# Principal Component-based Radiative Transfer Model (PCRTM) for Hyperspectral Remote Sensors for UV, VIS, NIR, IR, and FIR Spectral Regions


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# There are two key challenges in exploring information content of hyperspectral sounders

- Challenge No. 1: computation speed of Radiative Transfer Model (RTM)
  - Line-by-line: millions of monochromatic radiative transfer (RT) calculations
  - Channel-based RTMs: thousands of polychromatic RT calculations
  - Principal Component (PC)-based RTMs: hundreds of monochromatic RT calculations
- Challenge No. 2: need effective methods to deal with clouds
  - 90% of sounder FOVs contain clouds – need accurate and fast cloudy RTMs
  - Only 5-20% of channels due to RTMs speed and cloud RT accuracy limitations
  - Fitting cloud-cleared radiances does not satisfy radiometric closure requirement
- Principal Component-based RTM (PCRTM) addresses these challenges
  - Very fast
  - Includes all spectral channels using PC scores

# Principal Component Based Radiative Transfer Model (PCRTM)

- PCRTM was specifically for hyperspectral remote sensors
  - Number of RT calculations are << number of spectral channels
    - Orders of magnitude faster than LBL RTMs
  - RT calculations done monochromatically
    - Physical-based RTM and accurate relative to LBL RTMs

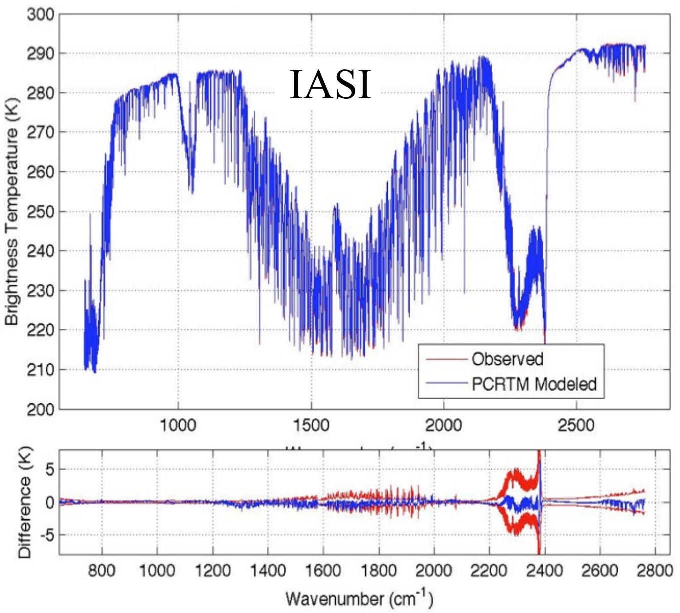
$$\vec{R}^{ch} = \sum_{i=1}^{N_{EOF}} c_i \vec{U}_i + \vec{\varepsilon} = \sum_{i=1}^{N_{EOF}} \left( \sum_{j=1}^{N_{mono}} a_j R_j^{mono} \right) \vec{U}_i + \vec{\varepsilon}$$

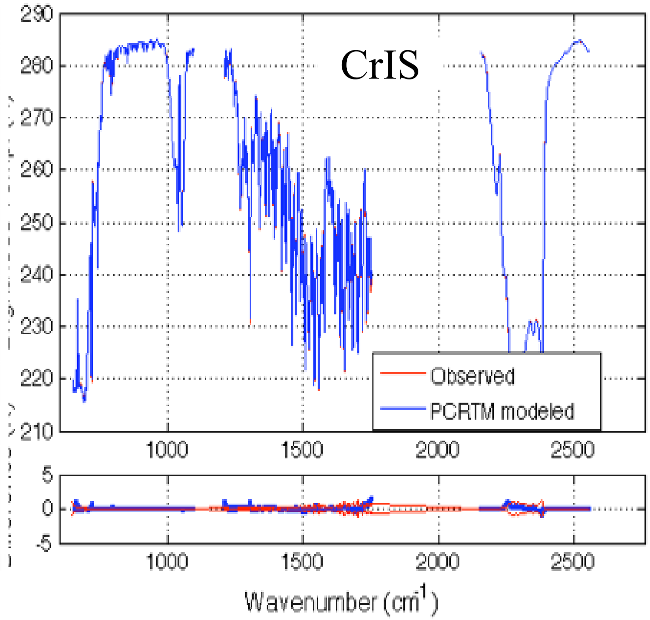
  - Provides analytical Jacobian needed for satellite data inversions

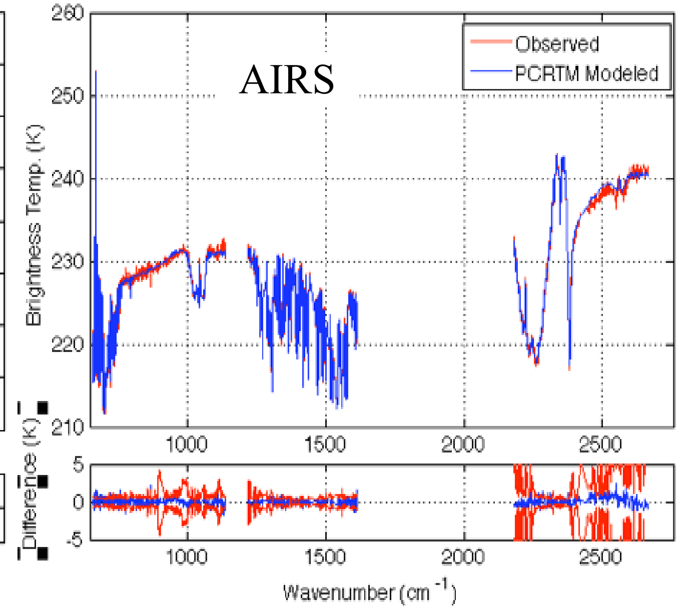
| Sensor | Channel Number | PC score (seconds) |
|---|---|---|
| CLARREO, 0.1 $cm^{-1}$ | 19901 | 0.014 s |
| CLARREO, 0.5 $cm^{-1}$ | 5421 | 0.011 s |
| CLARREO, 1.0 $cm^{-1}$ | 2711 | 0.0096 s |
| IASI, 0.25 $cm^{-1}$ | 8461 | 0.011 s |
| AIRS, 0.5-2.5 $cm^{-1}$ | 2378 | 0.0060 s |
| CrIS,0.625-2.5 $cm^{-1}$ | 1317 | 0.0050 s |
| NAST-I, 0.25 $cm^{-1}$ | 8632 | 0.010 s |
| S-HIS, 0.5 $cm^{-1}$ | 4316 | 0.008 s |
| CrIS, 0.625 $cm^{-1}$ | 2211 | 0.009 s |

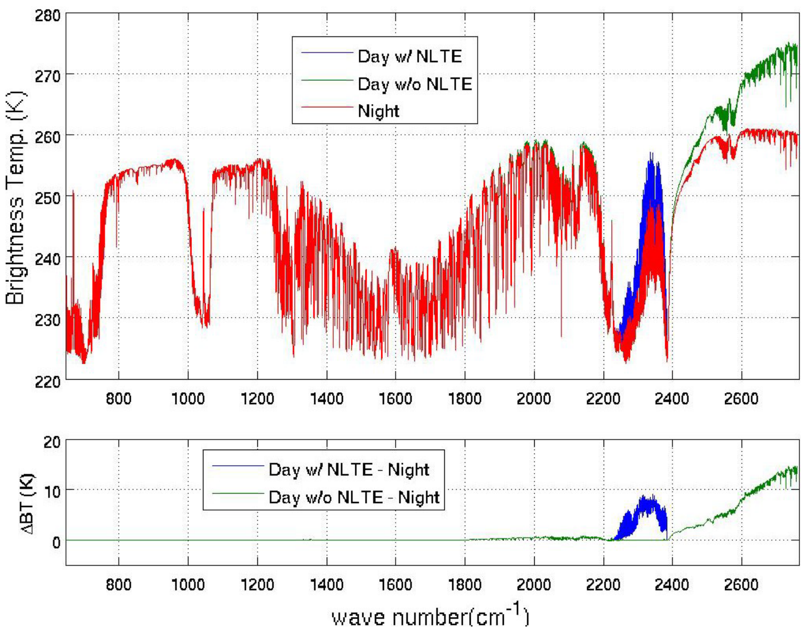
- Multiple scattering clouds and aerosols included
- Wide range of spectral coverage
  - Thermal: 50-3000 $cm^{-1}$
  - Solar: 200 nm – 2500 nm
  - Suitable for AIRS, CrIS, IASI, PREFIRE, IRS, IASI-NG, NAST-I, S-HIS, CLARREO, CPF, SBG, TEMPO, OMI, SCIAMACHY …
- Fast:
  - Milliseconds to fraction of seconds in IR
  - 3-4 orders of magnitude faster than LBL in solar
- Accurate relative to LBL:
  - Thermal: Bias error < 0.002 K  RMS error < 0.03 K
  - Solar: bias error < 0.001%, RMS error ~0.05%

# PCRTM Calculated Radiance Spectra Agree Well With Satellite Observations




Two PCRTM-based retrieval algorithms developed:

- L2 products: Single Field-of-view Sounder Atmospheric Product (SiFSAP)
- L3 Products: Climate Fingerprinting Sounder Products (ClimFiSP)
- Both products will be available at NASA GES DISC for public access

*Please visit Dr. Xu Liu's poster (13p.04) on Tuesday, March 21 for the retrieval results for 20 years of Aqua/AIRS, SNPP/CrIS, and NOAA20/CrIS*

# PCRTM Reduces RT Calculations by 3-4 Oders of Magnitude Relative to Correlated- Method for CPF-type Spectrometer

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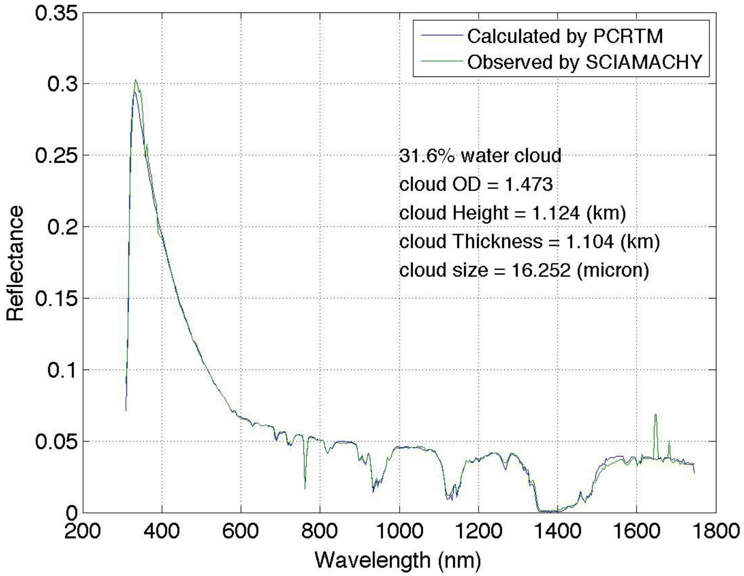


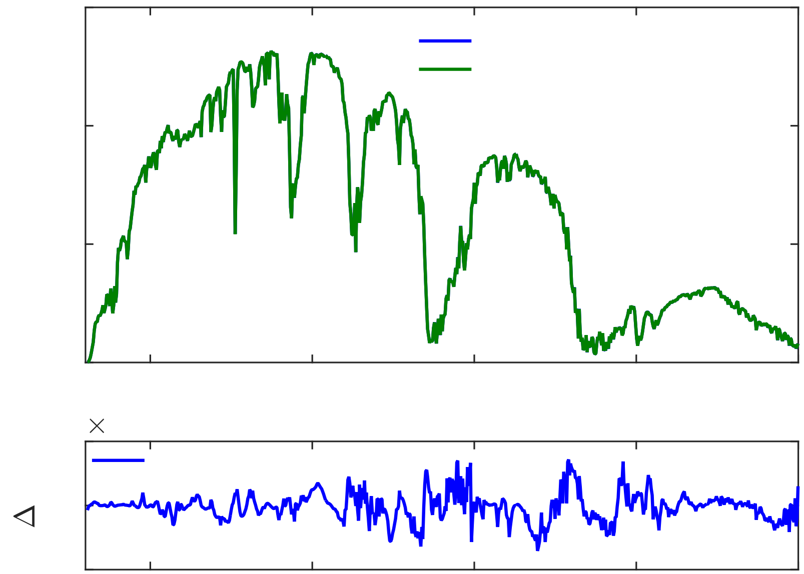

| PCRTM | *nmo* | *nch* | *npc* | *nsmo* | *Speed-up* |
|---|---|---|---|---|---|
| **Land (8 nm)** | 259,029 | 546 | 220 | 262 | 988 |
| **Ocean (8 nm)** | 259,029 | 546 | 267 | 240 | 1079 |

Number of radiative transfer calculations for PCRTM are reduced by 3 orders of magnitude relative to modtran for spectral range from 300 nm to 2500 nm

| PCRTM | M1 | M2 | Speedup to Regular PCRTM-SOLAR | Speedup to MODTRAN 5 |
|---|---|---|---|---|
| Land 8 nm | 263 | 49 | 5 | 5286 |
| Ocean 8 nm | 241 | 23 | 10 | 11,262 |

Hybrid Stream method further speed up PCRTM-SOLAR by another factor of 5-10 relative to 32-stream PCRTM

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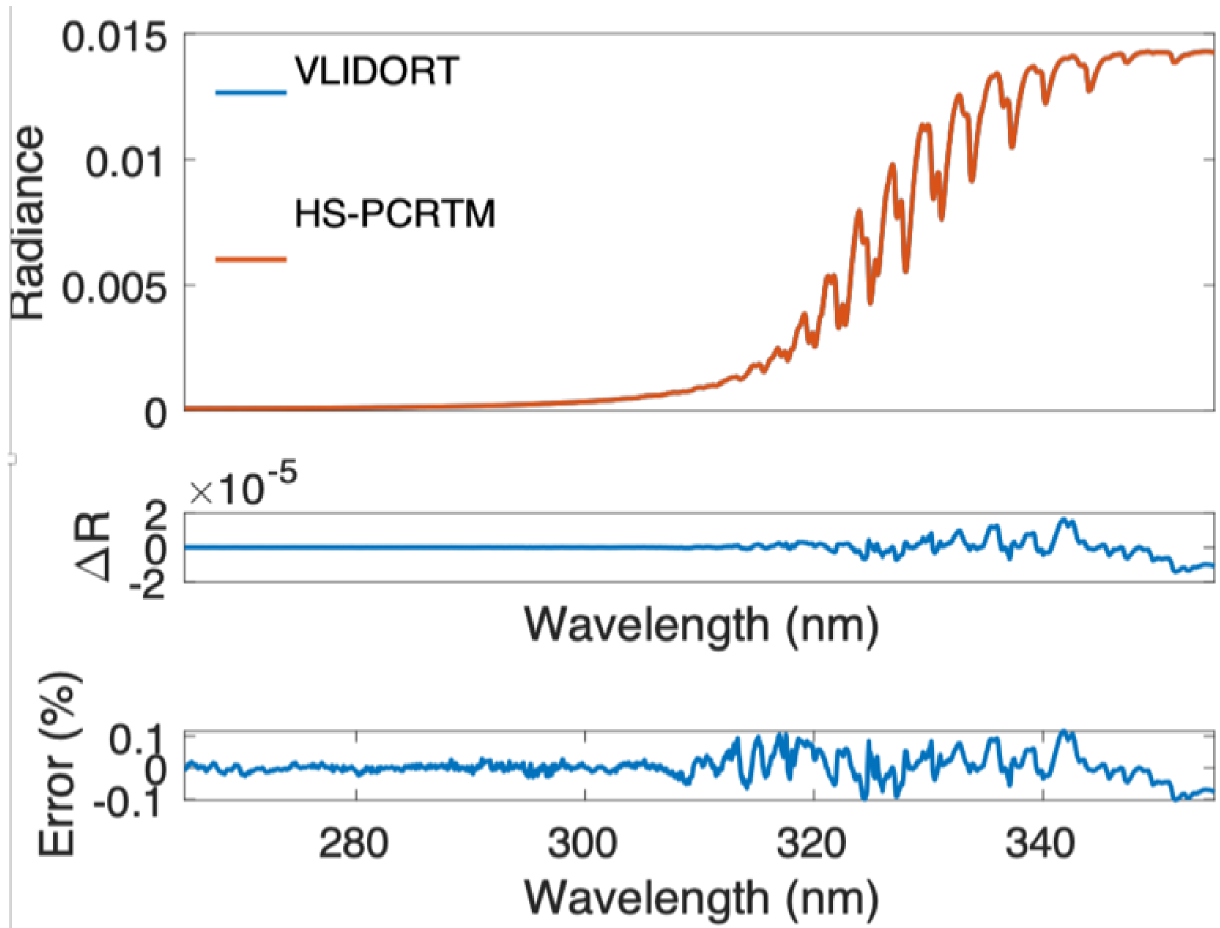
# Example of HS-PCRTM Accuracy Relative to VLIDORT for TEMPO/OMI Ozone Spectral Region

- The Hybrid Stream PCRTM (HS-PCRTM) can further reduce the computational time
  - Perform 2-stream monochromatic RT calculations at original PCRTM selected frequencies
  - Perform higher streams RT calculations at even less monochromatic frequencies
  - The accuracy is not comprised (see example below)

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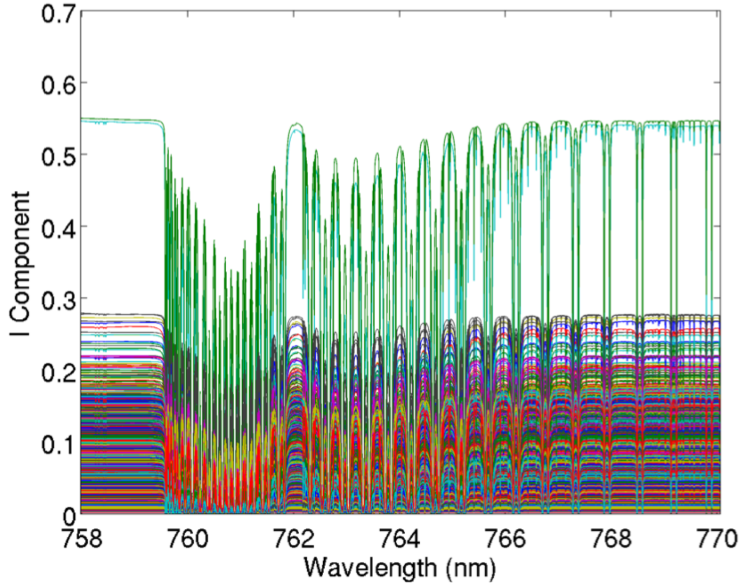
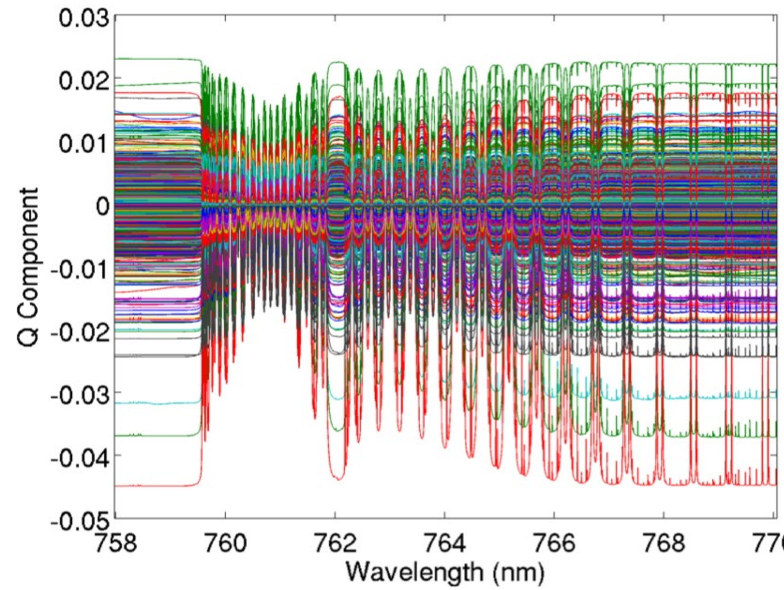
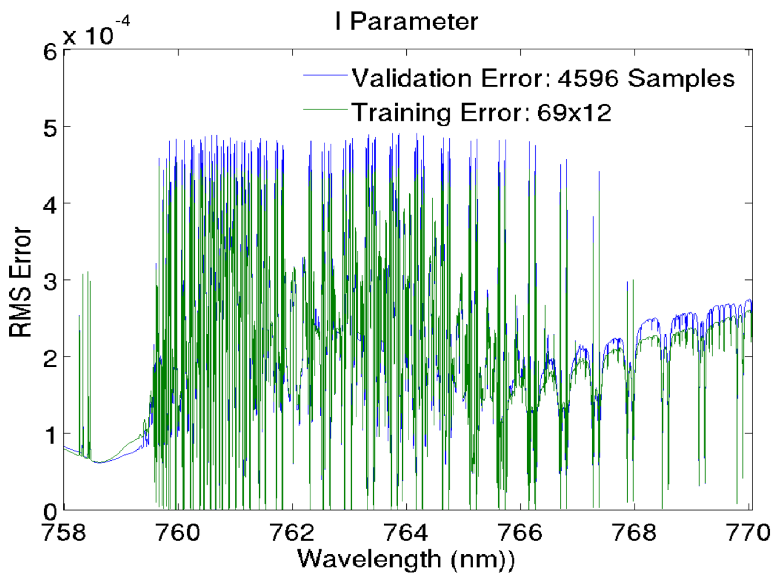
# Example of PCRTM for very high spectral resolution(0.001 nm) polarized $O_2$-A band




- Only 12 monochromatic RT calculations are needed to faithfully represent the 0.001 nm $O_2$-A band
- A few dozens more monochromatic RT calculations are needed to include Q, U polarized components of the Stokes vector

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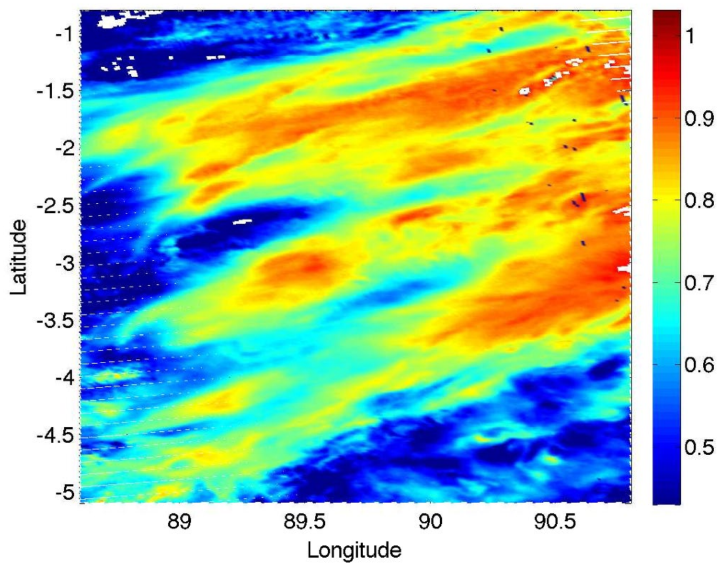
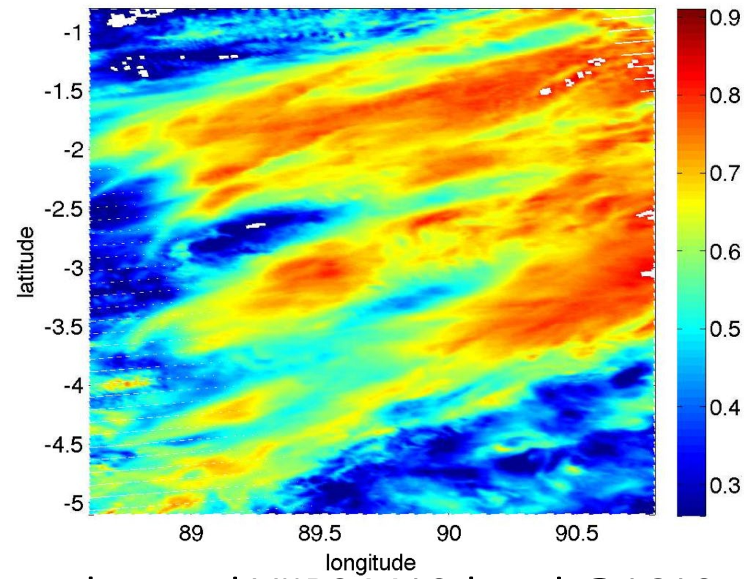
# Examples of using PCRTM to generate high-resolution Proxy Data for Satellite Remote Sensing Applications

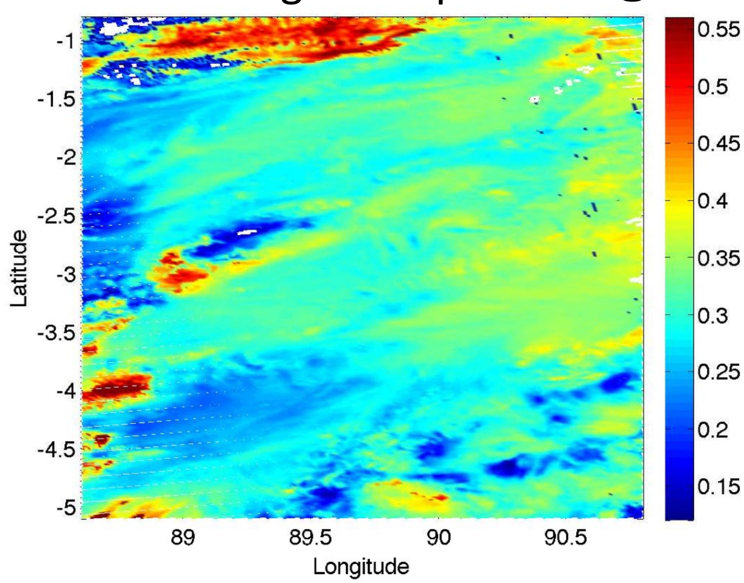
From PCRTM high-res Spectrum @488 nm



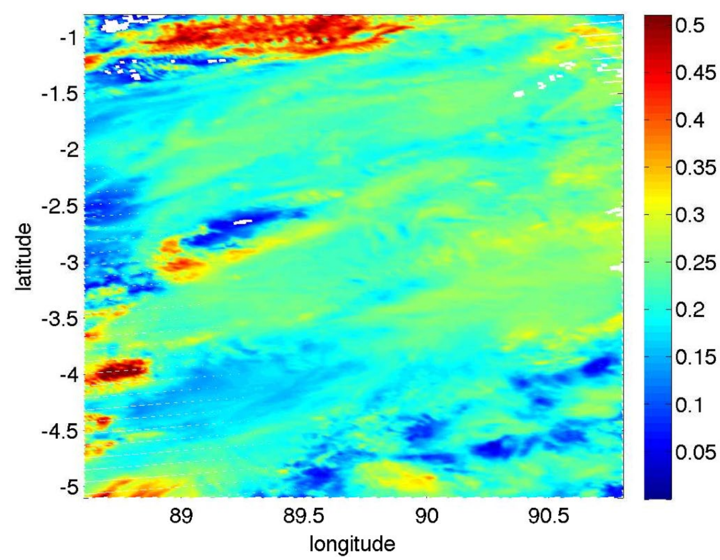

From observed VIIRS M3band @488 nm




From PCRTM high-res Spectrum @1610 nm




From observed VIIRS M10-band @1610 nm

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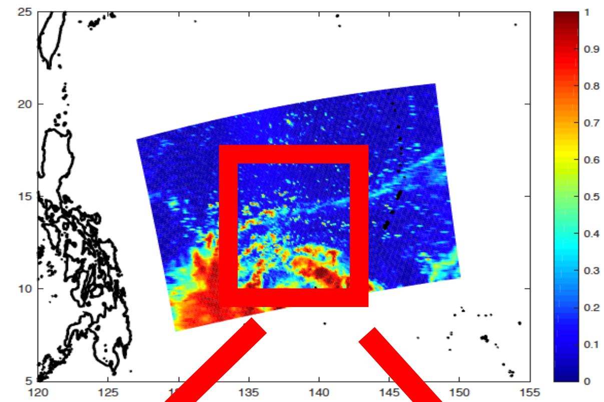
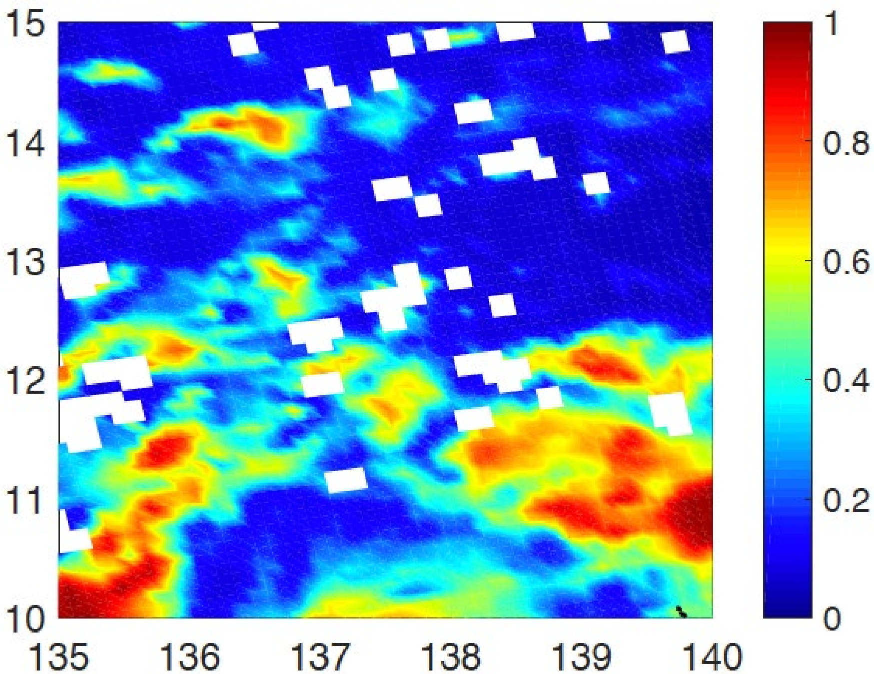
# PCRTM High-fidelity Simulator for CPF at Various Spatial Resolutions

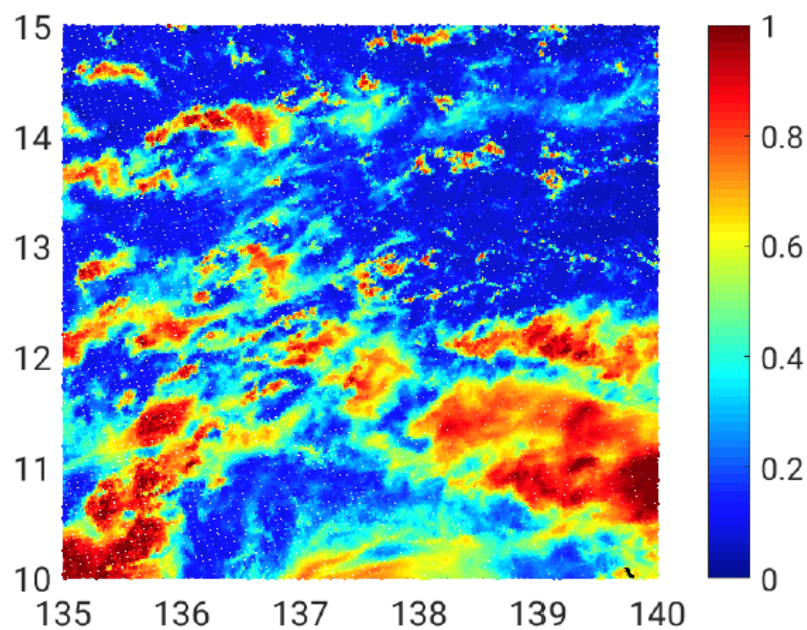
MODIS L2 + CPF simulator
Refl. @ 645 nm




10km X 10 km spatial resolution




1km X 1km spatial resolution

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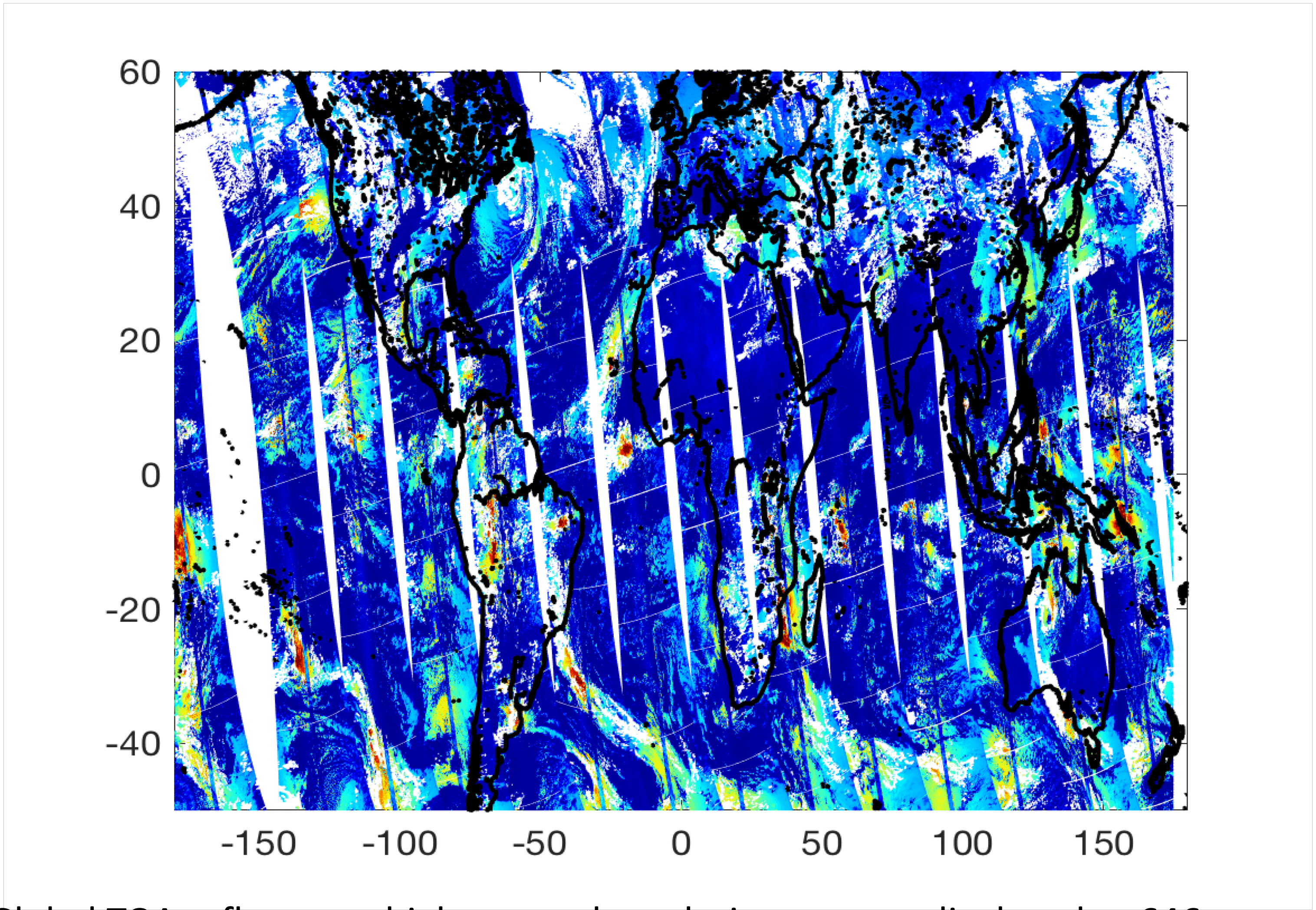
# Global Scale, Data Intensive Simulations




Global TOA reflectance high spectral resolution spectra displayed at 646 nm

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# Summary

- PCRTM was first developed in 2004 for NAST-I instrument with over 8600 channels
  - Extended to AIRS, CrIS, IASI, S-HIS, CLARREO-IR, PREFIRE..
  - Two Mature retrieval algorithms have been developed based on PCRTM
    - ➢ *Please visit Dr. Xu Liu's poster (13p.04) on Tuesday, March 21 for the retrieval results for 20 years of Aqua/AIRS, SNPP/CrIS, and NOAA20/CrIS*
- PCRTM Accelerates the RT calculations by exploring spectral correlations
  - PCRTM performs RT calculations monochromatically (i.e. accurate and physical)
  - Hybrid-Steam PCRTM (HS-PCRTM) can further reduces RT calculation times
  - Handle multiple scattering clouds
  - Works for polarized RT calcuations of (I, Q, U)
  - A few ms per spectrum in IR spectral region
  - 3-4 orders of magnitude faster than MODTRAN in solar spectral region
  - Accurate relative to line-by-line models
  - PCRTM provides Jacobian needed for a physical retrieval algorithm

- We have developed PCRTM for solar spectral region
  - Completed TEMPO/OMI spectral region
  - ➢ In the process of extending to the whole TEMPO spectral regions
  - ➢ VLIDORT is used for radiative transfer solver
  - ➢ In the process of developing PCRTM for SBG decadal service mission
  - ➢ In the process of testing the model using EMIT data



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