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Vertical structure and optical properties of Titan's aerosols from radiance measurements made inside and outside the atmosphere

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ABSTRACT

Prompted by the detection of stratospheric cloud layers by Cassini's Composite Infrared Spectrometer (CIRS; see Anderson, C.M., Samuelson, R.E. [2011]. Icarus 212, 762–778), we have re-examined the observations made by the Descent Imager/Spectral Radiometer (DISR) in the atmosphere of Titan together with two constraints from measurements made outside the atmosphere. No evidence of thin layers (<1 km) in the DISR image data sets is seen beyond the three previously reported layers at 21 km, 11 km, and 7 km by Karkoschka and Tomasko (Karkoschka, E., Tomasko, M.G. [2009]. Icarus 199, 442–448). On the other hand, there is evidence of a thicker layer centered at about 55 km. A rise in radiance gradients in the Downward-Looking Visible Spectrometer (DLVS) data below 55 km indicates an increase in the volume extinction coefficient near this altitude. To fit the geometric albedo measured from outside the atmosphere the decrease in the single scattering albedo of Titan's aerosols at high altitudes, noted in earlier studies of DISR data, must continue to much higher altitudes. The altitude of Titan's limb as a function of wavelength requires that the scale height of the aerosols decrease with altitude from the 65 km value seen in the DISR observations below 140 km to the 45 km value at higher altitudes. We compared the variation of radiance with nadir angle observed in the DISR images to improve our aerosol model. Our new aerosol model fits the altitude and wavelength variations of the observations at small and intermediate nadir angles but not for large nadir angles, indicating an effect that is not reproduced by our radiative transfer model. The volume extinction profiles are modeled by continuous functions except near the enhancement level near 55 km altitude. The wavelength dependence of the extinction optical depth is similar to earlier results at wavelengths from 500 to 700 nm, but is smaller at shorter wavelengths and larger toward longer wavelengths. A Hapke-like model is used for the ground reflectivity, and the variation of the Hapke single scattering albedo with wavelength is given. Fits to the visible spectrometers looking upward and downward are achieved except in the methane bands longward of 720 nm. This is possibly due to uncertainties in extrapolation of laboratory measurements from 1 km-am paths to much longer paths at lower pressures. It could also be due to changes in the single scattering phase functions at low altitudes, which strongly affect the path length through methane that the photons travel. We demonstrate the effects on the model fits by varying each model parameter individually in order to illustrate the sensitivity of our determination of each model parameter.

1. Introduction

The first results from the Descent Imager/Spectral Radiometer (DISR) experiment aboard the Huygens probe into Titan's atmosphere regarding Titan's aerosols were published in a series of articles in the first few years after the probe entry in January 2005. Tomasko et al. (2008) gave results for the vertical distribution and optical properties of aerosols in Titan's atmosphere based on many of the DISR observations. In this work we define aerosol as a non-gaseous scattering particulate. Recent work on the aerosols has been done by Hirtzig et al. (2013) and by Larson et al. (2014). Many results are summarized by West et al., in Müller-Wodarg et al. (2014). The DISR observations still stand as a unique data set on the nature of Titan's aerosols.

Limb scanning measurements by the Composite Infrared Spectrometer (CIRS) aboard the Cassini orbiter have indicated the presence of aerosols at high altitudes and revealed their optical properties at far and mid infrared wavelengths (Vinatier et al., 2010; Anderson and Samuelson, 2011). This has prompted us to

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examine the DISR observations to see if these particles were detected at the shorter wavelengths where DISR operates. Also, the first aerosol models of the DISR data did not include a study of the photometry of the DISR imagers. Since these imagers looked out toward the limb of Titan they are particularly sensitive to thin layers (~1 km) of aerosols that might complement the CIRS far infrared observations.

Table 1
List of acronyms.

Acronym	Meaning
DISR	Descent Imager/Spectral Radiometer
CIRS	Composite Infrared Spectrometer – an instrument on board the Cassini orbiter
SLI	Side-Looking Imager
ULVS	Upward-Looking Visible Spectrometer
DLVS	Downward-Looking Visible Spectrometer
HST	Hubble Space Telescope
ULIS	Upward-Looking Infrared Spectrometer
DLIS	Downward-Looking Infrared Spectrometer
ULV	Upward-Looking Violet Photometer
DLV	Downward-Looking Violet Photometer
ϖ_0	Single scattering albedo
VIMS	Visual and Infrared Mapping Spectrometer – an instrument on board the Cassini orbiter

Several new benefits result from a more careful examination of the unique DISR observations within Titan's atmosphere. The original models published earlier fit the observations to about 10%, while the data are thought to be accurate in a relative sense to ~5%. In addition, the original model's optical depth had discontinuities in the volume extinction coefficients that were simply the result of how the optical depths were characterized in our model. In the results presented here the optical depths are close to the original values and the aerosol volume extinction coefficients are continuous with altitude with one exception noted in Section 5. Finally, the single scattering phase functions and the variations of the single scattering albedo, ϖ_0, with altitude have been refined by including the photometry from the imagers, constraints from Titan's geometric albedo, and measurements of Titan's disk size variation with wavelength.

We restrict our analysis to the spectral range of the DISR visible spectrometers and imagers: 490–950 nm. This wavelength range is where aerosols are best measured by the DISR instruments. We note that extrapolation of our new aerosol model outside this range may not be accurate. For infrared (1–5 μm) studies, the model of Hirtzig et al. (2013) may be more accurate.

The next section provides some background in the DISR instrument, and the following section describes our method for analyzing the observations using radiative transfer modeling. Section 4 describes an improved search for thin layers using the Side-Looking Imager (SLI). That is followed by a new search for thicker layers (5–40 km) using a differential method involving the Downward-Looking Visible Spectrometer (DLVS) spectra. Section 6 begins a re-examination of the previously published aerosol model now including new data sources. Section 7 summarizes the altitude and wavelength dependences of the new aerosol model and shows the sensitivity of the radiative transfer model fits to the model parameters. We end with discussion and conclusions concerning what is known and unknown regarding Titan's aerosol properties.

2. DISR observations

2.1. The Upward-Looking Visible Spectrometer (ULVS)

The ULVS was critical to measuring properties of Titan's aerosols. Individual exposures measured the brightness of half the sky at 200 wavelengths between 480 and 960 nm with good sensitivity between 490 and 950 nm. The resolving power, $\frac{\lambda}{\Delta\lambda}$, is about 300. It viewed most of the sky within 90° of DISR's central azimuth, although about 15° near this azimuth was obstructed by a shadow bar, so that the solar aureole could be measured without direct sunlight. These combined observations constrain the extinction toward the Sun, the single scattering albedo, and approximately measure the magnitude of the forward scattering of aerosols.

The ULVS took 246 exposures during the descent starting at 144 km altitude. Constraints from single exposures are non-unique since the tip and tilt of the Huygens probe was unknown due to the probe swinging with high frequency. These tips caused erratic changes in the ULVS radiances of up to 30%, judging by the scatter in the data near 90 km altitude (Karkoschka et al., 2007; Karkoschka and Schröder, 2016). Thus, we divided the atmosphere into four altitude ranges with boundaries at 20, 40, and 80 km, and into four azimuth ranges with boundaries described in Section 6.4. This provided a sufficient number of exposures within each altitude range and each of the four azimuth groups so that reliable mean values and estimates of uncertainties could be obtained. A visual display of the ULVS observations is provided in Appendix A. In the bottom range, between 0 and 20 km altitude, the upward-looking radiance field is significantly influenced by light scattered up from surface albedo features, which makes a reliable analysis of aerosol properties difficult. Thus, we restrict most of our analysis to data taken from altitudes above 20 km.

2.2. Other DISR instruments

The Downward-Looking Visible Spectrometer (DLVS) had a similar spectral range as the ULVS, but probed 20 different nadir angles looking toward the surface. Large-scale information was analyzed from these data by Tomasko et al. (2008) refining the backscattering peak of the aerosol phase function. Small-scale information was used by Karkoschka and Schröder (2016) to define surface colors. Here, we use only the altitude variation of spectra obtained near the nadir, at about 15° nadir angle. This nearly downward-looking direction is less sensitive to uncertainties caused by probe tipping.

The main DISR imagers acquired more than 300 images covering nadir angles 6–96° (Karkoschka and Schröder, 2016) in one spectral band of 640–960 nm with an effective wavelength of 770 nm. They primarily recorded surface features, but their photometric accuracy also allows us to use them to refine Titan's aerosol parameters.

The DISR observations we concentrate on in this work are expected to be accurate to 3–5% in a photometric sense. The uncertainty in absolute calibration is probably twice as large. The sources of uncertainty include the pre-flight calibration and changes in instrument sensitivity during the 7-year flight to Titan. Some sources of uncertainty also vary during the descent. For example, uncertainties in pointing arose because the probe swung unpredictably with high frequency under the parachutes. Measurements that require averaging of several observations, such as azimuthal averages of measured radiance at a particular altitude, are more accurate if the descent velocity is slower through that altitude.

The other DISR instruments provided data at shorter and longer wavelengths and measured spatially resolved polarization and radiance of skylight. We were unable to improve the results from these instruments presented in Tomasko et al. (2008), although we discuss the effects of a new aerosol model on them in Section 6.5.

Additional details on the DISR instruments and operation can be found in Tomasko et al. (2002).