Monte Carlo Radiative Tranfer approach to determine BRDF for Airless Planetery Surfaces

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OBJECTIVES

- ***Exploring the Direct and Indirect Monte Carlo Radiative Transfer in order to study the reflectance spectra***
- Comparing it with the established Hapke model to gauge the accuracy of the model.
- Deriving physical properties from the reflectance spectrum measured from the lab or from the airless planetary body through remote sensing.

Radiative transfer Equation

- The propagation of EM radiation through a medium, considering absorption, scattering, and emission processes.
- Allows us to predict the resulting intensity of the radiation field.
- Crucial for interpreting observational data from telescopes and spacecraft, as well as for simulating the physical conditions on planetary bodies

Hapke Theory

- Describes how light scatters off the surfaces of airless planetary bodies.
- To interpret and analyze the photometric properties.
- Provide a BRDF that describes how light is reflected at different angles of incidence and emission.

$$r(i, e, g) = \frac{w}{4\pi} \frac{\mu_0}{\mu_0 + \mu_e} [(1 + B_{SH}(g))p(g) + H(\mu, w)H(\mu_0, w) - 1]$$

$$H(x, w) = \frac{1 + 2x}{1 + 2x\sqrt{1 - w}}$$

[Hapke, 2012]

Multiple Scattering Models: The Hapke model has gone through a series of modification since 1993 as:

- **IMSA 1993:** The initial model considering Isotropic scattering.
- **AMSA 2002:** Anisotropic scattering considered by including a term for the multiple scattering. [Hapke, 2002]
- **Hapke 2008:** Modified with the porosity correction factor. [Hapke, 2008]
- **Hapke 2012:** Modified with the consideration of opposition effect.

Limitation: Computationally time consuming

MONTE CARLO SIMULATION

- A computational algorithm to perform numerical integration that uses random sampling on certain probability distribution function to obtain numerical results.
- The RTE is Integro-differential equation which is too complicated to be solved analytically so statistical method gives accurate results.

Monte carlo Method

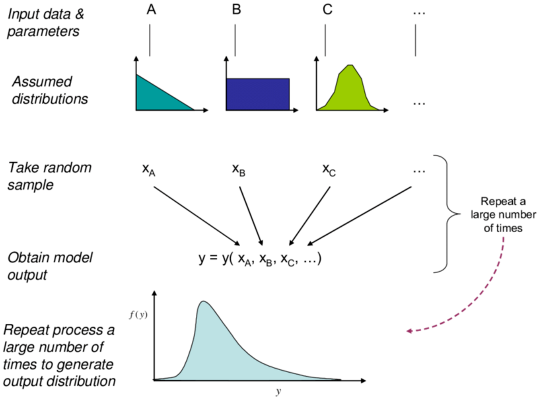

Figure 1: Graphical depiction of monte carlo simulation procedure [Henderson and Bui, 2005]

MONTE CARLO Ray Tracing

- A rendering technique used in computer graphics to simulate the interaction of light with various surface materials, helping to interpret observed reflectance spectra.
- In MCRT, Monte Carlo simulation is applied to solve the RTE, which describes how light i.e photon packets, interacts with surfaces and contributes to the observed reflectance.

MONTE CARLO RADIATIVE TRANSFER (MCRT)

- **Direct MCRT:** The photon packet is traced from source to medium to observer.
- **Indirect MCRT:** The photon packet is traced backward from the observer to medium to source.
- More efficient as it focuses on rays contributing to the final image.

Algorithm

- Define the Physical System
- Geometrical Model of the planetary surface i.e medium.
- Specify Initial Conditions
- Interaction Probabilities

Direct MCRT [Ciarniello et al., 2014]

- Define the no. of photons packets emitted from the source.
- Apply periodic boundary conditions.
- Define conditions for absorption and scattering.
- Determine the scattering angle using random sampling.
- Reintroduce escaping photons from one side of the box to the opposite side, maintaining direction and depth.
- Record the directions of scattered photons by using the selected phase angle
- Calculate reflectance by dividing the number of stored photons by the total number of propagated photons.

Indirect MCRT [Ciarniello et al., 2014]

- Consider a photon packet with initial energy E_0 travelling towards the medium from the observer.
- Define conditions for random absorption and scattering.
- Apply periodic boundary conditions and reintroduce escaping photons from one side of the box to the opposite side.
- Record the directions of scattered photons and reduce the photon packets energy by a factor ω after each scattering.
- Check the visibility of the photon packet in the direction of the source.
- Aggregate energy contributions from all photon packets scattered in the concerned direction.
- Calculate reflectance by dividing the total energy of scattered photon by the total energy incident to the medium.

Parameters

- i $= 30$deg
- $\phi = 0.2$
- N $\approx 10^4$
- Anisotropic scattering considered.
- $p(g) = \frac{1-b^2}{(1+b^2+2b\cos(g))^{3/2}}$
- $\omega = [0.2, 0.5, 0.7]$
- Semi-infinite medium with periodic boundary conditions

Plot for Direct MCRT

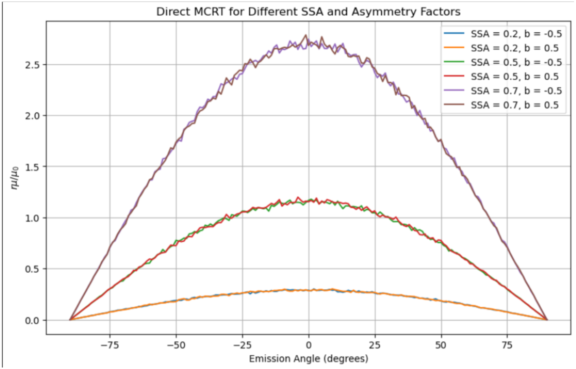

Figure 2: The resulting reflectance against emission angle by direct MCRT

Plot for Indirect MCRT

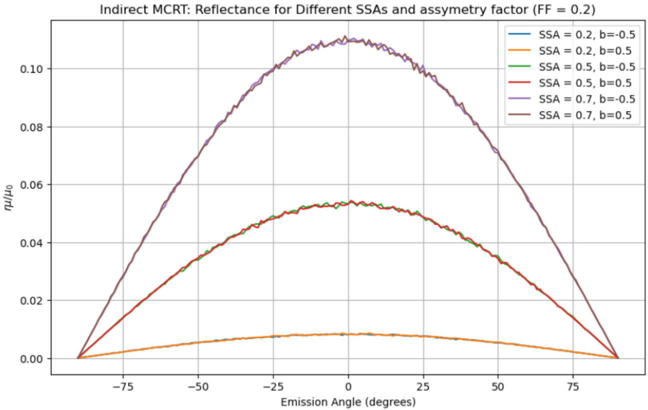

Figure 3: The resulting reflectance against emission angle by indirect MCRT

Observations

- Computationally time consuming(esp. Direct MCRT).
- Could not observe the effect of anisotropy.
- Could not observe the opposition effect.
- Reflectance values mismatch.

Inference

- Indirect MCRT is more efficient as expected.
- Some major error in defining phase function.
- Normalization mismatch.

This needs a lot of refinements and corrections!

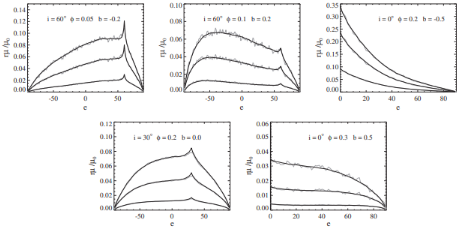

Figure 4: Simulated reflectances from indirect (black) and direct (gray) Monte Carlo ray-tracing [Ciarniello et al., 2014]

Challenges

- Observing and correcting errors at each step becomes tedious due to high computational time.
- Considered lower no. of photons (10^4 instead of 10^7) to simplify.
- Time Constraints.

Future Prospects

- Modify the simulations to develop the model as an in-hand tool.
- Compare it with the well-established Hapke models.
- Apply it either on lab-based studies or telescopic data to determine the the properties of various airless bodies like Moon and Mercury.

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THANK YOU