Progress on FAST and Accurate Radiative Transfer Model in the Presence of Multiple Scattering Clouds

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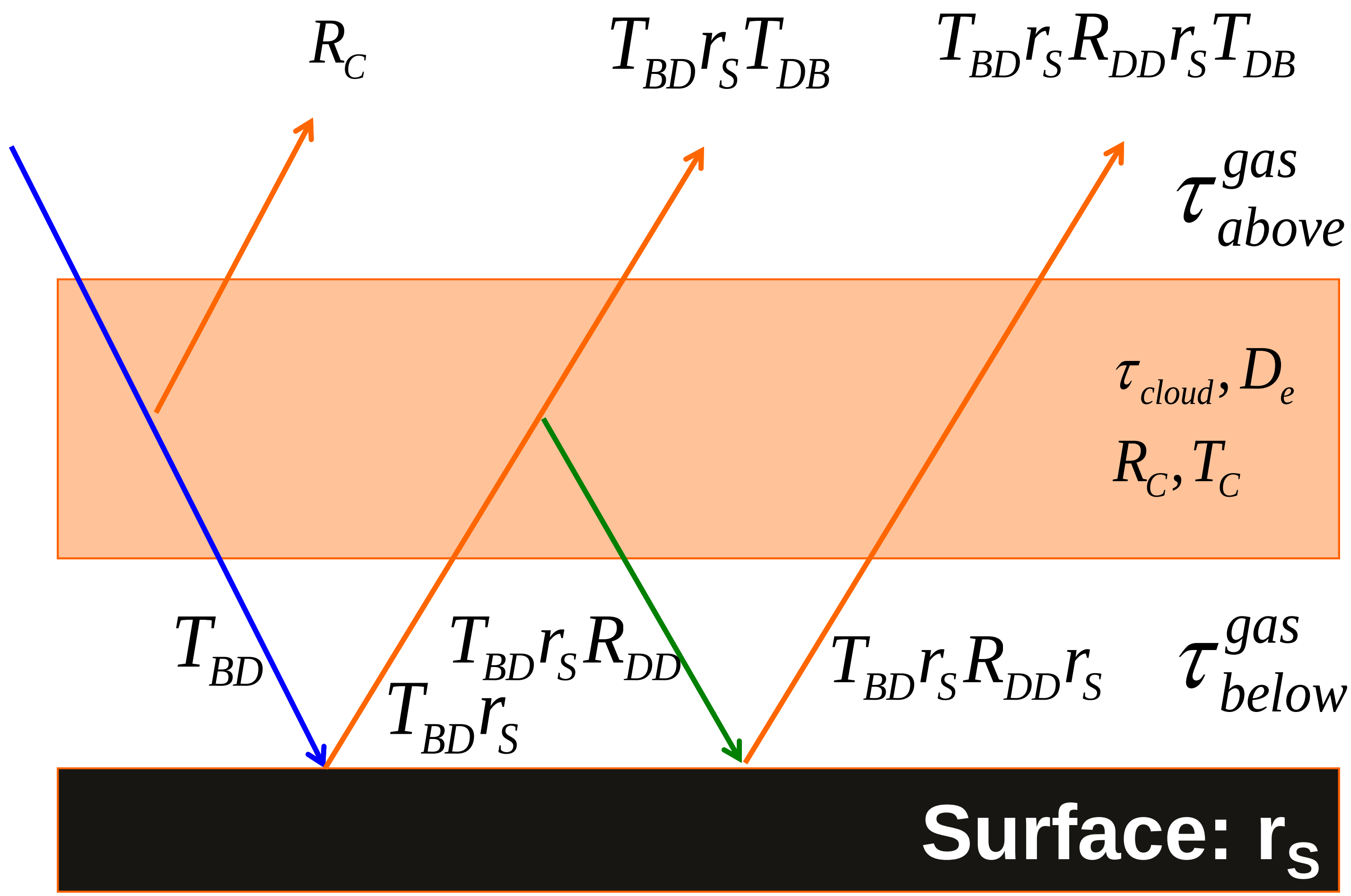
Outline

- Motivation
  - Add reflected solar radiance simulation in the exist fast infrared PCRTM
  - Increase the computation speed of RS radiance simulation for cloudy atmospheres while keep high accuracy
- LUTs for Multiple Scattering of Cloud and Aerosol
  - Generation
    - Stream Dependence in DISORT Simulation
    - Remove Stream Dependent Bad Points
  - Compression
    - From 3.3 GB to 0.024 GB
  - Rebuilt Accuracy
    - ΔBRDF < 10^{-4}
- TOA Reflectance Simulation
  - Accuracy
    - ΔRTOA < 10^{-3}
  - Speed
    - Five orders faster than 52-stream DISORT
    - PCRTM_SOLAR is faster than the exist infrared PCRTM
- Example of Application on IASI Spectral Data

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**

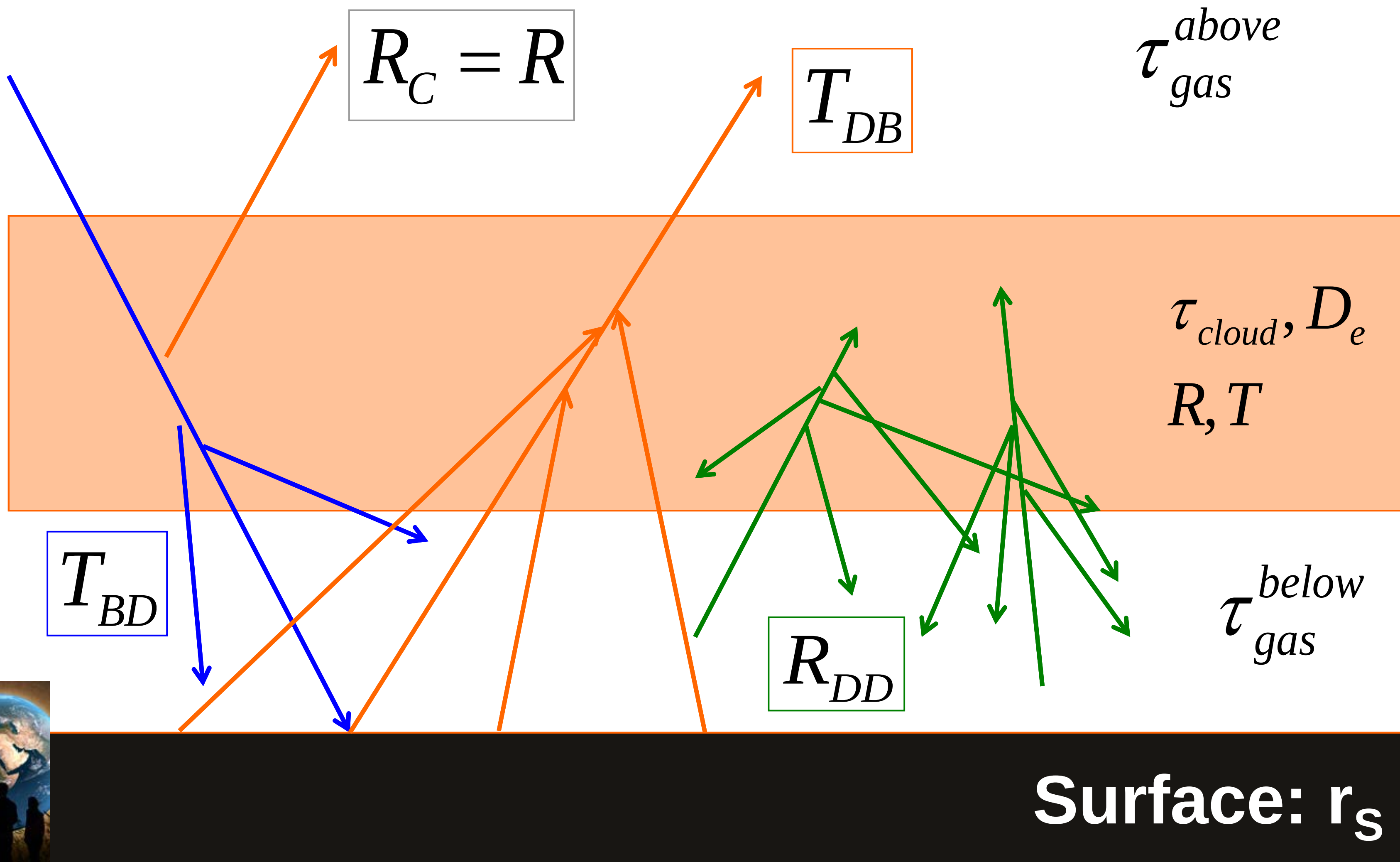
A Simple Cloud-Earth System



$$R = \left(R_C + \frac{r_S T_{BD} T_{DB}}{1 - r_S R_{DD}} \right) e^{-\frac{\tau_{gas}^{above}}{\mu_0} - \frac{\tau_{gas}^{above}}{\mu}}$$

Main Scattering Process:

Beam → beam; beam → diffuse; diffuse → beam; diffuse → diffuse



Parameters Related to the Main Scattering Processes

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

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

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

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

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

Downsize the Bidirectional Reflection Distribution Function

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

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

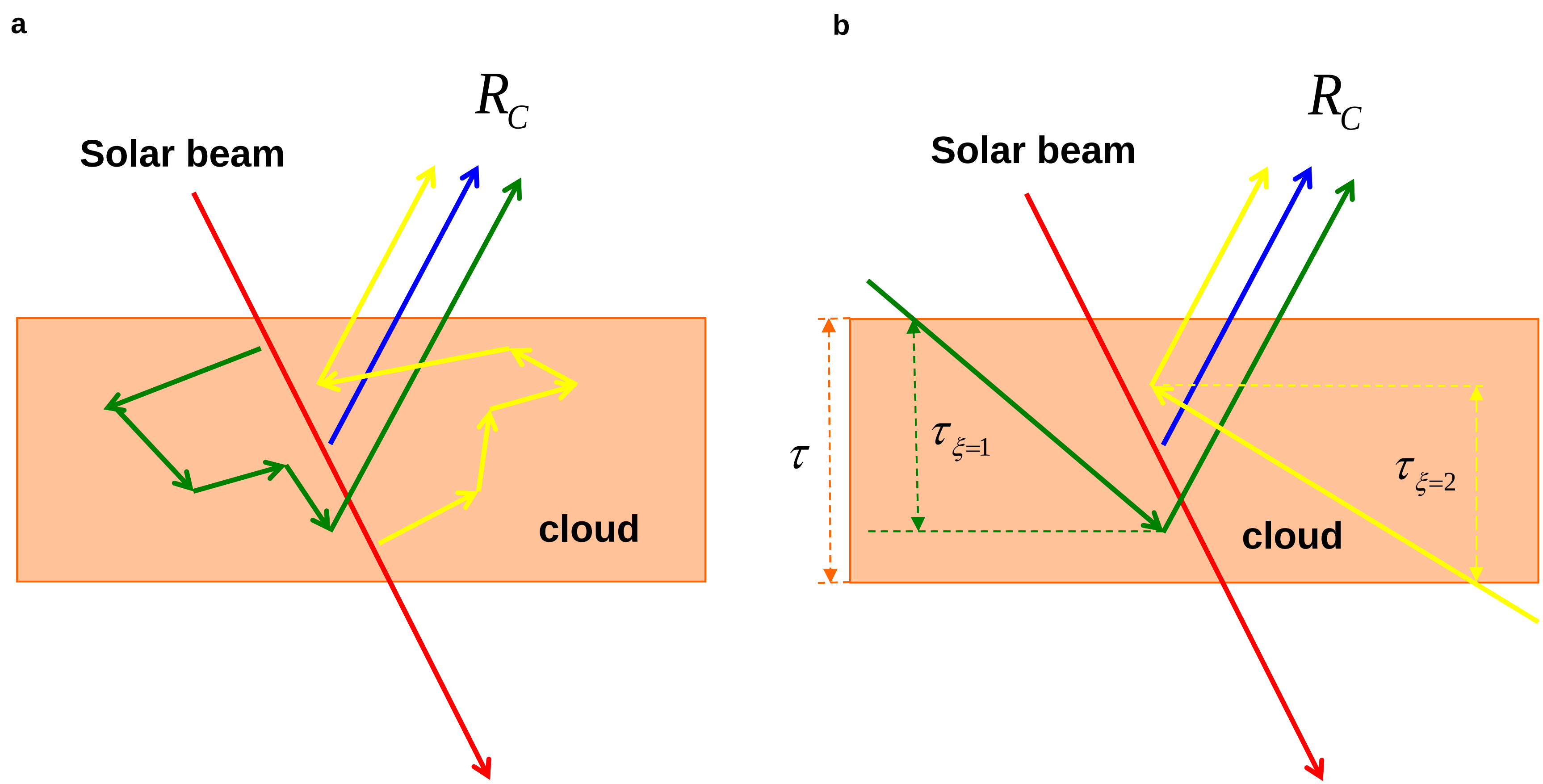
  45x10x30x30x30x100x4 = 4.86 GB

- **Size of Q LUT:**

  10x30x30x30x100x4 = 108 MB

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

Effective Multi-Scattering Stream Model (EMSSM)



Effective Multi-Scattering Stream Model (EMSSM)

Radiative Transfer Eqaution:

$$\mu \frac{dI}{d\tau} = I - J$$

Radiation Source:

$$J = Q^{thermal}(\tau) + \frac{\varpi}{4\pi} P(\tau,\mu,\phi;-\mu_0,\phi_0) I_0 e^{-\frac{\tau}{\mu_0}} + \frac{\varpi}{4\pi} \int_0^{2\pi} \int_{-1}^{1} P(\tau,\mu,\phi;\mu',\phi') I_{diffuse}(\tau,\mu',\phi') d\mu' d\phi'$$

Integration to Summation:

$$J \approx Q^{thermal}(\tau) + \frac{\varpi}{4\pi} P(\tau,\mu,\phi;-\mu_0,\phi_0) I_0 e^{-\frac{\tau}{\mu_0}} + \sum_{\xi=1}^{N} \frac{\varpi w_\xi}{4\pi} P(\tau,\mu,\phi;\mu_\xi,\phi_\xi) I_\xi e^{\frac{\tau}{\mu_\xi}}$$

BRDF:

$$R_C = R(0) = R_S^S(D_e,\mu,-\mu_0,\Delta\phi,\lambda)\left(1 - e^{-\tau_0\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)}\right) + \sum_{\xi=1}^{N} R_\xi^S(D_e,\mu,-\mu_0,\Delta\phi,\lambda)\left(1 - e^{-\tau_0\left(\frac{1}{\mu_0}-\frac{1}{\mu_\xi}\right)}\right)$$

Single Scattering Contribution

Multiple Scattering Streams

Effective Multi-Scattering Stream Model (EMSSM)

$$R_C = R(0) = R_S^S(D_e, \mu, -\mu_0, \Delta\phi, \lambda)\left(1 - e^{-\tau_0\left(\frac{1}{\mu_0}+\frac{1}{\mu}\right)}\right) + \sum_{\xi=1}^{N} R_\xi^S(D_e, \mu, -\mu_0, \Delta\phi, \lambda)\left(1 - e^{-\tau_0\left(\frac{1}{\mu_0}-\frac{1}{\mu_\xi}\right)}\right)$$

Single Scattering:

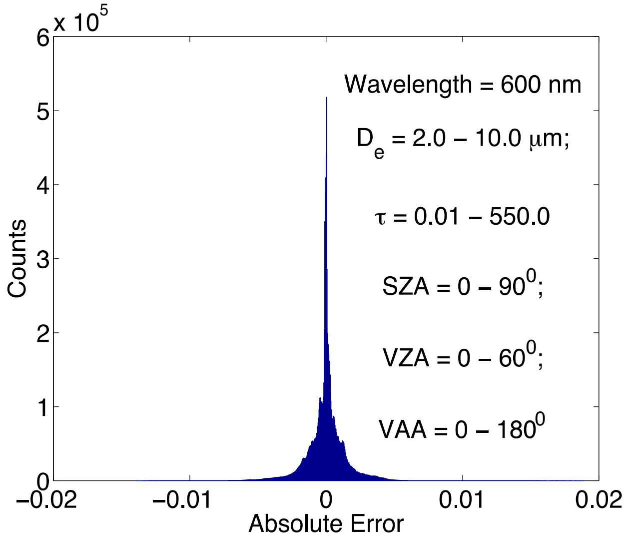
- **Source:** Directly from Sun, the intensity is known
- **Incident Angle:** Solar angle (known)

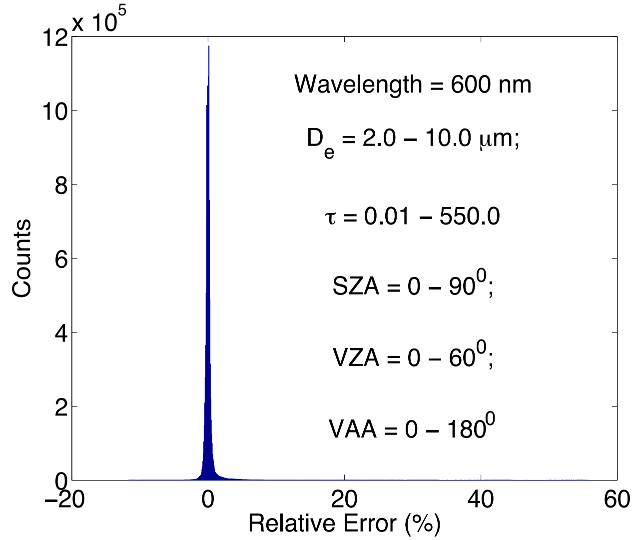
Multi-Scattering Stream:

- **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.

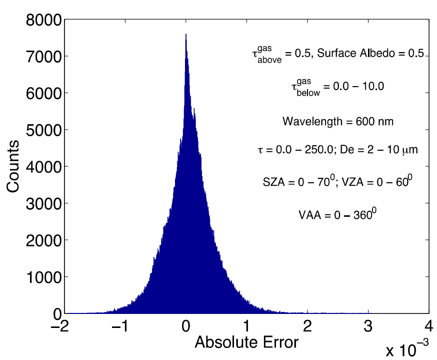
Accuracy of the Parameterized Ice Cloud BRDF @ 600 nm

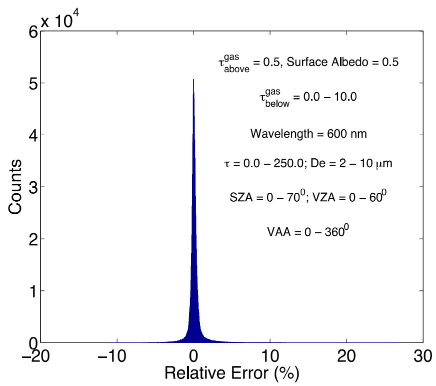




Conditions	Maximum Error	Mean Error	Standard Deviation Error
λ = 600 nm; De = 2.0 – 10.0 μm; τ = 0 – 550.0; SZA = 0 – 90^0; VZA = 0 – 60^0; VAA = 0 - 360^0	0.0189	-4.1×10^{-6}	1.4×10^{-3}

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



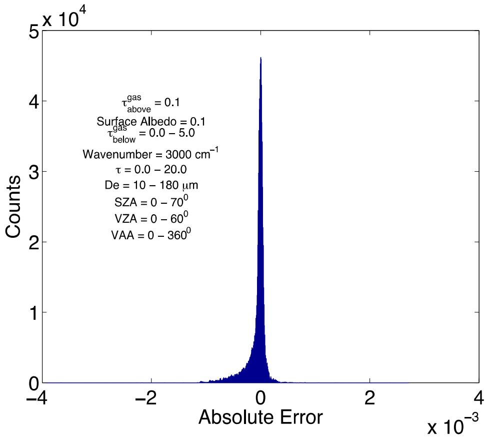


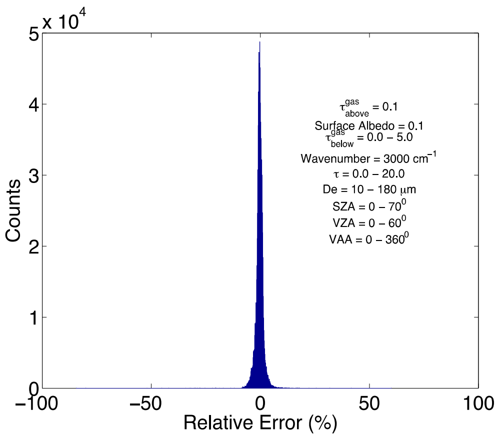
Results for R_s = 0.5 τ_{gas_above} = 0.5.

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

λ = 600 nm; De = 2.0 – 10.0 μm; τ = 0 – 550.0; τ_{gas_below} = 0 – 10.0; SZA = 0 – 90^0; VZA = 0 – 60^0; VAA = 0 - 360^0
All parameters except particle size were selected to be off grid.

Accuracy of the TOA Reflectance Calculation Using PCRTM Fast Model @ 3000 cm^{-1}



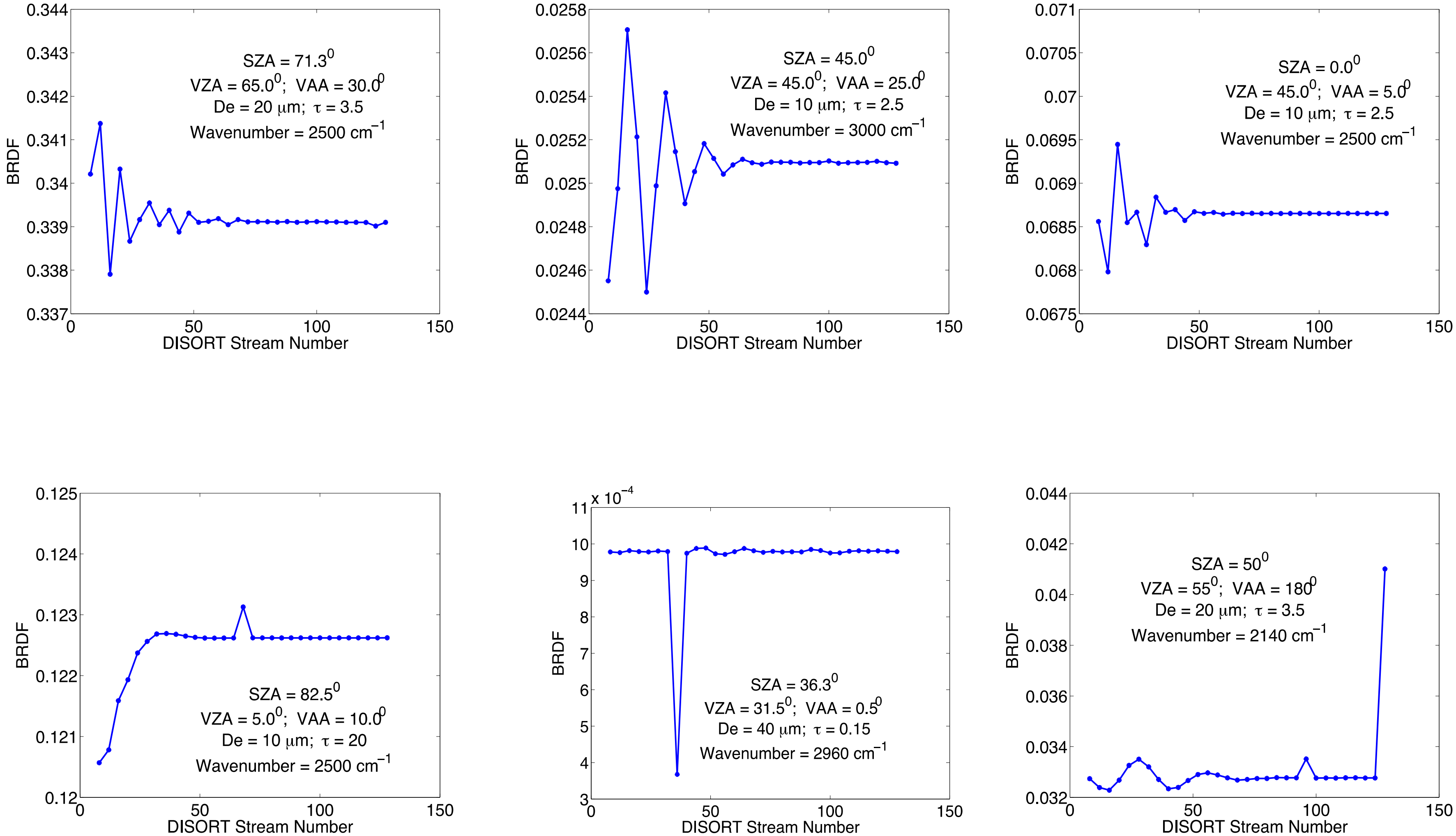


Results for R_s = 0.1, τ_{gas_above} = 0.1

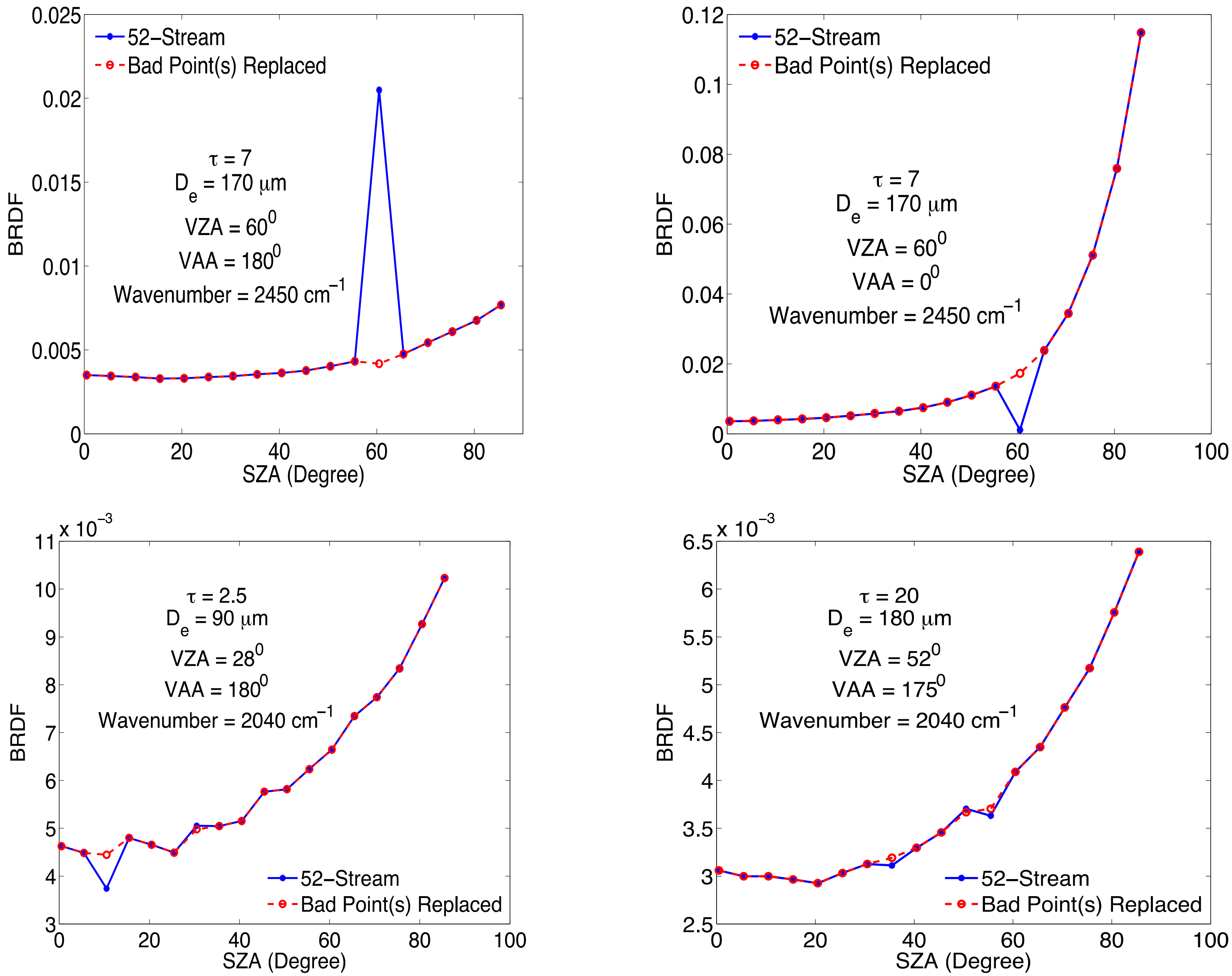
	Absolute Error		Relative Error	
Conditions	Mean Error	Standard Deviation	Mean Error	Standard Deviation
$R_s = 0.1$, $\tau_{gas\_above} = 0.1$	-6.44×10^{-5}	1.77×10^{-4}	-3.36×10^{-3}	1.88×10^{-2}
$R_s = 0.5$, $\tau_{gas\_above} = 0.1$	-3.24×10^{-4}	8.1×10^{-4}	-4.84×10^{-3}	2.19×10^{-2}
$R_s = 1.0$,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

υ = 3000 cm^{-1}; De = 10.0 – 180.0 μm; τ = 0 – 20.0; τ_{gas_below} = 0 – 5.0; SZA = 0 – 70^0; VZA = 0 – 60^0; VAA = 0 - 360^0
All parameters except particle size were selected to be off grid.

Generation of LUTs: Stream Number Dependence in DISORT Simulation



Generation of LUTs: Remove the Stream-Dependence in DISORT Simulation for the LUTs

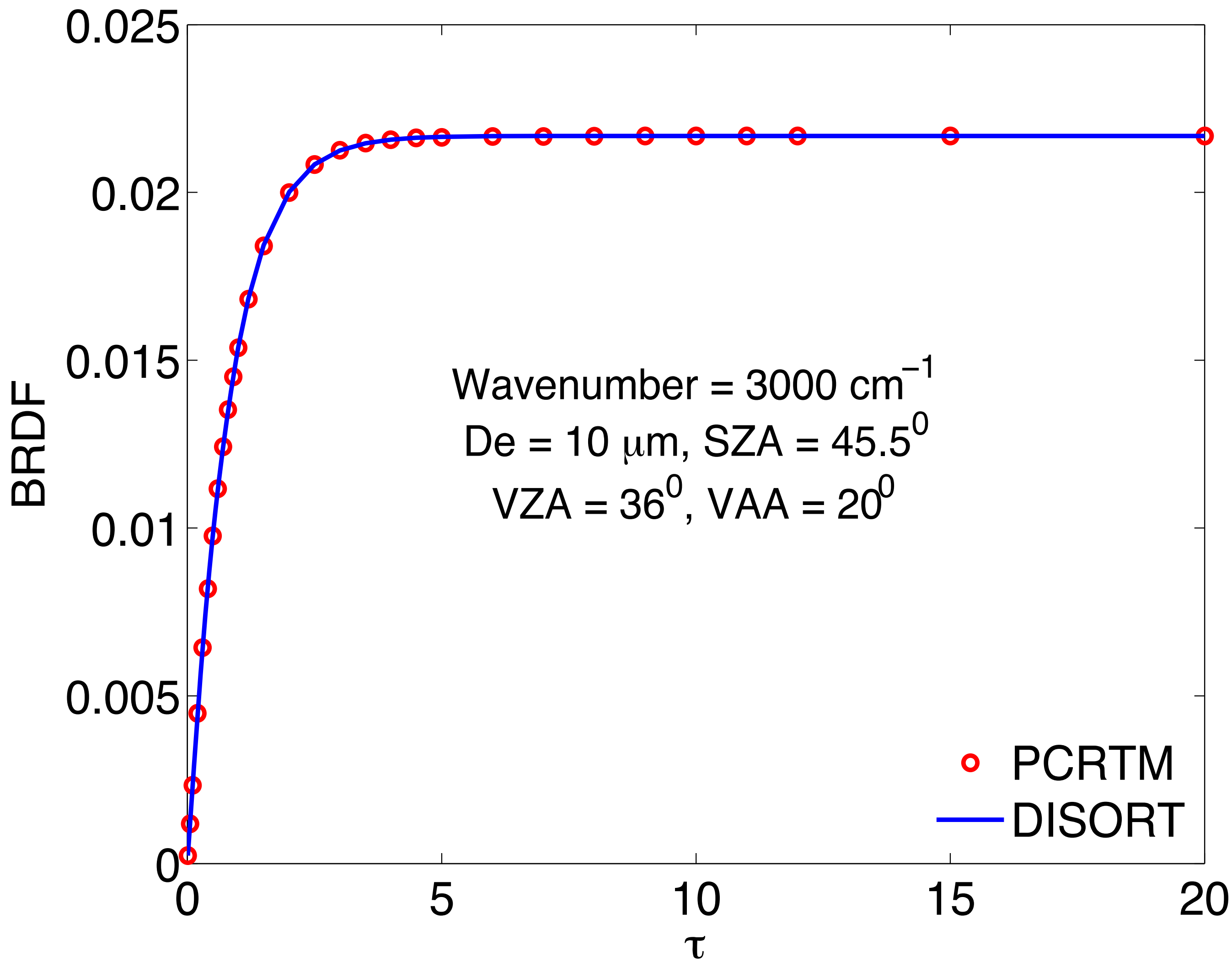


0.36% of the data were replaced due to stream-dependent errors.

Downsize of LUTs

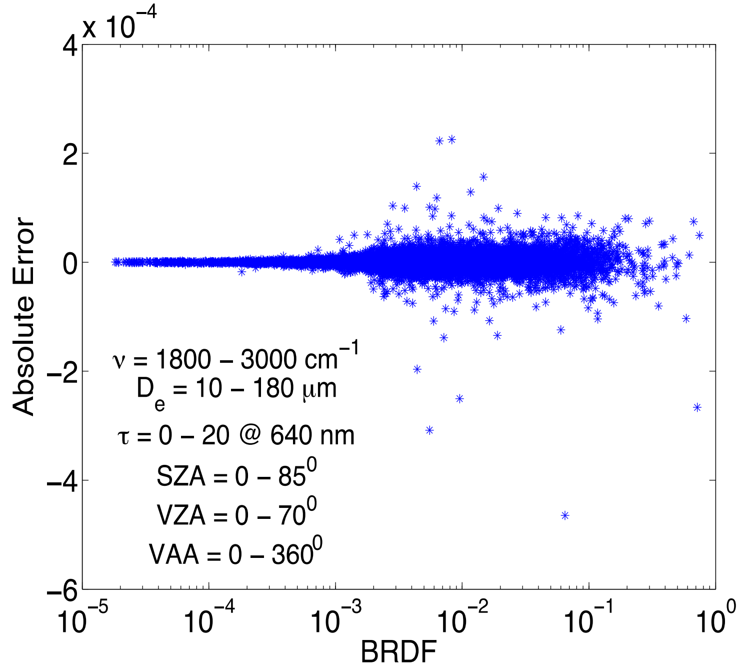
- BRDF: 3,300 MB to 23.68 MB
- T_{BD}: 157 MB to 11.66 MB
- T_{DB}: 157 MB to 11.66 MB
- R_{DD}: 5.23 MB

Rebuilt of LUTs in PCRTM_SOLAR



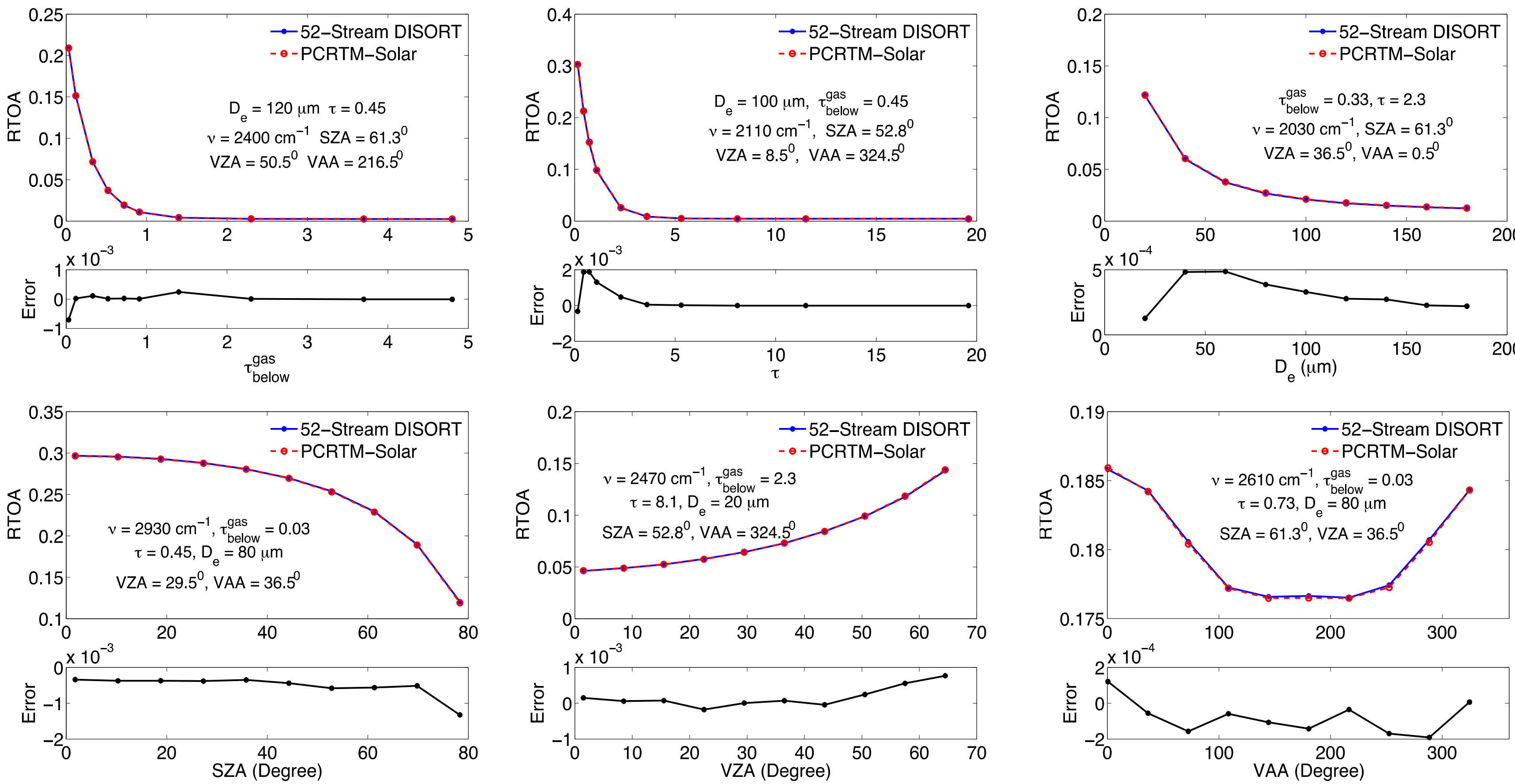
Accuracy of the Rebuilt LUTs in PCRTM_SOLAR

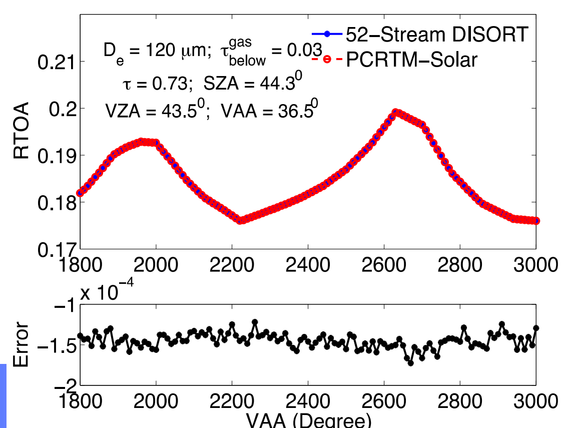
Accuracy of the Rebuilt BRDF LUTs (ice cloud) (compared to 52-stream DISORT)	
$\lvert\Delta\mathrm{BRDF}\rvert < 10^{-4}$	99.75%
$10^{-4} < \lvert\Delta\mathrm{BRDF}\rvert < 5\times10^{-4}$	0.24%
$\lvert\Delta\mathrm{BRDF}\rvert > 5\times10^{-4}$	0.01%
$\lvert\Delta\mathrm{BRDF}\rvert > 1\times10^{-3}$	0.0%



Parameters Used	
Cloud Type	Ice
D_e: 10 – 180 μm	SZA: 0 - 85^0
τ_{cloud}: 0 – 20 @ 640 nm	VZA: 0 - 70^0
ν: 1800 – 3000 cm^{-1}	VAA: 0 - 360^0

TOA Reflectance Simulation: PCRTM_SOLAR v.s. DISORT





In the case of background scattering with VAA = 0^0 or front scattering with VAA = 180^0, max errors were obtained. This is due to the inaccurate simulation of DISORT at these specific directions (singularity issue in DISORT).

Accuracy in TOA Reflectance: PCRTM_SOLAR v.s. DISORT

Difference in Reflectance at TOA (PCRTM_SOLAR v.s. 52 Stream DISORT)	
$\lvert\Delta R\rvert < 10^{-3}$	93.30%
$10^{-3} < \lvert\Delta R\rvert < 10^{-2}$	6.65%
$\lvert\Delta R\rvert > 10^{-2}$	0.05%
Max ΔR	0.0337

Parameters Used	
Cloud Type	Ice
D_e: 10 – 180 μm	SZA: 0 - 85^0
τ_{cloud}: 0 – 20 @ 640 nm	VZA: 0 - 70^0
ν: 1800 – 3000 cm^{-1}	VAA: 0 - 360^0
τ_{below_cloud} = 0 - 5	

Reasons for the difference:

1. **The stream-dependent errors in DISORT simulation (~ 0.36%).**
2. **The inaccuracy in front and back scattering directions in DISORT simulation (The percentage with $\lvert\Delta R\rvert$ larger than 10^{-3} reduced from 6.65% to 5% if these cases removed).**
3. **The interpolation errors in PCRTM_SOLAR.**

COMPUTATION SPEED: PCRTM_SOLAR v.s. PCRTM_THERMAL

- **Example Satellite Sensor: IASI 0.25 cm^{-1} Spectral Resolution Full Channel Set**
  - **PCRTM_SOLAR: 4.89 ms/run**
    - **1000 runs with the following parameters:**

      SZA = 10^0, VZA = 60^0, VAA = 72.5^0, υ changes with 439 different values, τ_{above} changes with wavenumber, τ_{below} changes with wavenumber, τ_{cloud} = 1.025, De = 48 μm, Rs = 0.02
  - **PCRTM_THERMAL: 6.06 ms/run**
    - **1000 runs with the following parameters:**

      VZA = 60^0, υ changes with 439 different values, τ_{above} changes with wavenumber, τ_{below} changes with wavenumber, τ_{cloud} = 1.025, De = 48 μm, Rs = 0.02
  - **PCRTM_SOLAR is a little bit faster than PCRTM_THERMAL.**
    - **Integrate PCRTM_SOLAR to PCRTM will NOT influence the computation speed of PCRTM greatly.**

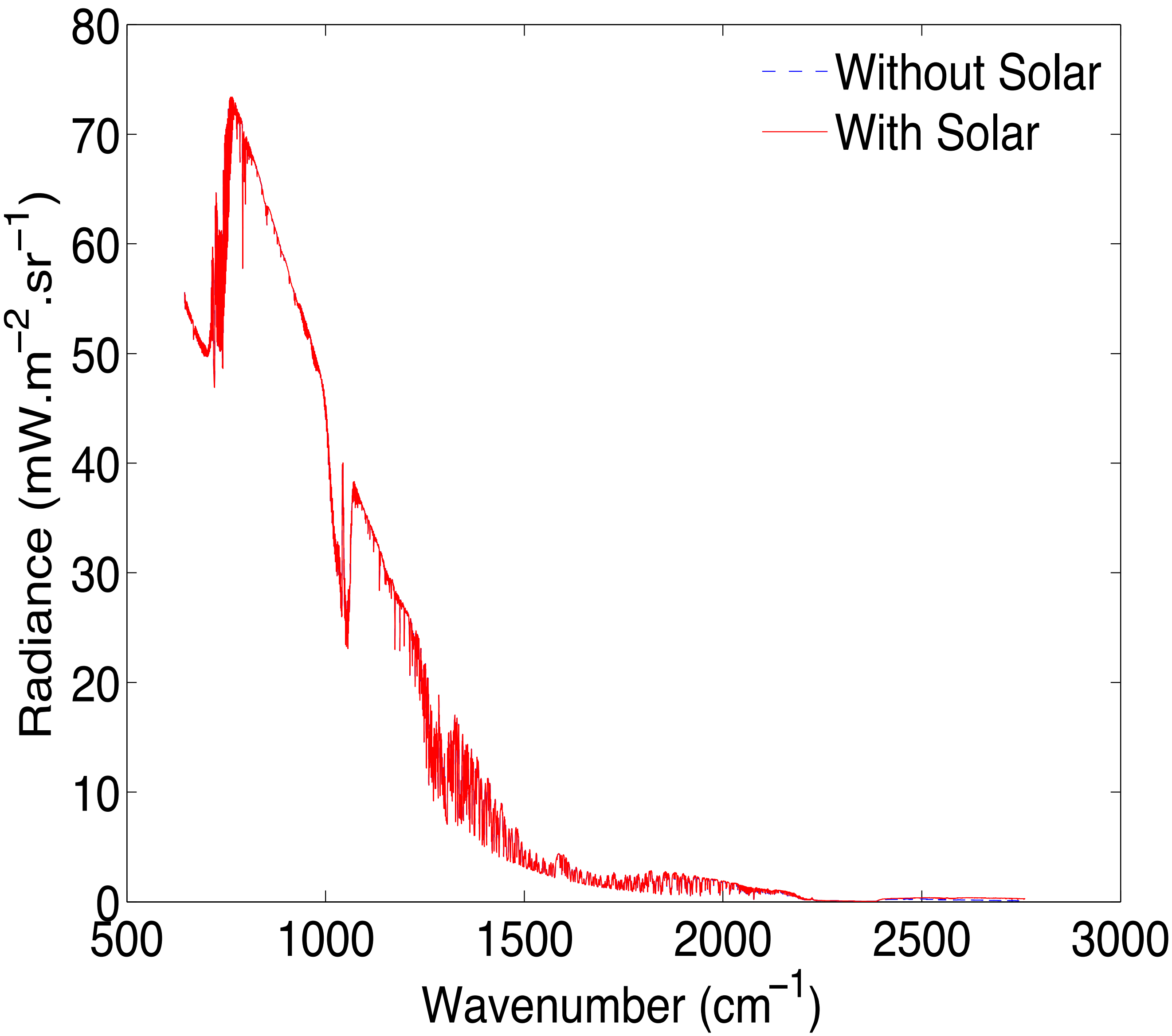
COMPUTATION SPEED: PCRTM_SOLAR v.s. DISORT

- **Example Satellite Sensor: IASI 0.25 cm^{-1} Spectral Resolution Full Channel Set**
  - **PCRTM_SOLAR: 0.52 ms/run**
    - **1000 runs with the following parameters:**

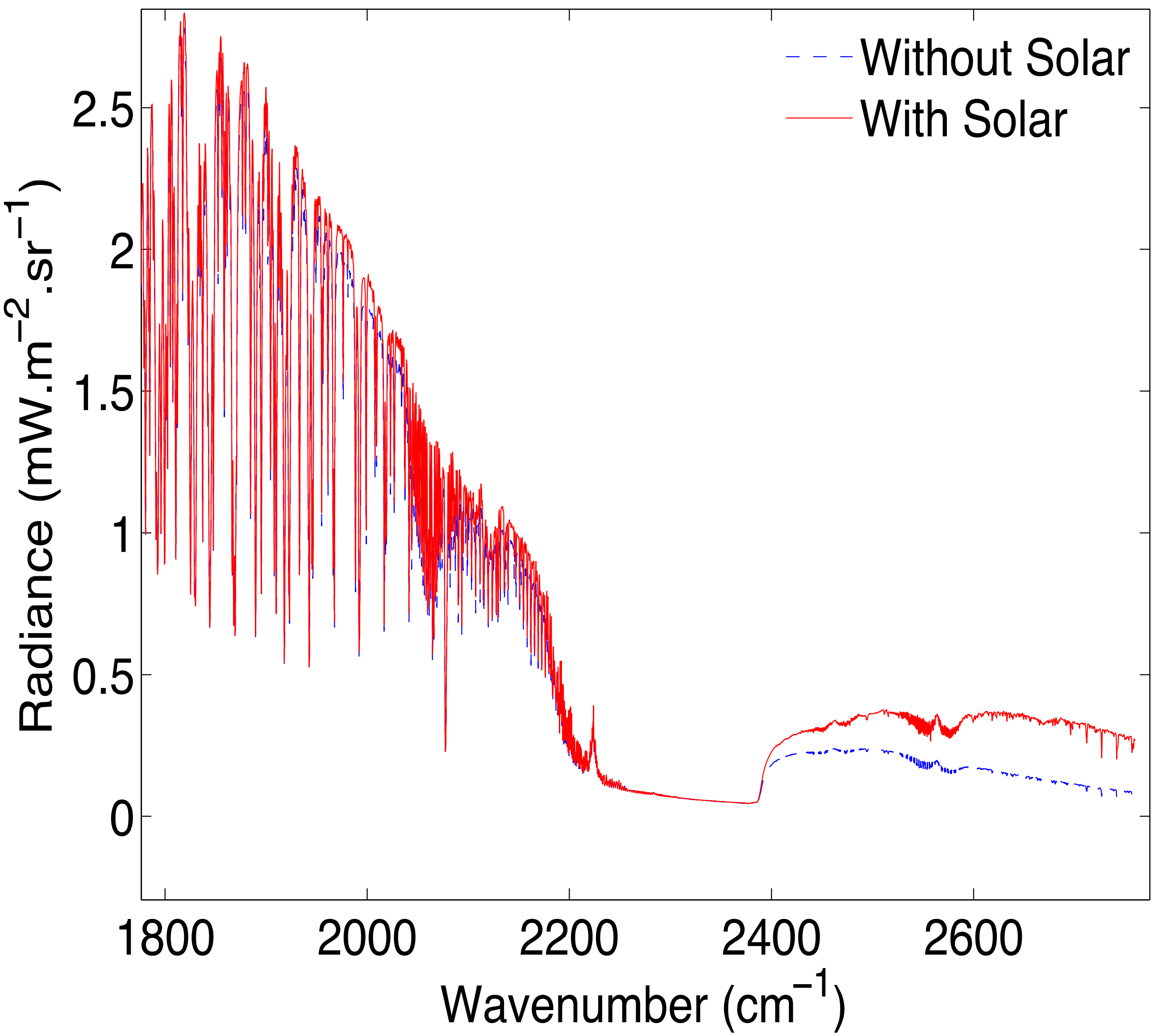
      SZA = 10^0, VZA = 60^0, VAA = 72.5^0, υ changes with 439 different values, τ_{above} changes with wavenumber, τ_{below} constant, τ_{cloud} = 1.025, De = 48 μm, Rs = 0.02
  - **DISORT (52-stream): 63.61 s/run**
    - **439 runs with the following parameters:**

      SZA = 15^0, VZA = 50^0, VAA = 30^0, υ = 2500 cm^{-1}, τ_{above} = 0.3, τ_{below} = 4.8, τ_{cloud} = 1.5, De = 10 μm, Rs = 0.2
- **PCRTM_SOLAR is 122,327 times (5 orders) faster than DISORT!!!**

Example for IASI 0.25 cm^{-1} Spectral Resolution Full Channel Set



Example for IASI 0.25 cm^{-1} Spectral Resolution Full Channel Set



Example for IASI 0.25 cm^{-1} Spectral Resolution Full Channel Set