A Unified-Principle-Component Radiative Transfer Model for High-Spectral Simulations

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Contents

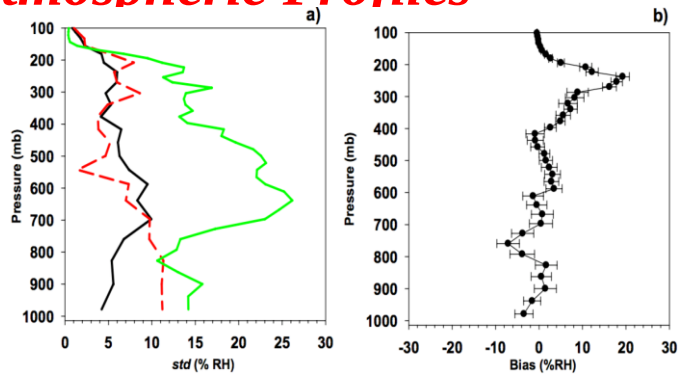
Motivation

Some of the high-spectral instruments

Instrument	Spectral Range (μm)	Number of Channels	Application
AIRS/Aqua	3.7 - 15.40	2,378	Temperature/water vapor/trace gases
Cris/Suomi-NPP	3.92 - 15.38	1,305	Temperature/water vapor/trace gases
IASI/METOP-A	3.62 - 15.50	8,461	Temperature/water vapor/trace gases
GIIRS/FY-4A	4.40 - 14.29	1,671	Temperature/water vapor/trace gases
HIRAS/FY-3D	3.92 - 15.38	2,287	Temperature/water vapor/trace gases
OMI/Aura	0.27 - 0.50	740	Trace Gases/Aerosol
TROPOMI/S5P	0.27 - 2.38	750	Trace Gases/Aerosol
OCO-2	0.76 - 2.08	3,048	CO_2/Aerosol
Carbon-Spec/TanSat	0.76 - 2.08	2,242	CO_2/Aerosol
CLARS (Ground)	0.63 - 3.30	21,000	Trace Gases/Aerosol

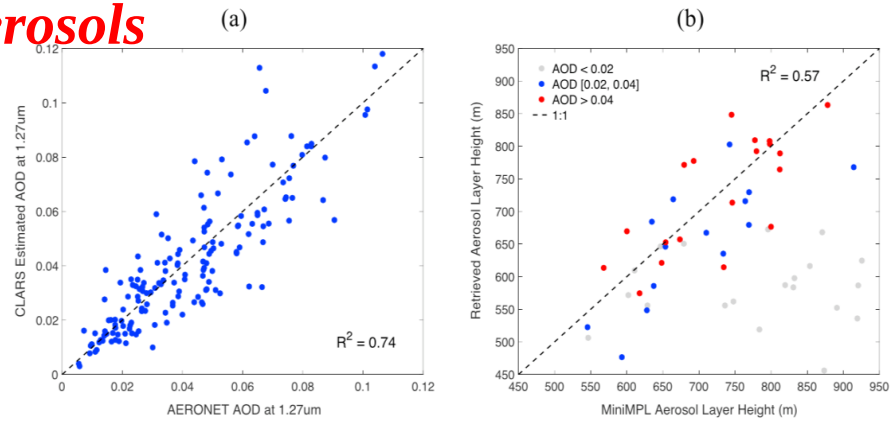
Motivation

Atmospheric Profiles



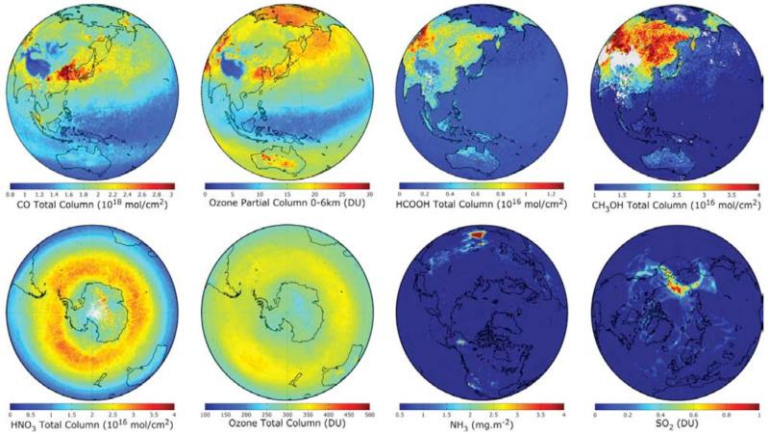
Pougatchev et al., 2009

Aerosols



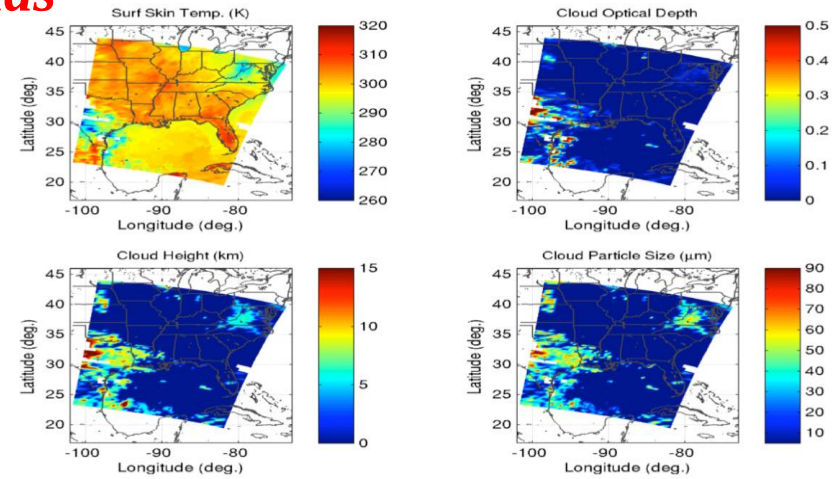
Zeng et al., 2018

Trace Gases



Hilton et al., 2012

Clouds



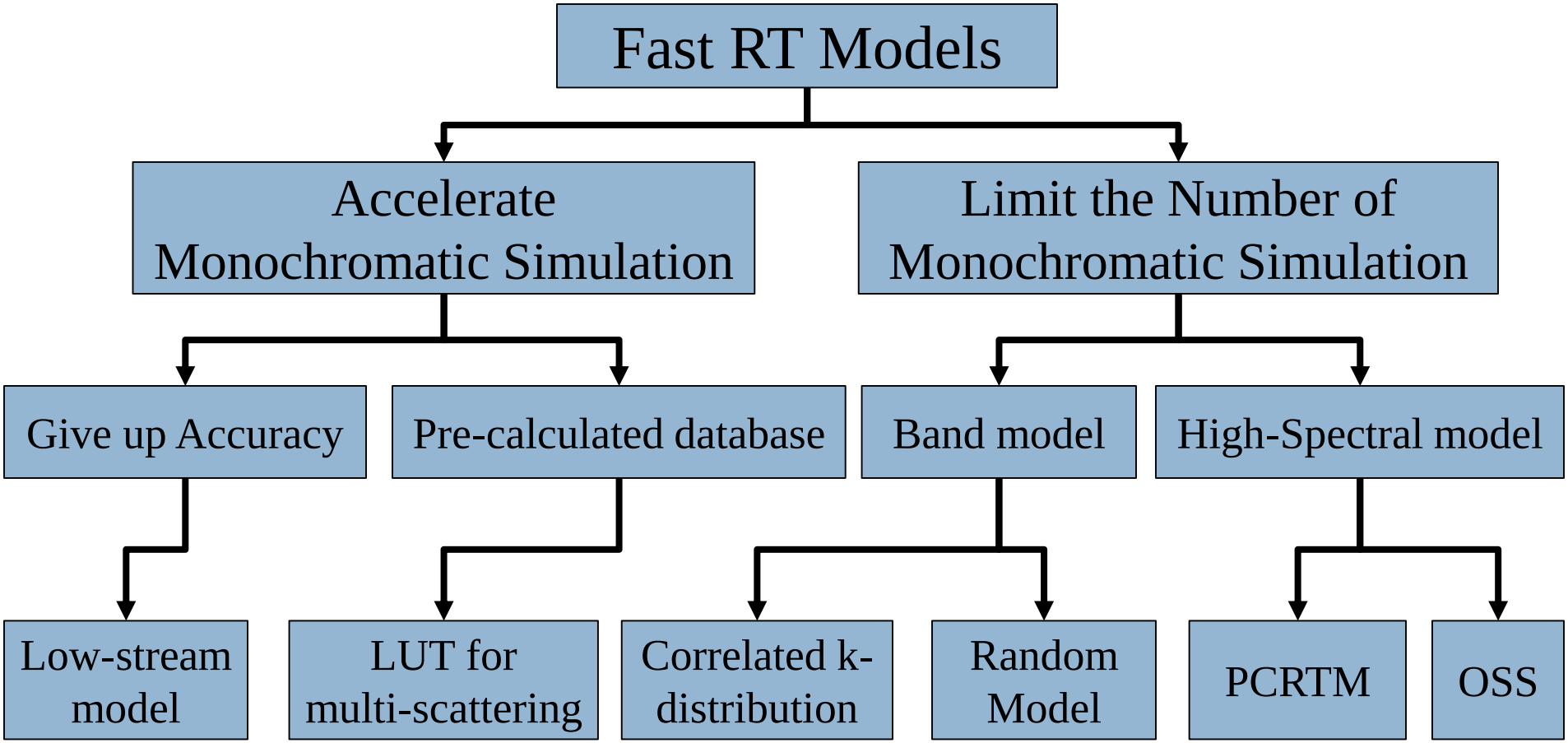
Liu et al., 2009

Motivation

- Forward simulations have to be ***efficient*** enough for applications of high-spectral observations.
- Satellite applications need ***accurate*** radiance simulations.
- High-spectral simulation is a fundamental and benchmark method for wide/narrow-band simulations.
- ***We always need more accurate and more efficient models.***

Contents

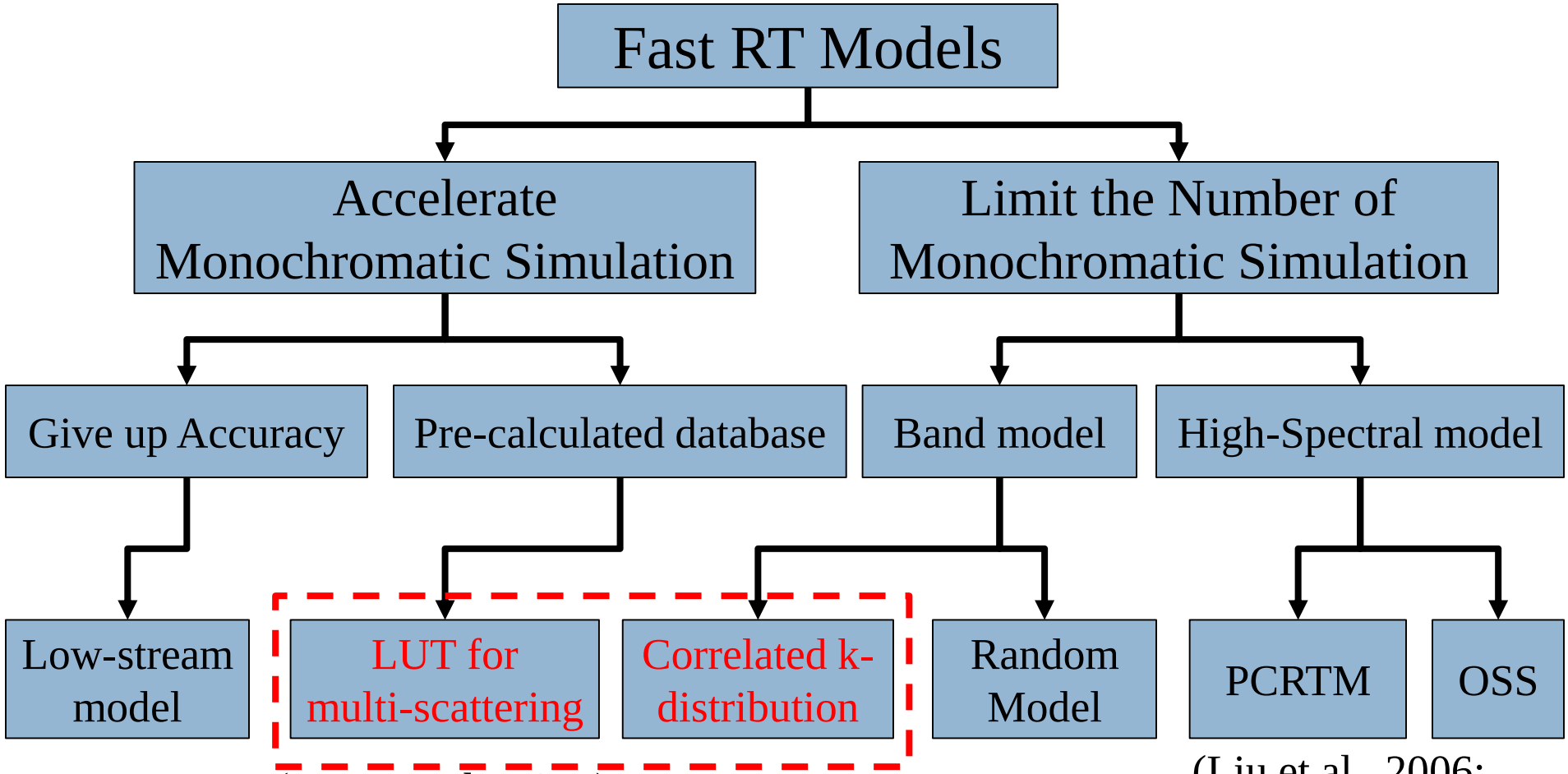
Some examples of fast RT models



(Wang et al., 2015)

(Liu et al., 2006; Natraj et al., 2006; Moncet et al., 2008)

Some examples of fast RT models



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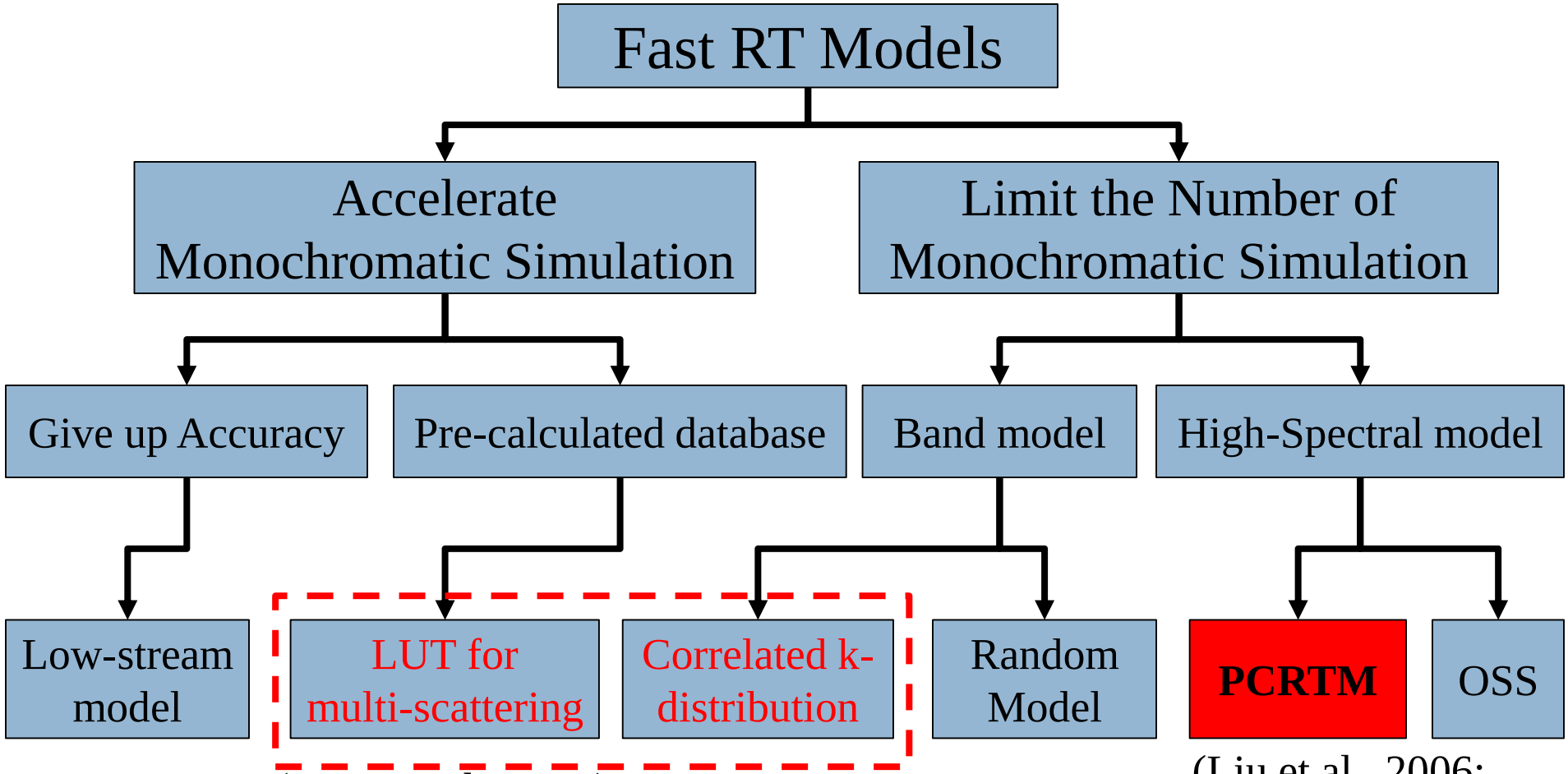
Some examples of fast RT models



(Wang et al., 2015)

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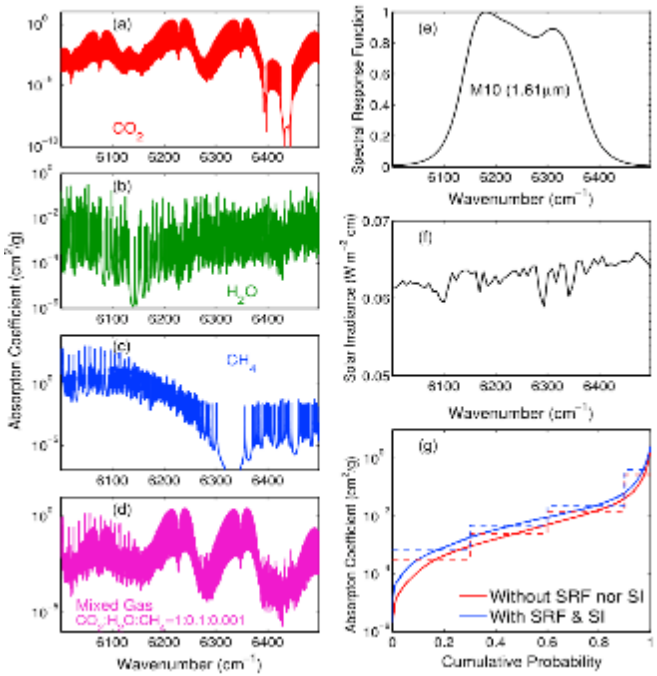
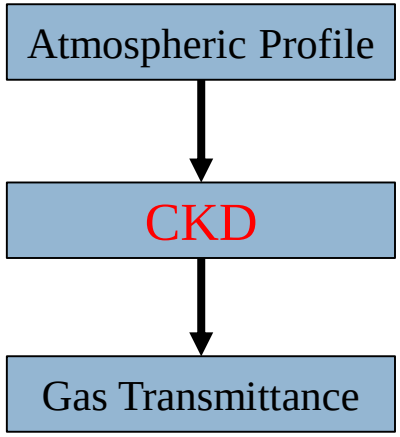
Moncet et al., 2008)

A Fast RT Model: CKD

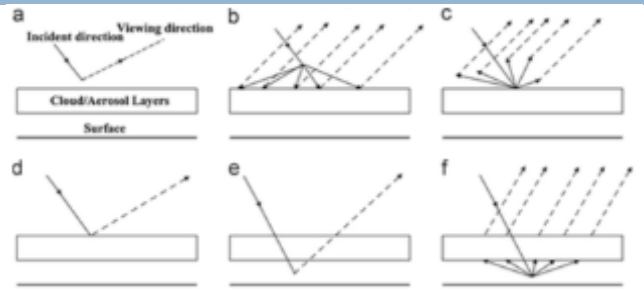
Instead of performing thousands of monochromatic RTMs, the CKD calculation needs only a few.



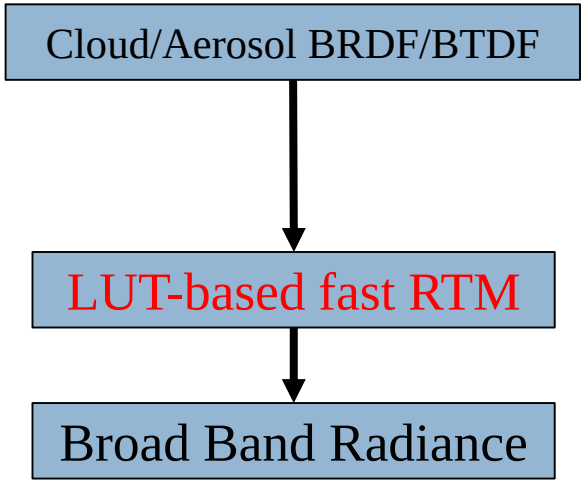


(Edwards and Francis, 2000)

A Fast RT Model: LUT-based Model



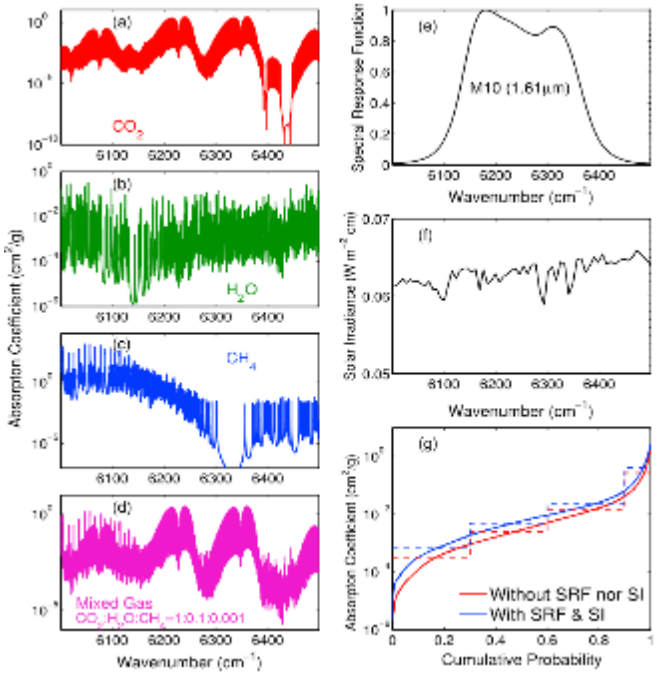
Instead of performing 128-stream DISORT for cloud multi-scattering, the BRDF/BTDF of cloud layers can be saved and used directly.



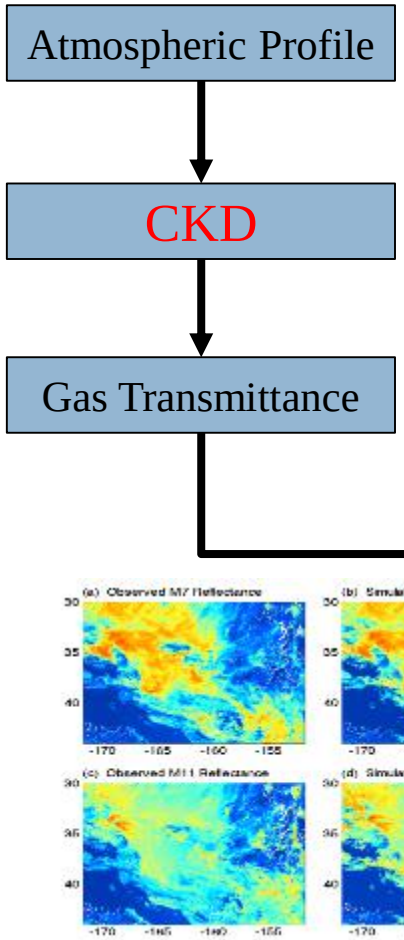
(Wang et al. 2013)

A Combination of Fast Models

Instead of performing thousands of monochromatic RTMs, the CKD calculation needs only a few.



(Edwards and Francis, 2000)



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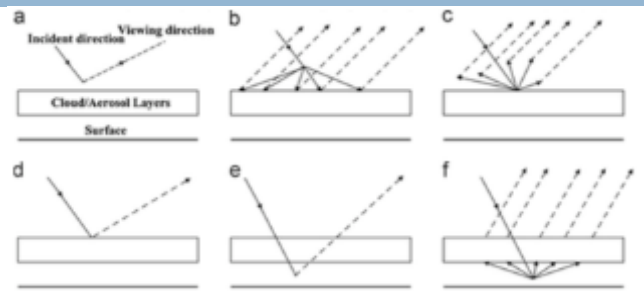
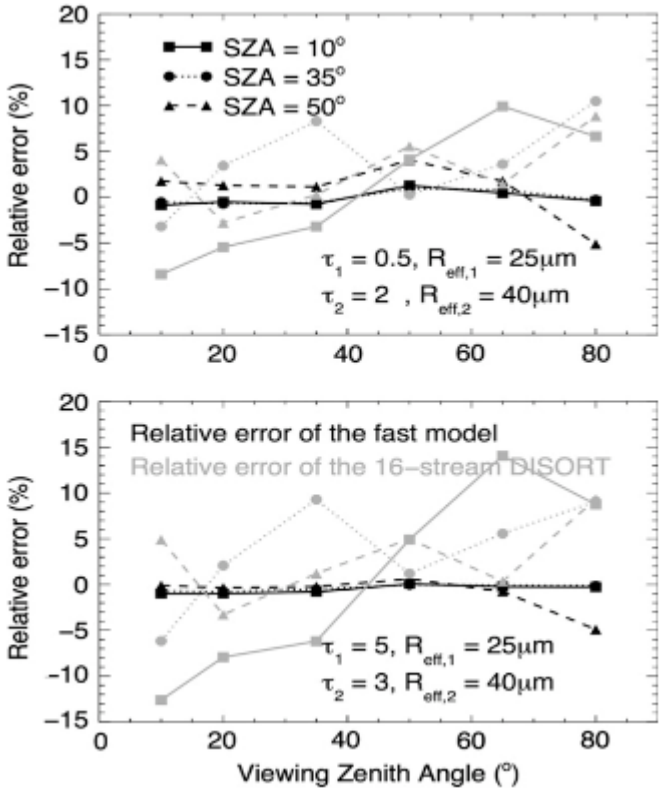


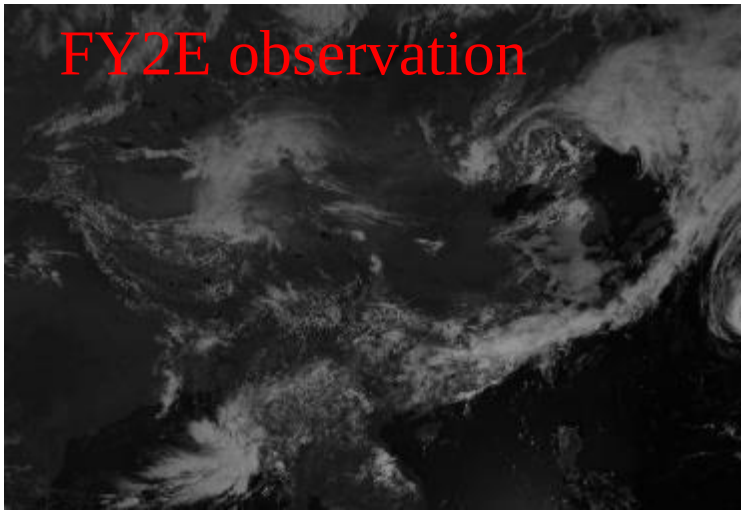
Instead of performing 128-stream DISORT for cloud multi-scattering, the BRDF/BTDF of cloud layers can be saved and used directly.

(Wang et al. 2013)

A Combination of Fast Models

The LUT based fast model takes similar computational time to those of the 16-stream DISROT, but gives much more accurate results.





The fast model has been extended for radiometers onboard the FY-2E and FY-4A satellites

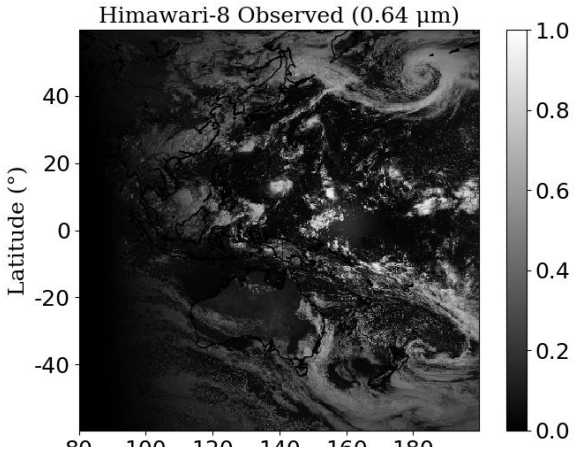
WRF

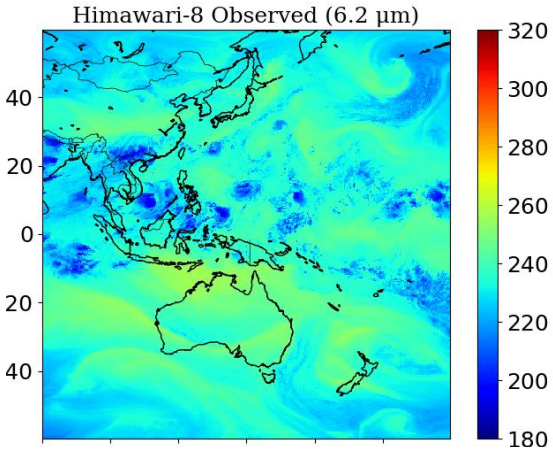
&

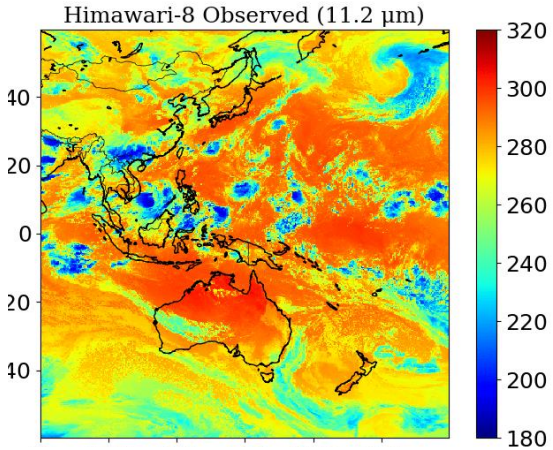
Fast RTM

A Combination of Fast Models

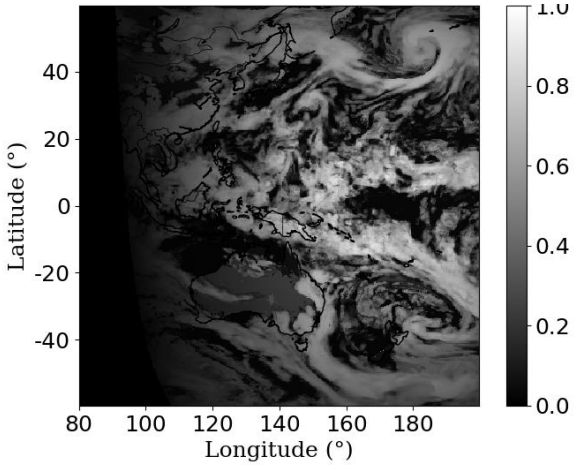
Comparison of the model with the AHI/H-8 observations for different channels.

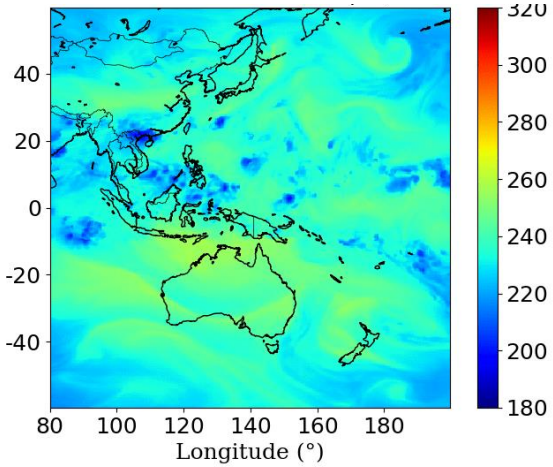


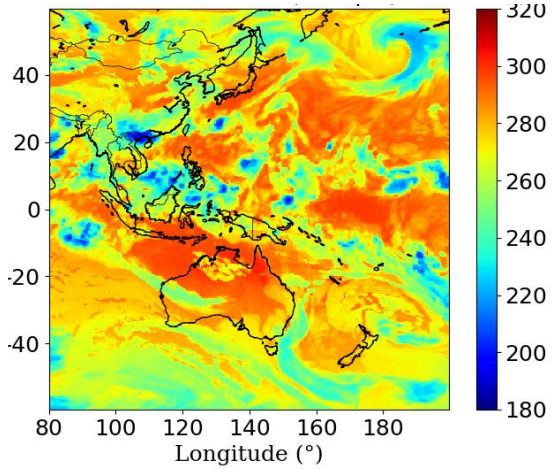




Works for the broad band instruments and channels







Contents

- Motivation
- A Combination of Fast RTMs
- PCRTMs and a Unified-PCRTM
- Conclusion

Fast Models for High-Spectral RT

- Double-*k* distribution Method (Duan et al., 2005)

  28 RT calculations for entire oxygen A-band (over 20,000 wavelengths)

- Principle Component RTM (Natraj et al., 2005; Liu et al., 2006)

  A PAC of optical properties of the system (Natraj et al., 2005);

  A PCA of monochromatic radiance over the spectrum (Liu et al., 2006)

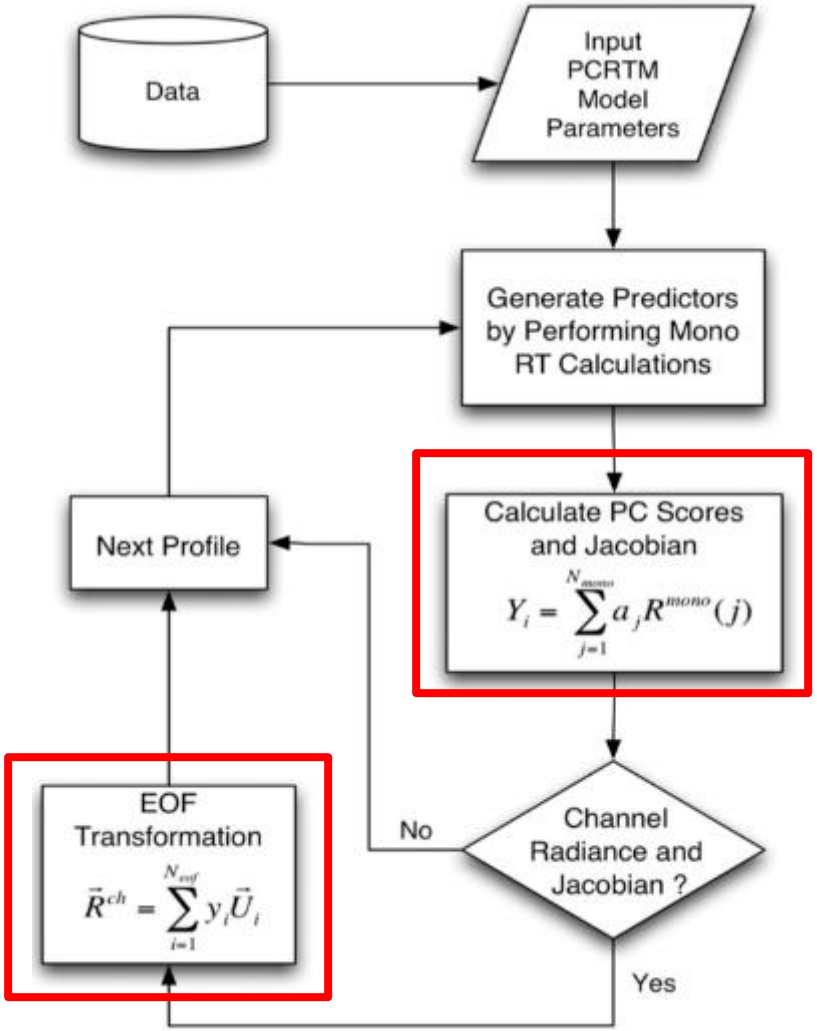
- Optimal Spectral Sampling (Moncet et al., 2008)

  A few RT calculations to model channel radiances with a BTD < 0.05K

- Look-up-table-based RTM (Wang et al., 2015)

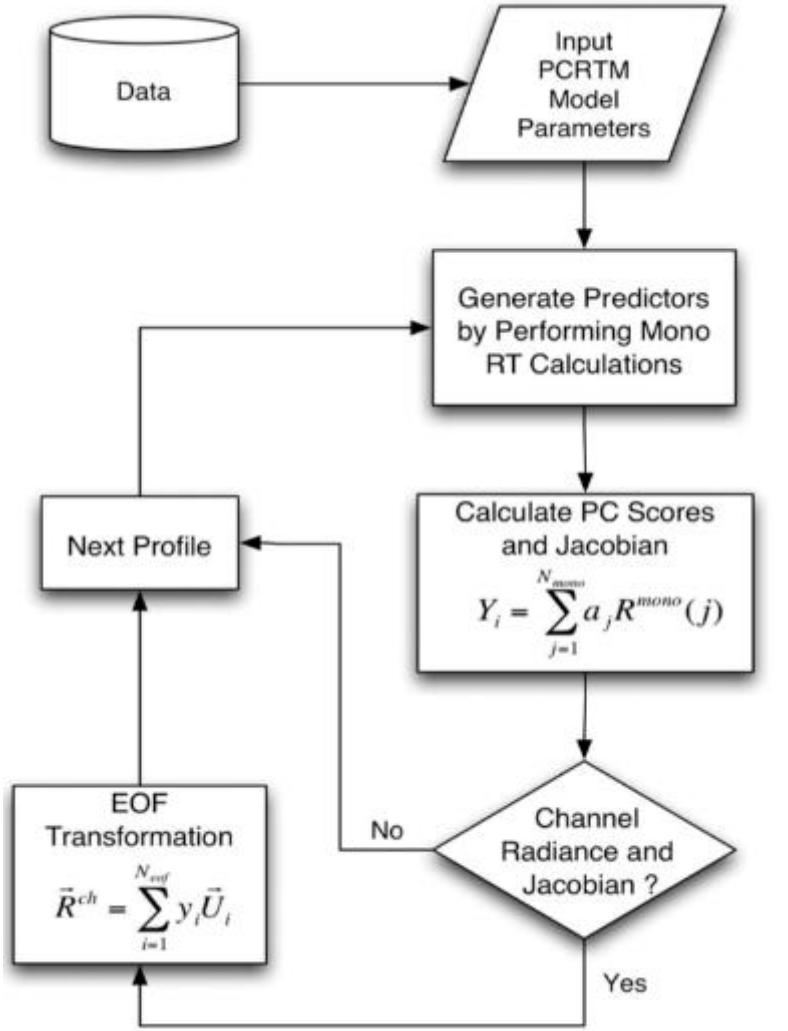
  Approximately four orders of magnitudes faster than the 32-stream DISORT

Radiance-Based PCRTM: R-PCRTM



(X. Liu, et al., 2006)

Radiance-Based PCRTM: R-PCRTM



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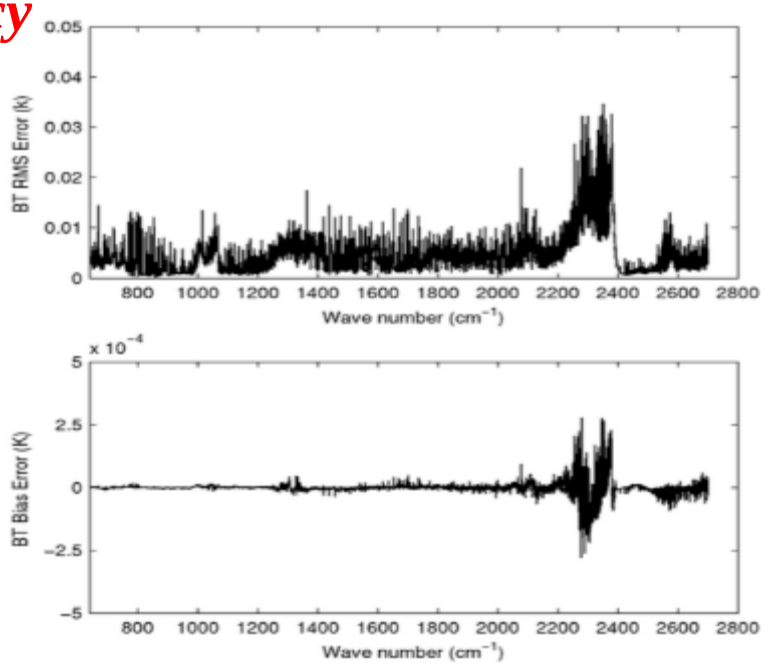
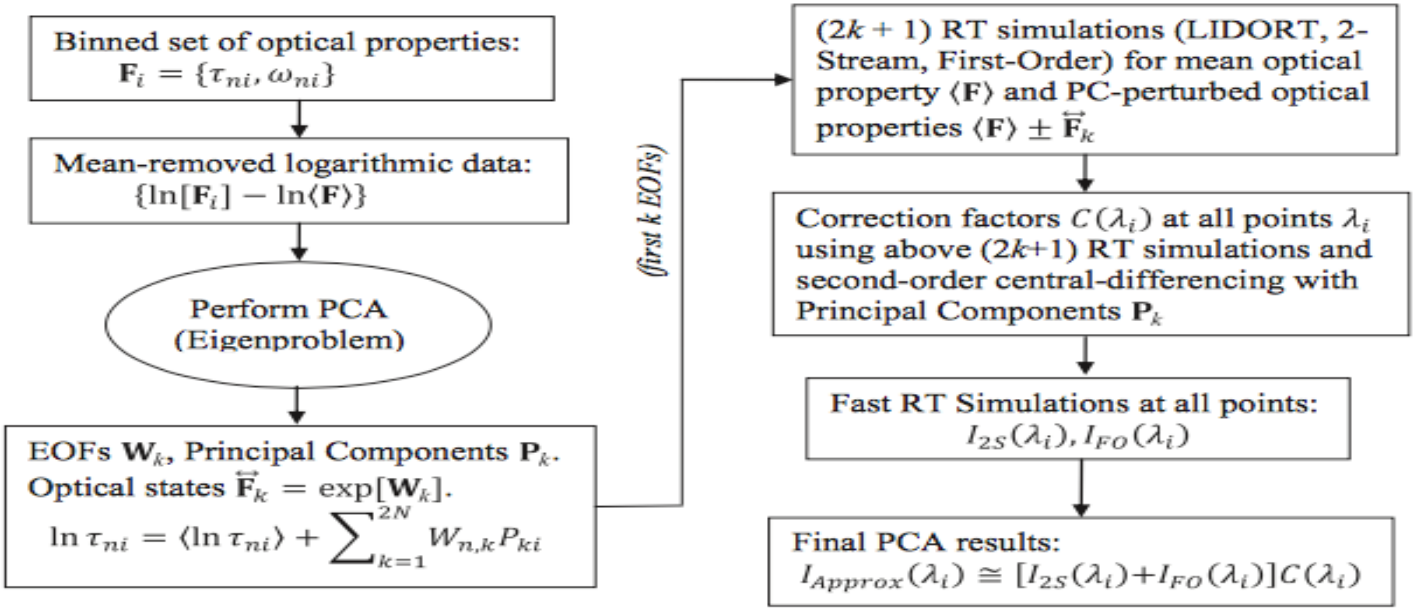
Accuracy



Efficiency

For the NAST-I instrument (8632 channels), only 305 monochromatic RT calculations are needed.

Optical-Based PCRTM: O-PCRTM



(Natraj et al., 2006;

Spurr, et al., 2013;

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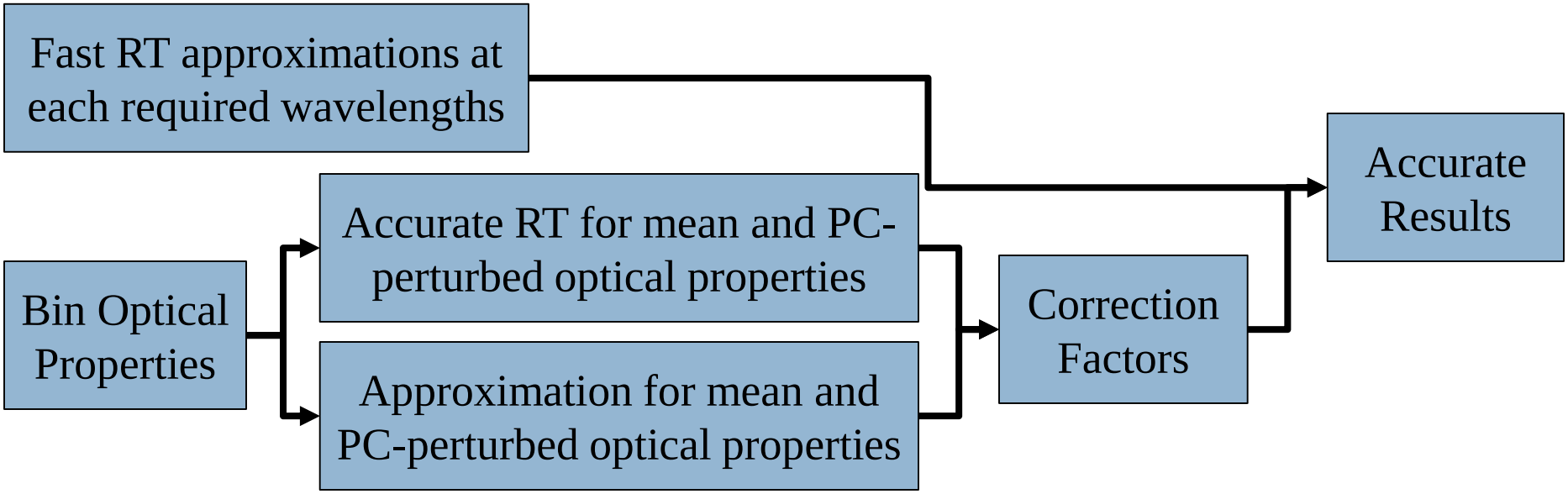
Kopparler et al., 2017)

Optical-Based PCRTM: O-PCRTM



Optical-Based PCRTM: O-PCRTM

Binned set of optical properties:
$\mathbf{F}_i = \{\tau_{ni}, \omega_{ni}\}$

Mean-removed logarithmic data:
$\{\ln[\mathbf{F}_i] - \ln\langle\mathbf{F}\rangle\}$

Perform PCA (Eigenproblem)

EOFs $\mathbf{W}_k$, Principal Components $\mathbf{P}_k$.
Optical states $\vec{\mathbf{F}}_k = \exp[\mathbf{W}_k]$.
$\ln \tau_{ni} = \langle \ln \tau_{ni} \rangle + \sum_{k=1}^{2N} W_{n,k} P_{ki}$

(first k EOFs)

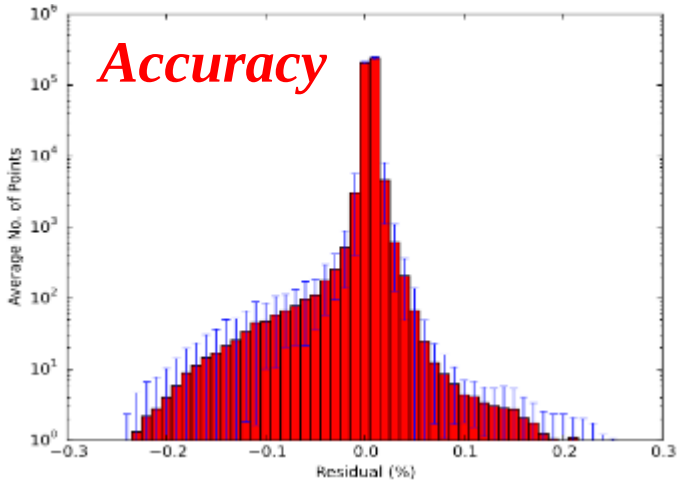
$(2k+1)$ RT simulations (LIDORT, 2-Stream, First-Order) for mean optical property $\langle\mathbf{F}\rangle$ and PC-perturbed optical properties $\langle\mathbf{F}\rangle \pm \vec{\mathbf{F}}_k$

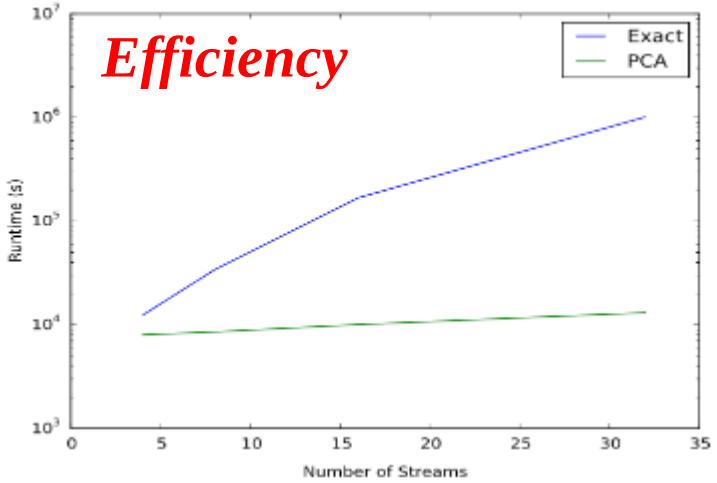
Correction factors $C(\lambda_i)$ at all points λ_i using above $(2k+1)$ RT simulations and second-order central-differencing with Principal Components $\mathbf{P}_k$

Fast RT Simulations at all points:
$I_{2S}(\lambda_i), I_{FO}(\lambda_i)$

Final PCA results:
$I_{Approx}(\lambda_i) \cong [I_{2S}(\lambda_i) + I_{FO}(\lambda_i)]C(\lambda_i)$

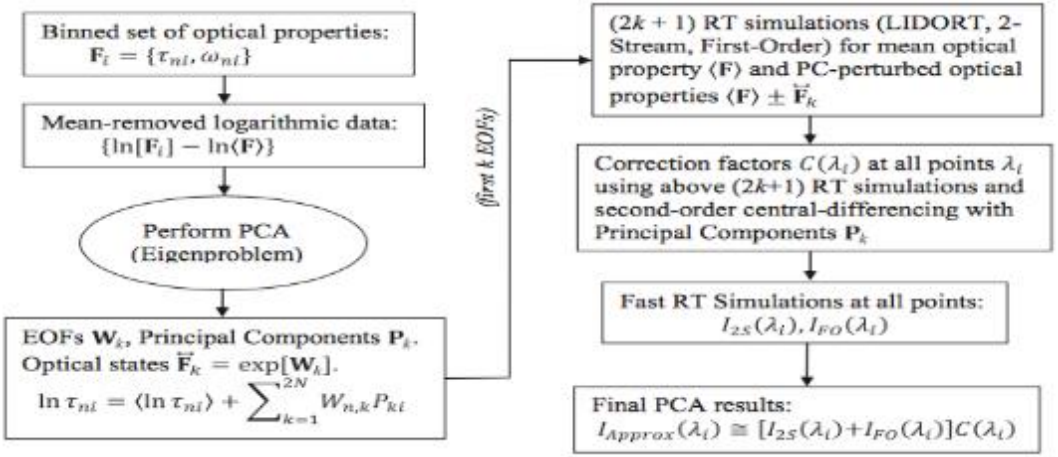
(Natraj et al., 2006;
Spurr, et al., 2013;
Kopparler et al., 2016;
Kopparler et al., 2017)



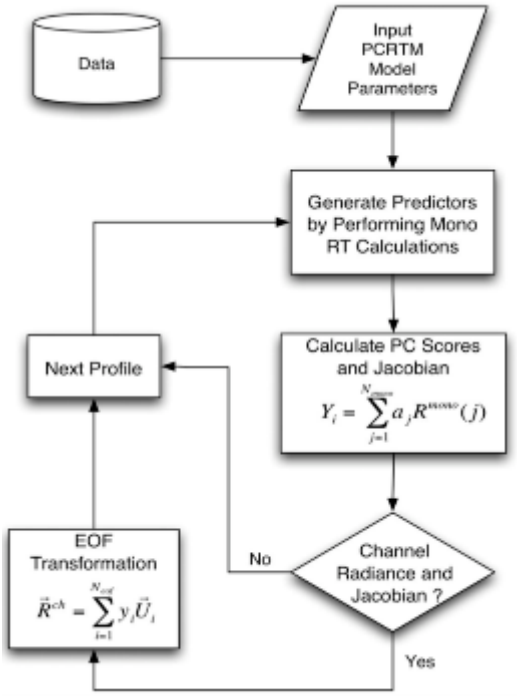


O-PCRTM & R-PCRTM

O-PCA

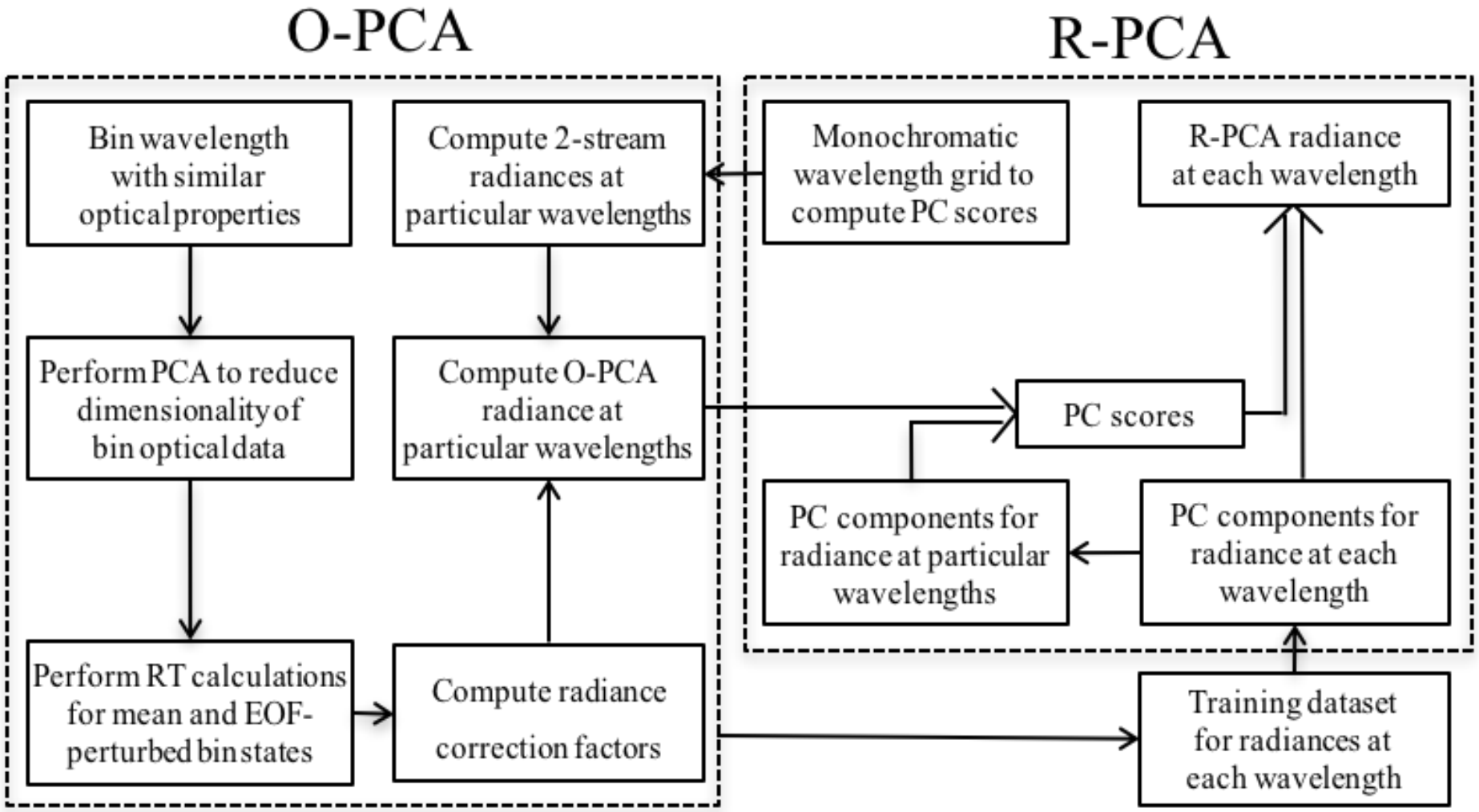


R-PCA

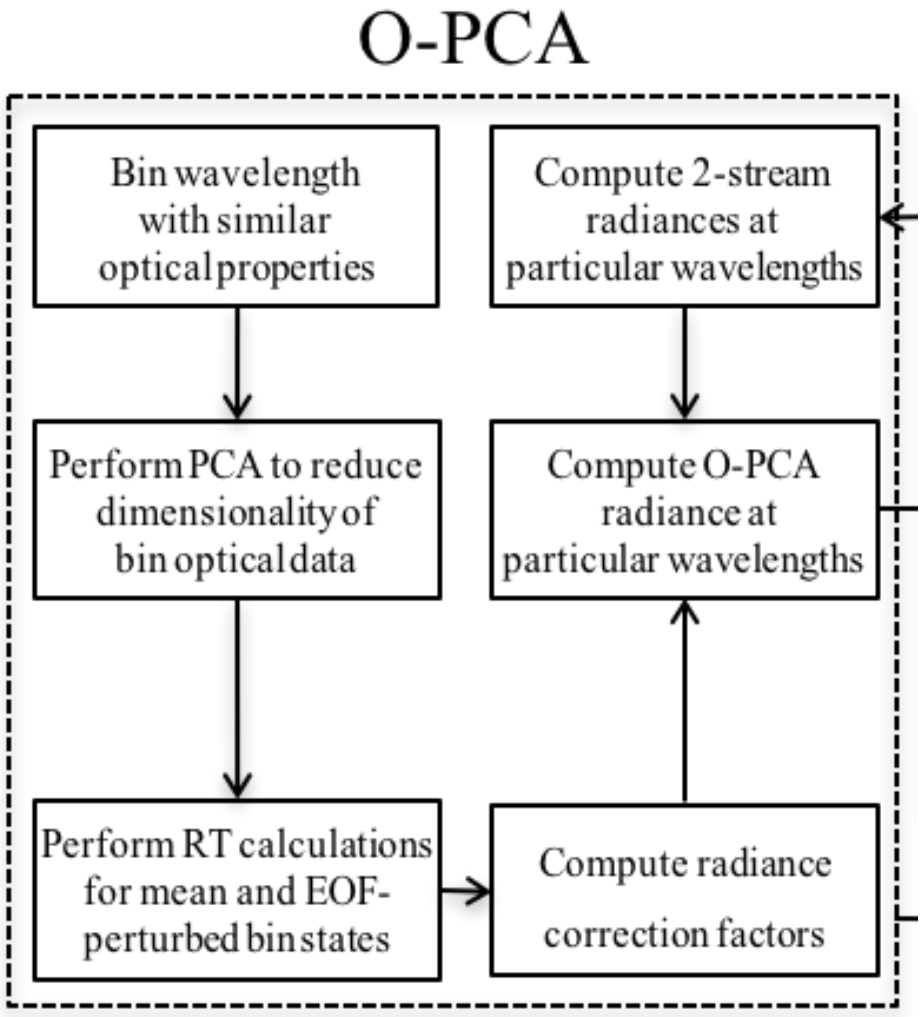


- ***Both PCRTMs are powerful (accurate and efficient)***
- ***The two PCRTMs are different***

A Unified-PCRTM

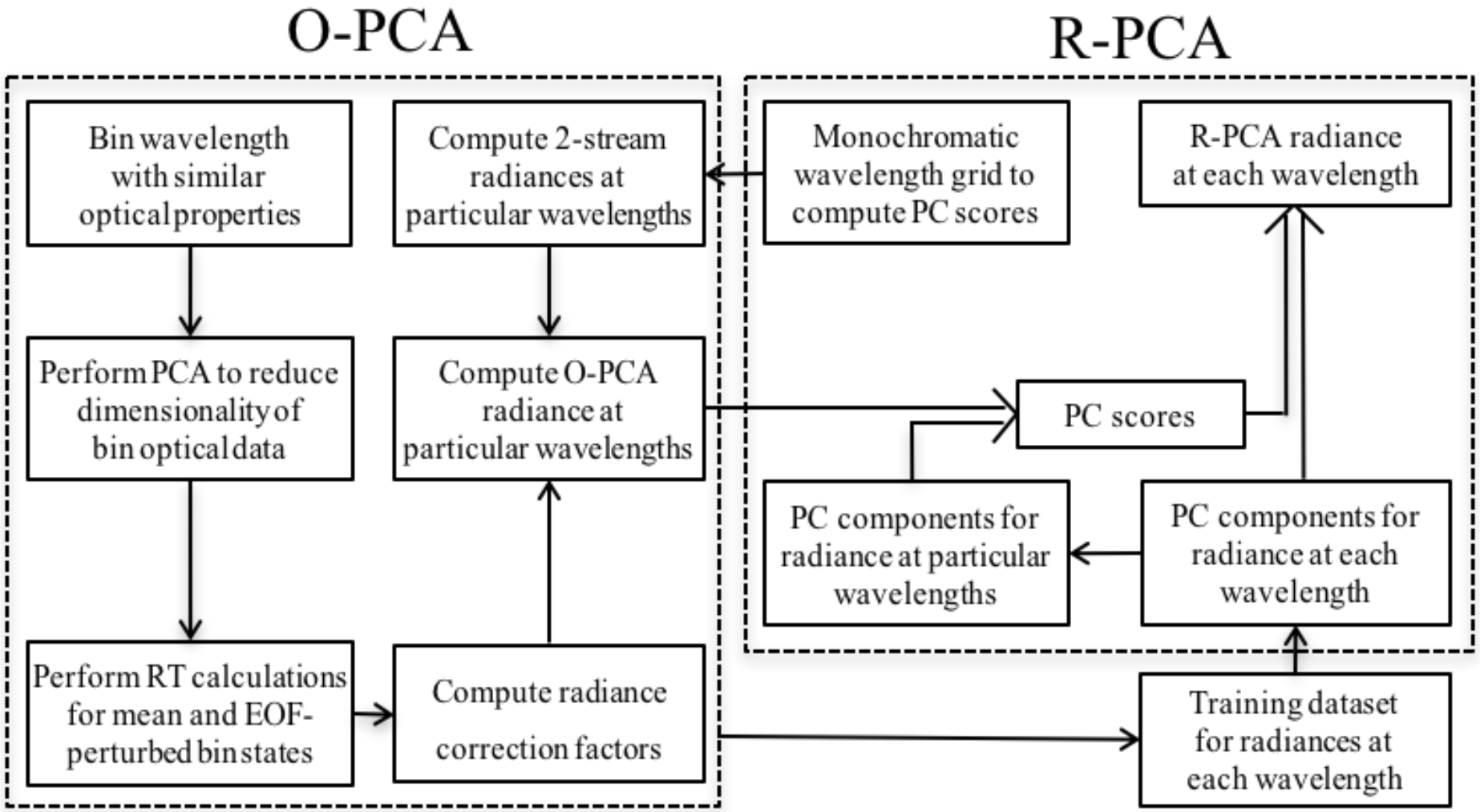


A Unified-PCRTM: O-PCRTM Part



- Accurate RT Model: LIDORT
- Approximated method: Two-Stream + First-Order Scattering
- Components in the model:
  - Aerosol Scattering
  - Rayleigh Scattering
  - Gas Absorption (HITRAN)

A Unified-PCRTM: R-PCRTM Part



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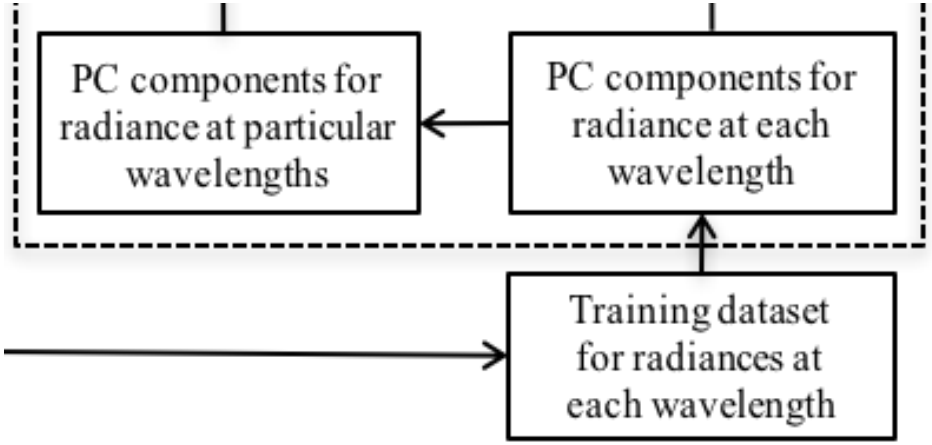
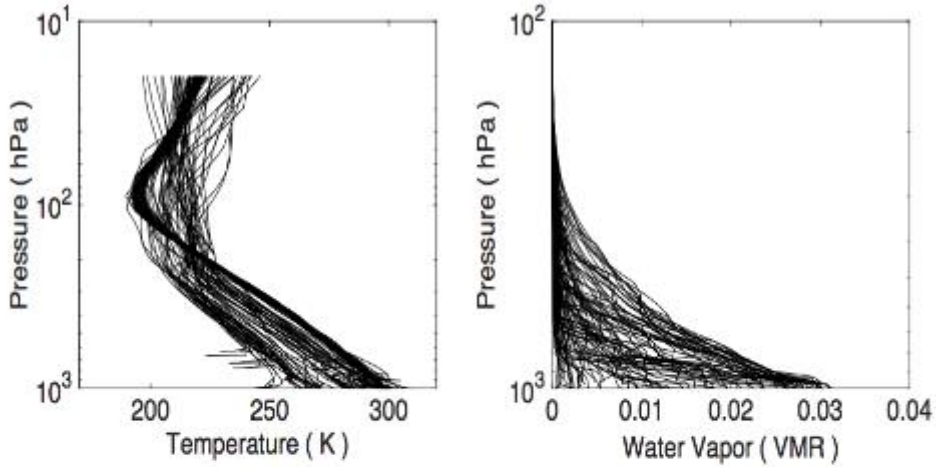
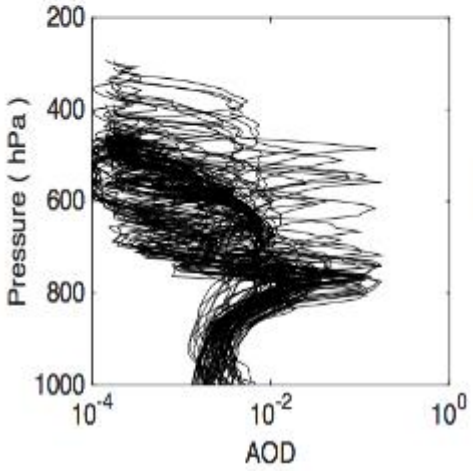
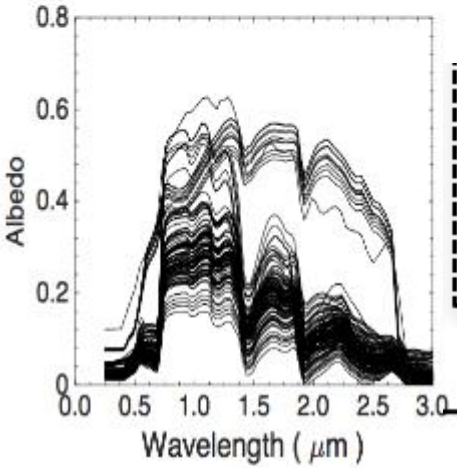


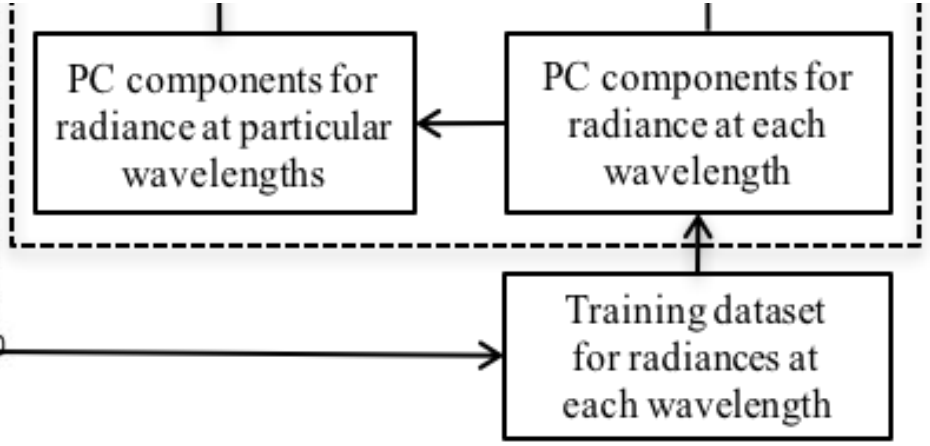
A Unified-PCRTM: R-PCRTM Part

Atmospheric profiles from ECMWF database



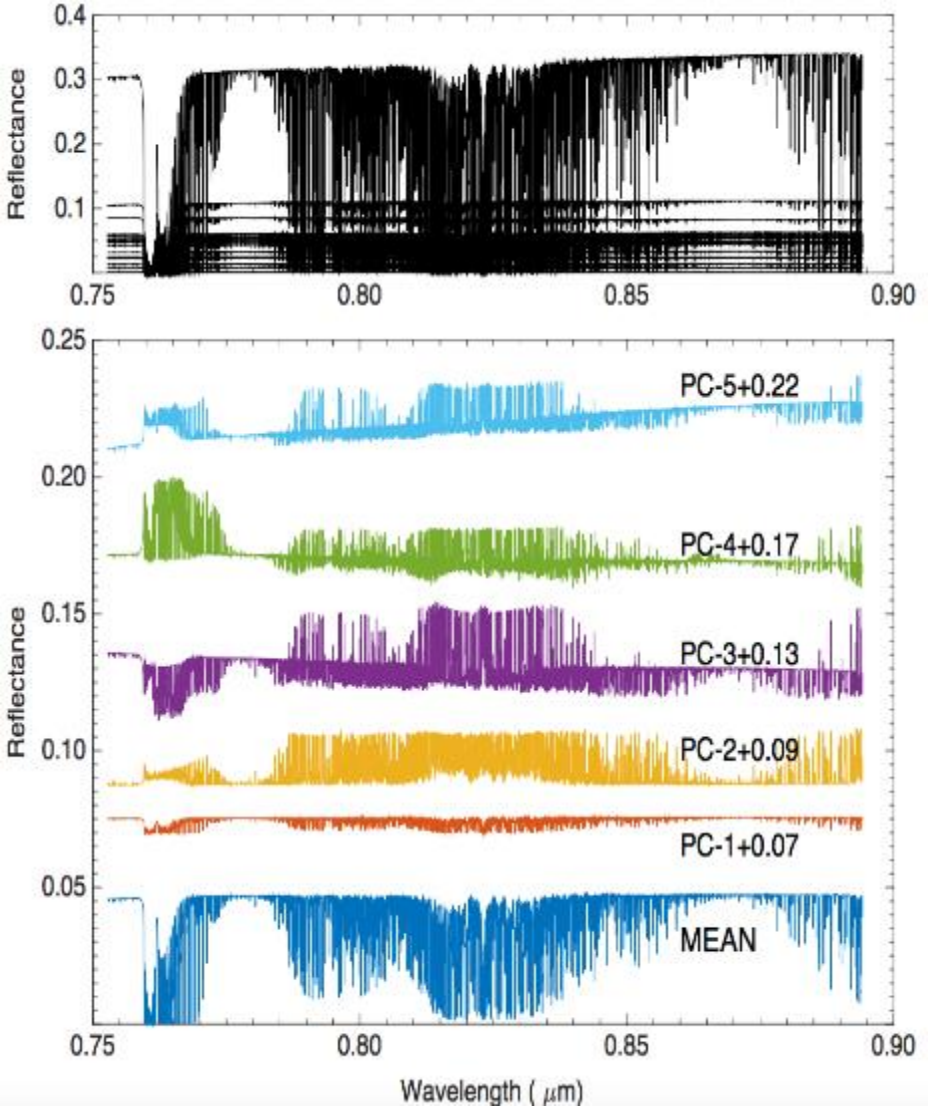


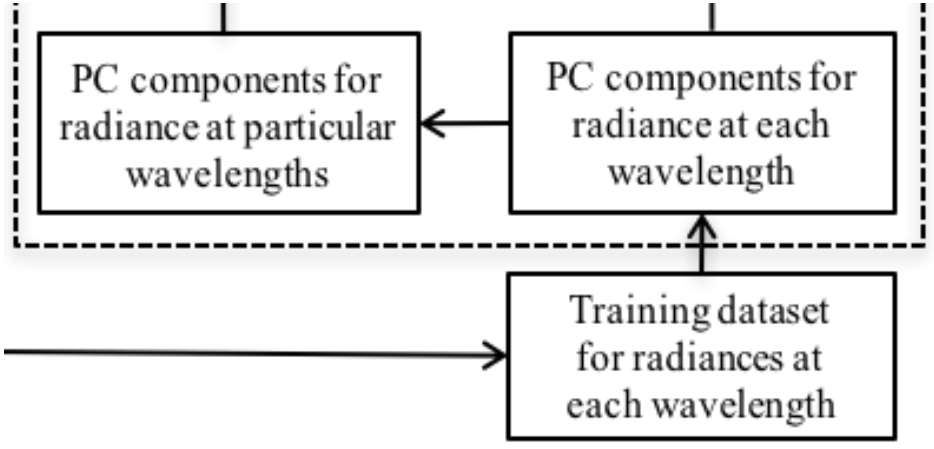




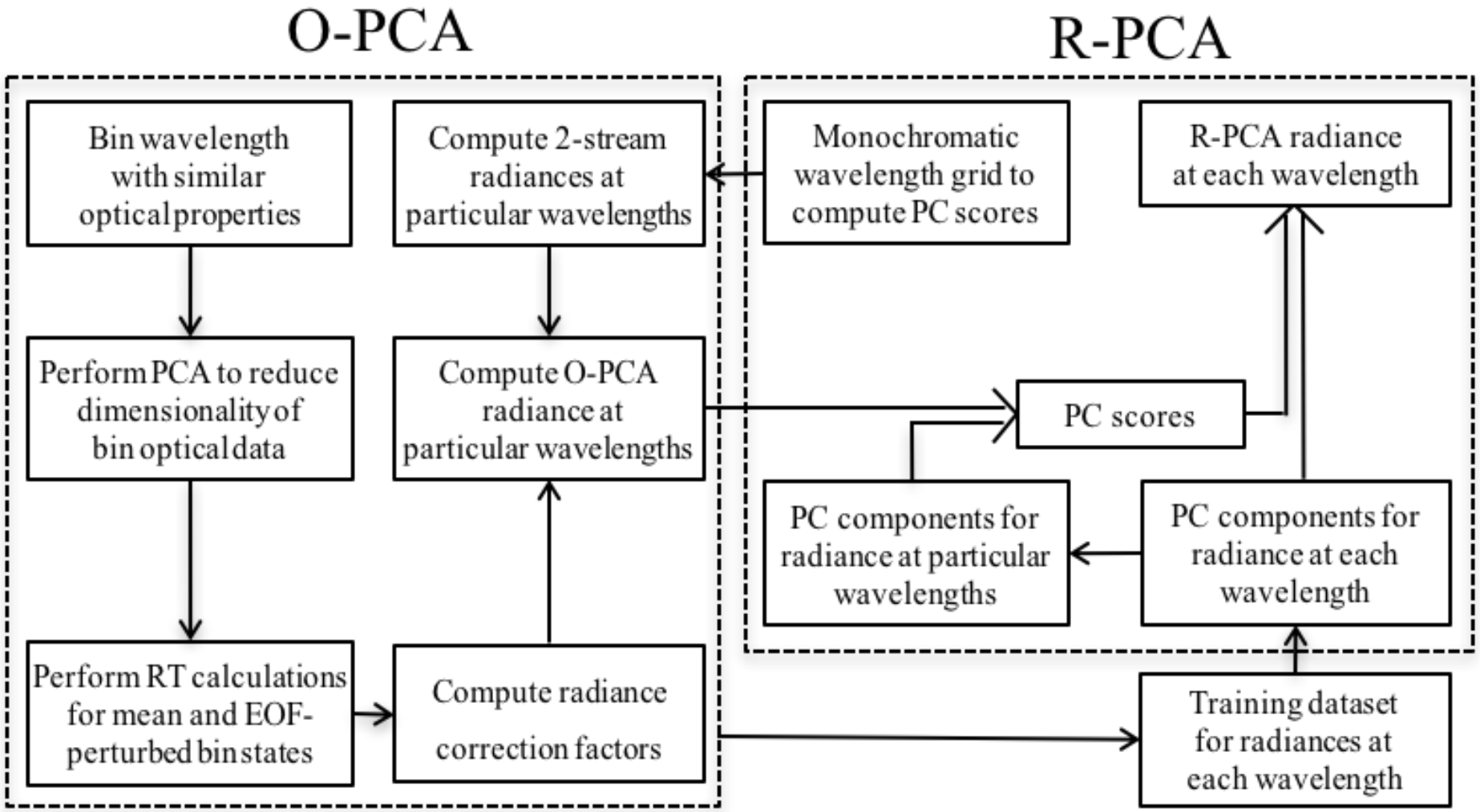
Aerosol profiles from WRF-Chem

A Unified-PCRTM: R-PCRTM Part





A Unified-PCRTM: R-PCRTM Part



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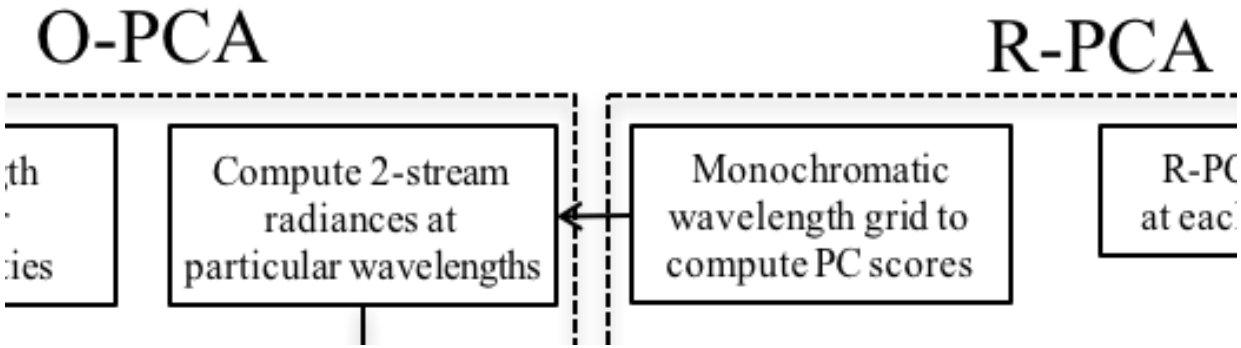
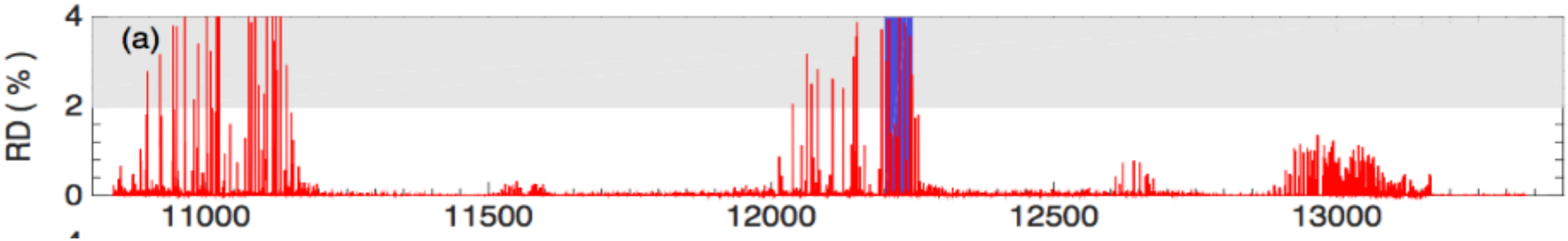
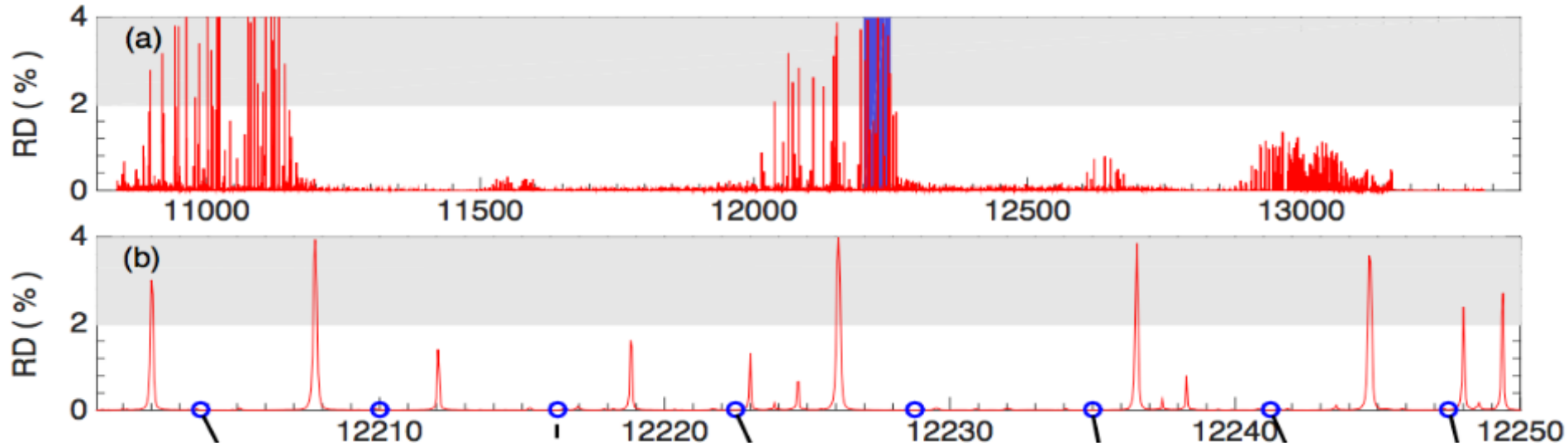


Start from equal-spaced grid points

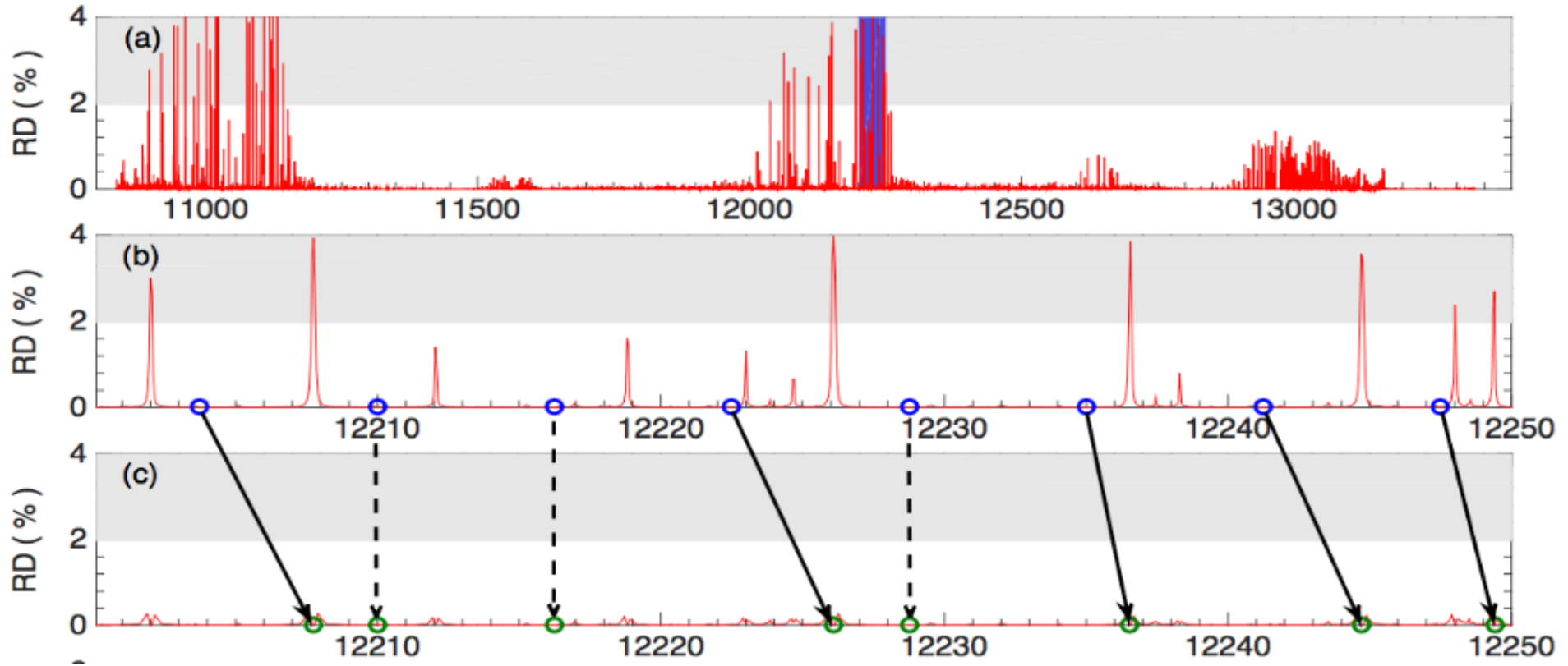
A Unified-PCRTM: R-PCRTM Part



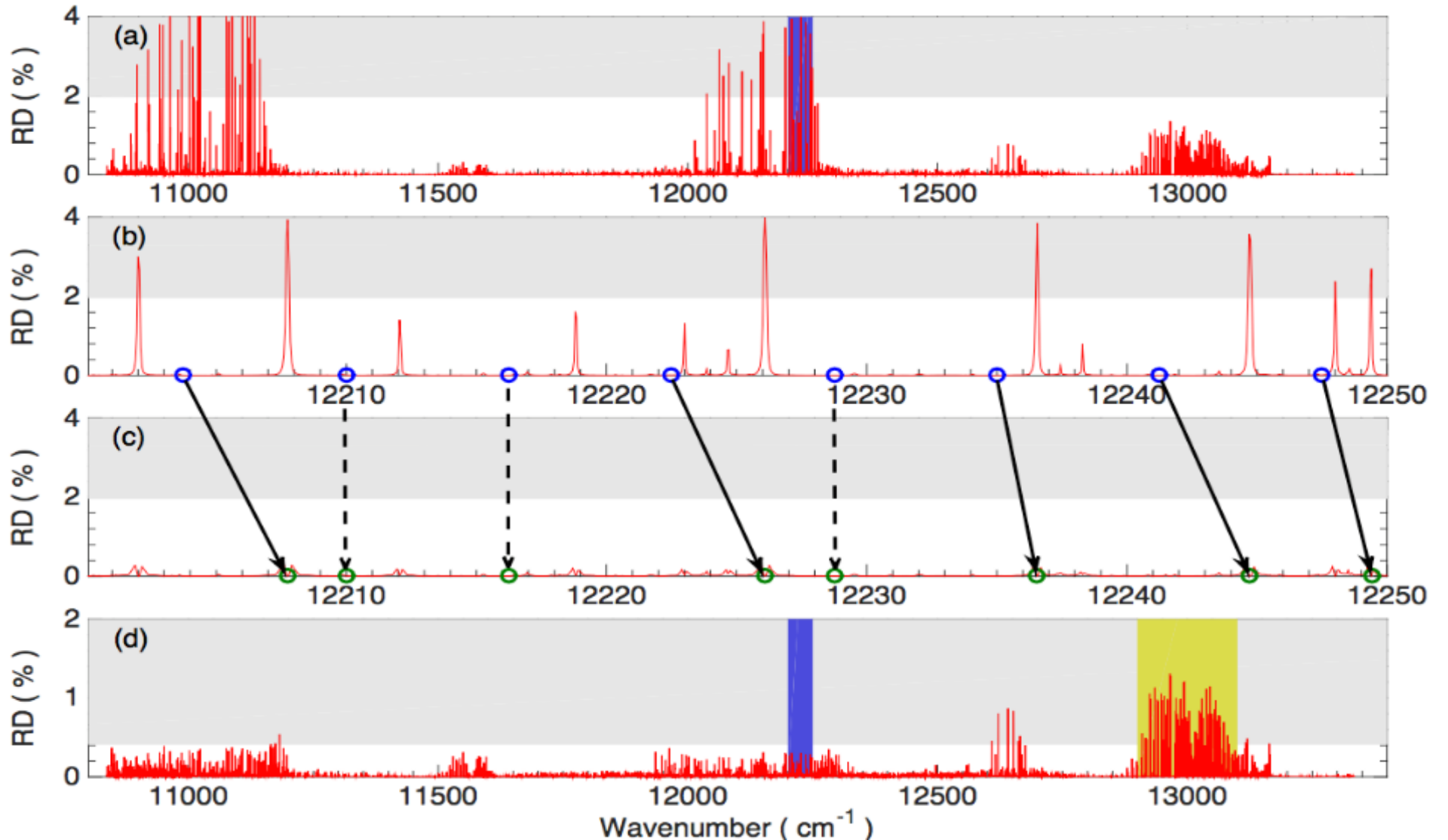
A Unified-PCRTM: R-PCRTM Part



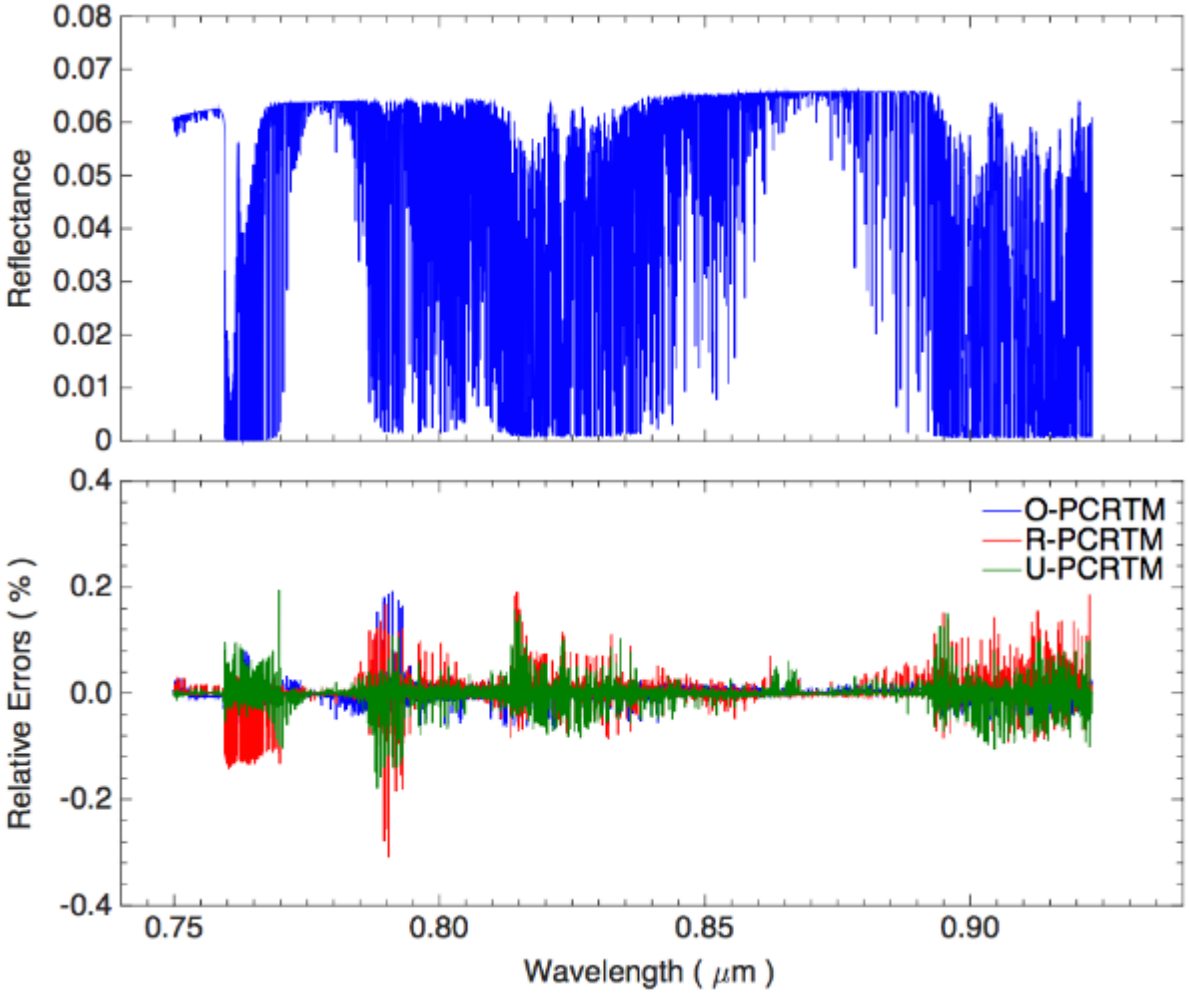
A Unified-PCRTM: R-PCRTM Part



A Unified-PCRTM: R-PCRTM Part

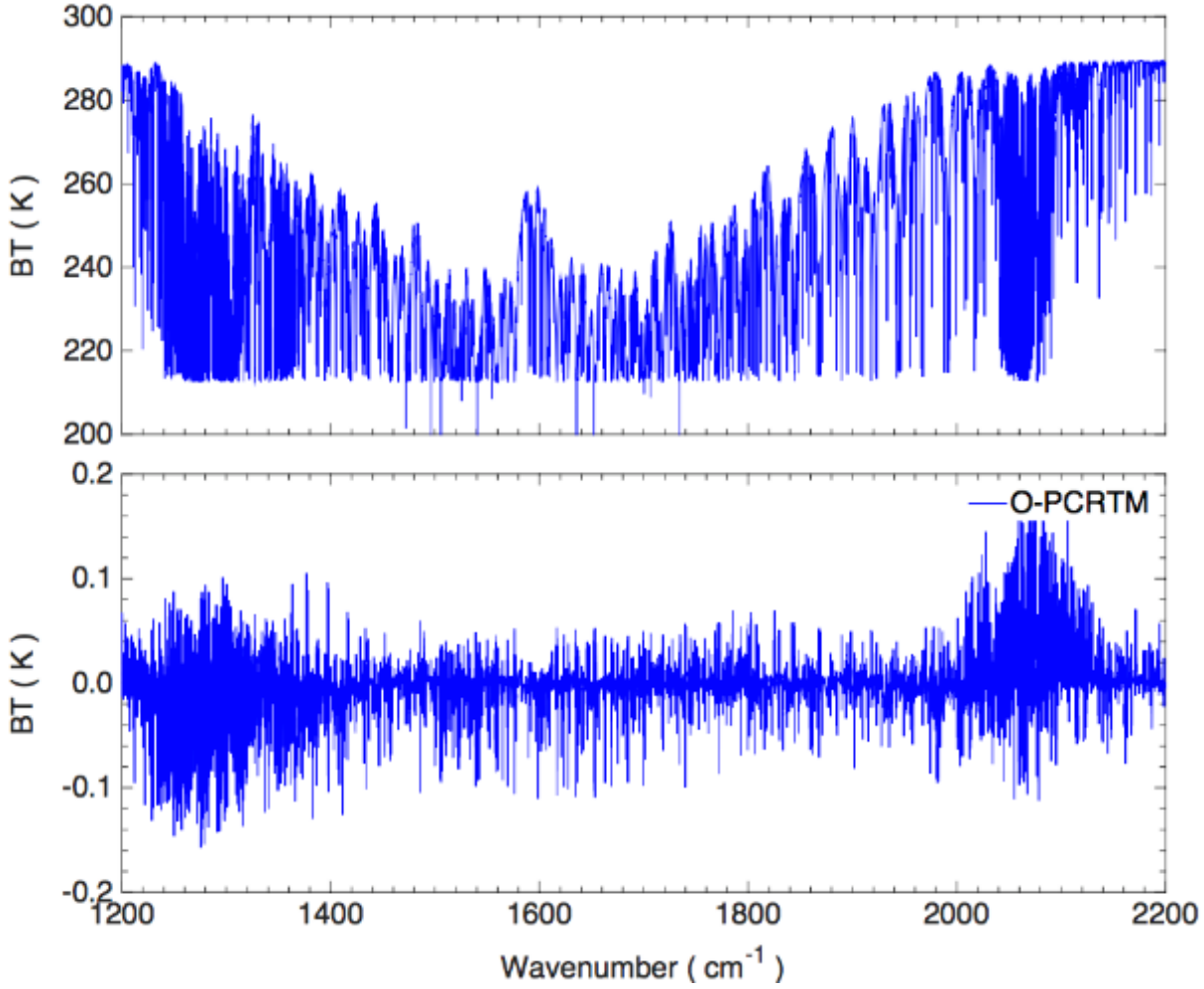


A Unified-PCRTM: Solar Band



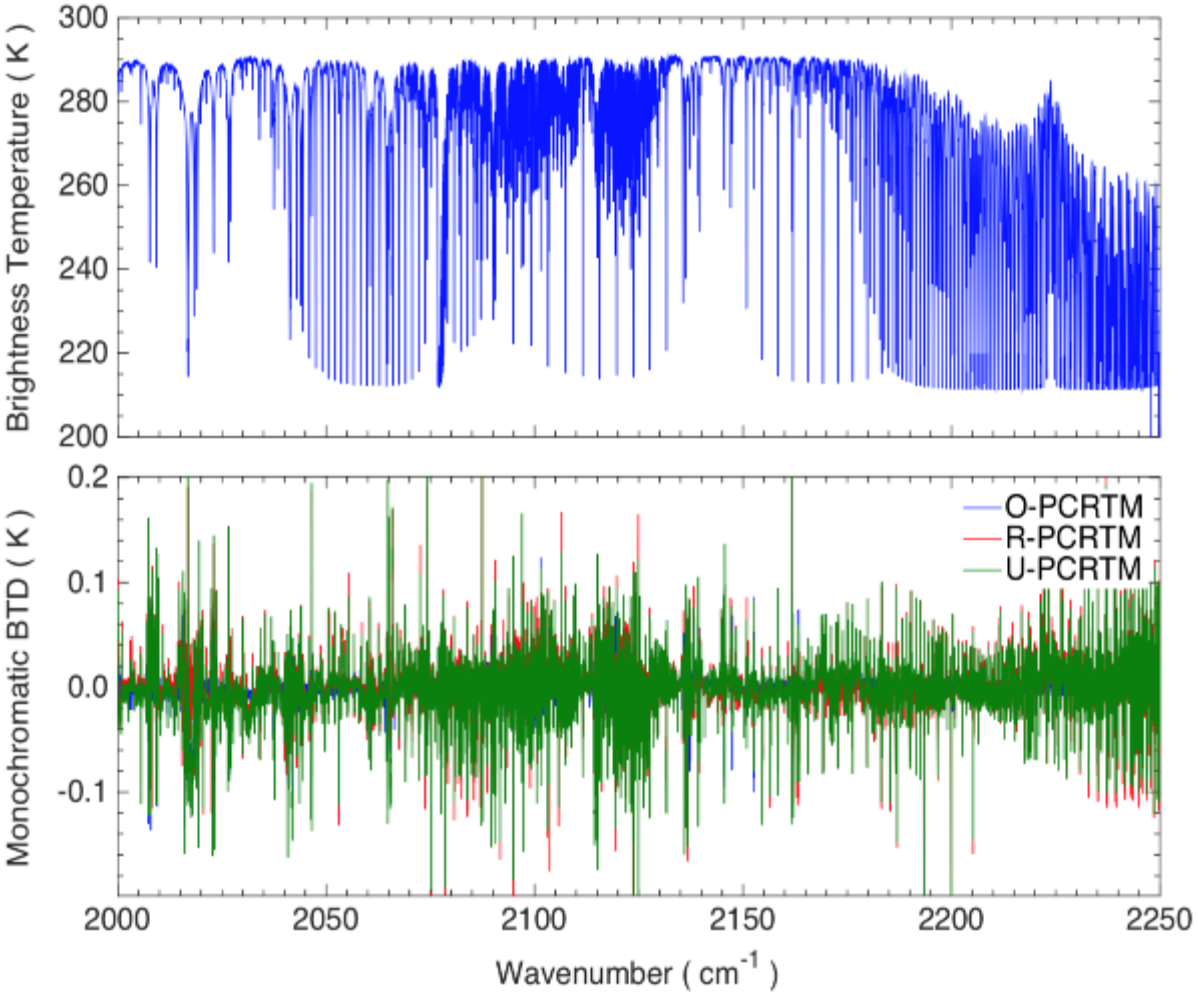
- 50,000 monochromatic radiances with a spectral resolution of 0.05 cm^{-1}.
- The O-PCRTM, R-PCRTM, and U-PCRTM show similar accuracy with relative differences less than 0.3%, and mean relative differences less than 0.01%.

A Unified-PCRTM: IR Band



- 20,000 monochromatic radiances with a spectral resolution of 0.05 cm^{-1}.
- Due to the "low" spectral resolution, the correlations among different wavelengths are relatively weak, so the U-PCRTM gives "relatively" poor results.

A Unified-PCRTM: IR Band



- 50,000 monochromatic radiances with a spectral resolution of 0.005 cm^{-1}.
- The accuracy of the current PCA is still questionable.
- ***It should be better.***

A Unified-PCRTM: Efficiency

Simulations needed for the three PCRTMs

Method	Accurate Model	O-PCRTM	R-PCRTM	U-PCRTM
Basic Simulations	50,000	~100	~ 400	~50
Additional simulations	None	50,000 Approximations	PCA	~ 400 Approximations & PCA
Simulations per wavenumber	1	~0.002	~0.008	~0.001

- For solar band, a few tens accurate monochromatic simulations are performed to give monochromatic radiances over 50,000 wavelengths.

Take home messages

- We developed the Unified-PCRTM (U-PCRTM) to further enhance the computational efficiency for high-spectral RT simulations by combining the O-PCRTM and R-PCRTM;
- The U-PCRTM shows relative differences less than 0.5% for solar reflectance, and brightness temperature differences less than 0.5K;
- The U-PCRTM is approximately three orders of magnitudes faster the the corresponding “accurate model”, and we can further work on the accurate model!
- Cloud scattering parameterization, irradiance simulations will be included in the U-PCRMT.

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