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## A spherical and heterogeneous radiative transfer code for near-infrared remote sensing: application to Titan

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The Cassini mission has gathered extensive near-infrared spectra and imagery of Titan, which pose challenges for analysis due to the significant scattering effects of its atmosphere with potential heterogeneous radiative properties. Traditional radiative transfer models used to analyze Cassini data often employ plane-parallel or pseudo-spherical approximations and assume that atmospheric layers are horizontally uniform. To address these limitations, a new radiative transfer code that solves a spherical and heterogeneous model based on the Monte Carlo method has been developed [1].

This new radiative transfer solver takes into account the geometry of a "ground" of arbitrary shape, described by a triangular mesh, with the possibility of using an arbitrary number of materials. The radiative properties of a gas mixture are provided on a tetrahedral mesh using the k-distribution spectral model. The radiative properties of an arbitrary number of aerosols and clouds can also be provided on their individual meshes.

Furthermore, to retrieve atmospheric (e.g., haze density, top of cloud altitude, etc.) or surface properties, not only the intensity but also its gradient (the so-called sensitivities) are needed. Since these gradient calculations cannot be done with finite differences with the Monte Carlo approach, we need to differentiate the Monte Carlo estimator of intensity to build the Monte Carlo estimator of sensitivities. By conserving the same random paths for the estimation of intensity and all sensitivities, the extra calculation time to estimate all these quantities is minimized. A vectorized Monte Carlo estimator is then built, which can estimate simultaneously the intensity and its gradient. Currently, the estimation of sensitivities of mixed gas radiative properties is not available because of its complexity, which needs further development.

The methodology is applied to Titan's atmosphere, where we perform sensitivity analysis. The results show that because of the strong scattering effect in the atmosphere, the heterogeneity of the

surface and atmosphere impacts a lot of the observable (i.e., the measured intensity), which cannot be investigated by classical parallel-plane and homogeneous layers radiative transfer solvers. For instance, we show that at around 933 nm, the surface reflectivity at 250 km away from the targeting point still has an unnegligible effect on the measured signal. Similarly, sensitivity analysis is also performed on the aerosol density in the atmosphere. These sensitivity analyses help understand the scattering effect in Titan's atmosphere and help design the inversion process of atmospheric properties. This project was funded by French National Research Agency (ANR-21-CE49-0020).

[1] htrdr, Meso-Star <https://www.meso-star.com/projects/htrdr/htrdr.html>