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Letter to the Editor

A new VLT surface map of Titan at 1.575 microns

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Abstract. We present a first high contrast 1.575 micron surface map of Titan, that is haze corrected by simultaneously imaging the stratospheric layer. At visible and most near-infrared wavelengths, the methane rich atmosphere completely obscures the surface; only in a few narrow wavelength windows does the atmosphere become optically thin. One of the most convenient windows (Griffith et al. 2003) lies at 1.58 μm, adjacent to the methane absorption feature at 1.62 μm. Our data span seven consecutive nights, resulting in phase coverage of 275° in longitude. The images were taken with NAOS-CONICA adaptive optics system at the VLT, using the recently commissioned Simultaneous Differential Imager mode (SDI). The combination of adaptive optics and simultaneous imaging through three filters sampling the methane absorption at 1.6 micron reveals extraordinary details of Titan's surface. Providing views of Titan's surface at high resolution (60 mas) is of particular topical importance, since the Cassini-Huygens mission is currently approaching the Saturn system and the Huygens probe will enter Titan's atmosphere in early 2005.

Key words. planets and satellites: individual: Titan – infrared: solar system – instrumentation: adaptive optics

1. Introduction

Saturn's moon, Titan, is the ongoing focus of intense research. It is the only moon in our solar system shrouded in a thick atmosphere with a surface pressure of 1.5 bar. This atmosphere is composed mainly of nitrogen and contains significant amounts of methane. The broad absorption bands of methane completely obscured the view of the Voyager missions, and since then, there have been several efforts to penetrate the atmosphere and investigate the surface.

One exciting motivation to study the atmosphere and the surface is given by the assumption that the environmental conditions could be comparable to earth before the appearance of life. Hence, Titan might be considered as a laboratory for prebiotic chemistry to study the formation of complex organic molecules, the fundamental compounds of life (Owen et al. 1997).

The advent of ground-based, high-resolution imaging with near-infrared adaptive optics (AO) has helped enormously in the study of Titan (Coustenis et al. 2001; Roe et al. 2002; Gendron et al. 2004). Earlier, observations with the Hubble Space Telescope and speckle imaging gave a first notion about the atmosphere and surface features (Smith et al. 1996; Gibbard et al. 1999; Meier et al. 2000). Only a few studies provided complete surface coverage. Moreover, the loss in contrast due to the global stratospheric haze layer concealed the shape of the surface features.

The Cassini-Huygens mission is predicted to reach the Saturn system in June 2004, and the Huygens probe will be dropped into Titan's atmosphere in early 2005. The goal of Huygens is to measure the physical, chemical, and meteorological properties of Titan's atmosphere, and to characterize (locally) the surface, in case the impact is survived.

High-resolution imaging (60 mas) of Titan's atmosphere (weather, wind) and Titan's surface will be strategically critical for the descent of the probe and the final selection of the landing site.

2. Simultaneous differential imaging with NAOS-CONICA

The VLT NAOS-CONICA instrument (Rousset et al. 2003; Lenzen et al. 2003; Lagrange et al. 2003), was recently upgraded with a new observing mode: the Simultaneous Differential Imager (SDI – Close & et. al 2004; Lenzen et al. 2004a,b). Its main application is high contrast imaging for the search for substellar companions with methane, but in addition, it turns out to be a powerful tool to investigate solar system objects with methane absorption.

The SDI mode allows the calibration of stellar speckle noise by *simultaneously* obtaining two images outside (1.575 μm, 1.600 μm) and two images inside (2 × 1.625 μm)

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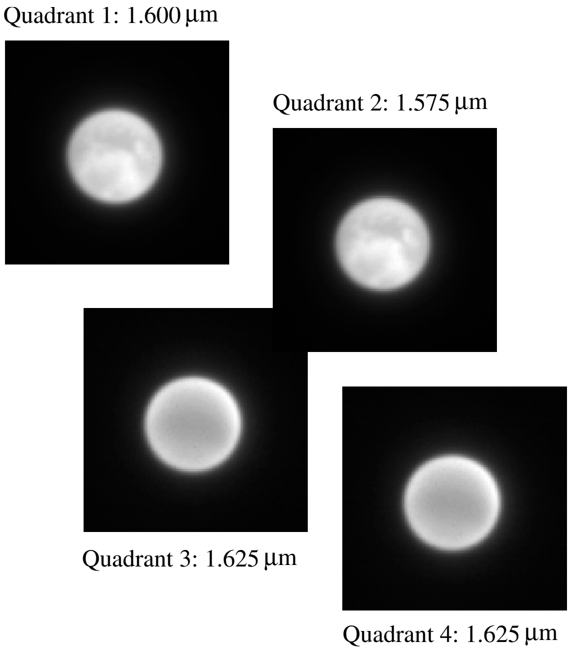

Fig. 1. Titan imaging with the SDI. Schematically, the rhomboid distribution over the detector of the four beams is visualized, but for clarity each of the Titan images (diameter of disk: 0.86″) in the different wavelength channels is magnified.

the methane absorption feature[1]. All filters have a *FWHM* of 25 nm. The platescale of the SDI optics is 17.25 mas/pixel, and the FOV is $5 \times 5''$.

Beam splitting is done by a double calcite Wollaston prism. The second Wollaston is rotated by 45° relative to the first one, resulting in a rhomboid distribution of the four sub-images on the detector. To avoid overlapping of the FOVs, a small $6 \times 6''$ mask is placed in the entrance focal plane. The four quadrant filter is located just in front of the detector. Particular care was taken to minimize differential static aberrations between the four beams (<10 nm RMS per Zernike mode), resulting in almost identical PSFs and residual speckle noise distributions (Lenzen et al. 2004a).

3. Observations and data reduction

Figure 1 shows an example of the SDI Titan imaging. The images are sky subtracted, flat fielded, and the jittered frames are realigned with sub-pixel accuracy and combined. The same intensity stretch applies for each sub-image. Figure 1 shows the impact of the sharp methane absorption feature at 1.62 μm. Even though the wavelengths of the four quadrant filter differ by only 25 nm, the methane absorption completely obscures all surface and even tropospheric features for the lower two quadrants. Only the thick methane haze of Titan's atmosphere is visible. Note the limb brightening due to the increased backscattering of sunlight in the 1.625 μm images. In the upper two quadrants, the atmosphere becomes optically thin, and surface features are revealed with remarkably contrast. The highest values for the contrast of low and high reflectivity regions are about 3.5, at a *S/N*-ratio of approximately 200 per pixel.

The double Wollaston prism makes the SDI sensitive to polarized light. We neglect the small polarization effects. It is worth mentioning that the upper quadrants (1.600 and 1.575 μm images) have perpendicular polarization vectors in respect to the lower quadrants (1.625 μm images).

Titan was observed on seven consecutive nights, with one night missed due to bad weather. The total integration time per night was 10 min, except for the case where frames had to be rejected (broken AO loop, thick cirrus). Typical infrared imaging techniques have been used: 5 dither positions and one sky position, with an exposure time of 120 s each. To allow for further resolution improvement through deconvolution, a PSF star was observed immediately after each Titan observation, using the same configuration of the adaptive optics instrument and at comparable airmass. For two nights, no PSF stars could be recorded due to rapidly changing weather conditions. The details of the observations are summarized in Table 1.

In order to remove residual methane haze, the 1.625 μm image (inside the methane absorption) was subtracted from the 1.575 and 1.600 μm images (outside the methane absorption). Then, the images of each wavelength channel were deconvolved with the PSF star. Deconvolution was done using the Lucy-Richardson algorithm provided by IRAF. To be conservative, the algorithm was stopped after 10 to 15 iterations. In the case where no PSF star observations could be done immediately after the Titan observations, we used a PSF star from another night with comparable seeing and airmass conditions. This was justified afterwards by an inspection of the resulting images. Constancy of prominent features for different observing phases showed that the PSF star selection and the number of iterations for the deconvolution was performed carefully and conservatively.

We generated pseudo-colour images using the three SDI channels, assigning green and red to the two channels outside the methane absorption and blue to the channel inside the methane absorption. The resulting images appear in Fig. 2. The blue color shows the atmosphere, while dark and bright regions correspond to low and high reflectivity surface regions, respectively.

4. Mapping Titan's surface

A first surface map of Titan was obtained by Smith et al. (1996) through an atmospheric window between 0.940 and 1.080 μm with the Hubble Space Telescope. Later monitoring programmes, with the Keck, Gemini, and VLT telescopes using adaptive optics and near infrared imaging improved the resolution of surface and atmospheric features remarkably (Combes et al. 1997; Brown et al. 2002; Gendron et al. 2004). In parallel to this paper, a 1.6-micron map from Keck imaging is currently being published (Roe et al. 2004). Now, with the availability of the SDI, we are able to present a high resolution surface map (60 mas) with the lowest contamination of stratospheric haze to date.

[1] Due to the way the four quadrant filter is manufactured, one wavelength is repeated.

Table 1. Titan observations with NAOS-CONICA in SDI mode. Ob.-lon. and Ob.-lat. indicate subearth longitude and latitude. JPL Ephemeris generator used (`http://ssd.jpl.nasa.gov/horizons.html`).

Night	Obs. date (UT)	Airmass	Seeing	Ob.-lon.	Ob.-lat.	Exp. time (s)	Comments
1	2004-Feb.-02 03:46	1.587	0.4″	254.34°	–25.66°	600	
2	2004-Feb.-03 03:13	1.516	0.6″	276.46°	–25.66°	600	
3							no observations
4	2004-Feb.-05 04:22	1.809	0.8″	322.79°	–25.67°	600	
5	2004-Feb.-06 03:35	1.605	0.9″	344.66°	–25.68°	400	no PSF, clouds
6	2004-Feb.-07 04:16	1.823	0.4″	7.92°	–25.69°	600	
7	2004-Feb.-08 02:52	1.516	0.8″	29.21°	–25.70°	600	no PSF, clouds

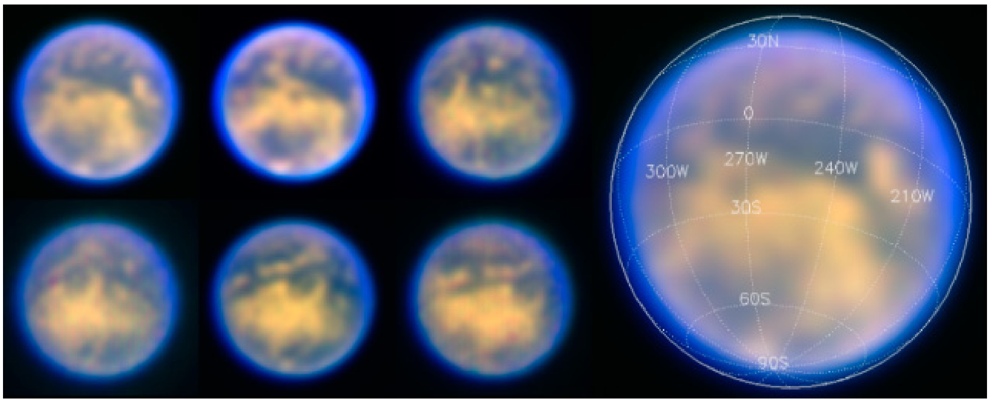

Fig. 2. The six observed phases corresponding to nights 1, 2, 4, 5, 6, and 7 (see Table 1) are displayed in an RGB pseudo-colour composite of the three wavelength channels: 1.575 μm red, 1.600 μm green, and 1.625 μm blue. The rotational phase changes by 22.6°/night. The enlarged image shows night 1 with a superposed coordinate grid. The images are deconvolved.

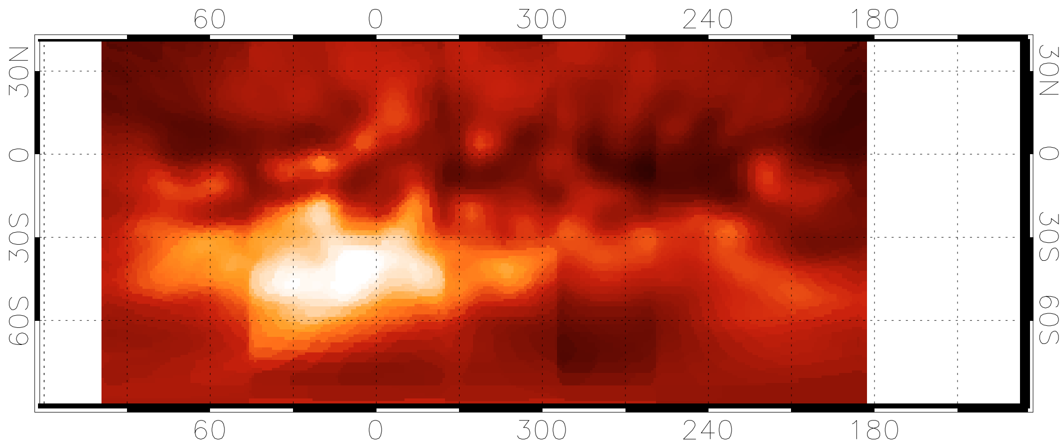

Fig. 3. Haze subtracted map of Titan in cylindrical projection at 1.575 μm with a bandwidth of 25 nm. In this wavelength window, the atmosphere is optically thin, and the surface is revealed. One degree in longitude corresponds to 45 km on Titan's surface. The intensity stretch is linear.

Comparison with the images of Brown et al. (2002), and other monitoring programmes[2] show that all prominent features of the different phases shown in Fig. 2 are persistent, except for a tropospheric cloud at the south pole (Brown et al. 2002; Roe et al. 2002).

We use the methane haze subtracted images (1.575 μm) for all observed phases to create a surface map. The observed center of disk longitudes range from 254°W to 29°W (Table 1), yielding a surface map covering 275° in longitude. For the construction of the surface map, we have chosen the highest quality data. The range of planetographic longitudes never exceeds 76° in longitude, but usually it is smaller, in order to limit center to limb effects. The exact longitudes used to combine the surface map appear in Table 2. The missing night is insignificant, since the phase coverage is otherwise complete (22.6° per night); furthermore, we decided to make no use of night 5 due to the lower quality of these data.

Before applying an inverse orthographic projection, the images have been aligned with sub-pixel accuracy, and the 3D axis tilt corrected. The projected axis tilt on the sky plane is

[2] The Keck Titan monitoring programme (`http://www2.keck.hawaii.edu/science/titan/`).

Table 2. Limiting longitudes for the combination of the surface map.

Night	Cen. lon.	Start lon.	End lon.	Range (in lon.)
1	254.34°	183.3°	259.3°	76°
2	276.46°	260.5°	295.5°	35°
3	No obs.	No obs.	No obs.	0°
4	322.79°	296.8°	335.8°	39°
5	344.66°	Not used	Not used	0°
6	7.92°	336.9°	46.9°	70°
7	29.21°	47.2°	98.2°	51°

de-rotated (–6.1°), and the tilt out of the sky plane is taken into account for the inverse orthographic projection (26°). Finally, we composed a continuous surface map out of the six de-projected maps by using the exact western longitudes for each observation as indicated in Table 1. The assembled surface map appears in Fig. 3.

Recently, Arecibo radar observations have provided evidence for liquid surfaces on Titan (Campbell et al. 2003). The low surface albedo regions could indicate the locations of these suspected surface reservoirs of liquid hydrocarbons, one possible source to compensate for the continuous decomposition of the methane in the atmosphere by solar ultraviolet photolysis.

Referring to the *low albedo structures* (dark features from right to left), we have tentatively named several features including the "dragon head" ranging from 220°W to 290°W, and, just in front of the dragon's open mouth, a "chased dog" (290°W to 350°W) playing with a "ball" (the circular structure centered at 5 W 10 S). Finally, we find the "lying H" from 10°W to 80°W. East of the "dragon head" at 210°W 10 S a bright slightly elongated and bended feature shapes to the "dragon wing". This bright feature can be identified in the 1.28 μm images taken by Gendron et al. (2004), more than 15 months separated from our observations. All of the described low reflectivity, large scale features can be identified in the *K*-band images in the Titan monitoring project of Keck. The only prominent feature missing in our map due to longitude coverage, is the well-known "bright feature" (Smith et al. 1996) ranging from 80°W to 130°W. Hence, our data set happened to cover the dark phases of Titan's surface.

5. Summary and outlook

The availability of the SDI, with its four quadrant filter sampling one of the most prominent near infrared methane absorption features in combination with the state-of-the-art VLT adaptive optics system NAOS-CONICA, made it possible to map the surface of Titan with unprecedented contrast at 60 mas resolution[3]. This resolution corresponds to 360 km on the surface. The complete phase coverage ranging over 7 nights allowed the construction of a map spreading over 275° in longitude (190°W to 100° W). The map suffers from very low contamination of the stratospheric haze layer, since we can subtract off the haze at 1.625 μm with a simultaneous PSF at the 1.575 μm image. The persistence of albedo features over months and years indicates that the prominent features are indeed surface features.

The SDI imaging mode is an excellent choice for Titan monitoring. Complete phase coverage over several orbits will enable removal of any residual atmospheric features. Monitoring and mapping will provide essential support for the upcoming Cassini-Huygens encounter.

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[3] The given resolution is the measured *FWHM* of the PSF star used for deconvolution.