3D Monte Carlo Radiative Transfer for Parameter Retrieval in Planetary Atmospheres

Zili HE[a], Sandrine Vinatier[a], Bruno Bézard[a], Vincent Eymet[b], Vincent Forest[b], Anthony Arfaux[a][c], Ema Salugova[d], Emmanuel Marcq[d], Pascal Rannou[c]
[a] LIRA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université Paris Cité, 5 place Jules Janssen, 92195 Meudon, France.
[b] Méso-Star, France, Toulouse, France
[c] GSMA, UMR CNRS 6089, Université de Reims Champagne-Ardenne, Reims, France
[d] LATMOS/IPSL, UVSQ Université Paris-Saclay, Sorbonne Université, CNRS, Guyancourt, France

Abstract:
Retrieving planetary atmospheric parameters from observational data is particularly challenging under large observation angles, in thick and highly scattering media (such as Titan and Venus), and in the presence of horizontal heterogeneities, like clouds and hazes. Traditional radiative transfer models, often based on plane-parallel or pseudo-spherical approximations, typically assume horizontally homogeneous layers, which limits their applicability in such scenarios.

To overcome these limitations, we have developed a novel 3D radiative transfer solver, htrdr-planets, based on the Monte Carlo method that solves models considering spherical and heterogeneous atmospheres[1]. This solver leverages recent advances from the computer graphics and statistical physics communities to ensure computational efficiency.

htrdr-planets supports arbitrary ground geometry, represented as triangular meshes with user-defined surface materials, and atmospheric properties defined on unstructured tetrahedral meshes. Gas absorption is modeled using the k-distribution method, and multiple aerosol and cloud populations with their own radiative properties can be described on separate spatial grids.

Critically, we address the need for gradients (i.e., sensitivities) in parameter retrieval. Since conventional finite-difference methods are inefficient or infeasible with Monte Carlo, we differentiate the Monte Carlo estimator itself [2]. By reusing the same radiative paths, we construct a Monte Carlo estimator that computes both the radiance and its gradient with respect to atmospheric and surface parameters at negligible additional time cost.

We apply this method to Titan and Venus, producing spatially resolved maps of sensitivity with respect to scattering, absorption, and surface-reflection properties. This framework enables retrievals in geometrically complex cases that defy traditional models, including Titan's polar cloud structure and haze distribution, using Cassini and JWST datasets.

[1] htrdr-planets, https://www.meso-star.com/projects/htrdr/htrdr.html
[2] He, Zili, et al. "Simultaneous Estimation of Radiance and its Sensitivities to Radiative Properties in a Spherical-Heterogeneous Atmospheric Radiative Transfer Model by Monte Carlo: Application to Titan." (Submitted to Journal of Quantitative Spectroscopy and Radiative Transfer.)