Towards Simulation of EarthCare-MSI Using the Eradiate 3D Radiative Transfer Model

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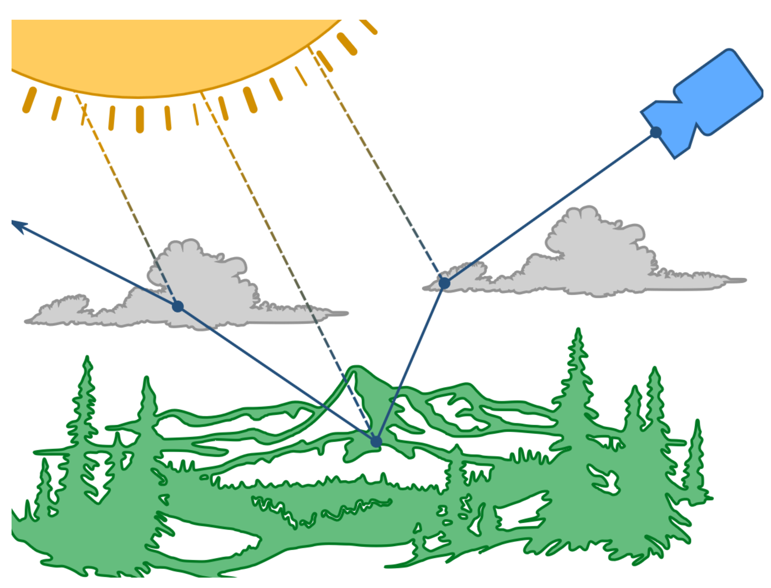
Eradiate is a next-generation Monte Carlo radiative transfer model for physically consistent simulation of satellite observations in complex atmospheric conditions. It combines spectrally resolved surface–atmosphere interactions with advanced 3D representations of topography, surface reflectance and vegetation canopies.

Recent developments include support for three-dimensional clouds and dedicated variance-reduction techniques that improve computational efficiency while preserving physical accuracy. Radiances for the EarthCARE Multi-Spectral Imager (MSI) can be simulated to investigate the impact of 3D cloud effects on top-of-atmosphere reflectances and to perform radiative closure studies.

ERADIATE

⇒ visit eradiate.eu

- Open source **3D radiative transfer model for Earth observation applications**
- Monte Carlo ray tracer based on computer graphics software Mitsuba

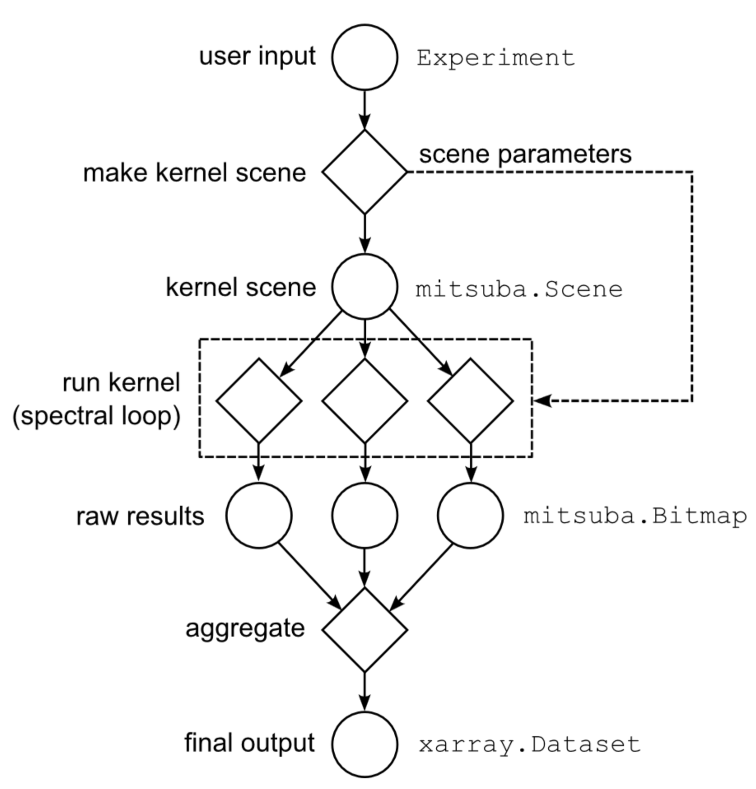


Earth surface-atmosphere system:

- Surface: BRDF models, 2D surface texturing, topography, DEM support, vegetation canopies
- Atmosphere: Molecular absorption parameterizations (CKD models), Rayleigh scattering, aerosol and cloud optical properties

Model geometry:

- 3D complex surface
- 1D plane-parallel / spherical atmosphere
- 3D atmosphere currently implemented

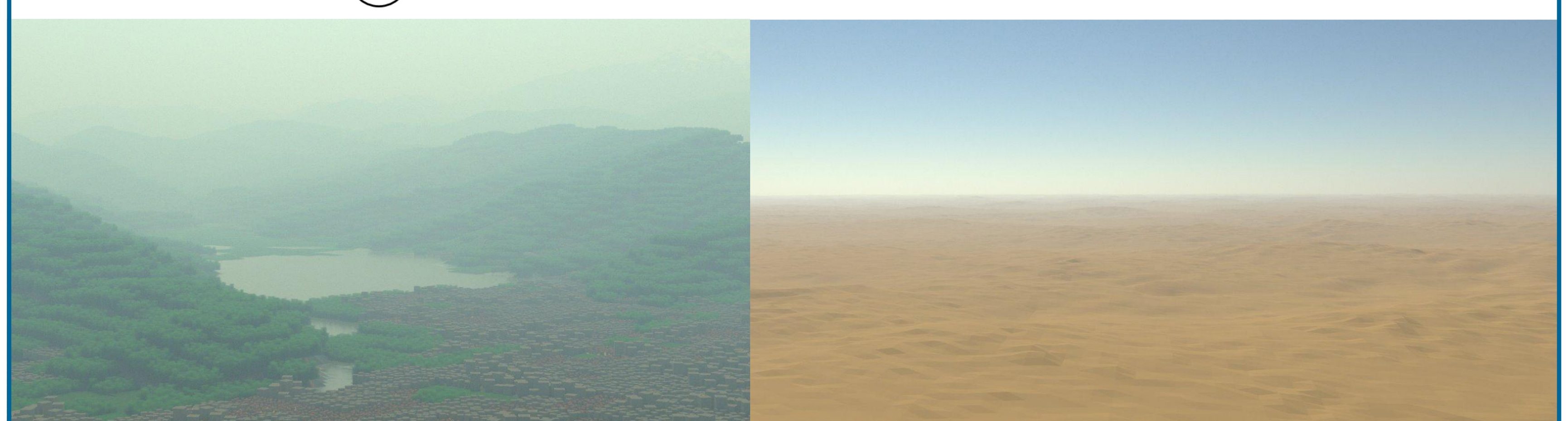


Output quantities:

- (polarized) radiances and fluxes
- Spectra and images
- Spectral response functions
- Various camera types available to generate images
- High accuracy, suitable for Cal/Val

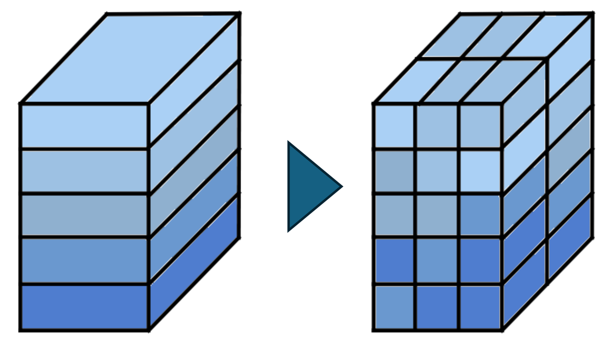
Architecture and Design:

- Python 3 and C++17
- High performance radiometric kernel (Mitsuba 3 [2], with additions for Earth remote sensing)
- Modular design
- Eradiate python interface: build and run simulations, collect output, provide convenient xarray format
- Interactive operation in jupyter notebooks



3D media including clouds, aerosols and molecules

- 1D grid extended to 3D regular grid
- Plane-parallel (cartesian) and spherical geometry



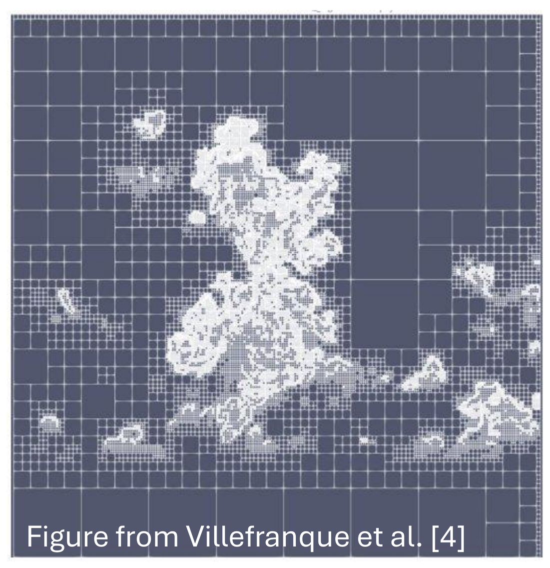


Figure from Villefranque et al. [4]

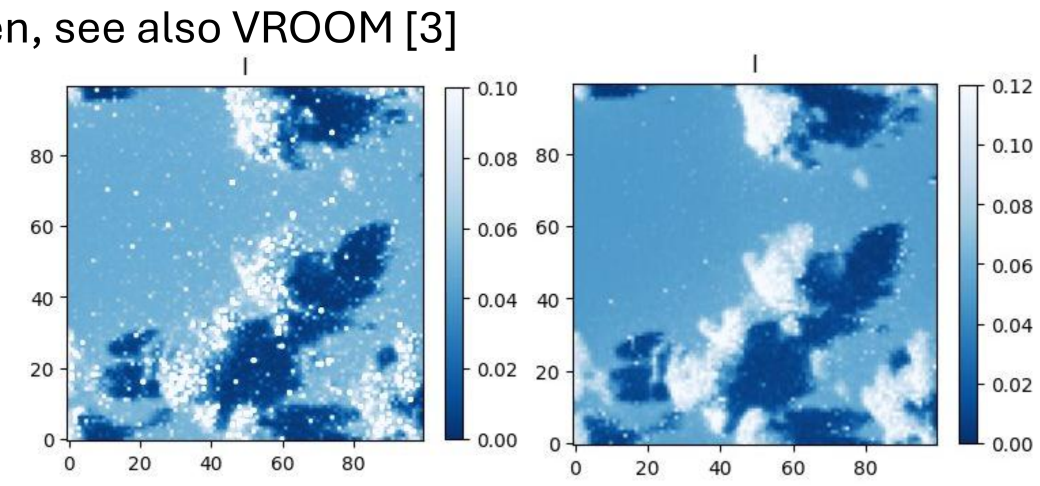
Way forward: More complex structure as Octree structure from [4] allowing irregular grids, extremum structures to speed up simulation for heterogeneous media.

Variance reduction methods for peaked phase functions

Problem: cloud particles scatter strongly in forward direction, this produces "fire flies" / "spikes" and convergence problems

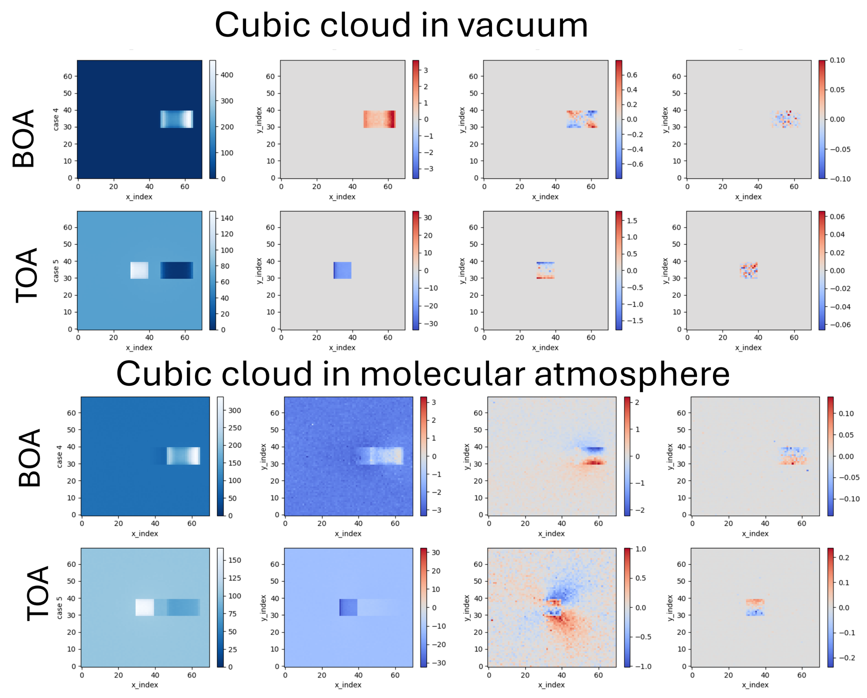
Unbiased Variance reduction methods: better convergence by sampling problematic directions more often, see also VROOM [3]

- Directional detector importance sampling (DDIS)
- Prediction based splitting (PBS)



Figures: Reflectance of a 3D cloud field, both calculated with 1000 samples. Left without, right with variance reduction methods.

Validation: Comparison against IPRT benchmark



IPRT provides benchmark results for polarized RT including 3D clouds [5]

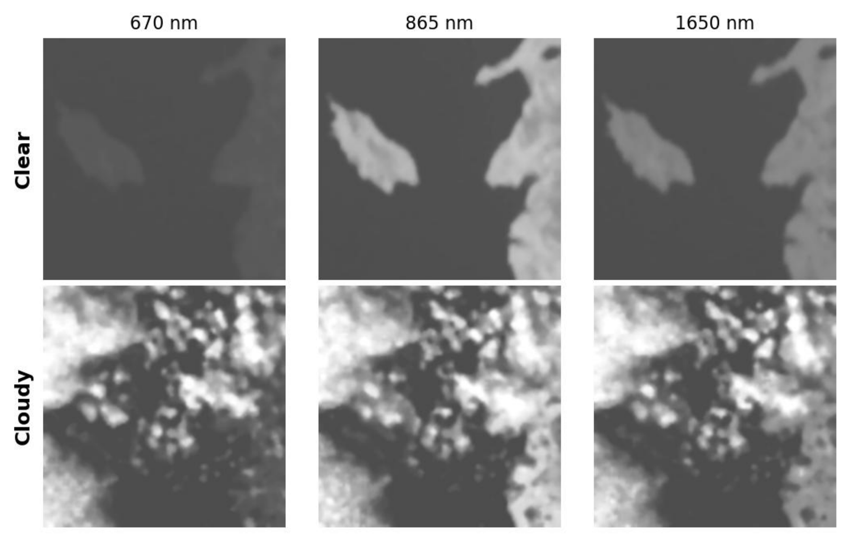
C2 - homogeneous cubic cloud

- Relative RMSE between Eradiate and benchmark <0.3% for all18 setups

C3 – inhomogeneous 3D cloud

- Droplet size (phase function) and extinction vary in the medium
- Validation ongoing

Application: Simulation of EarthCARE-MSI



Clear-sky simulation with 2D surface albedo from HAMSTER [6]

Cloudy-sky simulation with artificial cumulus cloud field

Next steps:

- Finish Eradiate cloud interface & validation
- Include more realistic cloud fields (e.g., based on ECMWF)
- Add instrument characteristics (spectral response functions)

Applications:

- Investigate 3D scattering effects (shadowing, in-scattering)
- Radiative closure studies

References:

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3. Buras, R., and Mayer,B.: *Efficient Unbiased Variance Reduction Techniques for Monte Carlo Simulations of Radiative Transfer in Cloudy Atmospheres: The Solution.* J. Quant. Spectrosc. Radiat. Transfer 112, no. 3 (2011): 434–47.
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