

Effective Multi-Scattering-Stream Model for Fast Radiative Transfer Simulation

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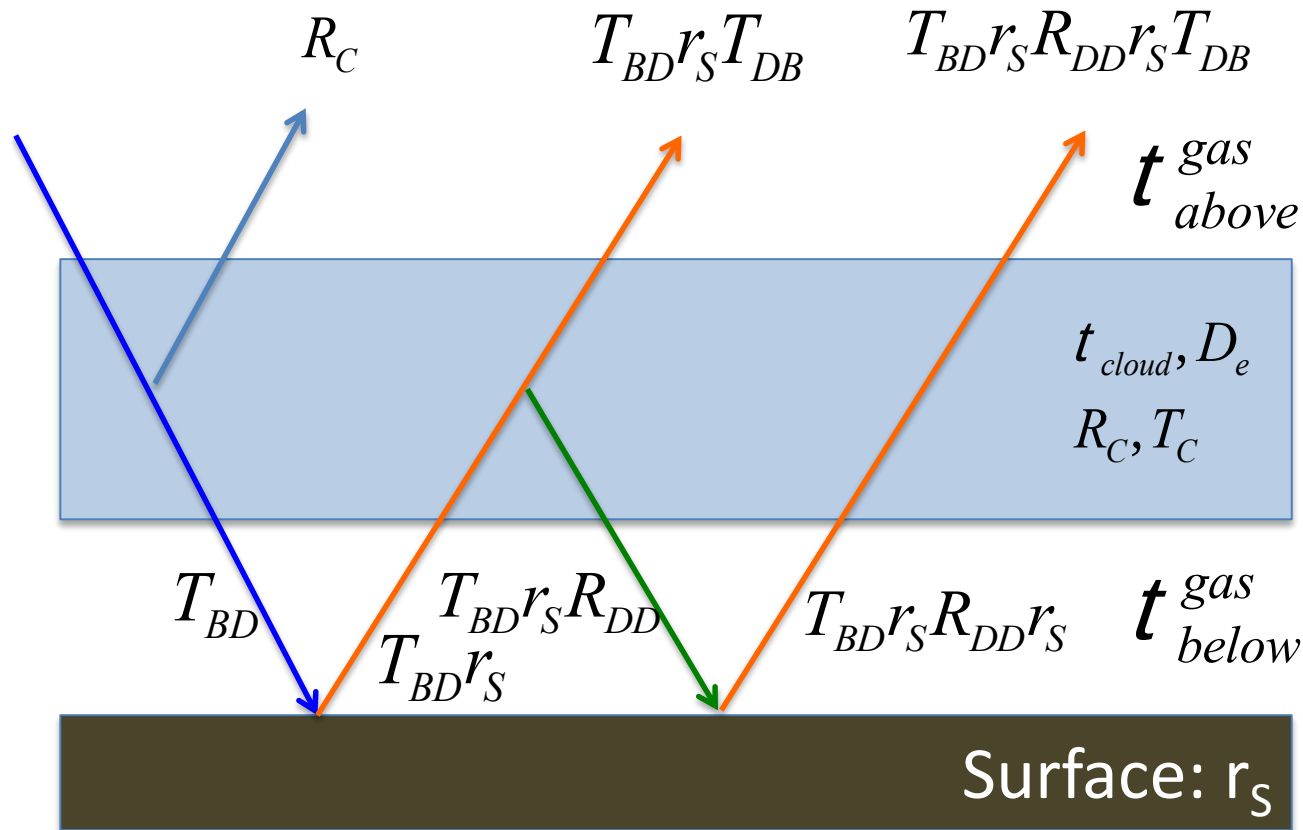
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Motivation

- RTM at a fixed wavenumber
 - Adding Doubling
 - DISORT
 - Our Way: Parameterization and LUTs, No Adding Doubling Calculation, 2-3 orders faster than DISORT.
- PCRTM - Principal Component-based Radiative Transfer Model
 - Uses PCA to compress information content
 - Reduce RT calculations by at least 3 orders of magnitude
- Expectation
 - over 4-5 orders faster than a reference radiative transfer model such as MODTRAN

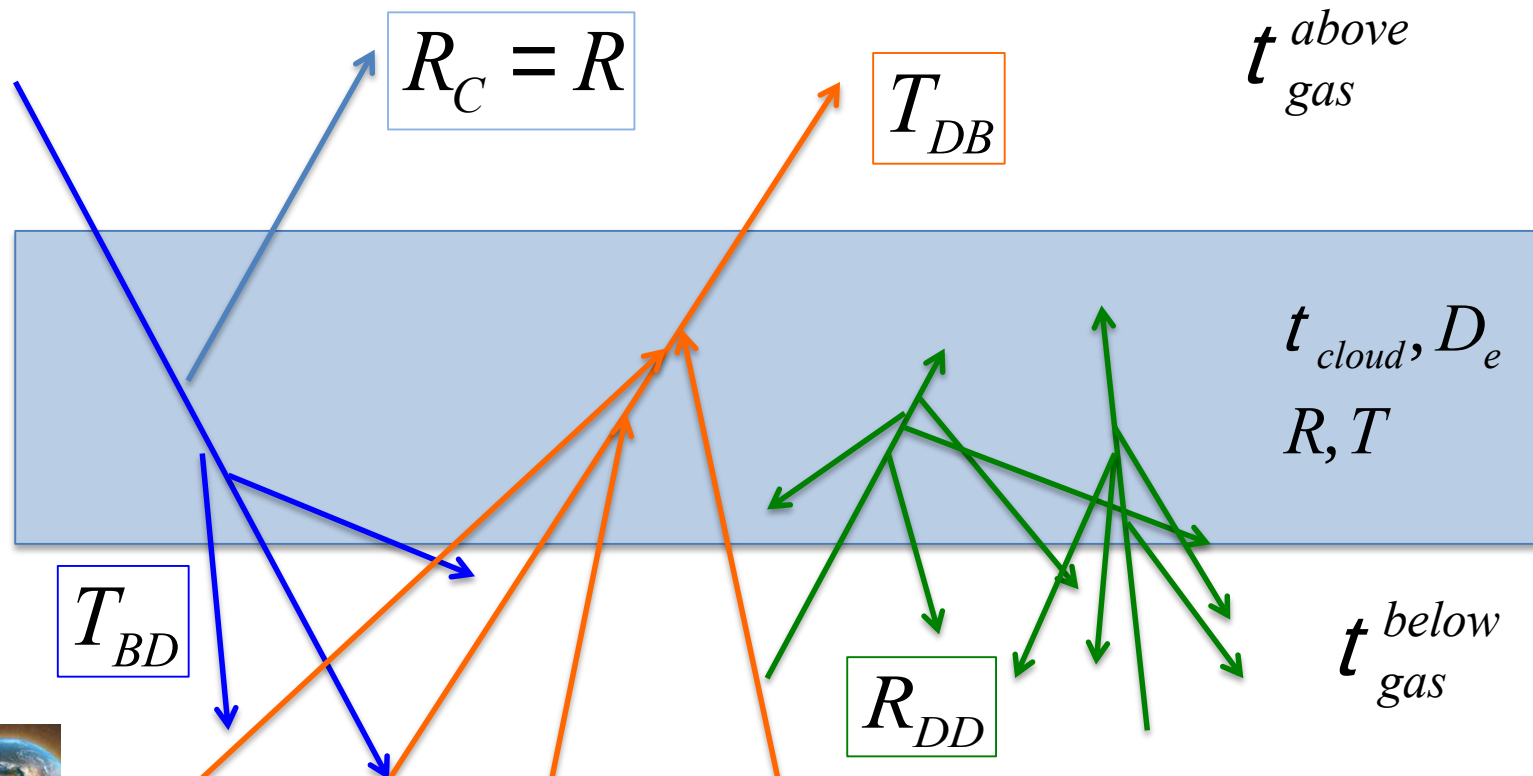
A Simple Cloud-Earth System



$$R = \frac{\alpha_c R_C}{\epsilon} + \frac{r_S T_{BD} T_{DB}}{1 - r_S R_{DD}} \frac{\ddot{\theta}}{\varnothing} - \frac{t_{gas}^{above}}{m_0} - \frac{t_{gas}^{above}}{m}$$

Main Scattering Process:

Beam $\rightarrow$ beam; beam $\rightarrow$ diffuse;
diffuse $\rightarrow$ beam; diffuse $\rightarrow$ diffuse



Parameters Related to the Main Scattering Processes

$$R_C = R(\tau, D_e, \mu_0, \mu, \phi - \phi_0, \lambda)$$

$$T_{BD} = \int_0^{2\pi} \int_0^1 \mu \left[\frac{1}{\pi} T(\tau, D_e, \mu_0, \mu'', \phi'' - \phi_0, \lambda) + e^{-\frac{\tau}{\mu_0}} \delta(\mu'' - \mu_0) \delta(\phi'' - \phi_0) \right] e^{-\tau_{gas}^{below}/\mu''} d\mu'' d\phi''$$

$$T_{DB} = \frac{1}{\pi} \int_0^{2\pi} \int_0^1 T(\tau, D_e, \mu, \phi, \mu', \phi', \lambda) e^{-\tau_{gas}^{below}/\mu'} \mu' d\mu' d\phi'$$

$$R_{DD} = \frac{1}{\pi^2} \int_0^{2\pi} \int_0^1 \int_0^{2\pi} \int_0^1 R(\tau, D_e, -\mu'', \phi'', \mu', \phi', \lambda) e^{-\tau_{gas}^{below}/\mu'} e^{-\tau_{gas}^{below}/\mu''} \mu'' \mu' d\mu' d\phi' d\mu'' d\phi''$$

All of these parameters were calculated using 36-stream DISORT to form the LUTs.

Downsize the Bidirectional Reflection Distribution Function



$$R_C = R(t, D_e, m_0, m, f - f_0, l)$$

- Size of R_C LUT in visible range with 100 wavelengths for 10 different particle size:

$$45 \times 10 \times 30 \times 30 \times 30 \times 100 \times 4 = 4.86 \text{ GB}$$

$$R_C = R(t, Q(D_e, m_0, m, f - f_0, l))$$

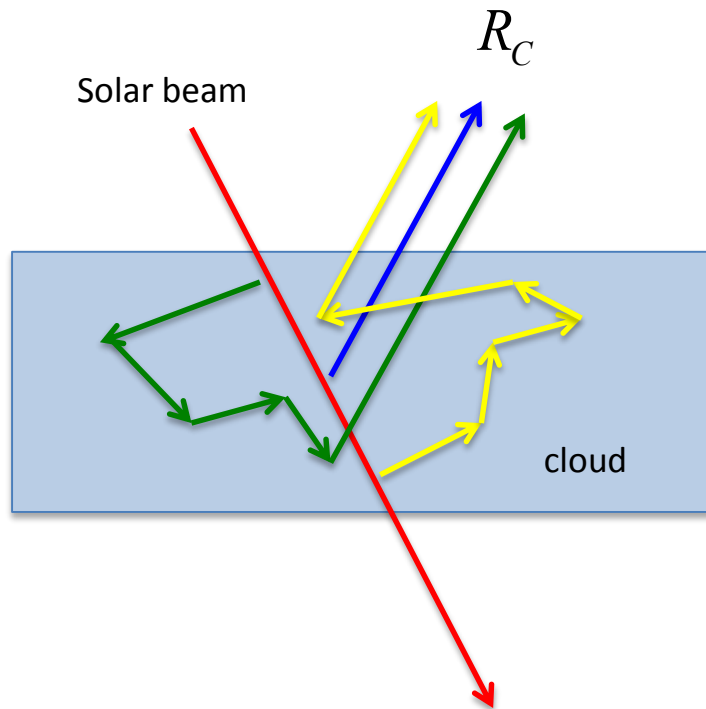
- Size of Q LUT:

$$10 \times 30 \times 30 \times 30 \times 100 \times 4 = 108 \text{ MB}$$

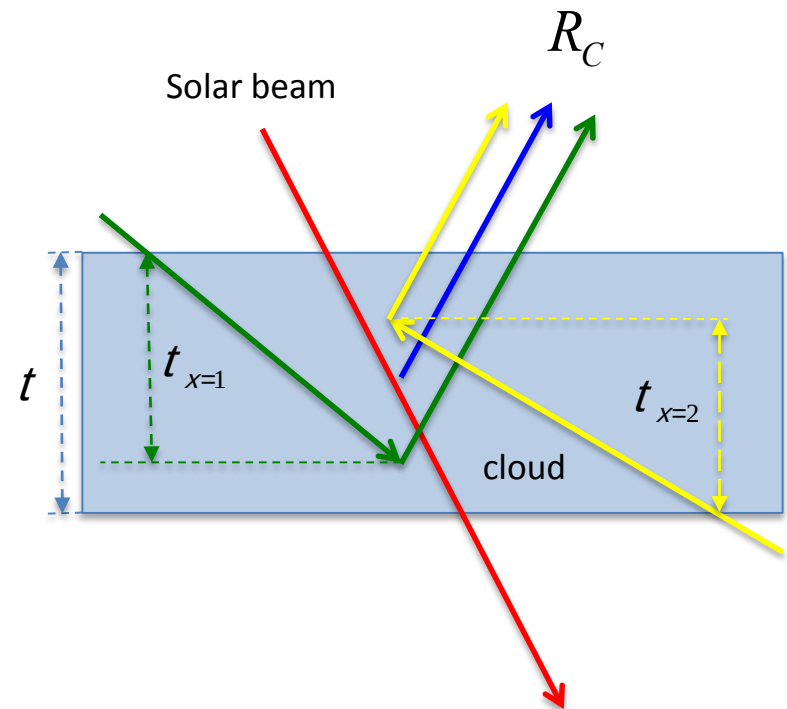


Effective Multi-Scattering Stream Model (EMSSM)

a



b



Effective Multi-Scattering Stream Model (EMSSM)

Radiative Transfer Equation: $m \frac{dI}{dt} = I - J$

Radiation Source:

$$J = Q^{thermal}(t) + \frac{V}{4p} P(t, mf; -m_0, f_0) I_0 e^{-\frac{t}{m_0}} + \frac{V}{4p} \int_0^{2p} \int_{-1}^1 P(t, mf; m, f) I_{diffuse}(t, mf; m, f) dm df$$

Integration to Summation:

$$J \approx Q^{thermal}(t) + \frac{V}{4p} P(t, mf; -m_0, f_0) I_0 e^{-\frac{t}{m_0}} + \sum_{x=1}^N \frac{V w_x}{4p} P(t, mf; m_x, f_x) I_x e^{-\frac{t}{m_x}}$$

BRDF:

$$R_C = R(0) = R_S^S(D_e, m, -m_0, Df, I) \left(1 - e^{-t_0 \left(\frac{1}{m_0} + \frac{1}{m} \right)} \right) + \sum_{x=1}^N R_x^S(D_e, m, -m_0, Df, I) \left(1 - e^{-t_0 \left(\frac{1}{m_0} + \frac{1}{m_x} \right)} \right)$$

Single Scattering Contribution

Multiple Scattering Streams

Effective Multi-Scattering Stream Model (EMSSM)

$$R_C = R(0) = R_S^S(D_e, m_T - m_0, Df, I) \left(1 - e^{-t_0 \left(\frac{1}{m_0} + \frac{1}{m} \right)} \right) + \sum_{x=1}^N R_x^S(D_e, m_T - m_0, Df, I) \left(1 - e^{-t_0 \left(\frac{1}{m_0} - \frac{1}{m_x} \right)} \right)$$

Single Scattering:

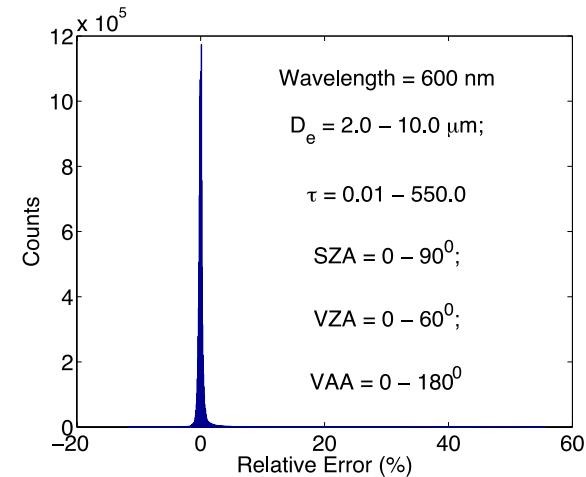
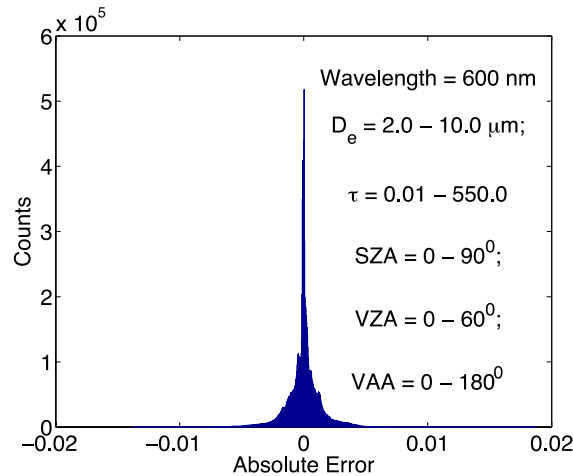
- **Source:** Directly from Sun, the intensity is known
- **Incident Angle:** Solar angle (known)

Multi-Scattering Stream:

- **Source:** diffused sun light by cloud, intensity is unknown, fitting parameter
- **Effective Incident Angle:** unknown, fitting parameter

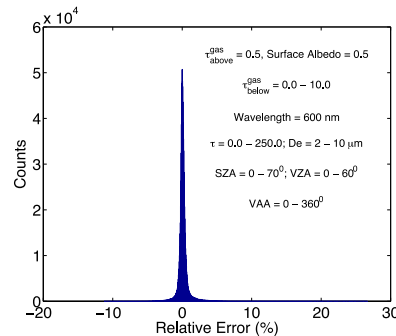
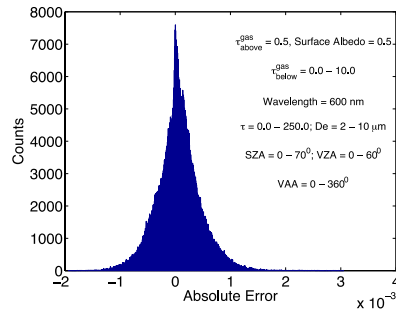
Each **scattering stream** may be considered as an **effective single scattering** with **unknown source intensity** and **unknown incident angle**. In this work, we using nonlinear regression method to fit the BRDF data to get these unknown effective source intensity and unknown effective incident angle for each of the scattering streams. These parameters are then used in the fast model calculation.

Accuracy of the Parameterized Ice Cloud BRDF @ 600 nm



Conditions	Maximum Error	Mean Error	Standard Deviation Error
$\lambda = 600 \text{ nm}$; $D_e = 2.0 - 10.0 \mu\text{m}$; $\tau = 0 - 550.0$; $\text{SZA} = 0 - 90^\circ$; $\text{VZA} = 0 - 60^\circ$; $\text{VAA} = 0 - 360^\circ$	0.0189	-4.1×10^{-6}	1.4×10^{-3}

Accuracy of TOA Reflectance Calculation Using PCRTM Fast Model @ 600 nm



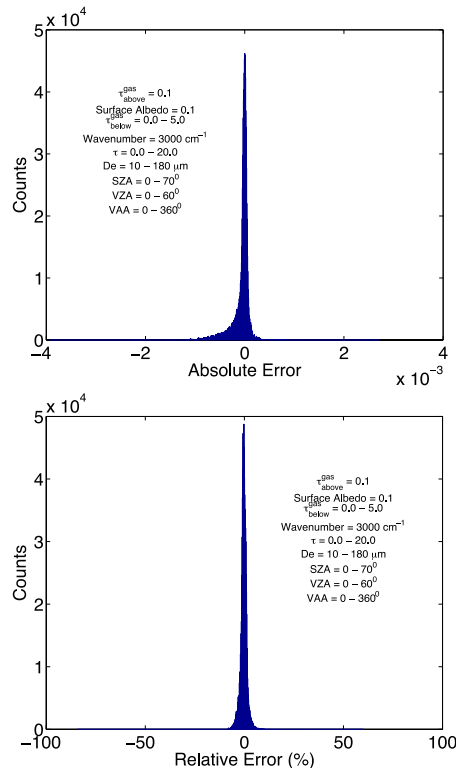
Results for $R_s = 0.5$
 $\tau_{\text{gas_above}} = 0.5$.

Conditions	Absolute Error		Relative Error	
	Mean Error	Standard Deviation	Mean Error	Standard Deviation
$R_s = 0.1$, $\tau_{\text{gas_above}} = 0.0$	9.35×10^{-5}	1.7×10^{-3}	7.48×10^{-4}	1.02×10^{-2}
$R_s = 0.1$, $\tau_{\text{gas_above}} = 0.5$	1.47×10^{-5}	3.93×10^{-4}	7.51×10^{-4}	1.02×10^{-2}
$R_s = 0.5$, $\tau_{\text{gas_above}} = 0.5$	5.78×10^{-5}	4.0×10^{-4}	1.46×10^{-3}	1.06×10^{-2}
$R_s = 1.0$, $\tau_{\text{gas_above}} = 0.5$	1.66×10^{-4}	4.78×10^{-4}	2.24×10^{-3}	1.23×10^{-2}

$\lambda = 600 \text{ nm}$; $De = 2.0 - 10.0 \mu\text{m}$; $\tau = 0 - 550.0$; $\tau_{\text{gas_below}} = 0 - 10.0$;
 $SA = 0 - 90^\circ$; $VZA = 0 - 60^\circ$; $VAA = 0 - 360^\circ$

All parameters except particle size were selected to be off grid.

Accuracy of the TOA Reflectance Calculation Using PCRTM Fast Model @ 3000 cm⁻¹



Conditions	Absolute Error		Relative Error	
	Mean Error	Standard Deviation	Mean Error	Standard Deviation
$R_s = 0.1,$ $\tau_{\text{gas_above}} = 0.1$	-6.44×10^{-5}	1.77×10^{-4}	-3.36×10^{-3}	1.88×10^{-2}
$R_s = 0.5,$ $\tau_{\text{gas_above}} = 0.1$	-3.24×10^{-4}	8.1×10^{-4}	-4.84×10^{-3}	2.19×10^{-2}
$R_s = 1.0,$ $\tau_{\text{gas_above}} = 0.1$	-6.50×10^{-4}	1.6×10^{-3}	-5.35×10^{-3}	2.36×10^{-2}

Results for
 $R_s = 0.1,$
 $\tau_{\text{gas_above}} = 0.1$

$\nu = 3000 \text{ cm}^{-1}; \text{De} = 10.0 - 180.0 \text{ } \mu\text{m}; \tau = 0 - 20.0; \tau_{\text{gas_below}} = 0 - 5.0; \text{SZA} = 0 - 70^\circ; \text{VZA} = 0 - 60^\circ; \text{VAA} = 0 - 360^\circ$

All parameters except particle size were selected to be off grid.

Computational Speed

- 2-3 orders faster than 36-stream DISORT
 - DISORT starts from: 0.0000000E+00
 - DISORT ends at: 4.540000 after 50 times run.
 - Rate of DISORT: 9.0800002E-02
 - PCRTM starts from: 0.0000000E+00
 - PCRTM ends at: 6.620000 after 50000 times run.
 - Rate of FSRTM: 1.3240000E-04
 - PCRTM runs **685.8006** times faster than 36-stream DISORT..

Recent Publications:

Professor Ping Yang: pre-computed BRDF and BTDF LUTs and a twisted icosahedral mesh for the AD algorithm.

- 2 orders faster than 128-stream DISORT
- ~ **10 times** faster than 36-stream DISORT



Conclusion

Based on the EMSSM model we proposed in this work, we successfully parameterized the cloud BRDF under various optical and physical properties of the cloud with various solar-satellite geometric configurations in a wavelength range from visible to near infrared. This parameterization significantly reduces the size of the LUTs and it is 2 to 3 orders faster than 36-stream DISORT in forward radiative transfer simulation. The high accuracy and the fast computation speed of the EMSSM based solar spectral radiative transfer model make it an promising candidate for fast radiative transfer calculation.

Future Works

- Further reduce the size of cloud BRDF and other matrices with very high accuracy.
- Expanse the results to the whole solar spectral range (300 nm to 2500 nm).
- Do the TOA reflectance using the LUTs from PCA method.
- Multiple cloud layers and aerosols.
- Integrate to PCRTM.