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Eight-color maps of Titan's surface from spectroscopy with Huygens' DISR

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ABSTRACT

During the descent of the Huygens probe in Titan's atmosphere, the Descent Imager/Spectral Radiometer (DISR) acquired spectra of 3660 locations within 250 km of the landing site. Each spectrum consisted of 200 resolution elements between 480 and 960 nm wavelength. With the help of radiative transfer models, contributions from the atmosphere and surface were separated. In eight methane windows, the data were combined into a map of Titan's surface reflectivity with 250 km diameter near the landing site. Principal component analysis revealed three significant components, a brightness component that is consistent with a mosaic based on DISR imaging of much higher spatial resolution, a spectral slope component, and a spectral curvature component. The brightness component has stronger contrasts at longer wavelengths, or brighter areas have a larger spectral slope, consistent with previous results (Keller et al. [2008]. Planet. Space Sci. 56, 728–752). The second component corresponds to small differences in spectral slopes that are not correlated with features seen before except for an area with unusual high spectral slope found by the same authors and confirmed here. Our map of the second component gives another important parameter in characterizing and understanding Titan's surface. The third principal component is somewhat noisy and describes variation in the spectral curvature that have never seen before at similar wavelengths. These variations require processes to differentiate surface spectra. To extend this work to longer wavelengths, 62 spectra from 850 to 1600 nm wavelength were investigated too, although the much lower number of spatial resolution points revealed only two significant components in the principal component analysis. They correlate with the first two components found in the shorter wavelength data. We also compare our results with an observation by Cassini's Visible Imager/Mapping Spectrometer (VIMS) that imaged part of our investigated area with 4096 spatial resolution elements. Both data sets are complementary. DISR data extend to about 1500 nm wavelength while most surface features are seen in the VIMS data beyond 1500 nm.

1. Introduction

Titan's color is unique in the Solar System. Its brownish color derives from the haze that absorbs at short wavelength with a minimum absorption near 900 nm wavelength (Tomasko et al., 2008). The surface spectrum contributes very little to Titan's color. The only reliable information about Titan's visible surface spectrum comes from the Descent Image/Spectral Radiometer (DISR) that measured a positive spectral slope of Titan's surface spectrum (Tomasko et al., 2005). We do not know whether Titan's surface is all of the same color or very colorful.

The visible spectrum of Titan's surface is difficult to measure because haze particles are responsible for large color variations. The haze optical depth decreases strongly with increasing wavelength, allowing red light to reach the surface more so than blue light. Blue light gets scattered in the atmosphere more so than red light, making the sky blue at high altitudes.

The distribution of light in Titan's atmosphere is governed by the single-scattering phase function of haze particles that changes significantly with wavelength (Tomasko et al., 2008). The backscattering is stronger at blue wavelengths than red ones, but at scattering angles below about 60° this trend reverses until 4° where the strong and narrow forward scattering peak at blue wavelengths takes over.

No significant light reaches Titan's surface at wavelengths where methane absorbs strongly, for example at 727 nm and at several longer wavelengths. In methane bands, the radiation field is roughly centered on the zenith even if the Sun is at low elevation angles, while at continuum wavelengths, a bright aureole

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surrounds the Sun. Each wavelength has its own radiation field. The color of light inside Titan's haze depends strongly on the viewing direction. Titan's surface is illuminated by light of different colors from different directions.

If Titan's surface were perfectly gray, it would reflect back the color of the sky since its phase function is strongly backscattering (Karkoschka et al., 2012). Therefore, it would appear to be colorful too, with the color depending on the viewing direction. Observed variations of color across Titan's surface would simply be due to the illumination, not due to intrinsic color variation of the surface. Accurate knowledge of the angular dependence of the illumination at the surface is essential to interpreting measured colors. At altitudes of a few kilometers or more, light from the surface scattering out of the beam and light from the haze scattering into the beam modifies the color. This effect grows for observations from higher altitudes and is maximized for observations from outside Titan's atmosphere. Thus, to determine colors of Titan's surface from space is almost impossible in the visible where the haze is thick, and possible but still difficult in the near infrared where the haze is more transparent.

In the 940-nm methane window, for example, we know the distribution of brighter and darker terrain from ground-based observations (de Pater et al., 2006), Hubble Space Telescope images (Smith et al., 1996), and the Cassini Imaging Science Subsystem (Porco et al., 2005). Even Voyager 1 saw features on Titan's surface (Richardson et al., 2004). Detecting features on Titan's surface is much easier than obtaining calibrated surface albedos below 1000 nm wavelength where most of the observed light comes from Titan's haze. Small errors in the estimation of scattering in Titan's haze cause huge errors in the estimation of Titan's surface albedo at those wavelengths. For example, at 600 nm wavelength, where the Orange filter of Voyager 1 recorded surface features, the vertical optical depth of Titan's haze is about 7 (Tomasko et al., 2008). Thus only $e^{-7} = 0.1\%$ of the photons make it through the atmosphere directly. Nevertheless, most of the scattered photons are scattered by small angles so that they contribute to the detectability of surface features. Accounting for this effect accurately is currently impossible since phase functions of aerosols are not known sufficiently well.

In 2005, the descent of the Huygens probe in Titan's atmosphere offered a unique opportunity to observe Titan's surface from below most of its haze. DISR instruments were looking downward to record the surface. At the same time, instruments with the same spectral coverage were looking upward to record the angular distribution of the illumination. For the first time, the needed data was available to determine reliable surface albedos. The goal of this work was to use the available data and determine spectrophotometric properties of the surface with the best possible surface coverage and spatial resolution.

Just before landing, the DISR surface science lamp was turned on and a few additional descent spectra were taken that were analyzed separately, including spectra taken from very close to the surface after landing (Tomasko et al., 2005; Keller et al., 2008; Karkoschka et al., 2012). The lack of spectral features was surprising, different from laboratory spectra of possible materials. However, recent laboratory spectra of mixtures of Titan tholins and water ice by Poch et al. (2015) give good fits to the observed spectra. Also, Rannou et al. (2015) reported promising fits to the spectra with their model of a layer of ice covered by a layer of fluffy aerosols. The question addressed in this study is how the visible spectrum of Titan's surface varies over the observed area in order to get clues about compositional variations.

While the DISR imagers onboard the Huygens probe covered only one wide spectral band centered near 770 nm wavelength, the Downward Looking Visible and Infrared Spectrometers (DLVS and DLIS) took spectra throughout the descent from 143 km altitude to landing. The DLVS recorded spectra of 3660 locations between 480 and 960 nm wavelength, and the DLIS recorded spectra of 52 locations between 850 and 1600 nm. These spectra are the input data for this work. The DLIS also took exposures with long integral integration times recording spectra with especially high signal-to-noise ratios, but those exposures are too smeared to be useful for surface analysis.

The 52 DLIS exposures were taken during two short periods at 18 and 4 km altitude. Two sets of DLVS spectra, 7% of the DLVS exposures, were also taken during the same periods. These data sets have been analyzed by Schröder (2007) and Keller et al. (2008). The result was that surface albedo contrasts were larger at longer wavelengths (especially at 1.6 μm) than at shorter ones. Brighter areas on Titan had a more "red" spectral slope than darker areas. We use their terms of brighter land and darker lakebed areas (Keller et al., 2008, Table 3). All observed areas pretty much followed the same trend. An exception was a small area about 5 km south of the landing site that Schröder (2007) noticed to have a significantly larger spectral slope than expected based on its albedo.

The remaining 93% of the DLVS exposures have been used for haze studies (Tomasko et al., 2008; Doose et al., 2016), but not for surface studies, providing us an opportunity to greatly expand knowledge about Titan's surface colors. They were spread out over the descent without clustered sets such as those at 18 and 4 km altitude. Therefore, these spectra show major variations from one exposure to the next due to different contributions of light scattered in Titan's haze, but typically only minor variations due to Titan's surface features. They contain information about the color or spectral shape of Titan's surface and its spatial variation, but this information is masked by typically large contributions from the haze. In order to retrieve information about color on Titan's surface from those data, one needs to accurately account for the scattering of light in Titan's haze. The original DISR aerosol model (Tomasko et al., 2008) was revised (Doose et al., 2016) and describes now the scattering for all altitudes, all azimuths, all nadir angles, and all DLVS wavelengths to an accuracy of about 5%. This model was a good start, but its accuracy was not sufficient to deduce surface reflectivities because contrasts seen from one to another DLVS spectrum due to surface features are typically less than 5%. Thus, we needed to better account for Titan's haze, so that Titan's surface spectrum can be measured wherever possible. This was the goal of this work.

The next section presents the data and calibration. Section 3 describes radiative transfer modeling and adjustments to the DISR haze model. Section 4 focuses on navigation, especially the unpredictable tilting of the Huygens probe. The following section describes the method of combining all data of each wavelength into a mosaic of Titan's surface. Section 6 brings out the main characteristics of eight maps with a principal component analysis. Section 7 adds wavelengths above 1000 nm with a comparison between Huygens and Cassini data. Section 8 describes an animation in the online version that shows all DLVS data and provides a good overview on how and where data were taken. The last section summarizes our results.

2. Data calibration

2.1. The DLVS data

The DLVS recorded on a 20×200 pixel area of the CCD with 200 spectral elements between 480 and 960 nm wavelength and 20 spatial elements roughly between 10° and 50° nadir angle, roughly aligned vertically (Tomasko et al., 2002). The rotating spacecraft provided the sampling of different azimuths. Each spatial pixel