Fast Radiative Transfer Model Development for Hyperspectral Sounders in the Presence of Clouds and Solar Radiation

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Outline

- Motivation
  - Find an Efficient and Accurate Way to Calculate the Multiple Scattering of Solar Radiance by Cloud/Aerosol
- Main Results of This Work
  - Multi-Layer Clouds (Include One-Layer)
    - Dual Stream PCRTM-SOLAR
  - One-Layer Cloud (LUT for Faster Performance)
    - Parameterization/LUT
- Conclusion

Motivation

- Efficient radiative transfer (RT) simulation for cloudy-sky is essential for operational satellite data processing and climate OSSEs
- Our Previous Works:
  - PCRTM-IR model
    - Multi-layer multiple scattering of clouds included
    - Been used to perform single FOV cloudy sky retrieval successfully
  - PCRTM-Solar
    - Includes azimuthal dependency
    - Fast and accurate
- Current Work:
  - To further increase the simulation speed and reduce the computational burden

RT Computational Burden & Our Strategies to Reduce It

- The channel radiances measured by a sensor are the result of monochromatic radiances convolved with the instrument lineshape function:

$$R_i^{channel} = \frac{\sum_{k=1}^{N} R_k^{mono} \rho_k}{\sum_{k=1}^{N} \rho_k}$$

- LBL Model: over hundreds of thousands or millions of mono radiances have to be calculated accurately to get one channel radiance spectrum of a hyperspectral sensor.
- Our Methods to reduce the computational burden of multi-scattering of solar radiance by cloud particles:
  - **Regular PCRTM-SOLAR**: only **FEW HUNDREDS** of mono radiances are needed to be calculated accurately.
  - **Dual Stream PCRTM-SOLAR (multi-layer clouds, this work):** only **FEW TENS** of mono radiances are required to be calculated accurately.
  - **One-Layer Cloud PCRTM-SOLAR (1-layer cloud, this work):** **no need** to call multi-scattering solver.

Using PCA to Reduce Computational Burden

Instrument	Apodization	# of Channels	# of Mono
IASI	Gaussian	8461	753
AIRS	Airs Filter	2378	500
HR CrIS	Boxcar	2211	540
HR CrIS	Blackman	2211	374
HR CrIS	Hamming	2211	398
CrIS	Boxcar	1317	485
CrIS	Blackman	1317	369
CrIS	Hamming	1317	384
NASTI	Boxcar	8632	748
NASTI	Kaiser	8632	559
SHIS	Boxcar	4316	647
SHIS	Kaiser	4316	647

Using PCA to Reduce Computational Burden

- CLARREO Reflected Solar (RS) spectrum from 300 nm to 2.5 μm with 1 cm^{-1} resolution (29,311 channel frequencies).
- MODTRAN: need radiances at 259,029 mono frequencies
  - Real Example: qsub to CLARREO machine at NASA LaRC, 16-stream, one spectrum)
    - CPU TIME = 2 hours 39 minutes = 9540 s
- PCRTM-SOLAR: need radiances at only 1,359 mono frequencies for land surface (~ 190 times faster)
  - Real Example: qsub to CLARREO machine at NASA LaRC, 16-stream, one spectrum)
    - CPU TIME = 67.736237 (radiances at 1359 mono frequencies)
- PCRTM-SOLAR is able to treat multi-layer cloud/aerosol

0.3-2.5 μm	PCRTM-SOLAR	MODTRAN	SPEED UP
Ocean 1 cm^{-1}	958	259,029	270
Land 1 cm^{-1}	1,359	259,029	190
Ocean 8 nm	241	259,029	1075
Land 8 nm	263	259,029	985

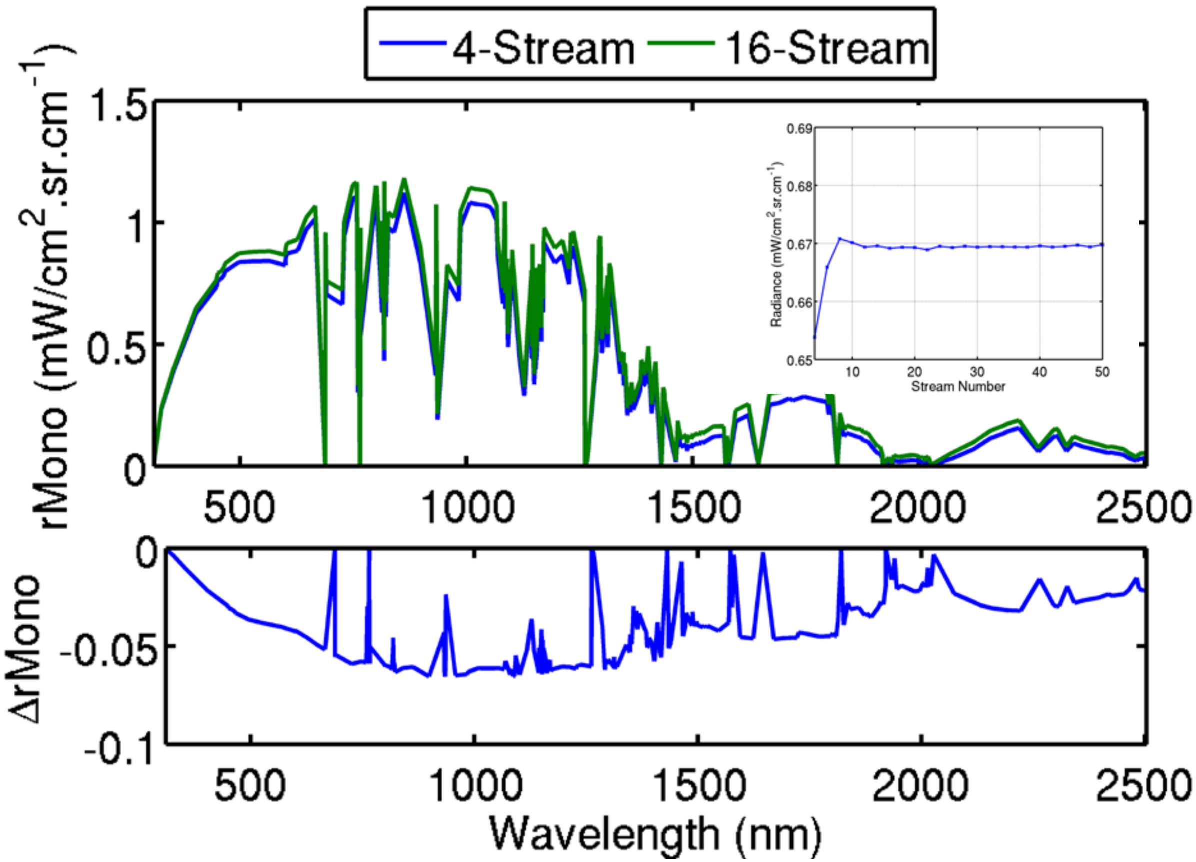
$$R^{chan}_{nch\times ns} = U_{nch\times npc} A_{npc\times nsmo} R^{mono}_{nsmo\times ns}$$

Methods to Solve Scattering Involved RT Equation

- Fast Approximate Methods:
  - Single Scattering Approximation
  - Two- and Four-Stream Approximation
  - Eddington and Delta-Eddington Approximation
- Slow Accurate Methods:
  - Discrete-Ordinate Method (if stream number big enough)
  - Adding-Doubling Method (if stream number big enough)
  - Successive Order of Scattering (if stream number big enough)
  - Monte-Carlo Method (if photon number is big enough)

Speed & Accuracy Dilemma to Solve RT Equation

- Speed and accuracy dilemma in DO/AD/SOS methods
  - The accuracy depends on stream number N. Larger N usually gives higher accuracy.
  - The computation time is approximately proportional to N^3.
- Do we have to compromise between accuracy and speed? (We want both!!!)



Strategy and Goal of This Work

- Strategy and Goal of This Work:
  - Multi-Layer Clouds:
    - Simulate thousands of mono radiances with both fast approximate methods and slow accurate methods
    - Find the relationship so that we may use the fast radiances to reconstruct the accurate radiances
    - Goals:
      - To quickly obtain highly accurate radiance spectrum by calculating few hundreds mono radiances with the fast approximation methods and few tens mono radiances with the slow accurate methods (Dual Stream PCRTM-SOLAR)
  - One-Layer Cloud:
    - Parameterize the 1-layer cloud results for operational application.

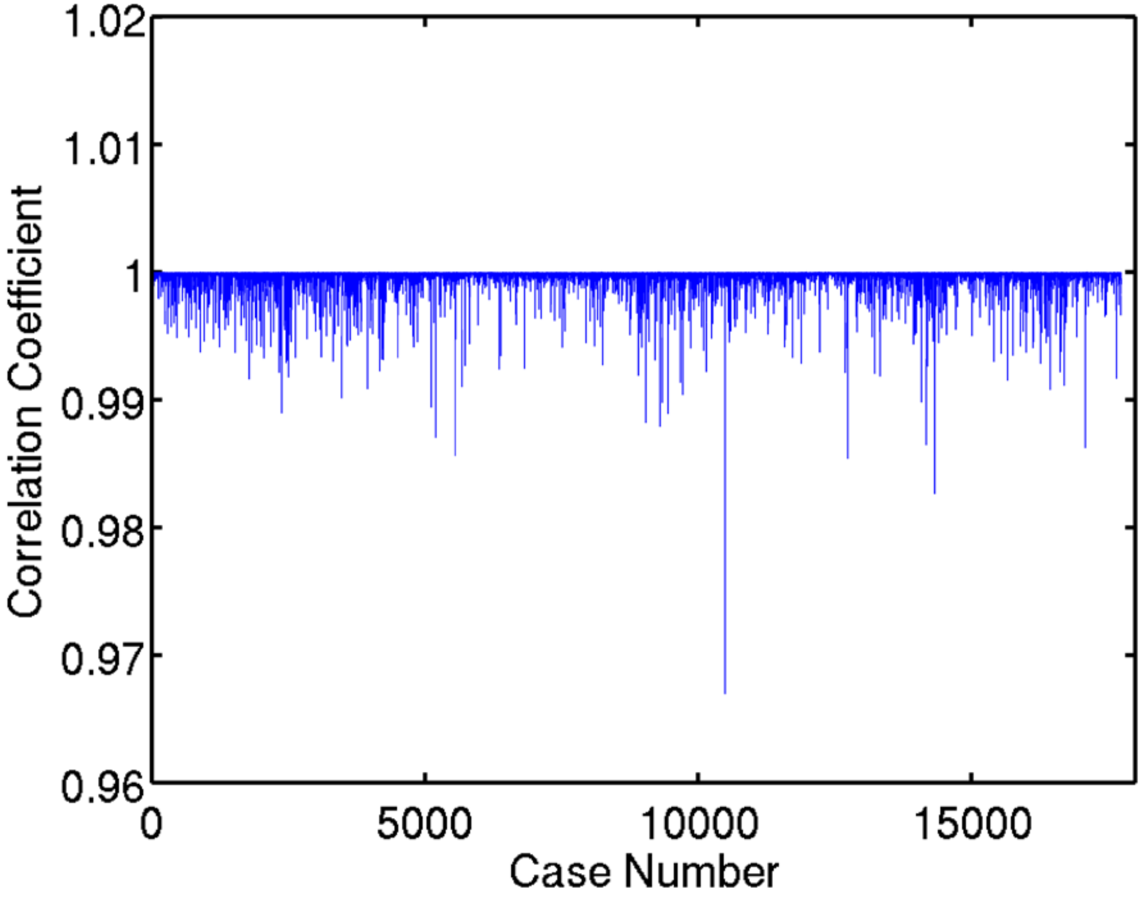
Dual Stream PCRTM-SOLAR: 4-Stream to N-Stream

- What we need:
  - Speed: 2-stream or 4-stream
  - Accuracy: N-stream (N >> 2)
- The link between 4-stream and N-stream (CLARREO: land surface, 1 cm^{-1} resolution case):

$$r_{Nstr}^{1359} = r_{4str}^{1359} + (r_{Nstr}^{1359} - r_{4str}^{1359}) = r_{4str}^{1359} + \Delta r^{1359}$$

They are highly related!

Correlation between mono radiances obtained from 4-stream and 16-stream DO method



Dual Stream PCRTM-SOLAR: 4-Stream to N-Stream

- Training the small difference:

$$\Delta r^{1359} = B^{1359\times M} \cdot \Delta r^{M}$$

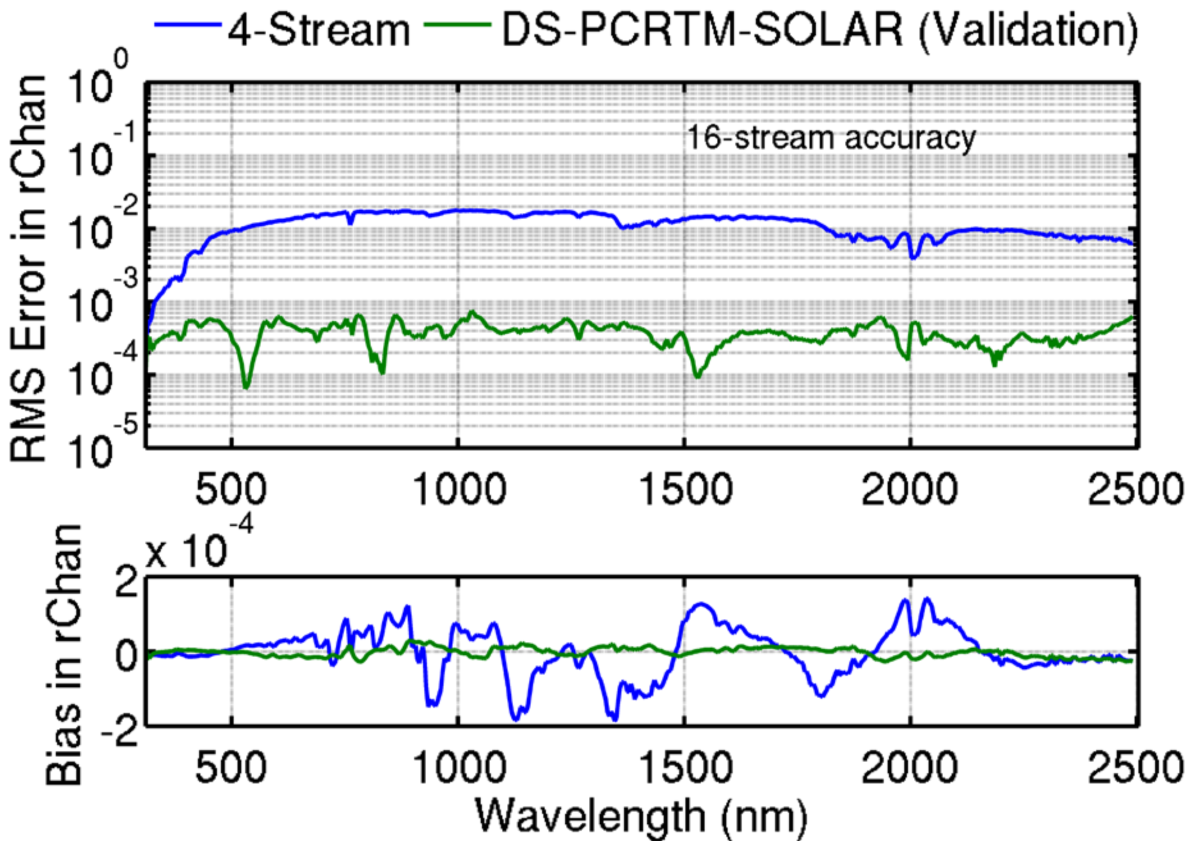
With M << 1359.

- The obtained radiance with N-stream accuracy is thus given by:

$$r_{Nstr}^{1359} = r_{4str}^{1359} + B^{1359\times M} \cdot \Delta r^{M} = r_{4str}^{1359} + B^{1359\times M} \cdot (r_{Nstr}^{M} - r_{4str}^{M})$$

- **Don't need N-stream calculation at all 1359 frequencies;**
- **Need N-stream calculation at M frequencies among the 1359 frequencies. (M << 1359)**
- **Need 4-stream calculation at all 1359 frequencies.**

RMS Errors of Dual Stream PCRTM-SOLAR



Dual Stream PCRTM-SOLAR: 4-Stream to N-Stream

- Estimated speed using the new strategy:

$$\text{time ratio} = \frac{\text{time for N-stream (all 1359 frequencies)}}{\text{time for 4-stream (all 1359 frequencies)} + \text{time for N-stream (M} \ll \text{1359 frequencies)}}$$

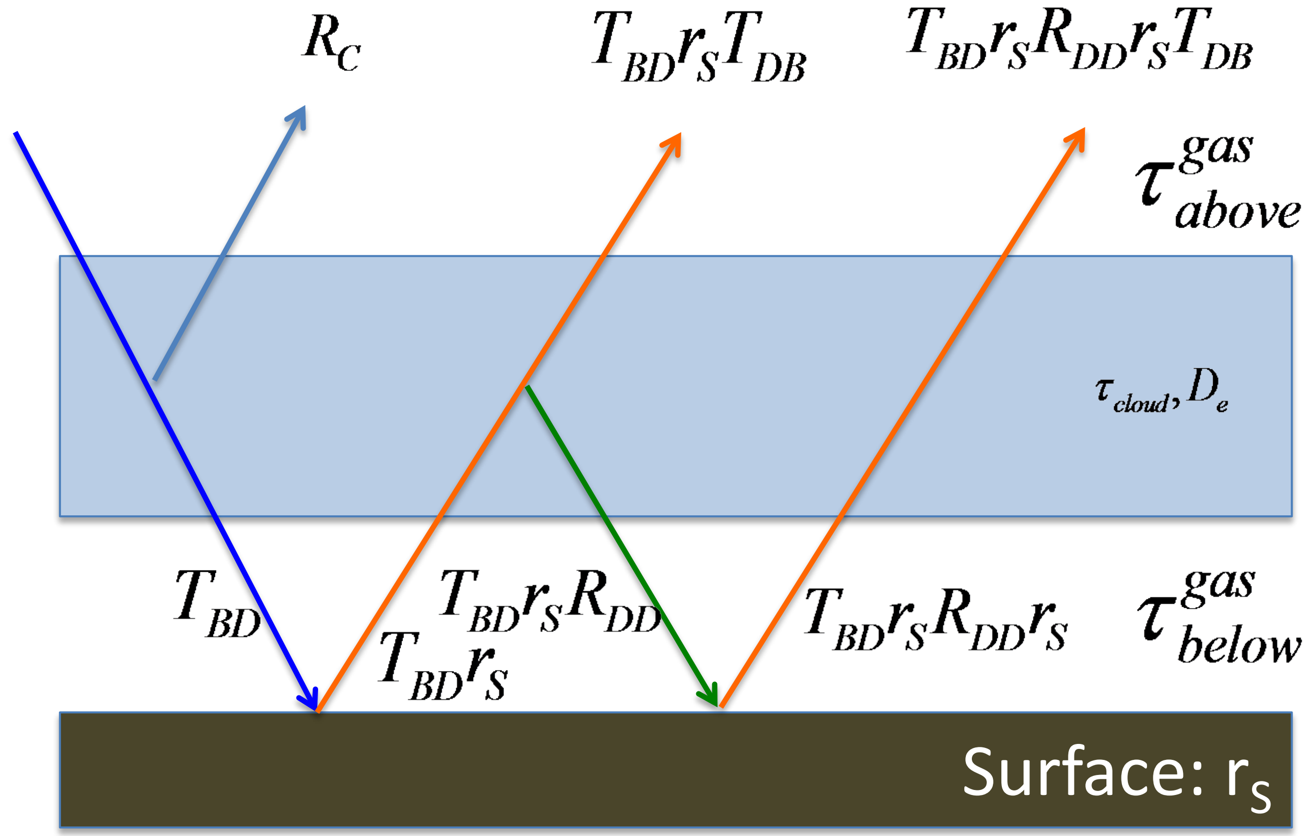
For 16-stream accuracy: N = 16

Method	Number of frequencies	Speed Up
MODTRAN	259,029	1
Regular PCRTM-SOLAR	1359	190
Dual Stream PCRTM-SOLAR	1359 (4 stream) + 35 (16 stream)	4560

M = 35

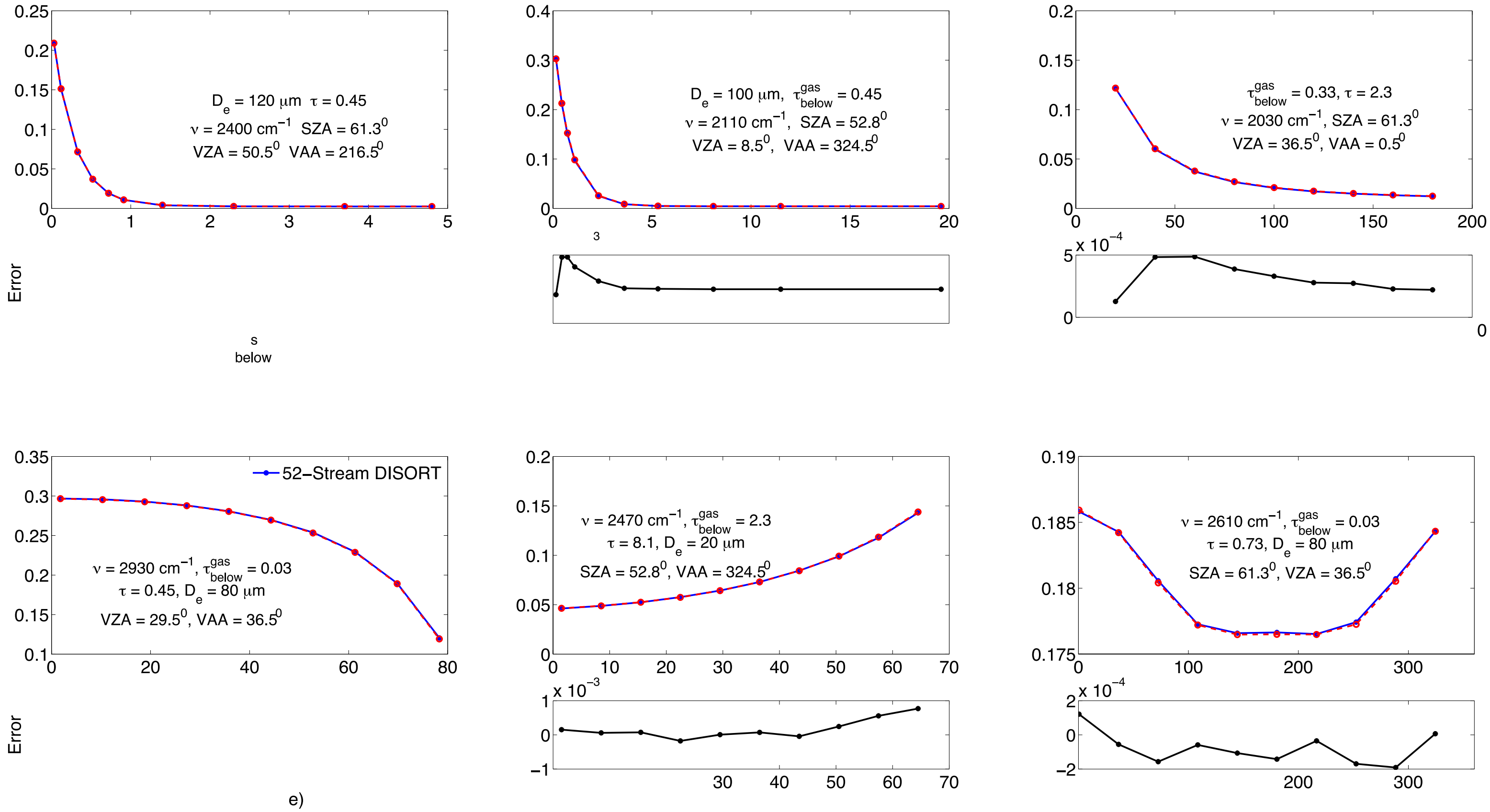
The dual stream PCRTM-SOLAR may complete one spectrum (**29,311 channels**) calculation in ~ 3 seconds, rather than ~ 3 hours (MODTRAN).

1-Layer Cloud PCRTM-SOLAR: Principal



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

1-Layer Cloud PCRTM-SOLAR: Error



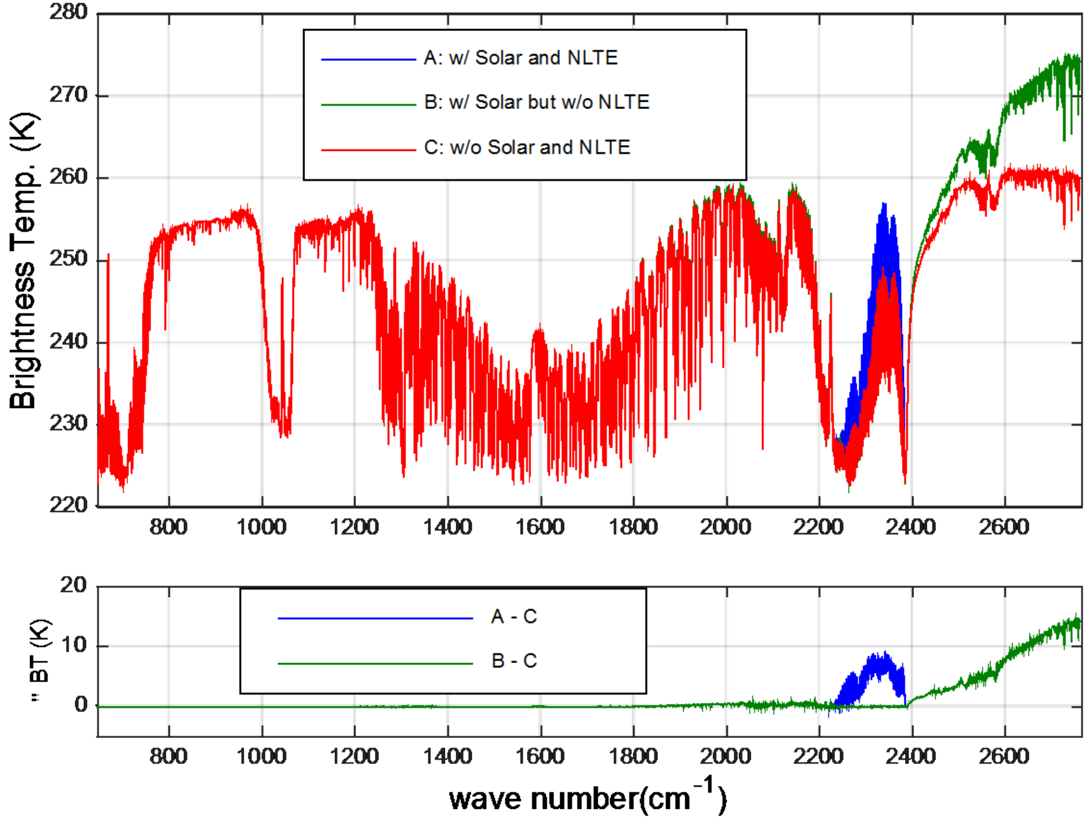
1-Layer Cloud PCRTM-SOLAR: Speed

- 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:

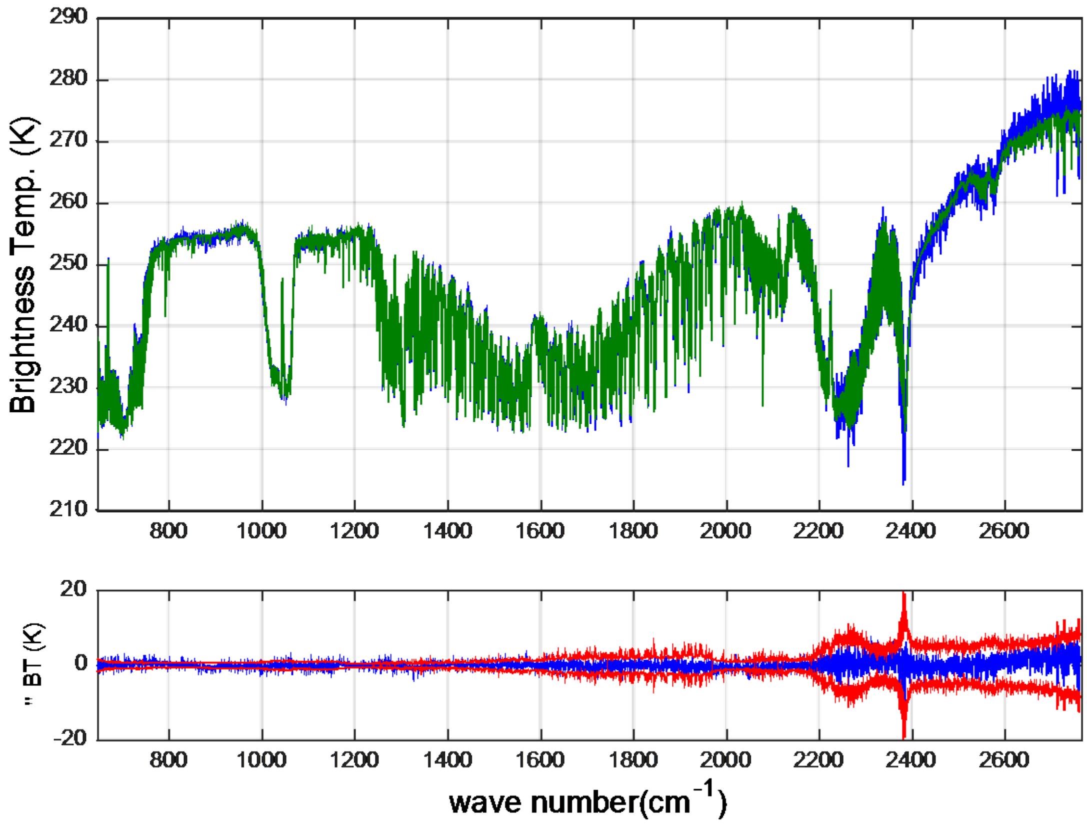
      SZA = 10^0, VZA = 60^0, VAA = 72.5^0, 439 mono frequencies, τ_{above} changes with wavenumber, τ_{below} changes with wavenumber, τ_{cloud} = 1.025, De = 48 μm, Rs = 0.02
  - PCRTM_IR: 20.86 ms/run
    - 1000 runs with the following parameters:

      VZA = 60^0, 735 mono frequencies, 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_IR.
    - Integrate PCRTM_SOLAR to PCRTM will NOT influence the computation speed of PCRTM greatly.

1-Layer Cloud PCRTM-SOLAR: Solar Contribution to the Brightness Temperature



1-Layer Cloud PCRTM-SOLAR: Compare to IASI Measured Data



Conclusion

- A fast and accurate dual stream PCRTM-SOLAR model has been developed to simulate the TOA radiances for multi-layer clouds sky with solar radiation.
- A superfast one-layer cloud PCRTM-SOLAR model has been developed for operational usage.
- The RMS error for both models are normally less than 10^{-3}.
- Dual stream PCRTM-SOLAR needs about 3 s to simulate the whole TOA RS spectrum (300 to 2500 nm, 29,311 channels) with 16-stream accuracy.
- One-layer cloud PCRTM-SOLAR needs about 5 ms to simulate the solar contribution (1800-2760 cm^{-1}, 3841 channels) to the IASI spectrum (645-2760 cm^{-1}, 8461 channels).

Backup

R. Bennartz, T. Greenwald, "current problems in scattering radiative transfer modelling for data assimilatio," Q.J.R. Meteorol. Soc. 137: 1952-1962 (2011)

Table I. Comparison of normalized CPU time (seconds per instrument channel) for the RTTOV v10 and CRTM v2.0.2 for each instrument separated into time spent in the radiative transfer solver and total overall time. For details see text.

	HIRS-4 (s/chan)	AMSU-A (s/chan)	MHS (s/chan)
RTTOV solver	0.755	1.18	1.21
RTTOV total	4.42	4.24	5.44
CRTM 2-strm solver	57.0	55.8	75.7
CRTM 2-strm total	107	132	163
CRTM 4-strm solver	106	91.2	118
CRTM 4-strm total	160	176	215