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TITAN'S GROUND REFLECTANCE RETRIEVAL FROM CASSINI-VIMS DATA TAKEN DURING THE JULY 2ND, 2004 FLY-BY AT 2 AM UT

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Abstract. An attempt to evaluate the preliminary values of the Titan's surface albedo at 2 μm from the first Cassini-VIMS observations of the moon is presented. The methodology is based on the application of radiative transfer calculations and a microphysical model of the Titan atmosphere based on fractal aerosol. As a first guess, the surface has been considered flat and lambertian. The results are presented as a function of the geographical coordinates associated to the image pixels. The libRadtran package, using the radiative transfer equation solver DISORT 2.0, has been applied for the calculations. A test run to evaluate the model performances, using ground based observations of Titan as reference in the range of wavelengths 0.3-1.0 μm, has been carried out.The retrieved values of the surface albedo range between 0.03 and 0.22.

Keywords: Titan, atmosphere, surface albedo, Cassini, radiative transfer calculation

1. Introduction

A methodology based on the application of radiative transfer calculations to a microphysical model of the Titan atmosphere has been developed to estimate the Titan surface albedo. In this perspective the image qube CM_1467426479.cub, acquired by VIMS during the 184T0 flyby, has been considered more suitable due to its favorable signal/noise ratio. The spectral band 166, corresponding to the methane window 2.0178 μm, has been selected for the retrieval algorithm application.

The microphysical model of the aerosol composing the haze layer in Titan's atmosphere will be described in Section 2. The results of this model provide the inputs to the radiative transfer calculations. Then the radiative transfer model used for the calculations will be presented in Section 3. The application of this methodology to the selected hyper-spectral image, aiming to evaluate the surface albedo of an image sub-area, will be the argument of Section 4.

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2. Aerosol Model

The dense atmosphere of Titan (about 1500 hPa at the surface, Lindal et al., 1983), composed principally by nitrogen (~95%) and methane (~2%) below 1000 km, is characterized by an aerosol layer enveloping the whole satellite. The process leading to this haze formation involves the interaction of energetic particles coming from Saturn's magnetosphere and Solar UV radiation with the atmospheric molecules, giving as result a production of hydrocarbons and nitriles. These compounds evolve through polymerization processes in aerosol particles, which grow by coagulation and settle down to the surface. McKay and co-workers in 1989 (McKay et al., 1989) used a simple analytic microphysical model to characterize physical and optical properties of this process treating the aerosol particles as compact spheres. The spectral geometric albedo, as measured from the Earth (Neff et al., 1984; Courtin et al., 1991), furnished the experimental data set on which McKay tuned his Titan's atmospheric model.

McKay's model matches the visible and near-infrared spectral region of the Titan's geometric albedo but fails in the UV region, unless a second mode of small spherical particles (<10 nm) is added (Courtin et al., 1991). Since 1993 Cabane and co-workers (Cabane et al., 1992, 1993) assumed a fractal structure to explain Titan's particles, giving reason of the aerosol spectral behavior in the UV region too. In 1995 and following years Rannou (Rannou et al., 1995, 1997, 1999, 2003) realized a model based on the adaptation of the microphysical laws, used in the McKay's model, to the growth and settling of fractal aggregates (Rannou et al., 2003). These fractal aggregates are characterized in their internal structure by a fractal dimension. This parameter (corresponding to a cluster–cluster aggregate and assumed to be equal to 2 in the Cabane theory), is considered, along with the production rate, the charging rate, the production altitude, the depth of the production zone and the eddy diffusivity coefficient of the particles, as a free parameter to adjust by means of the comparison with the observational data (Neff et al., 1984; Courtin et al., 1991; Karkoschka, 1994). In our methodology the Rannou's model is used to simulate microphysical and optical properties of the Titan's atmosphere, adjusting the free parameters for a best fitting of the Karkoschka data set for the 0.3–1 μm wavelength range and the Coustenis et al. results (1998) beyond 1 μm. At the present time, the Rannou's model appears to be the most appropriate and advanced to simulate the 1D Titan's atmosphere.

3. Radiative Model

Though the Rannou's model has been developed to calculate the radiative transfer through Titan's atmosphere, the methodology used to solve the radiative transfer equation is not the most suitable for an application to the observing scenarios given by VIMS once the pixel by pixel observing geometry has to be taken into account. Then, the libRadtran package (Mayer and Killing, 2005) has been preferred for simulating the Titan's atmosphere and interpreting the VIMS images. A great advantage of libRadtran is its extreme flexibility. It is a very user-friendly model package to calculate radiance, irradiance and actinic flux for arbitrary input conditions. The model is able to handle absorption and scattering by molecules and aerosols, as well as clouds. The surface may be described in terms of a Lambertian albedo or a bi-directional reflectance distribution function (BRDF). Angular models for liquid surfaces (Cox and Munk, 1954a, 1954b) are also implemented. LibRadtran provides a choice of radiative transfer solvers, including the discrete ordinate code DISORT by Stamnes et al. (1988), a fast two-stream code, and a polarization-dependent solver, polRadtran (Evans and Stephens, 1991). For the current results the DISORT code, version 2.0, has been used. DISORT is a generic scattering formalism that does not require direct specification of atmospheric constituent inputs and their optical properties at the microphysical level. Instead, it is only necessary to specify three optical inputs for each layer – the total single scattering albedo, the vertical optical thickness and the total phase function moments. The version 2.0, used in the libRadtran package, incorporates the single scatter correction procedure of Nakajima-Tanaka (Nakajima and Tanaka, 1988). This code solves the radiative transfer equation by using the discrete ordinate method (DOM hereafter) algorithm (Stamnes, 1982; Stamnes et al., 1988). This model uses the plane parallel hypothesis for the Titan's atmosphere, which is a quite good assumption if the calculations are not performed for large angles. Here we use zenith angles lower than 70°.

For the diffuse radiance $I(\tau, \mu, \varphi)$ (excluding the direct solar beam) in direction (μ, φ) and at optical depth τ, the form of the monochromatic integro-differential Radiative Transfer Equation (RTE) is:

$$\mu \frac{dI(\tau,\mu,\varphi)}{d\tau} = I(\tau,\mu,\varphi) - \frac{\omega}{4\pi}\int_{-1}^{1} d\mu' \int_{0}^{2\pi} d\varphi' P(\mu,\varphi;\mu',\varphi') I(\tau,\mu',\varphi') + \frac{\omega}{4\pi} P(\mu,\varphi;-\mu_0,\varphi_0) F_0 e^{-\tau} \quad (1)$$

where $P(\mu,\varphi;\ \mu',\varphi')$ is the phase function for scattering, ω is the single scattering albedo, μ and μ' are the cosines of the scattering angle for the incident and scattered radiation, φ and φ' are the relative azimuth angles and F_0 is the solar flux at the top of atmosphere. The source function (the last two term on the right of the (1)) comprises the scattered diffuse light term (the multiple scatter integral), and the scattered light from the direct solar beam. The thermal emission contribution is omitted here.

In common with a number of other radiative transfer solution methods, the azimuth dependence of the radiation field in DOM is expressed as a Fourier cosine series in the relative azimuth angle:

$$I(\tau, \mu, \varphi) = \sum_{m=0}^{2N-1} I^m(\tau, \mu) \cos m(\varphi_0 - \varphi) \quad (2)$$

This requires the phase function to be expanded in a finite series of Legendre polynomials in the cosine of the angle of scatter. This reduces the problem to the solution of the Fourier components $I^m(\tau,\mu)$. The DOM approach involves the use of a numerical quadrature scheme to approximate the integral over polar directions in dealing with the multiple scatter source term. It is customary to use a double-Gauss scheme, with quadrature abscissae and weights $\{\mu_i, w_i\}$, $i=1,...,N$ defined separately for the upwelling and downwelling hemispheres. The integer $2N$ is the total number of streams (16 in our selection). The RTE is then reduced further to the solution of a set of coupled linear first-order differential equations for the stream components $I^m(\tau,\mu)$.

Once this set of differential equations is solved, the boundary conditions are invoked in order to establish the integration constants arising from the solution. The stream components $I^m(\tau,\mu)$ may then be written down for any optical depth. To establish the solution away from the quadrature streams, the source function integration technique (Chandrasekhar, 1960) is used. This ensures that radiances at arbitrary μ satisfy continuity requirements at the boundaries.

Figure 1 shows the flowchart of the Titan atmospheric modeling starting from the Rannou's model of the atmospheric structure and ending with the libRadtran calculations of the radiative parameters. As in the Rannou's model, we consider the atmosphere from 700 km altitude down to the surface and divide this range into 70 layers. These layers, except for the first one under the 700 km level (thickness of about 50 km) are regularly spaced with $\Delta z \approx 9.4$ km thickness and the optical properties are assumed to be constant within each layer. The free parameters in the Rannou's model have been adjusted for finding the best correspondence between its geometric albedo calculations and the Karkoschka's measurements. Then the resulting aerosol model has been used for the libRadtran computations. A test of the goodness of the method has been done comparing Titan's geometric albedo calculated by the libRadtran and Rannou's models in the wavelength range 0.35–1.0 μm along with Karkoschka's measurements (1994). The results of the comparison are given in Figure 2a where libRadtran seems to better reproduce the Karkoschka's geometric albedo. In Figure 2b, this results from the values of the coefficient of determination $R^2=0.991$ and the angular coefficient $\beta=0.999$ for libRadtran vs. respective

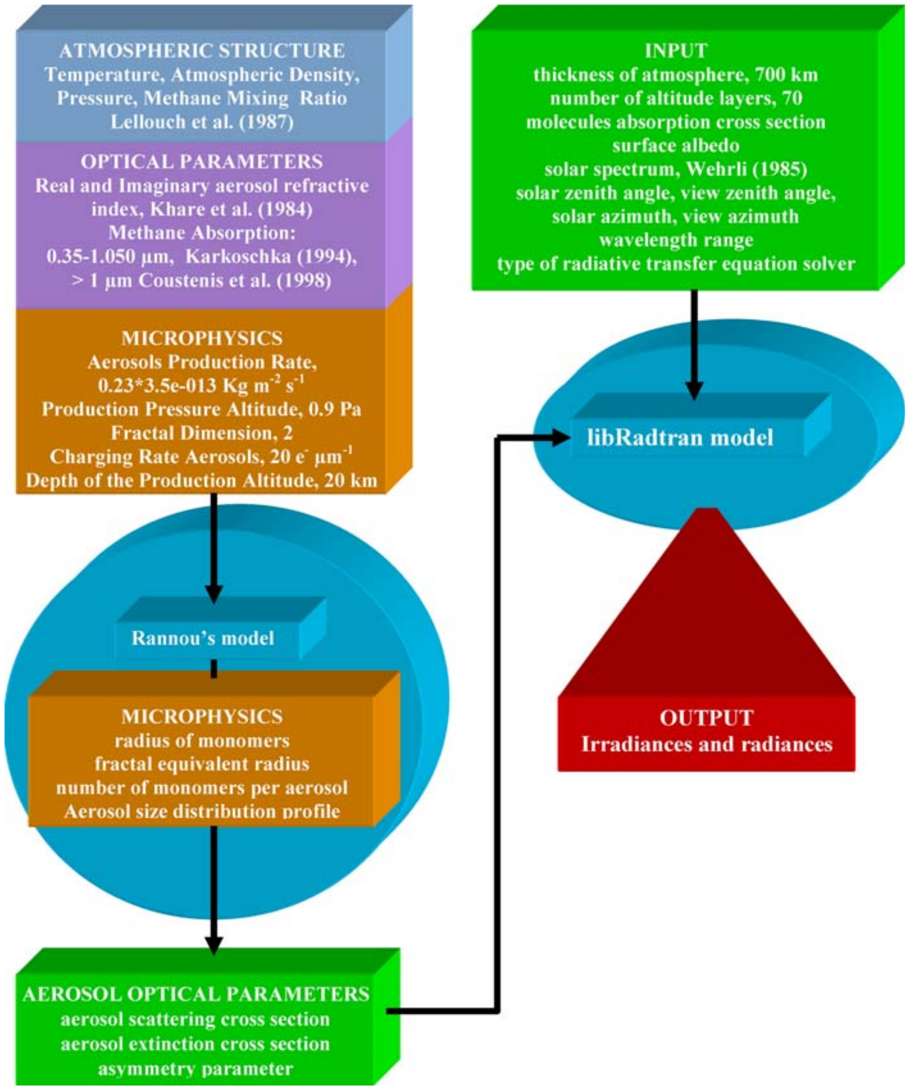

Figure 1. Flow-chart of Titan's atmosphere modeling.

values $R^2 = 0.988$ and $\beta = 0.867$ for Rannou's. This is particularly evident in the methane spectral windows around 0.83 and 0.94 μm. The largest difference between Karkoschka's and libRadtran results is where the aerosol play a predominant role namely in the methane absorption bands (i.e. around 0.9 and 1.0 μm) where also Rannou's results show a similar behavior. LibRadtran appears in good correspondence with measurements between 0.55 and 0.6 μm.

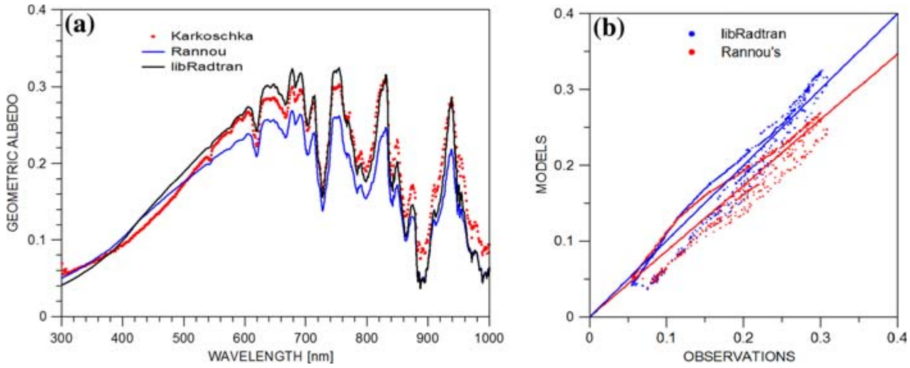

Figure 2. (a) Comparison between measured (Karkoschka, 1994) and calculated by (Rannou's and libRadtran models) geometric albedos in the range 0.35–1.0 μm. (b) Correlations between calculated and measured geometric albedos shown in panel (a).

4. Calculation of the Surface Albedo

The Rannou's code and the libRadtran package have been applied to interpret VIMS-CASSINI observations of Titan. The simulation of the scene observed at the methane window 2.0178 μm (band 166) of the hyper-spectral image CM_1467426479 has been realized by using atmospheric profiles (for the whole scene) calculated as described in Section 1. Quantities describing the geometry of observation for each pixel of the qube CM_1467426479 (such as geographical co-ordinates, solar zenith angle, observation angle and phase angle) have been computed through the SPICE program library provided by the Navigation and Ancillary Data Facility at NASA/JPL (Acton, 1996).

Surface albedo values have been retrieved starting from the reflectance measured by VIMS-IR in band 166 for each image pixel, depicted in Figure 3a. Assuming that the atmosphere is the same over all the moon, and assuming that the difference among the pixels is caused only by variations in the surface albedo, the illumination and the observing geometry, we obtain Titan's surface albedo equalizing radiance values calculated by libRadtran to radiances measured by VIMS as in the following expression:

$$\mathrm{I}_\lambda(\mu_0, \varphi_0; \mu, \varphi) = \frac{\rho_\lambda(\mu_0, \varphi_0; \mu, \varphi) \times F_{0\lambda} \times R_E^2}{\pi \times R_T^2} \tag{3}$$

where $\rho_\lambda(\mu_0, \varphi 0; \mu, \varphi)$ is the pixel measured reflectance, μ_0 and μ, φ_0 and φ are respectively the cosines of the angle for the incoming and outcoming radiation and the relative azimuth angles, R_{T} is the Sun-Titan distance to scale the solar flux $F_{0\lambda}$ (Wehrli, 1985) at the Earth distance, R_{E}.

On the other hand, radiances calculated by libRadtran for each pixel are obtained considering the surface albedo the only free parameter in the

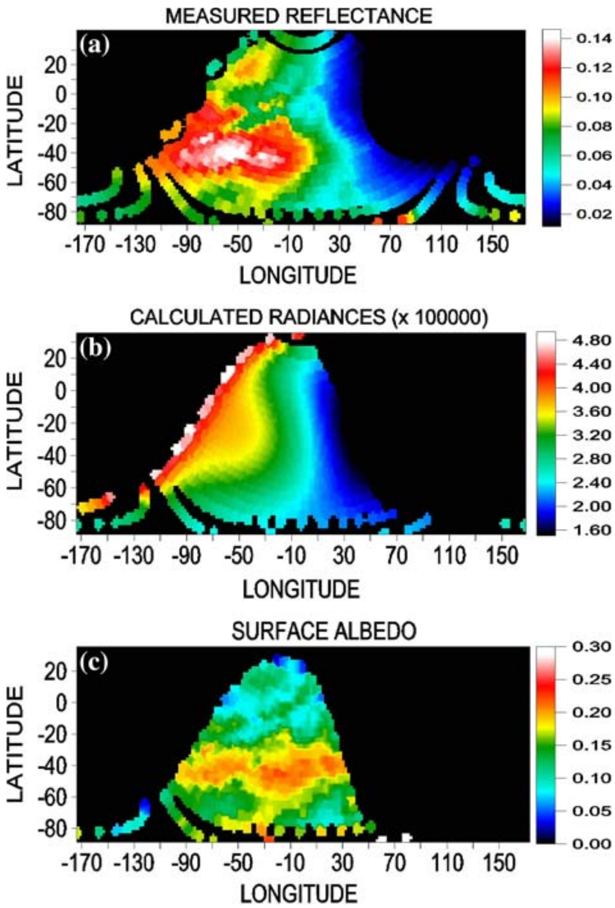

Figure 3. (a) VIMS-IR reflectance measured at 2.0178 μm for the qube CM_1467426479.cub. (b) Radiance [Wm^{-2} nm^{-1} sr^{-1}] calculated for a surface albedo equal to 0.1 over all Titan. (c) Calculated surface albedo.

calculation and varying its values between 0.02 and 0.3 with steps of 0.02. An example of this calculation for a surface albedo of 0.1 is given in panel (b) of Figure 3.

In such a way a look-up table has been created using these calculated radiances. Finally, the matching between measured and calculated radiances has permitted the estimation of the surface albedo pixel by pixel, interpolating its values, where necessary, for a best matching. The surface albedo is shown in Figure 3c. The calculations have been performed only for both incoming and outcoming radiation angles less than 70°, in the limits of the plane parallel approximation of the atmosphere and in the hypothesis that the differences in the values only depend on a different nature of the ground composition and basically flat topography. The values range between 0.03 and 0.22 with minima around the equator and the maxima grouping mostly around latitudes −40S–−50S. These results are consistent with those found in literature from ground based observations (Griffith et al., 2003; Bouchez, 2004).

5. Conclusions

We have presented here a methodology which combines part of different radiative transfer codes to better describe and interpret the observations through the Titan's atmosphere. The main idea has been to conjugate the best performances and the flexibility of each model to build a method easily re-adaptable to different planetary atmospheres and observation geometries by spacecraft. The model developed by Rannou et al. (1995, 1997, 1999, and 2003) has been used to build up the optical properties of the atmosphere, by using the fractal theory of Cabane et al. (1992 and 1993). Then the libRadtran package for radiative transfer calculation, primary developed for the Earth (Killing and Mayer, 1993–2004), has been adapted to receive the Titan's atmosphere inputs calculated by the Rannou's model. LibRadtran has been then tested for reproducing Karkoschka's (1994) measurements of geometric albedos of Titan in the range 0.3–1.0 μm. The agreement between measurement and simulation has been quantified in a coefficient of determination of 0.991 and an angular coefficient of 0.999.

Eventually, libRadtran has been applied to retrieve the surface albedo values from one of the first images taken by VIMS of the Saturn's moon at $\lambda = 2.0178$ μm (band 166). The obtained values range between 0.03 and 0.22.

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