupted to obtain an instrumental background spectrum. The data are saved in standard VIMS “cubes" of 64 X 64 spectra, but in this case there are no implied spatial variations. The last 8 channels in each spectrum are replaced with a time stamp, derived from the internal VIMS clock and periodically synchronized with Cassini's central SCLOCK system. Unlike ring occultations, the data from Titan occultations are not spectrally-summed or edited.

VIMS observed a total of 14 of stellar occultations by Titan, all but one during close flybys of the moon. Only two of these failed to return useful data. A complete list is provided in Table 1, including the stellar parameters, Cassini sequence, rev number and Titan flyby, approximate latitude, spacecraft range and duration, as well as observing mode parameters.

The requirement that VIMS obtain a star-finding cube prior to observing the occultation generally restricted Titan observations to ingress occultations, but in a few cases when the event geometry and allocated time permitted it was possible to observe both the ingress and egress occultations, especially for more distant events such as the RX Lep occultation on rev 228. In the case of the α Sco occultation on rev 49 the near-grazing geometry meant that the star never completely disappeared but could be tracked successfully throughout the occultation period at longer wavelengths. This observation is shown in Fig. 1. This was only possible because refraction is relatively unimportant for VIMS Titan occultations, so that the apparent stellar position remains almost unchanged throughout the event.

In a few cases, standard IMAGE mode was used rather than OCCULTATION mode, generally when it seemed likely that the usual starfinding algorithm might fail. Although only small images were obtained (10 X 8 pixels or less), the much lower rate at which the stellar signal was sampled makes these data probably useless for scientific analysis.

As for Saturn occultations, VIMS stellar occultations by Titan are affected by both differential refraction and molecular absorption, but for Titan we also see the effects of aerosol absorption, especially at shorter wavelengths. Aerosol extinction typically scales with wavelength as λ^{-n}, where for Titan n is ~ 1:5 (Bellucci et al. 2009). Aerosols appear to dominate the occultation light curves at wavelengths less than 2 μm, although quantitative models show that it is also necessary to include the effects of differential refraction (Bellucci et al. 2009). This is illustrated in Fig. 1, where the lightcurve at 1 μm is shown in the upper figure. Molecular absorption in Titan stellar (and solar) occultations is dominated by methane, with strong bands centered at 3.4, 2.3 and 1.65 μm and weaker bands visible at 1.3, 1.1 and 0.9 μm. Rapid signal variations due to refractive scintillation are either absent or very weak compared to those seen in VIMS Saturn occultations. They are more apparent at wavelengths greater than ~ 2:5 μm, as illustrated in the lower figure in Fig. 1.

Table 1.

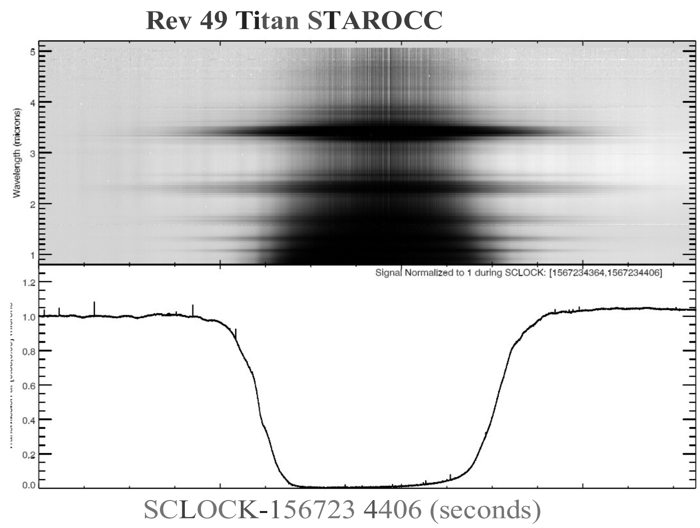
Star	Seq.	Rev.	Flyby	ϕ[2]	Δ[3] (km)	Dur'n (min)	τ (ms)	Mode[4]	cubes	Notes
					Stellar occultations:					
					VIMS STELLAROCCs & xxxOCCs					
α CMa[8]	S23	28	T17	+25°	5025	0:07	40	6x6	98	v. noisy
γ Cru	S27	38	T24	+30°	8410	0:06	40	occ	2	good
σ *Sgr*	S33	49	T35			0:23	80	occ	3	no data[5]
α Sco[8]		49	T35	+60°	6390	0:37	40	occ	6	v. good[6]
α Boo[8]	S36	55	T40	−20°	5265	0:15	40	10x8	280	noisy
α Tau	S57	125	T66	+5°	18100	0:33	40	occ	3	good[9]
χ Aqr	S70	153	T78	−20°	12000	0:16	40	occ	2	poor[11]
CW Leo[7]	S71	159	T80	−7°	131600	4:00	80	occ		poor[12]
R Leo(i)[7]		159		−48°			40	occ		OK[13]
R Leo(e)[7]		159		+65°			40	2x1		OK[13,14]
α Sco	S83	203	T100	+62°	17900	0:49	20	occ	10	OK[15]
η *UMa(i)*[17]		204	T101			3:00				not observed
η *UMa(e)*[17]		204	T101			4:29				not observed
RX Lep(i)	S92	228	—	−40°	168000	1:25	40	occ		OK[16]
RX Lep(e)			—	−50°	168000		40	occ		good
30 Her	S95	238	T121	−47°	25400	1:09	40	occ		good
α Boo	S96	243	T123	−68°	10800	0:33	20	occ		OK?[10]

NOTES:

1. Stellar diameter. Entries in () are estimated from spectral type and K magnitude.
2. Approx latitude.
3. Average S/C - Titan distance.
4. Image size or obsv'n. mode.
5. UVIS rider; Observation ID = UVIS-TI-SIGMASAG; star not detected.
6. Grazing geometry over N pole. Star remains visible beyond 2.7 microns.
7. Combined into one observation: ID = TI-STELLOCC
8. Observation ID = TI-STAROCC.
9. Rider on CIRS LIMBMAP. No spikes.
10. Peculiar light curve, possibly due to extended haze layers.
11. Stellar contrast low against sunlit limb.
12. Irregular baseline & sunlit limb; used CIRS-FP4 boresight.
13. Some data dropouts & sunlit limb.
14. Egress occ; observed 'blind' in IMAGE mode.

15. Unstable baseline; sunlit limb; final qube missing?
16. Distant occ; both ingress & egress occ'ns observed. Ingress limb bright.
17. UVIS rider, ID = TI-STELLOCC.

Total = 17 occs, including 3 "no data". Revised 12 May 2018: PDN.



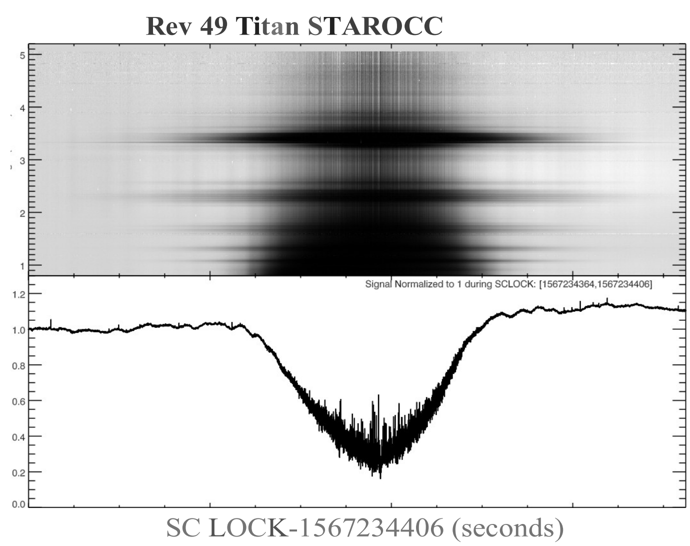


Fig. 1. A grazing occultation by Titan's atmosphere of the star α Sco, observed on rev 49, with an integration time of 40 ms. The average range to Titan was 6400 km, and the closest approach of the star to the limb was at a latitude of ~ 60_N. The upper panel shows the full data set as a 2D grey-scale image, with time on the abscissa and wavelength on the ordinate. The gradual reduction of stellar signal with time is largely due to aerosol extinction, which is much stronger at shorter wavelengths. The narrow horizontal bands are due to molecular absorption by CH_4. The lower panel shows the average lightcurve at 0.9-1.0 μm, where molecular extinction is unimportant but aerosol extinction is strongest. The lower figure shows a version of this plot with the average lightcurve at 2.8-3.0 μm. Some refractive scintillation is visible here. Note that the star never completely disappeared at longer wavelengths.

As was the case for Saturn stellar occultations, the quality of Titan occultations was severely degraded when they were observed against a bright limb; this was the case for five of the VIMS Titan occultations.

3. Solar occultations

As described by Brown et al. (2004), the VIMS IR solar port consisted of a small off-axis aperture within the primary telescope that intercepted ~1 % of the incident sunlight, and then passed this through a chain of 45_ prisms made of ZnSe which further attenuated the signal.[1] The resulting flux, attenuated by an overall factor of 2×10^{-7}, was then passed through the VIMS telescope and spectrometer optics in the same fashion as a normal target scene. In order to match the alignment of the solar port in the UVIS instrument, and to avoid damaging other sensitive optical systems on Cassini by directly observing the Sun, the VIMS solar port looked out in a direction 20° away from the main instrument boresight, offset in the -Z direction, towards the high gain antenna.

Because the Sun is not a point source as seen by VIMS, solar occultations could not be observed in single-pixel mode as were stellar occultations. Our approach was instead to observe solar occultations in IMAGE mode, obtaining a continuous series of small IR cubes of the Sun from which we could later estimate the solar flux as a function of time and wavelength. Cube sizes were either 8 X 8 or 12 X 12 pixels, with integration times of 20 or 40 msec per pixel. A single cube was acquired in 2-6 sec, including the necessary background measurements, which was generally satisfactory for most Titan occultations.

Unlike the situation with stellar occultations, the spatial resolution of solar occultations is usually set by the finite solar angular diameter rather than by the sampling time. At Saturn's mean distance from the Sun of 9.5 AU, the solar diameter is ~ 1:0 mrad, or 2 standard VIMS pixels. For Titan occultations at typical ranges of D ~10; 000 km the projected solar diameter was ~10 km, somewhat less than 1 atmospheric scale height. The large projected size of the solar disk means that the refractive scintillations characteristic of stellar occultations are not expected to be seen in solar occultations.

VIMS observed a total of 16 solar occultations by Titan, most as ingress/egress pairs. All were carried out as riders on observations designed by the UVIS team. Ranges from Titan to Cassini varied from 3600 to 20,000 km. A wide range of planetocentric latitudes has been probed, from -76_ to +81°, but with only a single near-equatorial solar occultation, on rev 109. A summary of all VIMS Titan solar occultations is provided in Table 2. In Fig. 2 we illustrate a typical ingress/egress pair, in the same format as used for stellar occultations in Fig. 1.

VIMS solar occultations are a useful tool for probing the vertical structure of Titan's lower atmosphere, including the nature and spatial distribution or aerosol layers. Analyses of several solar occultations have been reported by Bellucci et al. (2009) and Maltagliati et al. (2015), who find that it is necessary to include differential refraction, molecular absorption and aerosol extinction in order to model the data satisfactorily. At VIMS' longest wavelengths, ~ 5 μm, the solar signal penetrates almost to the surface of Titan according to these models. At

[1]. The solar port in the VIS channel worked, in part, by diffusing the solar image along the instrument's spectrometer slit. This, combined with partial saturation of the solar spectrum, unfortunately made it impossible to make quantitative measurements of the solar flux at visual wavelengths.

shorter wavelengths, aerosols limit the maximum depth of penetration. In addition to methane absorptions seen at 0.9, 1.1, 1.3, 1.65, 2.3 and 3.4 µm, some VIMS solar occultations show absorption by CO at 4.7 µm.

Given the large angular size of Titan at close approach, it was possible for the main VIMS boresight to pass across Titan itself while the solar port was tracking the Sun. This happened during four of the Titan solar occultations observed by VIMS, due to an unfortunate choice of secondary axis orientations for the spacecraft. In such cases, the instrument measured the combined signal from Titan and the Sun, which makes these occultation lightcurves very difficult to interpret (Maltagliati et al. 2015).

Table 2.

Type	Seq.	Rev.	Flyby	ϕ^2	Δ^3 (km)	Dur'n (min)	τ	Mode[4]	cubes	Notes
					Solar occultations:					
					UVIS SOLAROCCs & SOLOCCs					
Ingress	S17	20	T10	−40°	5800	2:40	40	12x12	620	poor[7]
Egress	S17	20	T10	−70°	8300		40	12x12	620	OK
Ingress	S28	40	T26	−76°	5700	0:36	20	12x12	173	confused[8]
Ingress	S31	46	T32	−45°	16100	0:27	40	12x12	367	OK
Egress[11]	S49	109	T53	+1°	6300	0:36	20	8x8	350	OK[8]
Ingress[11]	S51	114	T58	+81°	10400	1:05	20	8x8	260	no data[10]
Ingress	S54	119	T62	−17°	20000	0:57	40	8x8	400	good[5]
Egress	S54	119	T62	−76°	7300	0:46	40	8x8	355	good
Ingress[12]	S70	153	T78	+40°	9700	0:56	20	8x8	400	good
Egress[12]	S70	153	T78	+27°	8400		20	8x8	400	OK[8]
Ingress	S84	206	T103	−66°	7800	1:16	30	8x8		good
Egress	S84	206	T103	+31°	8400		30	8x8		good
Ingress	S92	231	T116	−63°	4200	2:03	20	8x8		good
Egress	S92	231	T116	+29°	10400		20	8x8		good
Ingress	S93	234	T118	−58°	3600	1:50	20	12x12		OK[8,9]
Egress	S93	234	T118	+35°	7200		20	12x12		OK[9]

NOTES:

1. Solar diameter.
2. Approx latitude.
3. Average S/C - Titan distance.
4. Image size.
5. First use of UVIS-SOL-OFF boresight.
7. Sun starts at edge of VIMS FOV, but pointing improves.
8. **VIMS boresight crossed Titan's limb during observation.**
9. S/C on RCS control.
10. Sun not detected; bad VIMS pointing?
11. Observation ID = UVIS-TI-LIMBMAP
12. Observation ID = UVIS-TI-SOLOCC

Revised 12 May 2018: PDN.
Total = 16 occs, including 1 "no data" and 4 with bright limb confusion.

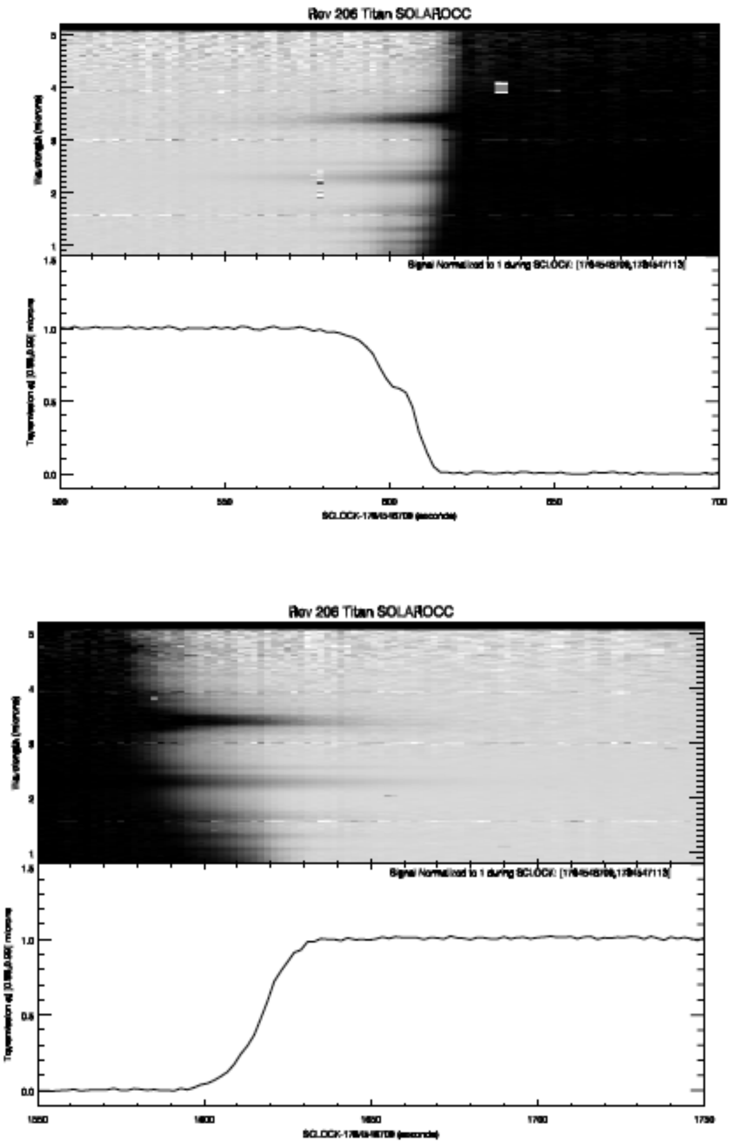


Fig. 2. A pair of solar ingress and egress occultations by Titan's atmosphere observed on rev 206, during the flyby designated as T103. The integration time was 30 ms per pixel and the data are displayed in the same format used in Fig. 1. In each case, the upper panel shows the full data set as a 2D grey-scale image, with time on the abscissa and wavelength on the ordinate, while the lower panel shows the average lightcurve at 0.9-1.0 μm. The gradual variation in stellar signal with time is due to a combination of differential refraction, which is almost independent of wavelength, and aerosol extinction. As in Fig. 1, the narrow horizontal bands are due to molecular absorption by CH_4. Aerosol extinction is strongest at short wavelengths. Note the distinct aerosol layer in the ingress profile. The latitudes of ingress and egress were -66_ and +31°, respectively, and the ranges to Titan were 7800 km and 8400 km.

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