Atmospheric Temperature and Moisture Profile Retrievals Using more than Eight Thousand Channels

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1. Introduction

Advanced satellite infrared sensors such as AIRS, IASI, and CrIS, all have one thing in common: large number of spectral channels. It is computationally intensive to retrieve atmospheric and surface properties using all the channels. Usually, only subsets of channels are used to perform physical inversions for atmospheric profiles. We will describe a compact inversion algorithm which compresses the hyperspectral channel information into principal component scores and performs both radiative transfer calculations and retrievals in the principal component domain. The PC scores of the observed radiance spectrum are generated by projecting the spectrum onto a set of pre-calculated principal components. The PC scores of the forward model calculated radiance are obtained by a Principal Component-based Radiative Transfer Model (PCRTM). The PCRTM predicts PC scores and associated derivatives with respect to various atmospheric and surface properties in PC space directly. Usually, less than 150 PCs are needed to regenerate the original radiance spectrum with accuracy better than the instrument noise level. Therefore, the dimension of the spectrum is reduced by an order of magnitude for hyper spectral sensors with thousands of channels. The reduction in dimension and the fast RTM make the physical inversion algorithm very compact and fast. Due to its significant savings in computational time, the approach uses information from all measured channels. There is no need to use only subset of channels.

2. Description of the PCRTM Radiative Transfer Model

PCRTM is not a channel-based RTM (*Reference*: *Liu et al. Applied Optics, 2006*).

– It predicts PC scores (*Y, alternatively called super channels*) instead of channel radiances (*R*)

$$\vec{Y} = A \times \vec{R}^{mono}, \qquad \frac{\partial Y_i}{\partial X} = \sum_{l=1}^{N_{mono}} a_l \frac{\partial R^{mono}(l)}{\partial X}$$

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

$$\vec{Y} = U^T \times \vec{R}^{chan}, \qquad R^{chan} = \frac{\sum_{l=1}^{N_{mono}} \phi_l R_l^{mono}}{\sum_{l=1}^{N_{mono}} \phi_l}$$

- Channel radiances can be obtained by multiplying the PC scores with pre-stored eigenvectors (or PCs):

$$\vec{R}^{chan} = U \times \vec{Y} = \sum_{i=1}^{N_{SCP}} y_i \vec{U}_i + \vec{\varepsilon}$$

- The accuracy of the PCRTM relative to LBL is very good (see figures 1-2)

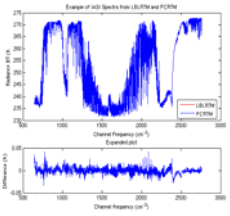

Figure 1. Example of IASI spectra calculated using LBLRTM and PCRTM. The bottom panel is the difference. The PCRTM are orders of magnitude faster in computational speed

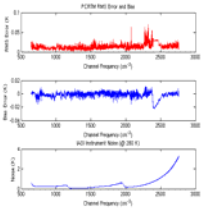

Figure 2. RMS and bias errors of the PCRTM model relative to reference LBL model. The 3rd panel shows a nominal IASI instrument noise spectra.

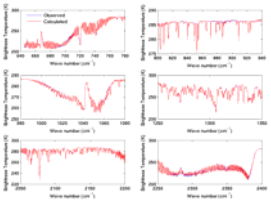

Figure 3. Comparison the observed and calculated IASI spectra in various spectral regions.

3. Description of the Inversion Algorithm

The inversion algorithm is based on a non-linear Levenberg-Marquardt method with climatology covariance and a priori information as constraints:

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

The PCRTM approach has the following advantages:

- All channels included
  - PC scores contains information from all channels
- The dimension of S_y is much smaller
  - Noise correlation included
    - Good to handle interferometer with strong apodization functions
    - Good to include correlated forward model errors
    - Good to include correlated bias correction covariance
- The dimension of S_x is much smaller
  - Inversion is faster
  - EOF transformation stabilize state vector inversions
  - Easy to increase state vector size when multiple pixels are used
- PCRTM provides *K* and *Y* in PC domain directly
  - No need to convert Jacobian and radiance to PC space at each iteration
  - Big computational saving
- Fast speed and small matrix sizes are good for
  - Cloud handling
  - Use spatial and temporal information

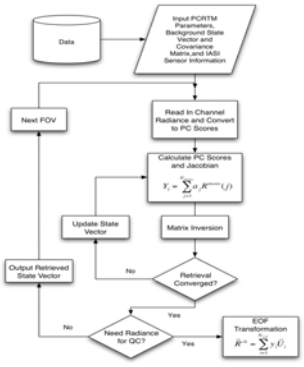

Figure 4. A flow diagram of the PCRTM retrieval algorithm

4. Application of the Retrieval Algorithm to IASI and NAST-I Data

A new physical inversion algorithm has been successfully applied to the NPOESS Airborne Sounder Testbed Interferometer (NAST-I) and the Infrared Atmospheric Sounding Interferometer (IASI) data. Both hyperspectral sensors are Fourier Transform infrared spectrometers with a nominal spectral resolution of 0.25 cm^{-1}. It will be very computationally intensive to included more than 8400 channels in a conventional physical inversion algorithm. On the other hand, the PCRTM retrieval approach uses PC scores generated from all available channels and performs physical retrieval very rapidly. The algorithm also compresses the state vector into profile-based principal components. It serves to reduce the dimension of the state vector and stabilize the solution. The retrieved parameters include cloud top pressure, cloud optical depth, cloud particle size,temperature, moisture, ozone, carbon monoxide vertical profiles, surface skin temperature, and surface emissivities. Since cloud is handled explicitly in this algorithm, a single field of view retrieval is performed. Figures 5-15 shows some results of applying the PCRTM retrieval algorithm to data taken by IASI and NAST during European Aqua Thermodynamic Experiment (EAQUATE) and Joint Airborne IASI Validation Experiment (JAIVEx).

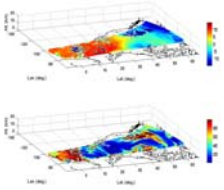

Figure 5. Cross-section of atmospheric temperature and moisture retrieved from IASI during the JAIVEX on April 19, 2007.

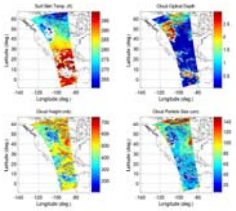

Figure 6. Cross-section of cloud parameters retrieved from IASI during the JAIVEX on April 19, 2007. The climatology background for cloud height and cloud size is set to 500 mbar

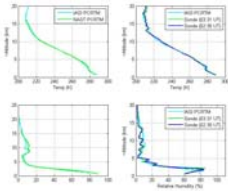

Figure 7. Comparisons of the PCRTM retrieved atmospheric temperature, moisture profiles from NAST-I and IASI over the DOE CART site with

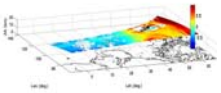

Figure 8. Cross-section of ozone retrieved from IASI during the JAIVEX on April 19, 2007.

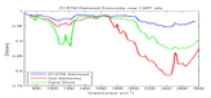

Figure 9. Retrieved surface emissivity over ARM site from IASI during the JAIVEX on April 19, 2007.

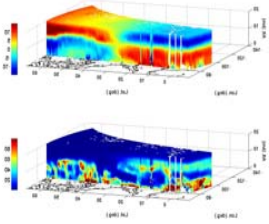

Figure 10. Cross-section of Temperature and moisture profiles retrieved from IASI during the JAIVEX on April 19, 2007. NAST-I underflew over ARM CART site.

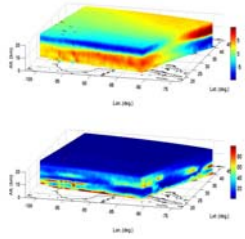

Figure 11. Cross-section of Temperature and moisture profiles retrieved from IASI during the JAIVEX on April 29, 2007. WB57 and BAE-134 underflew IASI over Gulf of Mexico

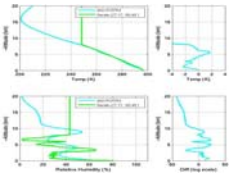

Figure 12. Comparisons of the retrieved atmospheric temperature, moisture profiles with dropsonde on April 29, 2007.

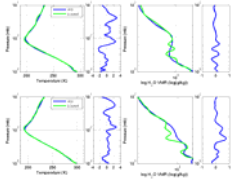

Figure 13. Comparisons of the retrieved atmospheric temperature, moisture profiles with ECMWF profiles

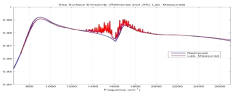

Figure 14. Retrieved sea emissivity from NAST-I spectra taken during EAQUATE campaign in September 2008 and the measured sea water emissivity from the John's Hopkins University emissivity library.

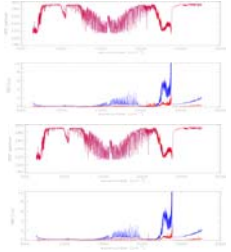

Figure 15. The upper two panels show spectral residuals between observed and fitted IASI spectra. The CO spectral features are clearly visible near 2020-2250 cm^{-1}. The bottom two panels show the spectral residuals after CO is included in the retrieval algorithm.

4. Conclusions

A fast radiative transfer model (PCRTM) and compact retrieval algorithm have been developed. Instead of calculating and inverting traditional channel spectra, the new approach models the eigenvector transformed super channels directly. The retrieval algorithm transforms measured spectra into PC scores and performs retrieval essentially using all available channels. The algorithm has been successfully applied to the NAST-I and IASI hyperspectral data with more than 8400 channels included in the retrievals. The algorithm retrieves cloud parameters explicitly, therefore provides better spatial resolution relative to cloud clearing method. The same mythology can be used for processing future NPP/NPOESS hyperspectral data.

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