Retrieval Algorithm Using Super channels

Xu Liu
NASA Langley Research Center, Hampton VA 23662

D. K. Zhou, A. M. Larar (NASA LaRC)
W. L. Smith (HU and UW)
P. Schluessel (EUMETSAT)
Hank Revercomb (UW)
Jonathan Taylor, Stuart Newman (UK MetOffice)
Stephen A. Mango, Karen St. Germain (NPOESS/IPO)
Outline

• Description of a super channel algorithm
  – Introduction to a Principal Component-based Radiative Transfer Model (PCRTM)
  – Description of a super channel physical retrieval algorithm
• Example of applying superchannel retrieval algorithm to IASI and NAST-I spectra
• Conclusions
Introduction

• Good New for hyperspectral remote sensing:
  – Modern Hyper/Ultra spectral remote sensors have thousands of channels
  – High spectral resolution provides more details of atmosphere properties
  – Examples hyperspectral sensors:
    • AIRS (Atmospheric Infrared Sounder): 2378 x 1 x 1
    • CrIS (Cross Track Infrared Sounder): 1305 x 3 x 3
    • NAST-I (NPOESS Airborne Sounder Testbed): 8632 x 1 x 1
    • IASI (Infrared Atmospheric Sounding Interferometer): 8461 x 2 x 2
    • GIFTS (Geostationary Imaging Fourier Transform Spectrometer): 1827 x 128 x 128
    • FIRST (FAR Infared Spectroscopy of the Troposphere): ~1500x10 (or more)
    • COSAIR (Calibrated Observations of Radiance Spectra from the Atmosphere in the far Infra Red): thousands
    • CLARREO (Climate Absolute Radiance and Refractivity Observatory): thousands

• Challenges:
  – Need fast and accurate forward model
    • Line-by-line radiative transfer model too slow
  – New ways to analysis data are needed
    • Transform data into more compact form (e.g. EOF)
  – A Principal Comonent-based Radiative Transfer Model (PCRTM) has been developed
    • Applied successfully to AIRS, IASI, and NAST-I
  – Example of observed IASI spectra and PCRTM calculated spectra is shown on the right corner
    • The blue curve: IASI instrument noise
    • The red curve: difference between observed and PCRTM calculated
Description of PCRTM

• Principal Component-based Radiative Transfer Model (PCRTM)
  – predicts PC scores ($Y$) instead of channel radiances ($R$)
  – PC scores (super channels) are linearly related to channel radiances
    \[ \hat{Y} = A \times \hat{R}_{\text{mono}} \]

• The relationship is derived from the properties of eigenvectors and instrument line shape functions:

\[ \hat{Y} = U^T \times \hat{R}_{\text{chan}} \]

\[ \hat{R}^\text{chan}_{i} = \sum_{k=1}^{N} \phi_k \hat{R}^{\text{mono}}_{ L_k } \]

• Very accurate relative to LBL
  – Accuracy of the model can be adjusted

• Very fast
  – No need to perform redundant calculations

• Cloud contributions included
  – Use cloud transmittances and reflectances
  – Use multiple scattering calculation at limited monochromatic frequencies

• Channel radiances (or transmittances ) can be obtained easily

\[ \hat{R}^\text{chan} = U \times \hat{Y} = \sum_{i=1}^{N_{\text{EOF}}} \hat{Y}_i \hat{U}_i + \hat{\varepsilon} \]

• Provide analytical jocabian

Results of Applying PCRTM to IASI

- An Example of the IASI spectrum and the difference between the LBL calculated radiance and the PCRTM calculated radiance
- Errors less than 0.05K

PCRTM accuracy:
- Top: RMS error
- Middle: Bias error
- IASI instrument noise
- Very good relative to LBL
- Much smaller error relative to instrument noise
Comparison with NAST-I and AIRS observations

- NAST-I spectrum take over Potenza Italy on September 9th, 2004
- Emissivity fix to 0.98 (not the truth)
- T, H2O taken from LIDAR measurements
- O3 fixed to US standard atmosphere
- PCRTM and LBLRTM calculated radiances agree with each other (< 0.07K)
- main sources of error between the NAST-I observed and PCRTM calculated radiances
  - Spectroscopy
  - Uncertainty in the “true atmospheric state”

- An example of Observe vs forward model calculated AIRS spectra
- Temperature, H2O and O3 profiles are taking from ECMWF model
- Spikes due to AIRS popping noise not completely removed
- Ozone truth has poor quality
Flow diagram of the PCRTM retrieval algorithm

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

- All parameters retrieved simultaneously
  - No need to estimate errors of non-retrieved parameters
- Very robust
  - Can start from either climatology or regression first guesses
- Single FOV retrieval
  - High spatial resolution (no need for cloud clearing)
  - Cloud parameters retrieved explicitly
  - Multiple scattering effect included
- Provide error covariance matrix of state vector without extra calculations
  - Provides info needed by 3D/4Dvar
  - Error correlations included
  - Compressed state vector and associated error covariance matrix
- Both radiance and state vectors are in EOF domain
  - Small matrix and vector dimensions
  - Only 100 super channels needed
  - Simply minimizing cost function
  - No ad-hoc tuning parameters
Cloudy Retrieval Over Angra dos Reis

- Top left: a 3-D plot of retrieved temperature and moisture profiles taken on April 15th, 2008 near Angra dos Reis, Brazil

- Top right: Observed and fitted IASI spectra (ice cloud) taken on April 15th, 2008 near Angra dos Reis, Brazil

- Top right: Observed and fitted IASI spectra (Clear sky) taken on April 15th, 2008 near Angra dos Reis, Brazil
Highlights of Research (JAIEX Campaign Retrievals)

- **Temperature, moisture, and ozone cross-sections** from 4/19/07
- Plots are deviation from the mean
- Fine water vapor structures captured by the retrieval system
- NAST-I under flew over the CART ARM site
- A very cloudy sky condition

- Retrieved atmospheric Temperature and moisture profiles from IASI and NAST-I during JAIEX campaign
- All parameters retrieved
  - T, H₂O, O₃, CO
  - Surface emissivity
  - Surface skin temperature
  - Cloud optical depth
  - Cloud height
  - Cloud particle size
- Good agreement between IASI and NAST-I
- Good agreement with radiosonde
- Figure below is the cloud and surface properties retrieval on 4/29/07
3-D Atmospheric Temperature and Moisture Structures

- 3 movies showing IASI temperature and moisture cross-sections on November 4, 2007 over Anglet France
  - T and H$_2$O as a function of altitude
  - T and H$_2$O along satellite track
  - T and H$_2$O x-track
  - Note fine atmospheric features capture
  - Coherent spatial features
Fine Atmospheric Features Captured from IASI Retrievals

Statistics (101 levels, no vertical averaging)
Examples PCRTM Retrieved land and ocean emissivities

- Over CART ARM Site on April 19, 2007 using IASI data
- Soil (or Quartz, or ?) + vegetation → produce ARM CART site observed emissivity
- Retrieval is not sensitive to emissivity at frequencies where the IASI does not see the earth’s surfaces
  → 645-750, 1400-2000 cm$^{-1}$

- NAST-I retrieved sea Emissivity
  → On Sept. 9, 2004 near Italy
  → Wind speed and scan angle dependencies included
- Retrieval is not sensitive to emissivity at frequencies where the IASI does not see the earth’s surfaces
  → 645-750, 1400-2000 cm$^{-1}$
Summary and Conclusions

• Super channel forward model and retrieval algorithm has been developed
  – PCRTM handles thousand of channels
    • Accurate relative to LBL
    • Very fast in speed
    • Cloud effect modeled (including multiple scattering)
    • Provides forward model and Jacobians in both spectral and EOF domain
  – Super channel retrieval algorithm provides atmospheric and surface properties
    • T, H$_2$O, O$_3$, CO vertical profiles
    • cloud optical depth, cloud height and cloud effective size
    • Surface skin temperature and surface emissivities
• Super retrieval algorithm has been tested with IASI and NAST-I data
  – JAIVEX field campaign provides good data for algorithm testing
  – Spatial resolution can be enhanced using single field of view retrievals
    • Perform cloud parameter retrievals using single FOV
    • No need to make assumptions about variations between adjacent FOVS as required by
      cloud clearing approach
  – Retrieval using more than 8000 channels with efficient computational time
    • Only possible with super channel approach
  – Retrievals agree well with radiosondes, drops soundes and ECMWF profiles
• Lessons learned from IASI, NAST-I, and AIRS are beneficial to future hyperspectral
  sensors
  – CrIS, CLARREO……