

## A new 1.6-micron map of Titan's surface

H. G. Roe,<sup>1</sup> I. de Pater,<sup>2</sup> S. G. Gibbard,<sup>3</sup> B. A. Macintosh,<sup>3</sup> C. E. Max,<sup>4</sup> E. F. Young,<sup>5</sup> M. E. Brown,<sup>1</sup> and A. H. Bouchez<sup>6</sup>

Received 2 March 2004; revised 13 April 2004; accepted 19 April 2004; published 17 June 2004.

[1] We present a new map of Titan's surface obtained in the spectral 'window' at  $\sim 1.6 \mu\text{m}$  between strong methane absorption. This pre-Cassini view of Titan's surface was created from images obtained using adaptive optics on the W.M. Keck II telescope and is the highest resolution map yet made of Titan's surface. Numerous surface features down to the limits of the spatial resolution ( $\sim 200\text{--}300 \text{ km}$ ) are apparent. No features are easily identifiable in terms of their geologic origin, although several are likely craters. *INDEX TERMS:* 5470 Planetology: Solid Surface Planets: Surface materials and properties; 5494 Planetology: Solid Surface Planets: Instruments and techniques; 6280 Planetology: Solar System Objects: Saturnian satellites. **Citation:** Roe, H. G., I. de Pater, S. G. Gibbard, B. A. Macintosh, C. E. Max, E. F. Young, M. E. Brown, and A. H. Bouchez (2004), A new 1.6-micron map of Titan's surface, *Geophys. Res. Lett.*, 31, L17S03, doi:10.1029/2004GL019871.

### 1. Introduction

[2] The first detection of Titan's surface was more than a decade ago, yet the nature of Titan's surface remains enigmatic. Titan's surface is visible in reflected sunlight in several spectral 'windows' in the near-infrared between methane and hydrogen absorption features [Griffith *et al.*, 1991]. Each improvement in observing technique, from disk-integrated photometry to more recent resolved imaging, has revealed new structure on Titan's surface to the limits of the spatial resolution. During this time there has been no discernible change on Titan's surface, although time-variable atmospheric phenomena have been observed, including seasonally varying stratospheric haze [e.g., Lorenz *et al.*, 2001], a south polar collar of haze [e.g., Roe *et al.*, 2002a], and the discovery of south polar tropospheric clouds [Brown *et al.*, 2002; Roe *et al.*, 2002b].

[3] The current work presents new  $1.58 \mu\text{m}$  wavelength high resolution images of Titan and a surface map derived from these data. Our new map is significantly higher resolution than any previous map in this spectral window and continues the trend of finding spatial structure at the limits of spatial resolution.

<sup>1</sup>Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California, USA.

<sup>2</sup>Department of Astronomy, University of California, Berkeley, California, USA.

<sup>3</sup>Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, Livermore, California, USA.

<sup>4</sup>Center for Adaptive Optics, University of California, Santa Cruz, California, USA.

<sup>5</sup>Southwest Research Institute, Boulder, Colorado, USA.

<sup>6</sup>W. M. Keck Observatory, Waimea, Hawaii, USA.

### 2. Observations and Data Reduction

[4] All observations were made using the adaptive optics (AO) system on the W.M. Keck II 10-meter telescope [Wizinowich *et al.*, 2000] and one of two narrowband filters centered near  $1.57 \mu\text{m}$  ( $1.5731\text{--}1.5871 \mu\text{m}$  and  $1.5688\text{--}1.5920 \mu\text{m}$ ). Both filters were chosen to probe in a wavelength region of extremely low methane opacity in order to see surface features with the highest possible contrast. This spectral 'window' to Titan's surface extends over  $\sim 1.51\text{--}1.61 \mu\text{m}$  with the clearest view of the surface in the range  $1.57\text{--}1.60 \mu\text{m}$ . Processing of the images was limited to the standard sky subtraction, correction for pixel-to-pixel sensitivity variations, interpolation across the few bad pixels, and summing the several observed images. The images are shown in Figure 1 in order of increasing central west longitude, along with relevant ephemeris information. The resolution in these images is nearly the diffraction limit of the telescope ( $0.04''$  or  $\sim 200 \text{ km}$  on Titan's surface at opposition).

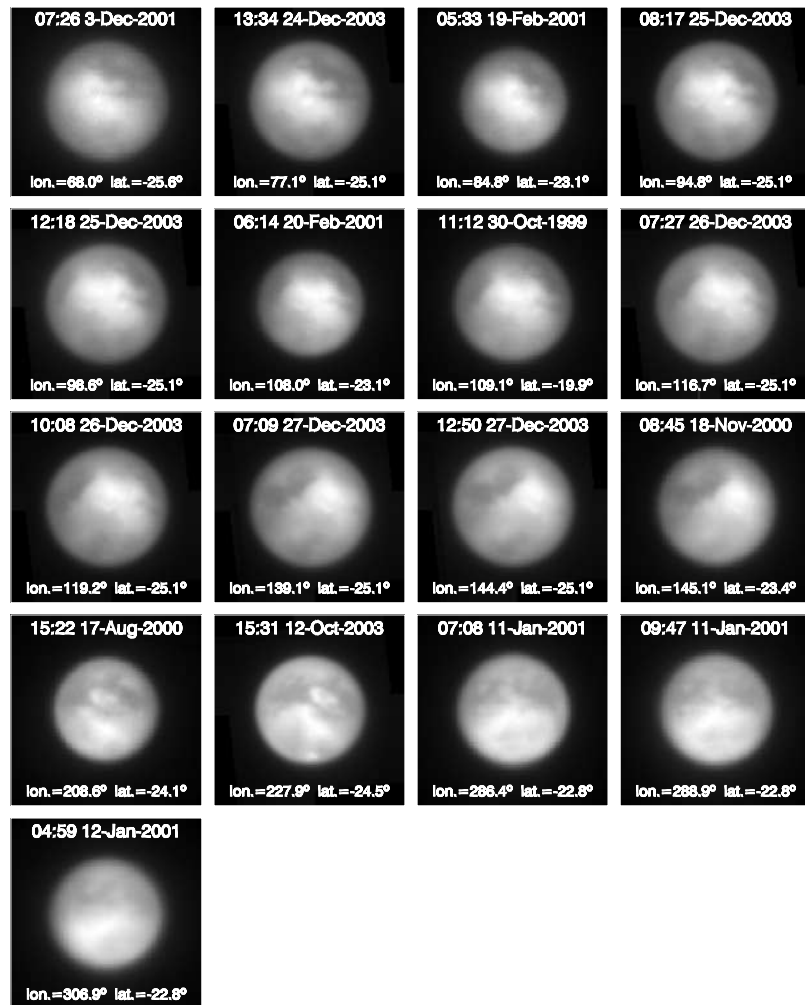
[5] To generate a map of Titan each image is deprojected on to a latitude-longitude grid and each pixel is corrected for phase angle using a simple Minnaert phase function,

$$I = I_{obs}(\mu_{obs}\mu_{solar})^{-k}, \quad (1)$$

where  $I_{obs}$  and  $I$  are the observed and corrected intensities,  $\mu_{obs}$  and  $\mu_{solar}$  are the cosines of the observer and solar zenith angles, and  $k$  is the adjustable Minnaert parameter. Restricting the deprojected data to  $\mu_{obs} > 0.5$ , we solve for a scaling factor for each image and a single  $k$  which best minimizes the standard deviation across our final map of Titan. The best-fit  $k$  is 0.18. This final map and maps of standard deviation and observing coverage are shown in Figure 2.

### 3. Discussion

[6] The presented map is in units of observed intensity, which is proportional to albedo plus an unknown constant. Calibrating this map to albedo is hampered by several factors. Although methane absorption at these wavelengths is extremely low, it is not zero. Long pathlength cold ( $<100 \text{ K}$ ) laboratory spectroscopy will be required to adequately account for the methane opacity. Haze scattering is also a poorly constrained factor in understanding the radiative transfer, particularly the variation in haze opacity with latitude. In these narrowband data haze opacity is degenerate with surface albedo. Our inability to separate the contributions of haze and surface has two important implications. First, a band of haze in one latitude range appears the same in our map as if the latitude band has a higher surface albedo. We cannot, for



**Figure 1.** Titan images ordered by central west longitude. Each panel is  $1.5''$  across. All dates and times are UT.

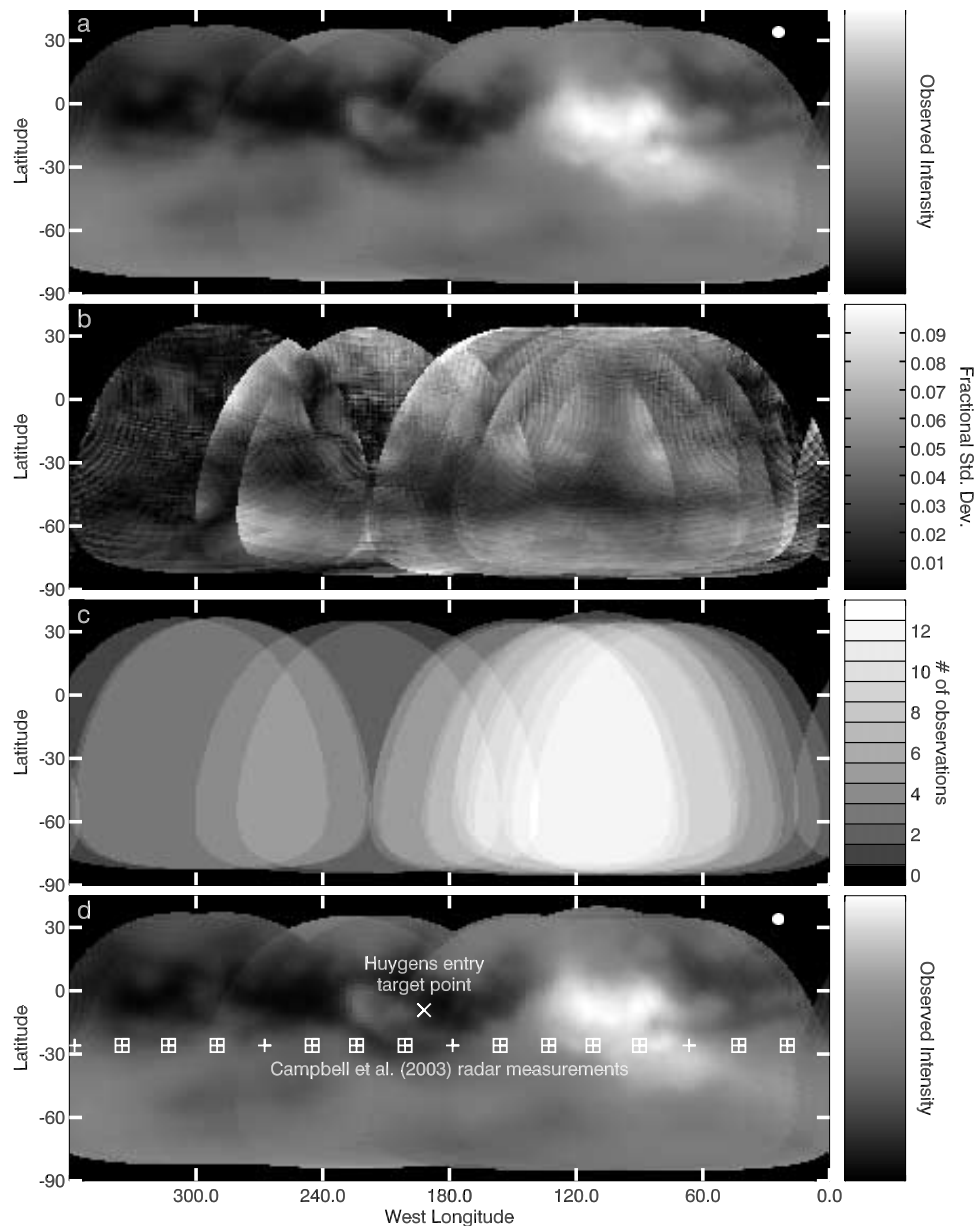
example, distinguish between a southern polar accumulation of haze and the south polar surface region having a higher albedo. Second, since the haze opacity is known to vary with latitude [see, e.g., *Lorenz et al.*, 2001] the contrast ratio of surface features in our map will vary with latitude. Our map shows much less high spatial frequency information at far southern latitudes than in the equatorial zone. This could be a real effect on Titan's surface, or could be simply due to higher haze opacity in the south, which has the effect of lowering the observed contrast.

[7] An alternative approach to creating a map of Titan was taken by *Smith et al.* [1996] who first subtracted an average image of Titan in an attempt to remove the effect of the haze. This approach suffers from the same degeneracy between haze and surface albedo as the technique we used to construct our new map. By doing a *Smith et al.* [1996] style quasi-subtraction of the atmosphere we find we can fit our map of Titan's surface with a value of  $k$  closer to unity, which was used by *Smith et al.* [1996].

[8] The performance of the AO system varies from epoch to epoch and is extremely difficult to measure at the necessary level of accuracy. While the resolution, full width half maximum (FWHM) of the spatial point spread function (PSF), stays roughly the same, another metric of image quality, Strehl ratio, varies considerably from image to

image. Without AO the PSF of a telescopic image is roughly a gaussian with a FWHM of  $0.5\text{--}1.0''$  depending on the atmospheric 'seeing'. The AO system takes a fraction of that light and pulls it into a narrow diffraction limited core ( $\sim 0.04\text{--}0.05''$  for these data). Thus the PSF of an AO image is more complicated than in typical imaging data and includes a broad halo as well as a narrow near-diffraction-limited core. Strehl ratio is a measure of how well the AO system is performing at pulling light from the broad halo into the narrow core and is equal to unity when the AO system is achieving its theoretically optimum performance. Typical estimated Strehl ratios for the presented data are  $0.1\text{--}0.4$  and the higher the Strehl ratio the better the contrast in the resulting image. Careful modeling of the varying AO performance and the use of diffraction limited spectroscopy [*Adamkovics et al.*, 2004] should allow the absolute calibration of this map in the future.

[9] Few maps of Titan with complete longitude coverage have been published previously. These are: Hubble Space Telescope (HST) at  $0.94$  and  $1.08\ \mu\text{m}$  with spatial resolution of  $\sim 470$  km [*Smith et al.*, 1996], HST at  $1.1$ ,  $1.6$ , and  $2.0\ \mu\text{m}$  with spatial resolutions of  $550$ ,  $800$ , and  $1000$  km [*Meier et al.*, 2000], and speckle imaging with the Keck I telescope at  $2.1\ \mu\text{m}$  with spatial resolution of  $\sim 350$  km [*Gibbard et al.*, 2004a, 2004b]. A. H. Bouchez et al. (manuscript in

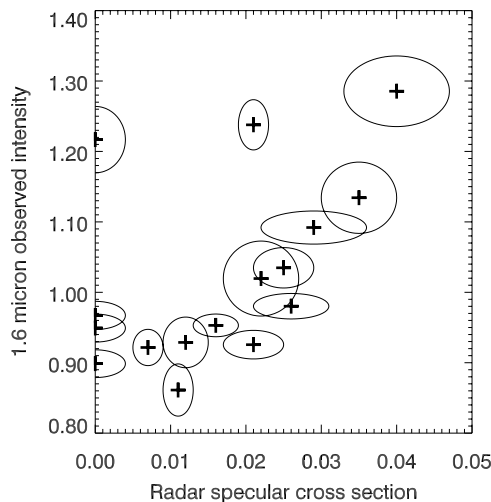


**Figure 2.** (a) Surface map of Titan. The typical spatial resolution at the center of Titan's disk in these data is indicated by the circle in the upper right corner. (b) Fractional standard deviation (a). (c) Map of observing coverage. (d) Surface map with Huygens entry target and positions of the *Campbell et al.* [2003] radar measurements. Radar measurements were performed at points marked with '+'s. Positions where a statistically significant specular reflection was measured are marked with boxes.

preparation, 2004) have a forthcoming map made using adaptive optics imaging with the Keck II telescope at  $2.1 \mu\text{m}$  with spatial resolution of  $\sim 250 \text{ km}$ . In every case the cited resolution is the full width half maximum of the spatial point spread function at the center of Titan's disk. Our new map presented here has a similar resolution to that of A. H. Bouchez et al. (manuscript in preparation, 2004), although with somewhat lower contrast due to the decreased performance of the adaptive optics system at shorter wavelength. Comparison of the longer wavelength map of A. H. Bouchez et al. (manuscript in preparation, 2004) with our  $1.6 \mu\text{m}$  map reveals no obvious color differences across Titan's surface to within 20–40% albedo ratio. Most regions

agree to within 20% or better, while the larger differences are primarily at far southern latitude.

[10] The resolution of our Titan data ( $\sim 20$ – $25$  resolution elements across Titan's apparent disk) is similar to the resolution of typical human naked eye viewing of the Moon ( $\sim 30$  resolution elements across the lunar disk). Even with the new improved view of Titan's surface, the nature of the dark and bright areas remains mysterious. No obviously recognizable craters, valleys, lakes, mountains, or other geographic features appear on the map, although there are a number of very suggestive features, several of which may be craters and one long linear feature wrapping around nearly the whole planet at latitudes between  $0^\circ$  and  $30^\circ\text{S}$



**Figure 3.** Observed intensity from the new 1.6  $\mu\text{m}$  map versus *Campbell et al.* [2003] radar specular cross section. Note the four points where no statistically significant specular reflection was detected. Uncertainties on these radar non-detections are assumed to be similar to the uncertainties for the detected cases. Note that albedo is proportional to this observed intensity minus an unknown constant.

and bisecting the bright region on the leading hemisphere at  $\sim 100^\circ\text{W}$ .

[11] For some time the dominant hypothesis for Titan's surface has been that the bright areas are icy highlands and the dark areas are lower lying lakes or tar pits of hydrocarbons deposited from the atmosphere. *Griffith et al.* [2003] report spectral evidence that the bright region near  $90^\circ\text{W}$  contains exposed water ice. *Campbell et al.* [2003] measured the radar reflectivity at the sequence of points overplotted on Figure 2d and found specular reflection from most of the surface. In their work, *Campbell et al.* [2003] found a remarkably strong correlation between diffuse radar cross section and near-IR albedo. In Figure 3 we compare their measured specular cross sections with the new 1.6  $\mu\text{m}$  observations. This comparison is complicated by the spatial resolution of our data (several hundred km) compared to the few tens of kilometers sampled by the radar specular reflection, and thus the lack of correlation between specular cross section and map intensity at some points is not surprising. Thus far the spatial complexity of Titan's surface has always equaled or exceeded the spatial resolution of available observations. The current record for spatial complexity is held by one observation of *Campbell et al.* [2003] at  $80^\circ\text{W}$  that suggested spatial variation on the scale of 10 km or less.

[12] The Huygens probe is scheduled to descend into Titan's atmosphere on 14 January 2005 (UT) and currently is targeted at longitude  $192.0^\circ \pm 2.2^\circ\text{W}$  and latitude  $9.2^\circ \pm 0.26^\circ\text{S}$  (R. Lorenz, personal communication, 2004), where the quoted uncertainties are one sigma and atmospheric

winds may drag the probe outside this range. This target point is near the edge of a large ( $\sim 700$  km diameter) dark feature, which might be a crater filled with hydrocarbons. Assuming Titan's winds are prograde, the probe will likely impact somewhere in this feature and soon we will hopefully know if this is in fact a hydrocarbon sea. With the planned numerous close flybys of Titan by the Cassini spacecraft in the next few years and the landing of the Huygens probe, we anticipate that our understanding of Titan's surface will dramatically increase in the near future.

[13] **Acknowledgments.** We thank the incredibly dedicated staff of the W. M. Keck Observatory for their hard work and R. Lorenz for a careful reading. This research was in part funded by NSF grant AST-0205893 to the University of California at Berkeley. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

## References

- Adamkovics, X. X., et al. (2004), Spatially-resolved spectroscopy at 1.6  $\mu\text{m}$  of Titan's atmosphere and surface, *Geophys. Res. Lett.*, *31*, L17S05, doi:10.1029/2004gl019929, in press.
- Brown, M. E., A. H. Bouchez, and C. A. Griffith (2002), Direct detection of variable tropospheric clouds near Titan's south pole, *Nature*, *420*, 795–797.
- Campbell, D. B., G. J. Black, L. M. Carter, and S. J. Ostro (2003), Radar evidence for liquid surfaces on Titan, *Science*, *302*, 431–434.
- Gibbard, S. G., et al. (2004a), Titan's 2 micron surface albedo and haze optical depth in 1996–2004, *Geophys. Res. Lett.*, *31*, L17S02, doi:10.1029/2004GL019803, in press.
- Gibbard, S. G., B. Macintosh, D. Gavel et al. (2004b), Speckle imaging of Titan at 2 microns: Surface albedo, haze optical depth, and tropospheric clouds 1996–1998, *Icarus*, in press.
- Griffith, C. A., T. Owen, and R. Wagener (1991), Titan's surface and troposphere, investigated with ground-based, near-infrared observations, *Icarus*, *93*, 362–378.
- Griffith, C. A., T. Owen, T. R. Geballe et al. (2003), Evidence for the exposure of water ice on Titan's surface, *Science*, *300*, 628–630.
- Lorenz, R. D., E. F. Young, and M. T. Lemmon (2001), Titan's smile and collar: HST observations of seasonal change 1994–2000, *Geophys. Res. Lett.*, *28*, 4453–4456.
- Meier, R., B. A. Smith, T. C. Owen, and R. J. Terrile (2000), The surface of Titan from NICMOS observations with the Hubble Space Telescope, *Icarus*, *145*, 462–473.
- Roe, H. G., I. de Pater, B. A. Macintosh et al. (2002a), NOTE: Titan's atmosphere in late southern spring observed with adaptive optics on the W. M. Keck II 10-meter telescope, *Icarus*, *157*, 254–258.
- Roe, H. G., I. de Pater, B. A. Macintosh, and C. P. McKay (2002b), Titan's clouds from Gemini and Keck adaptive optics imaging, *Astrophys. J.*, *581*, 1399–1406.
- Smith, P. H., M. T. Lemmon, R. D. Lorenz et al. (1996), Titan's surface, revealed by HST imaging, *Icarus*, *119*, 336–349.
- Wizinowich, P., et al. (2000), First light adaptive optics images from the Keck II telescope: A new era of high angular resolution imagery, *Publ. Astron. Soc. Pac.*, *112*, 315–319.
- A. H. Bouchez, W. M. Keck Observatory, Waimea, HI 96743, USA.  
 M. E. Brown and H. G. Roe, Division of Geological and Planetary Sciences, California Institute of Technology, M/S 150-21, Pasadena, CA 91125, USA. (hroe@gps.caltech.edu)  
 S. G. Gibbard and B. A. Macintosh, Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA.  
 C. E. Max, Center for Adaptive Optics, University of California, Santa Cruz, CA 95064, USA.  
 I. de Pater, Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA.  
 E. F. Young, Southwest Research Institute, Boulder, CO 80302, USA.