Toward operational Monte Carlo simulation of 3D line-by-line radiation for remote sensing

Atmos 2024

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Outline

The framework: remote sensing in Earth's atmosphere

- In some retrieval procedures we need:
  - the forward model
  - the derivative of the forward model.

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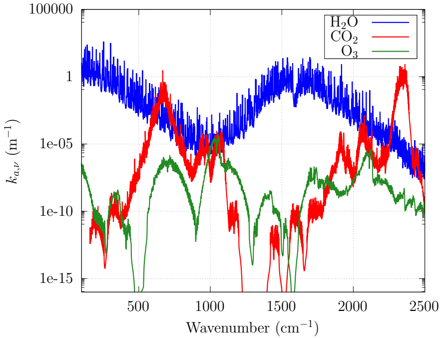
- There are some cases where precision is necessary (line-by-line, scattering, 3D realistic atmosphere, ...).



The framework: remote sensing in Earth's atmosphere

- Possibility to use the Monte Carlo method:
  - a reference method in radiative transfer which can treat multi-scattering.

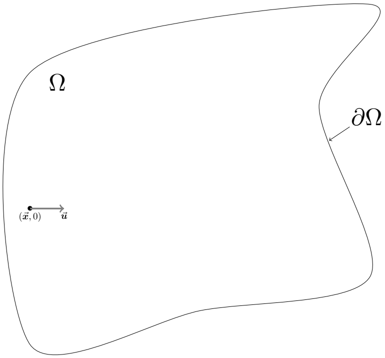
The framework: remote sensing in Earth's atmosphere

- Possibility to use the Monte Carlo method:
  - a reference method in radiative transfer which can treat multi-scattering.
- Monte Carlo benefit from recent work of computer graphics for
  - line-by-line
  - 3D atmospheres handling.

Outline

Forward model with Monte Carlo

- Radiance estimation with Monte Carlo : we follow photons along paths.



Building a path γ :

succession of free paths and direction changes

Forward model with Monte Carlo

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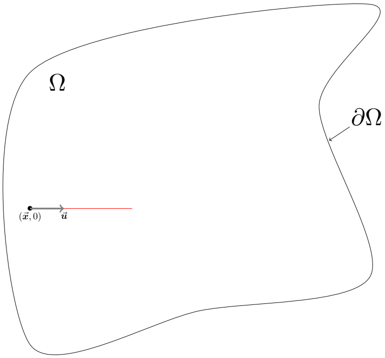

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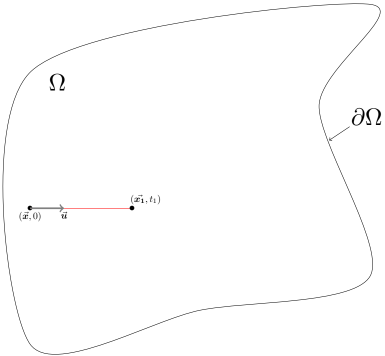

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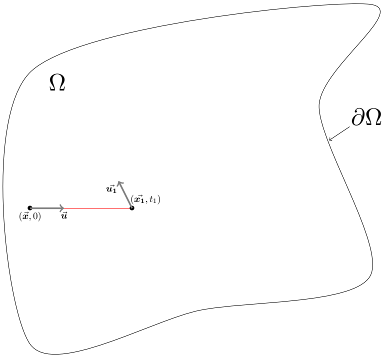

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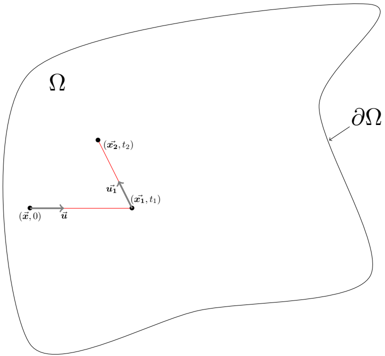

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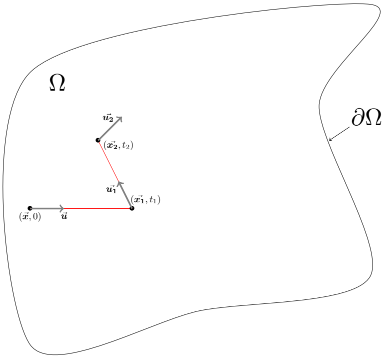

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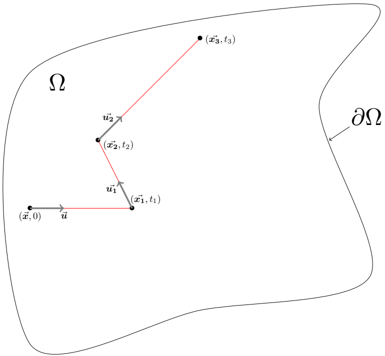

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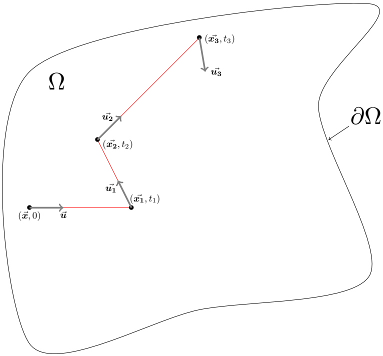

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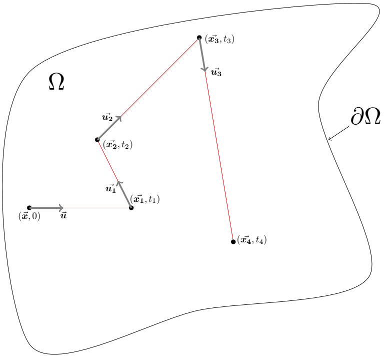

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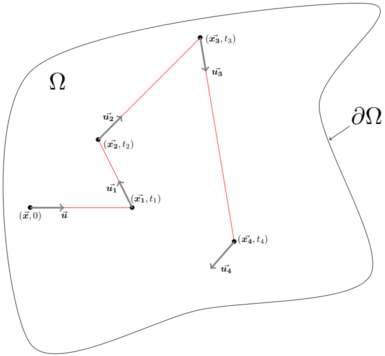

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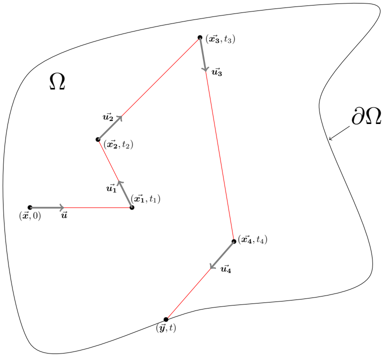

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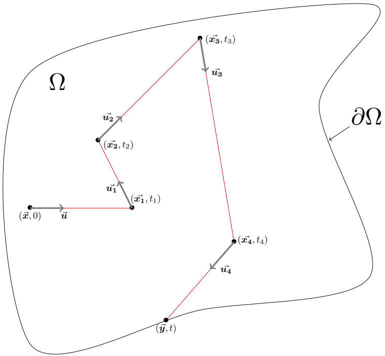


Building a path γ :

succession of free paths and direction changes

Paths space: D_Γ

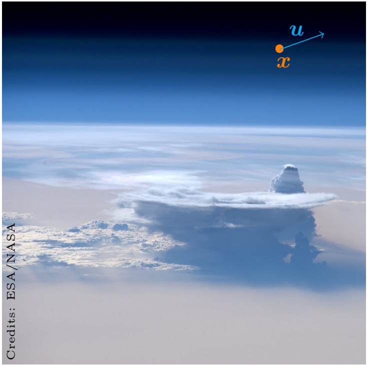
Paths integral: $\int_{D_\Gamma} d\gamma ...$

Radiance as an expectancy

$$I_\nu(\vec{x}, \vec{u}) = \int_{D_\Gamma} p_\Gamma(\gamma) g(\gamma) d\gamma$$

Forward model with Monte Carlo

- Radiance estimation with Monte Carlo



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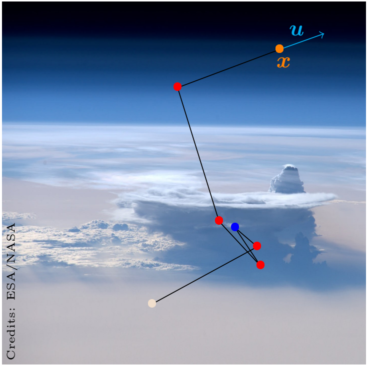

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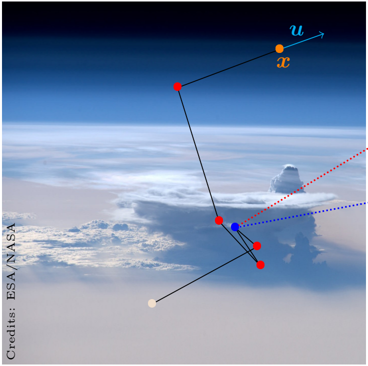

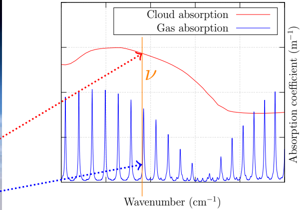

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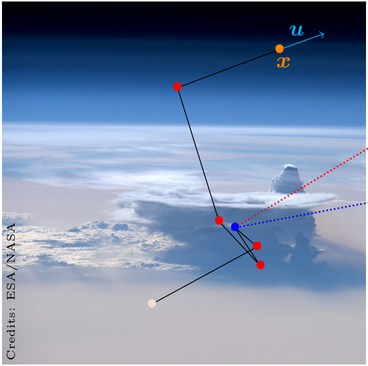

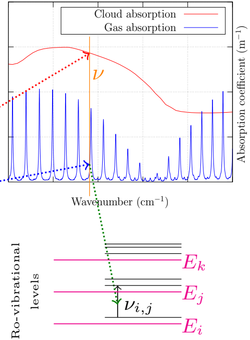

Forward model with Monte Carlo

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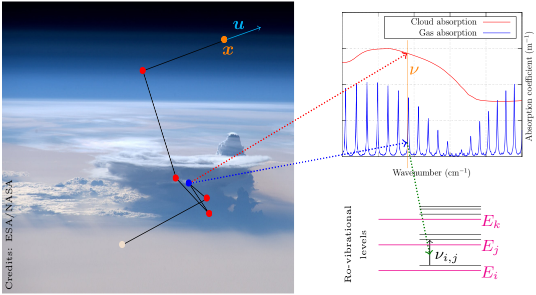

- The absorption coefficient is never calculated.
- Only one line is selected : line-sampling method [1].

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Spectrally refined unbiased Monte Carlo estimate of the Earth's global radiative cooling

Yaniss Nyffenegger-Péré[a,b,1], Raymond Armante[c], Mégane Bati[d], Stéphane Blanco[a], Jean-Louis Dufresne[c], Mouna El Hafi[a,e], Vincent Eymet[f], Vincent Forest[f], Richard Fournier[a], Jacques Gautrais[g], Raphaël Lebrun[c], Nicolas Mellado[d], Nada Mourtaday[a], and Mathias Paulin[d]

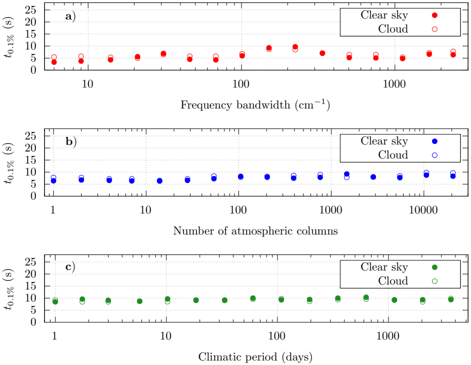
Edited by Mark Thiemens, University of California San Diego, La Jolla, CA; received October 9, 2023; accepted December 15, 2023

The Earth's radiative cooling is a key driver of climate. Determining how it is affected by greenhouse gas concentration is a core question in climate-change sciences. Due to the complexity of radiative transfer processes, current practices to estimate this cooling require the development and use of a suite of radiative transfer models whose accuracy diminishes as we move from local, instantaneous estimates to global estimates over the whole globe and over long periods of time (decades). Here, we show that recent advances in nonlinear Monte Carlo methods allow a paradigm shift: a completely unbiased estimate of the Earth's infrared cooling to space can be produced using a single model, integrating the most refined spectroscopic models of molecular gas energy transitions over a global scale and over years, all at a very low computational cost (a few seconds).

climate change | radiative forcing | line-by-line | Monte Carlo

Forward model with Monte Carlo

- Mean flux estimation with Monte Carlo [1] : computation time insensitivity



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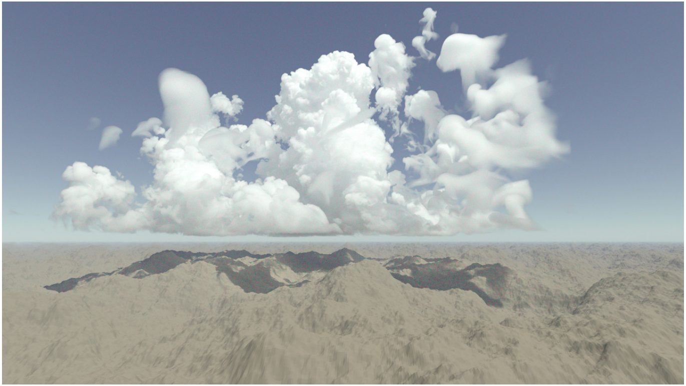
Forward model with Monte Carlo: 3D atmospheres

- Atmos 2021 recommendation: modelisation of realistics 3D clouds
  - HTRDR (but in CK-distribution) [1]



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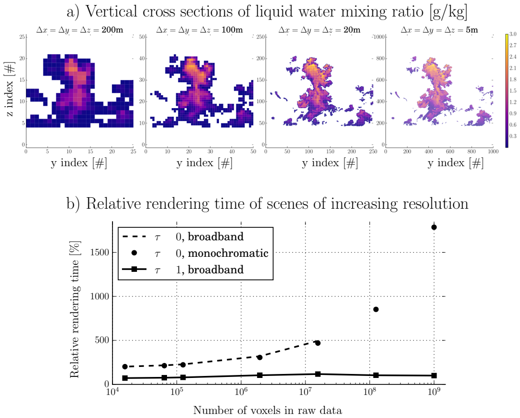
- Computation time insensitivity to the 3D complexity [1]



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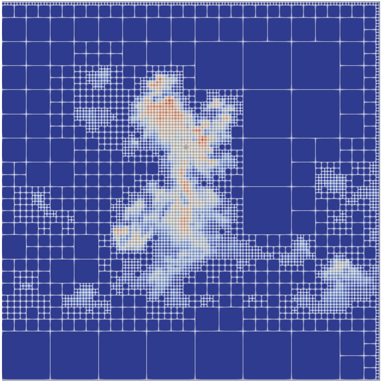
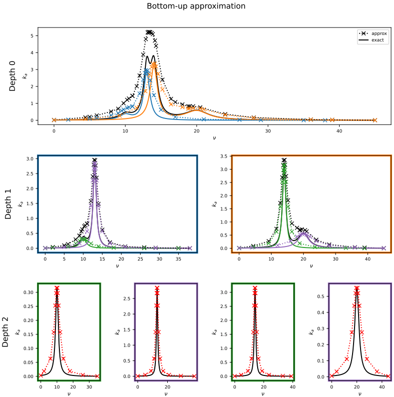
Forward model with Monte Carlo: merging in progress

- Cloud spatial grid [2]



- Line-sampling frequential grid [1]



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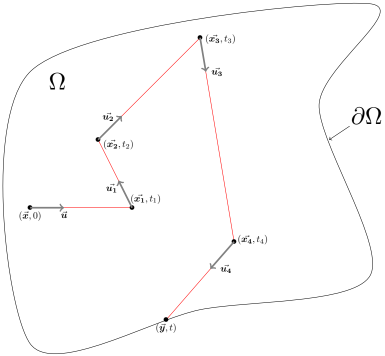
Jacobian with Monte Carlo

- Radiance estimation with Monte Carlo : we follow photons along paths



Radiance as an expectancy

$$I_\nu(\vec{x}, \vec{u}) = \int_{D_\Gamma} p_\Gamma(\gamma) g(\gamma) d\gamma$$

Jacobian with Monte Carlo

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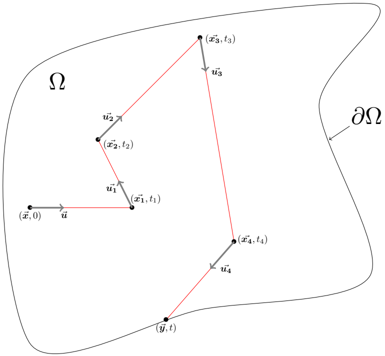
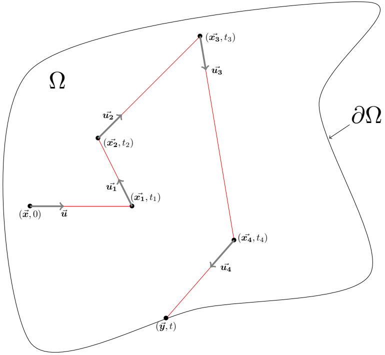


Radiance depending on α

$$I_\nu(\vec{x}, \vec{u}, \alpha) = \int_{D_\Gamma} p_\Gamma(\gamma, \alpha) g(\gamma, \alpha) d\gamma$$

Jacobian with Monte Carlo

- Radiance derivative of a parameter α with Monte Carlo [1]:



Radiance derivative as an expectancy

$$\frac{\partial I_\nu(\vec{x}, \vec{u}, \alpha)}{\partial \alpha} = \int_{D_\Gamma} p_\Gamma(\gamma, \alpha) h(\gamma, \alpha) d\gamma$$

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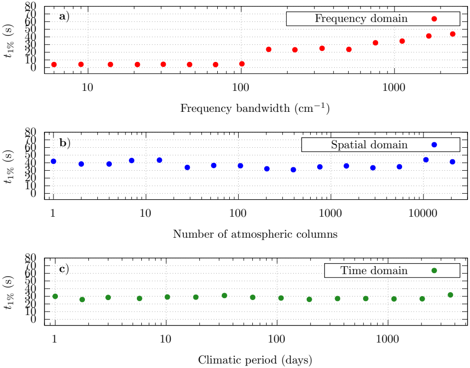
Jacobian with Monte Carlo

- Mean flux derivatives to the CO_2 concentration with Monte Carlo [1] : computation time insensitivity



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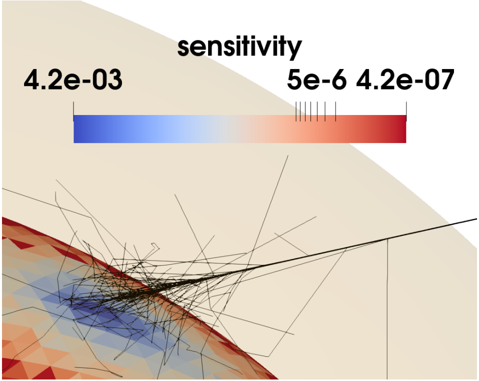
Jacobian with Monte Carlo: 3D atmospheres

- Estimation of several derivatives simultaneously on Titan atmosphere:

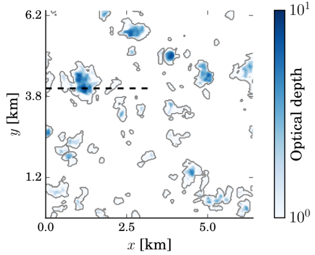


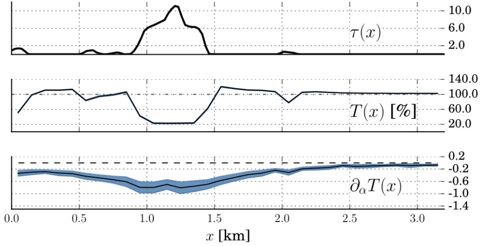
- Possibility to have the whole Jacobian matrix alonside the observable in one Monte Carlo.

Outline

Perspectives: Optically thick media

- Radiance derivative to the cloud scattering cross-section [1].





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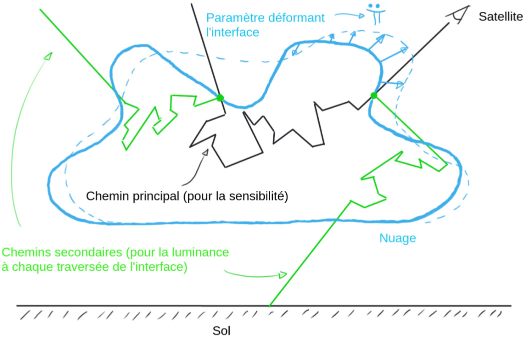
Perspectives: Derivative of the geometry

- Application to the cloud border : sensitivity model [1].



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