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ADVANCED RADIATIVE TRANSFER MODEL FOR REAL-TIME REMOTE SENSING APPLICATIONS

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1. INTRODUCTION

The development cycle of remote sensing instrumentation and the algorithms to derive geophysical quantities from radiometric data is a complex, multi-phase process requiring multiple levels of feedback and interaction between scientists and engineers. The primary phases of this process are the sensor/ algorithm design phase, the implementation phase, the deployment phase and maintenance phase. Though commonly separated into distinct phases, the entire life cycle is by no means a linear process and well-defined mechanisms are essential for incorporating the knowledge acquired at each stage into the overall system. The ability to capture this feedback and rapidly assimilate the information is critical to timely and cost-effective implementation.

The Atmospheric and Environmental Research (AER) Interactive Algorithm ToolBox (IATB) provides a common software framework for effectively accomplishing these tasks. The primary focus has been to provide a software environment for the rapid and effective implementation of the first two phases of this process (design and implementation), however the concepts embodied in this approach could easily be extended to the entire process. The IATB design attempts to balance the programmatic needs for a structured development environment, which in many cases is very application specific, with the needs of the individual contributors.

The basic concept behind the IATB approach is to provide a set of common tools and well-defined interface standards for use across the entire sensor/algorithm development cycle. In particular the IATB provides a general infrastructure including defined interfaces and a generic set of tools for data ingest and export, a database of realistic scenes containing both observed and modeled geophysical parameters and the associated radiances, a library of modules for use as building blocks in the design and analysis, and a set of common analysis and display tools for evaluating designs and performance. A more complete description of the IATB is given in Zaccheo et al. (2004). In addition the IATB also provides a protocol for developing new tools for use in both current and future applications. One of the primary goals of this design was to minimize the amount of software redevelopment that occurred during the development of suites of algorithms with common interface requirements or data needs.

The key aspect of the IATB is the ability to simulate a range of sensor types across the spectrum in a wide range of application scenarios. This requires the ability to accurately model the radiative transfer in all spectral regions, from microwave through the visible, with sufficient radiometric accuracy. It is important that this accuracy is evaluated in both the absolute sense (important for instrument design and for matching measured and modeled radiances) and in a relative sense (important for multi-sensor data fusion, such as the simultaneous use of infrared sounder and visible imager data).

The requirements for accuracy and run-time speed of the radiative transfer models can vary depending upon their use for sensor simulation studies or for the development of remote sensing retrieval algorithms. Thus the IATB is designed to include a suite of models for which there is a traceable path of model cross-calibration and validation. This is accomplished by leveraging AER's extensive development of radiative transfer models. The primary reference model for the IATB is the Line-by-Line Radiative Transfer Model (LBLRTM) (Clough et al., 1992, 1995, 2004), which is widely used in the scientific community. This model uses spectroscopic data from the HITRAN database and has been extensively validated against data collected by the Department of Energy's Atmospheric Radiation Measurement Program (DOE-ARM).

A line-by-line model is typically too slow for application studies, thus the IATB also incorporates several other fast models. These include MonoRTM, RRTM, and OSS. MonoRTM is based on the same theory and structure as

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LBLRTM, but has been designed to perform the monochromatic calculations over relatively narrow spectral regions with much higher efficiency. MonoRTM is valid for all spectral regions from microwave to UV (Boukabara et al., 2002). RRTM is a broader-band model typically used for infrared heating-rate calculations, but may also be used for wider-band infrared sensors (Mlawer et al., 1997). Optimal Spectral Sampling (OSS) is a new approach to radiative transfer modeling which addresses the need for algorithm speed, accuracy, and flexibility (Moncet et al., 2004).

The OSS technique allows for the rapid calculation of radiance for any class of multispectral, hyperspectral, or ultraspectral sensors at any spectral resolution operating in any region from microwave through UV wavelengths by selecting and appropriately weighting the monochromatic points that contribute over the sensor bandwidth. The OSS is currently used as part of the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) CrIS, VIIRS, CMIS, and OMPS-IR environmental parameter retrieval algorithms. The method has recently been incorporated into the Joint Center for Satellite Data Assimilation (JCSDA) Community Radiative Transfer Model (CRTM) (Weng, 2005) and in the near future OSS will be part of the MODTRAN radiative transfer code. The OSS method is particularly well suited for remote sensing applications because of its high computational speed and accuracy that can be made as close as needed to the reference line-by-line model.

In the following sections we will discuss the use of OSS within the IATB in the context of current and future remote sensing systems. The focus is on illustrating the flexibility of the IATB and the OSS model, allowing for convenient testing of various instrument designs and algorithm approaches. In particular we present atmospheric state retrieval results for several on-orbit and future instrument designs.

2. OPTIMAL SPECTRAL SAMPLING (OSS) RADIATIVE TRANSFER MODEL

The OSS technique represents an automated, unsupervised node and weight generation process that can be used to develop a fast radiative transfer model with reasonable constraints on computational speed, accuracy and flexibility. The OSS technique is designed such that no tuning is needed and it is easily adaptable to changes in sensor parameters, mission objectives, variable observer levels or viewing geometry, or to simply update the spectroscopy. Application of OSS-derived nodes and weights allows for monochromatic radiative transfer calculations and accurate treatment of surface reflection. Because the radiative transfer is performed monochromatically it is amenable to thermal and solar multiple scattering applications. The overall radiometric accuracy can be traded for computational speed depending on factors such as the signal-to-noise level of the measurement and the computational requirements of the problem. An OSS-based radiative transfer model has been applied to a number of remote sensing problems and is described in more detail in Moncet et al. (2004).

Within the OSS framework the radiative transfer is performed monochromatically from pre-computed absorption coefficients at each selected node. The molecular absorption coefficients are stored for each vertical layer as a function of temperature. For a given profile the tabulated absorption properties are scaled by the actual molecular amount within each layer and linearly interpolated between temperature entries in order to preserve the computational efficiency. A big advantage of OSS over other fast models is that the OSS optical depth tables are designed to be instrument independent, which allows for the easy interchange of instrument designs within the retrieval algorithm framework with no change to the IATB infrastructure. Further, the radiative transfer remains monochromatic, allowing for a direct coupling with multiple scattering methods. OSS is applicable to both wide- and narrow-band instruments, as well as to those with extended instrument line shapes, such as an un-apodized interferometer. The radiance jacobians necessary for the retrieval of atmospheric parameters are calculated analytically and simultaneously with the radiances, resulting in both high radiometric accuracy and minimal additional computation time (Moncet et al., 2004).

The first major use of OSS was within the NPOESS program. AER produced the Environmental Data Record (EDR) retrieval algorithms for the both the Cross-track Infrared and Microwave Sounding Suite (CrIMSS) and the Conically-Scanning Microwave Imager Sounder (CMIS), and OSS played a key role in both the simulation and retrieval components in the algorithm development. The CrIMSS algorithms, including the OSS components, were delivered and successfully incorporated into the NPOESS/NPP operational retrieval system (Gu et al., 2005); CMIS algorithm development continues with planned conversion into operational code within the next two years. However, extensive testing of the CMIS algorithms has been performed at AER using on-orbit AMSU instruments, where OSS tables have been generated for both the NOAA satellite series based AMSU and the similar instrument on the EOS Aqua platform. OSS continues to evolve and, in addition to CrIMSS and CMIS, OSS tables have been generated for NPOESS-VIIRS. Outside of NPOESS, AER has participated in an international intercomparison of fast models (Saunders et al., 2005). This intercomparison established for the community the speed and accuracy of OSS and led to its selection for incorporation into the Joint Center for Satellite Data Assimilation (JCSDA) Community Radiative Transfer Model (CRTM) (Weng, 2005). The IATB and OSS have been applied to other sensors including AIRS, AMSU, NAST-I, and the GOES-R HES. Work is also on-going to include OSS as an option within the MODTRAN radiative transfer framework.

3. IATB APPLICATIONS AND EXAMPLES

The focus of this paper is to highlight the versatility of the OSS model and the atmospheric retrieval algorithm within the IATB framework. AER has a long history in the field of atmospheric parameter retrievals, including temperature and composition profiles and cloud product retrievals (Isaacs, 1989; Moncet and Isaacs, 1994). In this paper we focus specifically on the retrieval of atmospheric temperature and water vapor profiles for existing and future satellite sensors.

The IATB retrieval algorithm is based on AER's "unified retrieval" (UR) approach, which was successfully applied to microwave sounder data and then further extended in the development of both the CrIMSS and CMIS profile retrieval algorithms (AER, 2001, 2004). As implemented in the IATB, the nonlinear iterative physical retrieval method is augmented with a variable noise matrix to account for errors arising from the nonlinear nature of the retrieval problem. The physical retrieval is one of several retrieval options within the IATB framework, another being a simple linear regression. Also, the retrieval component and the forward model, OSS in this case, are separate modules, allowing for easy coupling of addition pre- and post-processing steps. This separation allows for the same core driver modules to access retrieval methods matched with the instrument design under consideration. This includes retrievals incorporating data simultaneously and/or sequentially from multiple sensors while they are observing the same spatial scene. An example of this is the sequence for the CrIMSS retrieval, with an ATMS (microwave) retrieval followed by a simultaneous infrared and microwave (CrIS and ATMS) retrieval. We should point out that other retrieval options are available within the IATB aside from those pertaining to which inversion algorithm or forward model to use. The most important of these is the treatment of clouds. All three of the most common choices are available within the IATB: cloud-clearing (Chahine, 1974), hole-hunting or above-cloud retrievals, and simultaneous cloud parameter retrieval (AER, 2004). The optimal way to handle clouds is an active research area and the structure and flexibility of the IATB makes it a straightforward process to perform retrieval studies with any or all of these techniques.

In the following sections we focus on clear sky retrievals, emphasizing the role of OSS in the overall retrieval scheme. We present studies performed using three different sensor designs. The scenes for each are very different, and two of the cases involve real measurements from current on-orbit sensors. We first illustrate the IATB as applied to global AMSU data, collected from NOAA-16. This data has been used at AER as part of the CMIS EDR risk reduction program. We next look at retrievals performed on AIRS clear sky observations where the clear sky determination is based upon mapping the MODIS cloud mask to the AIRS field-of-view. Finally we illustrate the application of the same basic retrieval methods to simulated observations based upon a notional GOES-R HES instrument. We should emphasize that the object of these examples is to highlight the utility of the IATB infrastructure with the focus on the fast forward model component, OSS, and that the overall accuracy of the retrievals using real measurements is a subject of current investigation. We should also point out that we are presenting atmospheric profile retrievals, yet the retrieved profiles near the surface are highly correlated with surface properties and temperature. Again, all components of the overall retrieval scheme are under further investigation: This is exactly the purpose of the IATB infrastructure, evaluate and improve the quality of remotely sensed variables.

3.1. AMSU Retrieval

Through a Cooperative Research and Development Agreement (CRADA) with the Air Force Weather Agency (AFWA), we obtain various meteorological and measurement data on a daily basis. These data include AMSU measurements from the NOAA platforms, NCEP AVN forecast and analysis fields, and surface and radiosonde *in situ* measurements. The data is ingested into what has evolved into an operational retrieval/validation scheme. To date only NOAA-16 AMSU data is running operationally on a daily basis, but the same procedures and routines are periodically used to analyze results for other instruments including the AMSU instrument on other NOAA platforms, AMSU on EOS Aqua and AIRS on EOS Aqua.

The processing of a single day of AMSU data begins with data ingest and footprint matching of the AMSU-A and AMSU-B data. Bias and antenna pattern corrections are then applied to the measurements and fed into the retrieval algorithm. Retrieval calibration and validation is performed by mapping the AVN data to the AMSU FOV, feeding the profiles through the forward model (OSS) and comparing simulations with true measurements to generate bias coefficients. In addition, AMSU observation points are co-located with local radiosonde observations to further measure retrieval performance.

An example AMSU measurement for the 22 GHz channel and the corresponding temperature retrieval are illustrated in Figure 1 for the ascending orbits collected on October 19, 2005. There are several reasons for missing retrieval data, first is the fact we are plotting 850 mb data thus any regions that have surface pressures below that are not plotted. Also, the retrieval is considered complete only if the residual between the final simulation and the true measurement is within the sensor noise specifications. Typically this will happen only randomly and for a very small percentage of the scenes except for scenes with precipitation within the FOV. The non-convergent patterns over ocean are those of rain events, which are not modeled. In fact hurricane Wilma can be observed in the Caribbean. The procedures described above have been applied to NOAA-16 AMSU, but the infrastructure is in place to process other on-orbit sensors with only a change in the OSS tables used by the retrieval algorithm to calculate radiances.

3.2. AIRS Retrievals

As part of an internal effort at AER to test retrieval methodologies for infrared sounders, we have performed case studies by applying a scaled down version of the AMSU infrastructure described above to clear-sky AIRS observations. The determination of clear sky comes from mapping the MODIS cloud mask to the AIRS fields-of-view. The same basic retrieval methodology, software and ancillary data sets used for AMSU are applied to AIRS, with the exception of sensor-specific information such as OSS tables for the AIRS channel set. We should point out that the validation of the OSS AIRS forward model is a separate (on-going) effort, and errors not yet uncovered in the spectroscopy will manifest as retrieval errors. Lessons learned from these more focused efforts will be folded into the IATB procedures via the OSS tables. Thus, the retrieval algorithm can be tested to ensure the results are at least within reason while the more in-depth spectroscopy issues are being managed. In the end they are merged but with almost no change to the overall retrieval infrastructure.

As a first step in the testing process we have focused only on ocean scenes because the surface emissivity is much less variable than over land. The AIRS granule shown in Figure 2 contains many potentially clear AIRS scenes, and Figure 3 illustrates the corresponding temperature and water vapor retrievals. The results are presented on the 101 atmospheric levels used by OSS in performing the radiative transfer, and no layer averaging was performed. By performing similar case studies at different locations on a global basis we can begin a first- order evaluation of the retrieval performance. Regions are chosen in which there is a fairly high likelihood of finding an appropriate radiosonde observation for validation. The co-location issue with radiosondes is of high concern when drawing conclusions about retrieval quality, particularly with regard to water vapor retrievals. Temperature fields have weaker gradients in general, thus the radiosonde co-location requirements for temperature are less rigid.

3.3. GOES-R HES Studies

The final example of the utility of the IATB uses the proposed instrument specifications for the GOES-R HES instrument(GOES, 2005). For these tests OSS tables were generated for both grating and interferometer designs, assuming a gaussian line shape for the grating and un-apodized interferograms for the interferometer. The spectral channel set, sensor noise specifications and sample spectrum are shown in Figure 4. A clear-sky scene was generated using global NWP model data interpolated to the proposed HES footprint pattern (Figure 5).

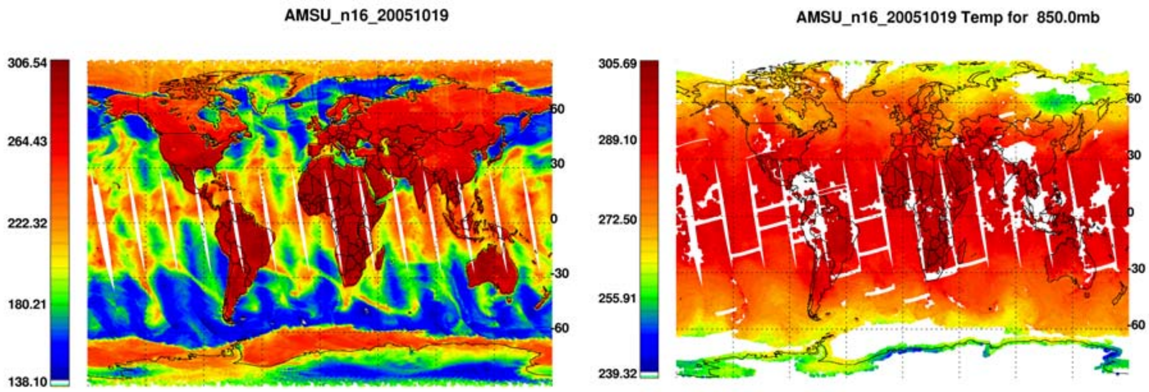

Figure 1 Left) 22 GHz Brightness Temperatures, Right) 850 mb Retrieved temperature. Both for AMSU data collected 19 October 2005, ascending pass.

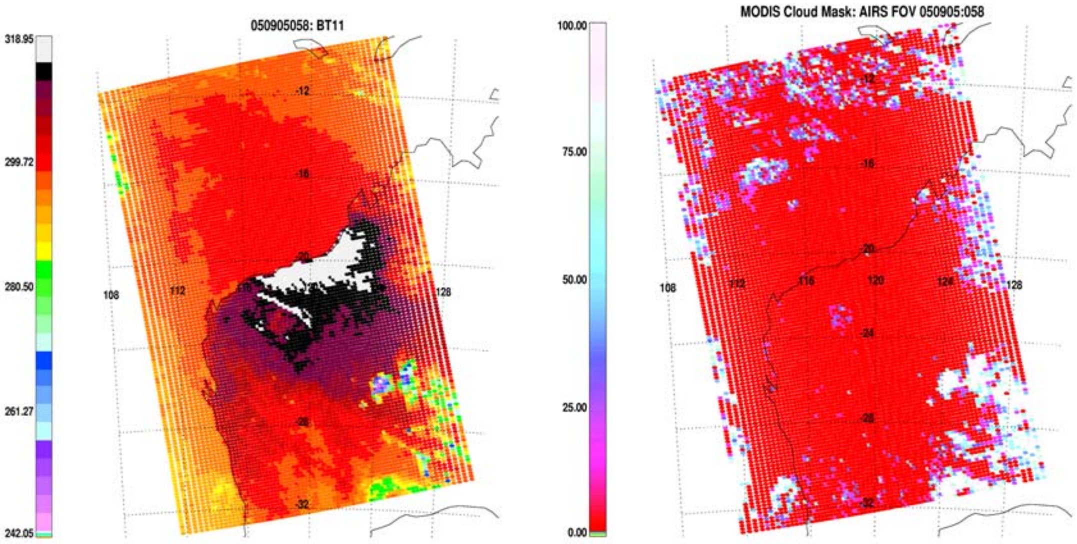

Figure 2 Left) 11μm Brightness temperature, Right) MODIS cloud mask mapped to AIRS FOVs. Both for granule 58 from 9 May 2005.

All inputs to the retrieval algorithm were the same except for the OSS tables. In this case, since we have the “truth” fields we were able to generate error metrics to evaluate the retrieval performance. In Figure 6 we present the errors in temperature and relative humidity for the fields shown in Figure 5. The above procedure can be repeated for instrument design updates and/or design options. Further, trades that require only subsets of channels or only a portion of a larger bandwidth do not require new OSS tables since an channel selection file can be used which will activate only the desired subset within the retrieval scheme. Also, as we pointed out above, instrument noise trades do not require new OSS tables, as the noise file is separate input that is coupled to noise-free radiances at run-time.

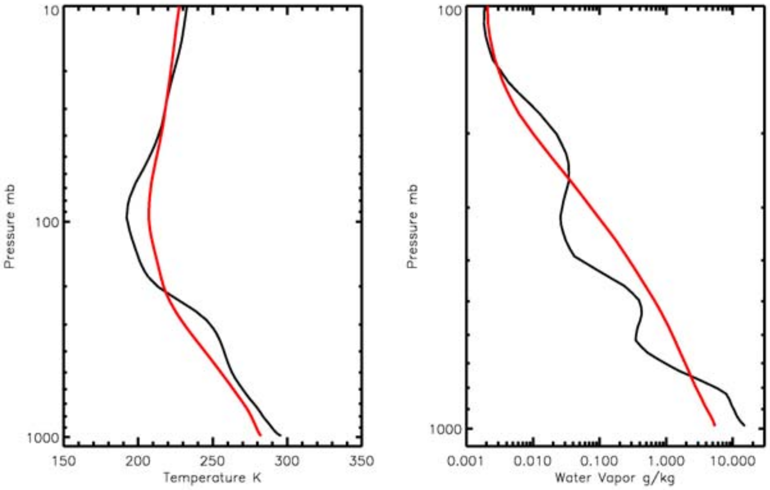

Figure 3.Example temperature and water vapor retrievals for AIRS data granule 58 from 05/09/05. Black: UR retrieval, Red: background (first-guess) profiles.

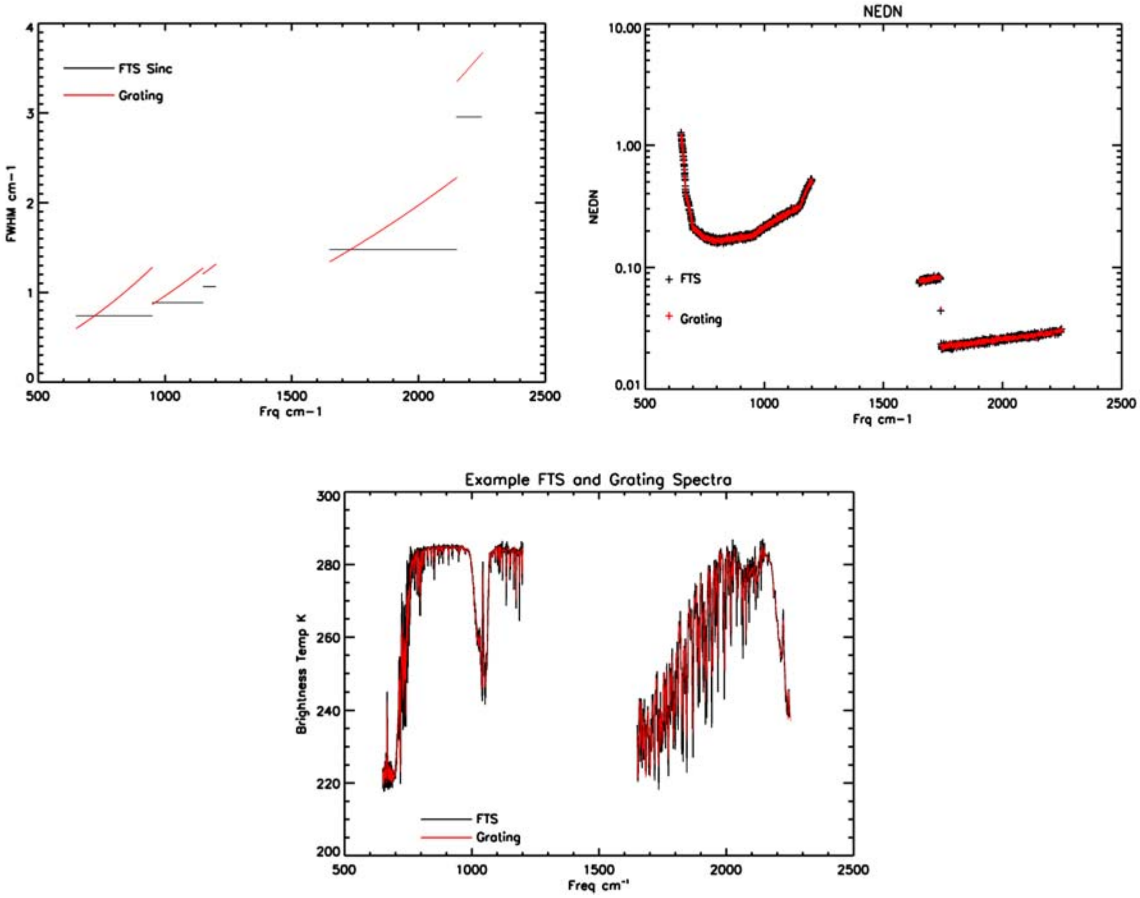

Figure 4 Top Left) FTS and Grating Full-Width-Half Max, Top Right) Instrument noise for each design, Bottom) example spectra for the PORD option we implemented.

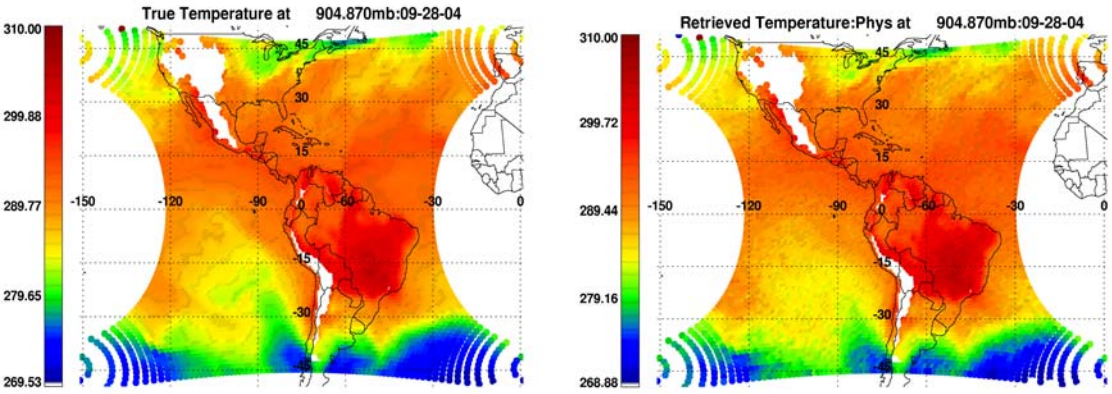

Figure 5 Left) True Temperature field at 904 mb Right) Retrieved temperature field at 904 mb. The missing pixels had surface pressure less then 904 mb.

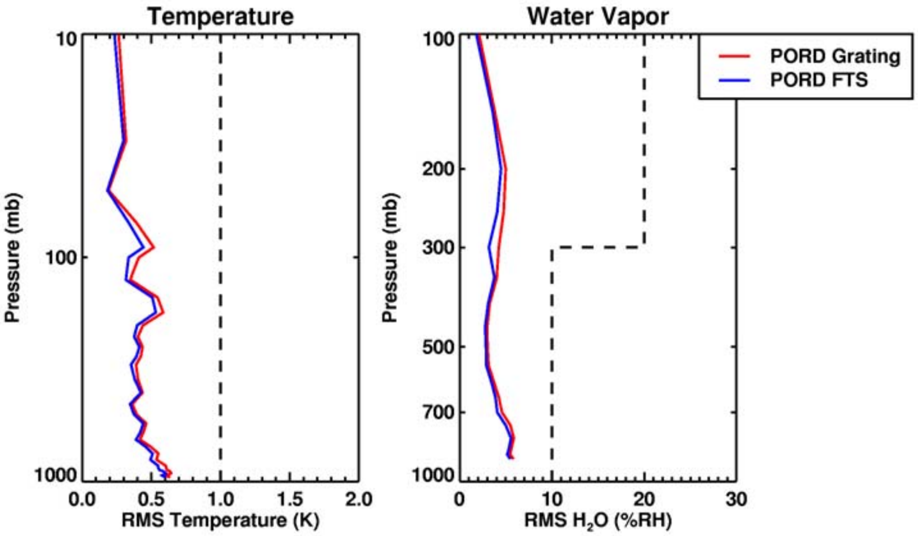

Figure 6. RMS retrieval error for both temperature and water vapor.

4. CONCLUSION

The Interactive Algorithm Tool Box (IATB) is a multi-layered architecture designed to aid in the rapid implementation and end-to-end assessment of algorithms for estimating environmental parameters from remote sensing data. The IATB provides a self-consistent mechanism for performing radiative transfer calculations over a broad spectral range from the microwave to the infrared and visible regions of the spectrum and provides standard mechanisms for building first-order sensor models. The IATB architecture has been applied to algorithms for existing remote sensing systems (e.g. GOES, MODIS, AMSU and AIRS) as well as to sensor suites that will be flown on next generation satellites (e.g. NPOESS and the GOES-R). In this paper we have discussed application of the OSS radiative transfer model within the IATB framework. One of the key advantages of OSS over other fast models is the high accuracy/low computational time overhead for the calculation of the jacobians. In the three examples we illustrated the ease with which the IATB can be used to test the various instrument designs. For each example the same basic IATB modules were used and the only major change was the spectral channel sets used in the calculations.

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