Explicit Retrieval of Cloud and Atmospheric Properties from CrIS, IASI, and AIRS

X. Liu¹, W. Wu², D. Zhou¹, A. Larar¹, S. Kizer², W. Smith³, Yong Han⁴, Mark Liu⁴, P. Yang⁵
1. NASA Langley Research Center
2. SSAI, Hampton VA
3. University of Wisconsin
4. NOAA STAR
5. Texas A & M

Acknowledgement: JPSS cal/val team, NASA CLARREO science team, Eumetsat, UK MetOffice, D. Sergio, Lihang Zhou…
Presentation outline

• Motivations
• Principal Component-based Radiative Transfer Model (PCRTM)
• PCRTM retrieval algorithm (PCRTM-RA) and applications
• Summary and Conclusions
Motivations

- Need fast radiative transfer model to handle hyperspectral data
  - Modern sensors have thousands of channels and 0.1-1 million spectra per day
  - Only 4-10% of spectral channels are used in satellite data assimilations
  - Examples hyperspectral sensors:
    - AIRS 2378 x 1 x 1
    - CrIS 1305 x 3 x 3
    - NAST-I 8632 x 1 x 1
    - IASI 8461 x 2 x 2
    - FIRST ~1500x10 (or more)
    - CLARREO thousands

- Need a forward model that can treat cloud radiative transfer accurately and efficiently
  - Most of the sounder footprints contain cloud signatures
  - Cloudy radiance data assimilation is a big challenge
  - Current Cloud Clearing algorithm has limitations
    - Need to make assumptions about the inhomogeneity of the scene
    - Hard to characterize the error of the cloud cleared radiances and products

- PCRTM (Principal Component-based Radiative Transfer model) was developed to satisfy the need listed above
  - Initially developed in 2004
  - Extends from 50 cm\(^{-1}\) (200 \(\mu\)m) to 33333 cm\(^{-1}\) (300 nm)
  - Milliseconds per spectrum in IR
  - 2-3 orders of magnitude faster than MODTRAN in solar spectral region
  - 10% extra computation to include multiple scattering clouds
Introduction to PCRTM Forward Model

- Explore spectral correlation in hyperspectral data
  - No need to calculate spectrum one channel at a time
  - Compress spectra into compact form using PCA, wavelet, Fourier Series etc
  - Reduce dimension of the data

- PCA is a good approach for compressing spectra and capture information
  - Leading EOFs captures all essential information of thousands of channels
  - PCA has been used to reduce instrument noise and to compress spectra

- PCRTM parameterization is physical-based fast model
  - Radiative transfer done monochromatically at very few frequencies
  - Very accurate relative to line-by-line (LBL) RT model (< 0.05K or 0.05%)
  - 3-4 orders of magnitude faster than LBL RT models
  - A factor of 2-100 times faster than channel-based RT models
  - Provides Jacobian or radiative kernel needed for retrievals and climate studies
  - Includes accurate cloud RT

\[
y_i = \tilde{R}^{ch} \times U_i = \sum_{j=1}^{N_{ mono}} \phi_j R_j^{mono} \tilde{U}_i = \sum_{j=1}^{N_{ mono}} A_j R_j^{mono}
\]

\[
\tilde{R}^{ch} = \sum_{i=1}^{N_{ EOF}} y_i \tilde{U}_i + \tilde{\epsilon}
\]
PCRTM is Physical and Fast

- Example of $O_2$ A-band
  - 12000 monochromatic RT LBL calculations needed to cover 759-771 nm spectral region
- PCRTM reduces monochromatic RT calculation to 7
  - 1700 times faster than LBL
  - Been trained for OCO (~0.04 nm) and SCIAMACHY (~0.2 nm) spectral resolutions
Computational Speed up in Solar Spectral Region

- PCRTM reduces MODTRAN RT calculation by a factor of 28-928 depending on spectral resolution and MODTRAN accuracy chosen
  - PCRTM can handle ice and water clouds
  - Aerosols
  - Various trace gases
  - Land and ocean surfaces
  - Multiple scattering calculation uses 4-32 streams
- It takes 1 day to simulate 1 year of all sky SCIAMACHY spectra using PCRTM with 30 CPUs
- It will take more than 2 years for the MODTRAN to do the same

<table>
<thead>
<tr>
<th></th>
<th>PCRTM RT</th>
<th>MODTRAN RT</th>
<th>speed up</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean 1cm⁻¹</td>
<td>956</td>
<td>259029</td>
<td>270</td>
</tr>
<tr>
<td>Land 1cm⁻¹</td>
<td>1339</td>
<td>259029</td>
<td>193</td>
</tr>
<tr>
<td>Ocean 4nm</td>
<td>279</td>
<td>259029</td>
<td>928</td>
</tr>
<tr>
<td>Land 4nm</td>
<td>354</td>
<td>259029</td>
<td>731</td>
</tr>
</tbody>
</table>
Computational Speed in IR Spectral Region

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Channel Number</th>
<th>PC score (seconds)</th>
<th>PC score + radiance</th>
<th>PC score + PC Jacobian</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLARREO, 0.1 cm⁻¹</td>
<td>19901</td>
<td>0.014 s</td>
<td>0.022 s</td>
<td>0.052 s</td>
</tr>
<tr>
<td>CLARREO, 0.5 cm⁻¹</td>
<td>5421</td>
<td>0.011 s</td>
<td>0.013 s</td>
<td>0.039 s</td>
</tr>
<tr>
<td>CLARREO, 1.0 cm⁻¹</td>
<td>2711</td>
<td>0.0096 s</td>
<td>0.012 s</td>
<td>0.036 s</td>
</tr>
<tr>
<td>IASI, 0.25 cm⁻¹</td>
<td>8461</td>
<td>0.011 s</td>
<td>0.012 s</td>
<td>0.044 s</td>
</tr>
<tr>
<td>AIRS, 0.5-2.5 cm⁻¹</td>
<td>2378</td>
<td>0.0060 s</td>
<td>0.0074 s</td>
<td>0.031 s</td>
</tr>
<tr>
<td>CrIS, 0.625-2.5 cm⁻¹</td>
<td>1317</td>
<td>0.0050 s</td>
<td>0.0060 s</td>
<td>0.021 s</td>
</tr>
<tr>
<td>NAST-I, 0.25 cm⁻¹</td>
<td>8632</td>
<td>0.010 s</td>
<td>0.013 s</td>
<td>0.045 s</td>
</tr>
<tr>
<td>S-HIS, 0.5 cm⁻¹</td>
<td>4316</td>
<td>0.008 s</td>
<td>0.008 s</td>
<td>0.038 s</td>
</tr>
<tr>
<td>CrIS, 0.625 cm⁻¹</td>
<td>2211</td>
<td>0.009 s</td>
<td>0.009 s</td>
<td>0.033 s</td>
</tr>
</tbody>
</table>

- CrIS, CrIS-full-res, IASI, NAST-I and S-HIS have multiple databases corresponding to different apodization functions including unapodized spectra
- Spectral coverage (50-3000 cm⁻¹)
- Multilayer, multiple scattering clouds included
- 15 variable trace gases
- It provide radiative kernel/Jacobian with minimum additional computations
- Non-LTE included
Accuracy of PCRTM is very good relative to reference RT models

- Bias error relative to LBL is typically less than 0.002 K
- The PDF of errors at different frequencies are Gaussian distribution
- RMS error < 0.03K for IR and < 5x10^{-4} mW/cm²/sr/cm⁻¹ for solar (< ~0.02%)
PCRTM has been validated using CrIS, IASI, AIRS, NAST-I, and SCIAMACHY real data.
A brief description of the Optimal Estimation PCRTM Retrieval Algorithm (PCRTM-RA)

\[ X_{n+1} - X_a = (K^T S_y^{-1} K + \lambda I + S_a^{-1})^{-1} K^T S_y^{-1} [(y_n - y_m) + K(X_n - X_a)] \]

PCRTM models PC scores directly
- Small matrix and vector dimensions
- 100 super channels instead of thousands of channels
- Simply minimizing cost function
- Channel-to-channel correlated noise handled
- A Climatology covariance and background used as OE constraint
- Climatology background used as first guess

All parameters retrieved simultaneously
- No need to estimate errors of non-retrieved parameters
- Temperature
- Water
- Trace gases (CO2, CO, CH4, O3, N2O)
- Surface temperature and emissivities
- Cloud optical depth/size/phase/height/temperature
- Product error covariance and averaging kernel provided for each retrieval at not extra computational cost

MW retrieval capability added
- CRTM used as forward model
- PCRTM-RA can operate in 3 Modes
  - MW-only, IR-only, MW+IR
Example of Applying PCRTM-RA to CrIS/ATMS data

Comparison of PCRTM-RA Retrieved and ECMWF Atmospheric Water Vapor from 5-15-2012 focus day CrIS/ATMS data 90% convergence rate.

Retrieved 300 hPa from CrIS/ATMS using PCRTM-RA

300 hPa from ECMWF
Comparison of PCRTM-RA Retrieved and ECMWF Atmospheric Temperature from 5-15-2012 focus day CrIS/ATMS data

500 hPa Retrieved from ATMS/CrIS using PCRTM_RA

500 hPa Temperature from ECMWF
Comparison of PCRTM Temperature Retrieval with IDPS Operational CrIMSS EDR Algorithm
Comparison of PCRTM retrieval with radiosondes

• Temperature, moisture, and ozone cross-sections
• Plots are deviation from the mean
• Fine water vapor structures captured by the retrieval system
• A very cloudy sky condition
Example of retrieved cloud properties
PCRTM-RA Retrieved Cloud Top Pressure and Optical Depth from 5-15-2012 CrIS/ATMS focus day data
Example of retrieved surface temperature and emissivity and comparison with field validation data

Comparison of PCRTM retrieved surface skin temperature with ARIES measured Tskin

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Surface Pressure (hPa)</th>
<th>ARIES Measured skin temperature (K)</th>
<th>IASI-retrieved surface skin temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 April 2007</td>
<td>ARM CART site</td>
<td>972.0</td>
<td>284.7</td>
<td>284.8</td>
</tr>
<tr>
<td>29 April 2007</td>
<td>Gulf of Mexico</td>
<td>1021.7</td>
<td>297.8</td>
<td>297.6</td>
</tr>
<tr>
<td>30 April 2007</td>
<td>Gulf of Mexico</td>
<td>1017.5</td>
<td>298.6</td>
<td>298.1</td>
</tr>
<tr>
<td>4 May 2007</td>
<td>Gulf of Mexico</td>
<td>1009.9</td>
<td>297.4</td>
<td>297.1</td>
</tr>
</tbody>
</table>

Comparison of retrieved ocean emissivity with ARIES aircraft measurements
Example of retrieved global distribution of climate related properties retrieved using the PCRT-RA

Atmospheric temperature at 9 km for July 2009

Surface skin temperature for July 2009

Surface emissivity for July 2009

Atmospheric carbon monoxide mixing ratio for July 2009
Application of PCRTM-RA to Full Resolution CrIS Data

Switching between nominal and full resolution CrIS/ATMS retrieval is very easy
- change instrument ID
- change observational error covariance matrix

<table>
<thead>
<tr>
<th></th>
<th>CrIS (LW)</th>
<th>CrIS (MW)</th>
<th>CrIS (SW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Res</td>
<td>0.625 cm⁻¹</td>
<td>1.25 cm⁻¹</td>
<td>2.5 cm⁻¹</td>
</tr>
<tr>
<td>High Res.</td>
<td>0.625 cm⁻¹</td>
<td>0.625 cm⁻¹</td>
<td>0.625 cm⁻¹</td>
</tr>
</tbody>
</table>
CO retrieved from full-resolution CrIS data (3-12-2013)

From nominal resolution CrIS using PCRTM-RA

From high resolution CrIS using PCRTM-RA
Trace gas retrievals from CrIS with different spectral resolutions

Graphs showing the altitude versus mixing ratio for CO, CO₂, CH₄, and O₃. The graphs compare the "truth," low-resolution, and high-resolution data.
PCRTM-RA Retrieved Atmospheric Temperature from High Resolution CrIS/ATMS

Retrieved 300 hPa H2O from CrIS/ATMS using PCRTM-RA

Retrieved 500 hPa H2O from CrIS/ATMS using PCRTM-RA
PCRTM-RA Retrieved Atmospheric Temperature from High Resolution CrIS/ATMS

Retrieved 300 hPa Temperature from CrIS/ATMS using PCRTM-RA

Retrieved 500 hPa Temperature from CrIS/ATMS using PCRTM-RA
Summary and conclusions

- Forward model is a key component in analyzing hyperspectral data
  - PCRTM has been applied: AIRS, IASI, CrIS, NAST-I, S-HIS, SCIAMACHY
  - Covers spectral range from 0.3 $\mu$m to 200 $\mu$m
  - With 15 variable trace gases
  - Multiple scattering clouds included
  - Physical and accurate
  - Very fast relative to LBL and traditional fast RT models

- PCRTM-RA developed to use full spectral information
  - Atmospheric temperature profile
  - Atmospheric water vertical profiles
  - Trace gas profiles,
  - Cloud height, particle size, phase, effective temperature, optical depth
  - Surface properties (Tskin, emissivity …)

- PCRTM-RA system now includes MW channels
  - CRTM used as forward model
  - Improves performance below thick clouds
  - Designed for ATMS/CrIS, ATMS/Hi-Res CrIS, AMSU/AIRS, AMSU/IASI, CLARREO
  - Can do MW-only, IR-only, or MW+IR

- Advantages over existing methods
  - Full spectral channels used with all relevant parameters retrieved simultaneously
  - No need to estimate cloud-clearing error or errors due fixing some parameters
  - Cloud properties explicitly retrieved
  - Product error estimates and averaging kernels provided