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**RADIATIVE TRANSFER MODELING IN TITAN'S ATMOSPHERE AND SURFACE: APPLICATION TO CASSINI/VIMS DATA ANALYSIS AT REGIONAL TO GLOBAL SCALE.** M. Es-sayeh<sup>1,2</sup>, S. Rodriguez<sup>2</sup>, C. Ntinos<sup>2</sup>, L. Maltagliati<sup>3</sup>, T. Cornet<sup>4</sup>, P. Rannou<sup>5</sup>, M. Coutelier<sup>6</sup>, M. Vincendon<sup>7</sup>, S. Le Mouélic<sup>8</sup>, C. Sotin<sup>8</sup>. <sup>1</sup> SQUARES, Université Libre de Bruxelles, 50 Av. F.D. Roosevelt, Brussels, Belgium ([mael.essayeh@ulb.be](mailto:mael.essayeh@ulb.be)). <sup>2</sup> Université Paris Cité, Institut de physique du globe de Paris (IPGP), CNRS, Paris, France. <sup>3</sup> Nature Astronomy, London, UK. <sup>4</sup> Aurora Technology BV for ESA – European Space Agency, ESA-ESAC, Villanueva de la Canada, Madrid, Spain. <sup>5</sup> GSMA, Université de Reims, Reims, France. <sup>6</sup> LATMOS/IPSL, UVSQ Université Paris-Saclay, Sorbonne Université, CNRS, Guyancourt, France. <sup>7</sup> Institut d'Astrophysique Spatial, CNRS-Université Paris-Saclay, Orsay, 91400, France. <sup>8</sup> Laboratoire de Planétologie et Géosciences, CNRS UMR 6112, Nantes Université, Université d'Angers, Université du Mans, Nantes, France.

**Introduction:** The atmosphere of Saturn's moon Titan is strongly absorbing and scattering in the infrared due to the presence of molecular gases (mostly N<sub>2</sub> and CH<sub>4</sub>) and of a thick organic haze. Despite the presence of this thick atmosphere, the Cassini Visual and Infrared Mapping (VIMS) instrument is able to acquire images of Titan's surface through atmospheric transmission spectral windows centred at 0.93, 1.08, 1.27, 1.59, 2.01, 2.7-2.8 and 5 μm in the infrared [1]. Since 2004, VIMS contributed to reveal the geological diversity of the surface, populated by organic dark dunes [2], dark absorbing lakes [3,4,5], 5 μm-bright evaporitic deposits [6], possibly water-ice rich exposed icebeds [7,8,9]; but the interpretation of these features in terms of composition is often limited due to the heavy data processing required to detect the surface through the haze [10,11].

In this context, accurate and fast radiative transfer model and inversion scheme have to be developed for Titan in order to massively invert the Titan VIMS dataset (126 flybys, tens of thousands of data cubes). We aim at developing such a model to determine the main chemical species present on Titan's surface and follow the atmospheric extinction evolution over time.

**Radiative Transfer (RT) model description:** We base our approach on the Radiative Transfer model developed by [12], updated by [9]. The model consists in a plane-parallel radiative transfer solver (SHDOMPP) developed by [13], fed by Titan's atmospheric properties. The atmosphere is divided into 70 layers, the pressure, temperature and molar mass of which are given by the Huygens/HASI measurements recorded during the descent of the module in 2005 [14]. The atmosphere is composed of gases (CH<sub>4</sub>, N<sub>2</sub>, HCN, CO, and C<sub>2</sub>H<sub>2</sub>) producing molecular and collision induced absorption as well as Rayleigh scattering. Gas abundance profiles are set thanks to the Huygens/GCMS (CH<sub>4</sub>) [15] or Cassini/CIRS (CO, C<sub>2</sub>H<sub>2</sub>) measurements [16]. The optical properties of the aerosols (single-scattering albedo, opacity, phase function) are primarily inherited from a fractal aggregate scattering model [17] constrained by Huygens/DISR meas-

urements in the visible-near infrared range [18,19] and from experiments [20], as in [8]. These properties are then extrapolated to the VIMS wavelength range. Finally, the surface is considered lambertian.

The model is therefore calibrated for the atmospheric profile corresponding to the Huygens landing time and location, and is adapted to other time periods and locations by shifting the haze extinction profile by two "haze factors", as in [8] and [9].

**Inversion optimization using Look-Up Tables:** Inverting a single spectrum (pixel) with a classical approach is time consuming (~1-10 mins) and unrealistic for our work given the size of the VIMS archive. We adopted an inversion strategy based on the use of reference Look-Up Tables (LUTs) computed from the RT code for an optimized set of geometric conditions (incidence, emission, azimuth angles), haze factors and surface albedo, that allow to retrieve the specific conditions of the observation thanks to interpolations between LUT nodes. In doing so, the inversion is performed using the LUT itself, in two steps: 1) determination of a single haze factor needed to fit all atmospheric absorption bands; and 2) determination of the surface albedo for the same haze factor needed to fit the atmospheric windows at each window wavelength. This methodology allows to reduce the computation time by a factor of 10,000 with respect to classical inversions [21] and to proceed to the inversion of regional to global mosaics of thousands of VIMS cubes.

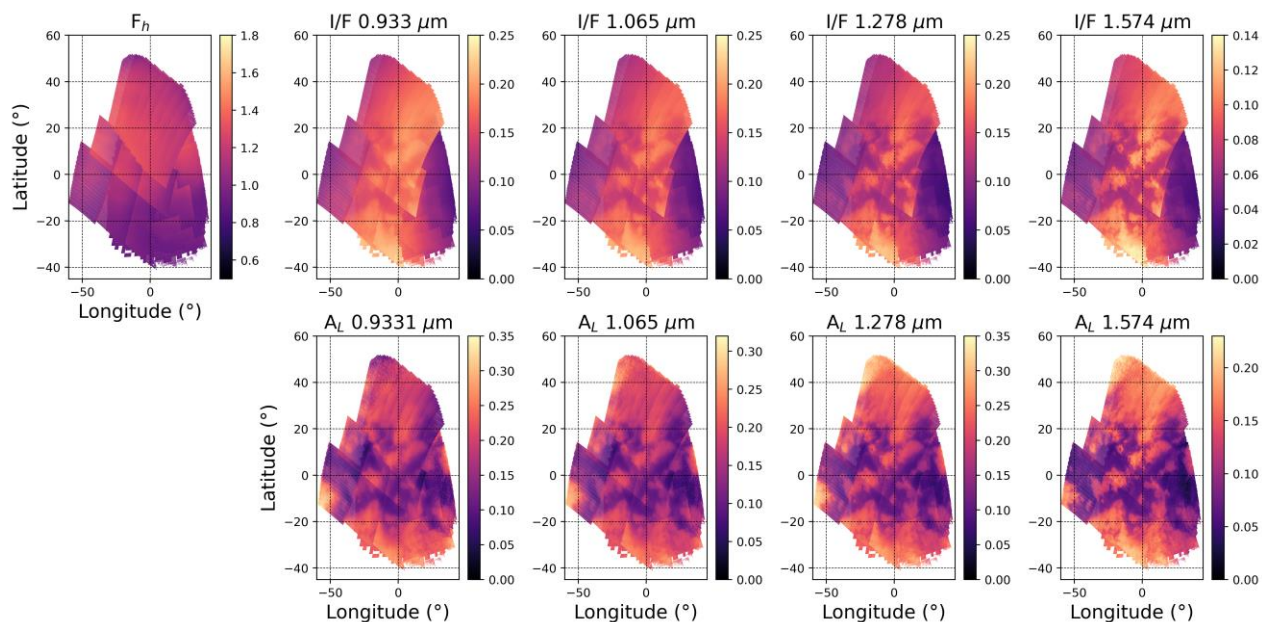
**Preliminary results and conclusion:** Figure 1 illustrates the test case of the mosaic of the T17 onto the T13 flyby mosaics, two distinct flybys close in time (September and April, 2006, respectively). The mosaics taken in the atmospheric windows display strong seams between the two flybys due to the different viewing geometries and associated optical pathway in the atmosphere, as well as an increasing blurring effects toward short wavelengths due to increasing scattering efficiency of the organic haze.

After the inversion, the strongest seams between T13 and T17 almost disappear in the surface albedo

maps and in the haze factor map. The albedo and haze factor variations are consistently not correlated with each other nor with the viewing conditions. The images in the atmospheric windows display also sharper details of the surface, especially at short wavelengths.

Further work will improve the atmospheric constraints on the aerosol optical properties by directly using the VIMS dataset, and refine the constraints provided by the DISR instrument on the atmospheric haze properties. The next step will be to massively invert the entire VIMS dataset in order to draw the very first global maps of Titan's haze factors and surface albedo, with the aim to try to determine Titan's surface composition with a greater accuracy and confidence.

**References:** [1] Sotin C. et al. (2005), *Nature*. [2] Rodriguez S. et al. (2014), *Icarus*. [3] Brown R.H. et al. (2008), *Nature*. [4] Barnes et al. (2009), *Icarus*. [5] Cornet T. et al. (2012), *Icarus*. [6] MacKenzie S. et al. (2014), *Icarus*. [7] Griffith G.A. et al. (2019), *Nat. Astronomy*. [8] Coutelier M. et al. (2020), *Icarus*. [9] Essayeh M. et al. (2023), *PSJ*. [10] Hayne P.O. et al. (2014), *Icarus*. [11] Le Mouélic S. et al. (2019), *Icarus*. [12] Hirtzig M. et al. (2013), *Icarus*. [13] Evans K. (2007), *JAS*. [14] Fulchignoni M. et al. (2005), *Nature*. [15] Niemann H. et al. (2010), *JGR*. [16] Vinatier S. et al. (2010), *Icarus*. [17] Rannou P. et al. (2003), *PSS*. [18] Tomasko M. et al. (2008), *PSS*. [19] Doose L. et al. (2016), *Icarus*. [20] Khare B. et al. (1984), *Icarus*. [21] Maltagliati L. et al. (2015), *EPSC*.



**Figure 1:** T13-T17 initial (top line) and inverted (bottom line) VIMS mosaics using our radiative transfer code based on the LUT use for the atmospheric windows comprised between 0.93 and 1.57  $\mu\text{m}$ . Haze factor mosaic is shown on the upper left.