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RETRIEVAL ALGORITHM FOR NPOESS-CRIMSS AND FUTURE OPERATIONAL SOUNDERS

Hilary E. Snell*, Richard Lynch, and Jean-Luc Moncet
Atmospheric and Environmental Research, Inc., Lexington, MA

1. INTRODUCTION

The Cross-track Infrared and Microwave Sounder Suite (CrIMSS) represents the future of operational sounding technology and will fly as part of the National Polar-Orbiting Operational Environmental Satellite System (NPOESS), beginning with the NPOESS Preparatory Project (NPP) in 2006. These satellites will provide global coverage flying in a Polar orbit of approximately 833 km. The NPP and NPOESS satellites carry a diverse set of sensors operating at wavelengths from the microwave through the ultraviolet portions of the spectrum (details may be found on the NPOESS website, listed in the references). Atmospheric and Environmental Research, Inc. (AER) is the Environmental Data Record (EDR) algorithm developer for the CrIMSS, CMIS, and OMPS-IR retrieval algorithms (as described in the ATBDs listed in the references).

The core algorithm upon which the CrIMSS retrieval algorithm is based was initially developed and tested with data from the DMSP Block 5D3 sensor suite. The inversion approach is based upon an improved maximum likelihood method. In particular, a non-linear physical retrieval scheme is used with both radiometric and geophysical constraints (Rodgers, 1976; Rodgers, 1996). The algorithm is designed for computational efficiency, but is also flexible enough to adapt to other sensors and is well-suited for combining multi-sensor and/or multi-footprint information within the same retrieval, either simultaneously or sequentially. The inversion is stabilized through the use of an empirical orthogonal function (EOF) decomposition of retrieval parameters. A regularization method was developed to dynamically adjust the step size to ensure proper convergence by using the difference between observed and simulated radiance as a proxy for the linearization error.

One of the drawbacks of adopting a physical retrieval algorithm is the computationally intense nature of the forward radiative transfer model. Consequently we have developed the Optimal Spectral Sampling (OSS) approach to provide a fast and accurate calculation of the radiative transfer and radiance Jacobians (Moncet et al., 2004). This model enables the simultaneous retrieval of all required parameters while minimizing computation time, since OSS computes the Jacobians analytically rather than by a finite-difference scheme. For CrIMSS the radiance calculation is performed upon a 101 pressure level grid, but the grid is flexible and dependent upon the specifics of the retrieval problem (sensor type and operating spectral region, spectral resolution, and retrieval quantities of interest). With this flexibility re-training of the model is minimized for changing sensors (i.e. during algorithm/sensor trade studies) and measurement geometry (i.e. aircraft platforms). The advantage of using the same basic forward radiative transfer model in all spectral regions is that it allows for a consistent treatment of the physics when performing multi-sensor data fusion.

This paper describes the retrieval approach developed for CrIMSS and the algorithm testbed used to validate algorithm performance using a combination of simulated and real sensor data.

2. CRIMSS

2.1. *Sensor Description*

The Cross-track Infrared Microwave Sounder Suite (CrIMSS) consists of infrared and microwave sensors designed to provide global measurements of atmospheric temperature, water vapor and pressure profiles with a high degree of accuracy at reasonable spatial resolution. The microwave sounder for CrIMSS will be the Advanced Technology Microwave Sounder (ATMS). The

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[*] Corresponding author address: Hilary E. Snell, AER, Inc., 131 Hartwell Ave., Lexington, MA 02421; hsnell@aer.com

channel characteristics, frequency, nominal channel bandwidth, and field-of-view (FOV) size are given in Table 1. The infrared component is the Cross-track Infrared Sounder (CrIS), an interferometer with 1305 channels from 650 – 2550 cm^{-1} (Table 2). The CrIS focal plane is designed such that 9 FOVs are grouped in a 3x3 array pattern that is considered a single field-of-regard (FOR). Both ATMS and CrIS scan across the satellite sub-track, with 30 CrIS FORs per scanline. In practice the scan rate is slightly different (ATMS performs 3 cross-track scans for every CrIS scan), as shown in Table 3. The sensors are appropriately synchronized at the nadir sample point and a footprint matching process is performed in order to provide co-located microwave and infrared measurements. Additional information about the sensor characteristics relevant to the algorithm design and implementation is given in the CrIMSS EDR Algorithm Theoretical Basis Document, available from the NPOESS website (see references).

Channel	Center Frequency (GHz)	Bandwidth (GHz)	Beamwidth (deg)	Approx. FOV size (km) for 833 km orbit
1	23.8	0.27	5.2	75
2	31.4	0.18	5.2	75
3	50.3	0.18	2.2	32
4	51.76	0.40	2.2	32
5	52.8	0.40	2.2	32
6	53.596 ± 0.115	0.17	2.2	32
7	54.40	0.40	2.2	32
8	54.94	0.40	2.2	32
9	55.50	0.33	2.2	32
10	57.290334	0.33	2.2	32
11	57.290334 ± 0.217	0.078	2.2	32
12	57.290334 ± 0.3222 ± 0.022	0.036	2.2	32
13	57.290334 ± 0.3222 ± 0.010	0.016	2.2	32
14	57.290334 ± 0.3222 ± 0.0045	0.008	2.2	32
15	57.290334 ± 0.3222 ± 0.048	0.003	2.2	32
16	88.2	2.0	2.2	32
17	165.5	3.0	1.1	16
18	183.31 ± 7	2.0	1.1	16
19	183.31 ± 4.5	2.0	1.1	16
20	183.31 ± 3	1.0	1.1	16
21	183.31 ± 1.8	1.0	1.1	16
22	183.31 ± 1	0.5	1.1	16

Table 1: ATMS Sensor Characteristics

Band	Spectral Range	Un-Apodized Spectral Resolution	Number of Channels
LWIR	650 – 1095 cm^{-1}	0.625 cm^{-1}	713
MWIR	1210 – 1750 cm^{-1}	1.25 cm^{-1}	433
SWIR	2155 – 2550 cm^{-1}	2.50 cm^{-1}	159
Total			1305

Table 2: CrIS Sensor Characteristics

Parameter	CrIS	ATMS
Maximum Scan Angle (edge-of-scan)	+/- 49.395 degrees	+/- 52.725 degrees
FOV Spacing	1.11 degrees	1.11 degrees
FOV Beam Diameter	0.963 degrees	5.2 degrees (ch 1 & 2) 2.2 degrees (ch 3-16) 1.1 degrees (ch 17-22)
Scan Duration	8 seconds	8/3 seconds
FOR Rotation	49.395 degrees at EOS	N/A

Table 3: Comparison of CrIS and ATMS Geometry Characteristics

2.2. Retrieval Algorithm

The CrIMSS EDR algorithm was developed to meet the NPOESS requirements under both clear and cloudy conditions. (See the CrIMSS EDR ATBD for more information on specific NPOESS requirements.) The algorithm is executed in two distinct stages in order to exploit all of the available microwave (MW) and infrared (IR) radiometric information.

In the first stage a retrieval is performed on an FOR-sized footprint using only the ATMS channels. Since the MW channel radiances are much less affected by clouds than the IR channel radiances, this step provides a reasonable estimate of the profile structure under all weather conditions. Before performing the second retrieval stage, the FOR is classified as clear or cloudy. This is accomplished using information about the radiometric contrast between the 9 IR FOVs within the FOR. The second stage retrieval incorporates both MW and IR channels, with the specifics of the retrieval dependent upon the classification of the scene.

In particular, several tests are applied to extract cloud information from the observations. As a first step, each IR FOV is designated as clear or cloudy by comparing simulated IR clear radiances, generated using the MW-retrieved state vector, with the measured IR radiances. Next, the information content in the measurements is used to estimate the number of “cloud formations” (Chahine, 1977) within the FOR. This information is used to group the FOVs in a way designed to optimize the retrieval quality and maximize the retrieval spatial resolution. Each group, or cluster, will have a cloud condition classification assigned to it, and this designation will be used to determine the retrieval strategy. Table 5 shows the conditions and retrieval strategy implemented. For clusters determined to be clear, the retrieval is performed upon an averaged radiance. This is the optimal situation since averaging the measurements will reduce the noise. For clusters labeled partly cloudy the cloud-clearing algorithm will be used to generate a “cloud-cleared observation” for which the retrieval is performed (Smith, 1968; Chahine, 1974; Chahine, 1977; Chahine and Susskind, 1989). This is the opposite of the clear sky retrieval in the sense that the noise is amplified by the cloud-clearing method. For overcast scenes, the cloud top is estimated and only the IR channels not sensitive to the cloud and MW channels are used in the retrieval.

Classification	Retrieval Strategy
clear	Clear retrievals
partly cloudy	Cloud-clearing
overcast	Cloud retrieval followed by retrieval above cloud

Table 5: Retrieval Flags and Associated Retrieval Strategies

Several methods to reduce the dimensionality of the inverse problem (and thus stabilize the solution) have been proposed in the literature (e.g., Pseudo Inverse, Single Value Decomposition). In the CrIMSS algorithm, this is achieved by projecting the state vector onto a set of pre-computed Empirical Orthogonal Functions (EOFs). The EOFs are obtained by applying principal component analysis (PCA) to a background covariance matrix derived from a large ensemble of temperature and moisture profiles representative of global climatology. The two main purposes of a transformation into the EOFs domain are: 1. Eliminating EOFs with small eigenvalues in order to stabilize the solution, and 2. Reducing the number of retrieved parameters (and thus reducing the time needed for inversion). It should be noted that the background covariance matrix for moisture is ill-conditioned in the upper troposphere and the stratosphere, owing to the lack of measurements above 300 mb. Moreover, this problem becomes worse as the number of vertical levels increases, because inter-level correlation increases with an increasing number of levels. The PCA approach avoids these complications.

Retrieval/simulation studies and EOF analyses were conducted to determine the optimal number of retrieval parameters, listed in Table 4. Note that carbon dioxide is considered to be a fixed gas, but a reasonable value must be used for accurate temperature retrievals (future versions will likely include CO_2 as a retrieved parameters). Also note that channels between 950 and 1095 cm^{-1} are excluded in the retrieval in order to limit the impact of ozone (thus requiring only a single EOF).

Parameter	Number of Elements
Temperature	20 EOFs
Water Vapor	10 EOFs
Ozone	1 (column correction)
Other Trace Gases	1 (column correction)
Surface Skin Temperature	1 for MW and IR
MW Surface Emissivity	5 EOFs
MW Cloud Liquid Water	1
MW Cloud Top Pressure	1
IR Surface Emissivity	12 hinge points
IR Surface Reflectivity	12 hinge points

Table 4: Parameters Retrieved by the CrIMSS Algorithm

3. DATA FOR TEST AND VALIDATION

AER has developed an Integrated Algorithm Toolbox (IATB) to provide infrastructure for the development and testing of retrieval algorithms (Zaccheo et al., 2004). The IATB infrastructure contains a living library of both environmental state vectors and a wide spectrum of radiance data obtained from both simulated sources as well as observed data from a variety of Earth-observing sensors. Data is obtained in real-time from the Air Force Weather Agency (AWFA) and the Air Force Research Laboratory (AFRL), by means of Cooperative Research and Development Agreements (CRDA). Additional data arrives directly from NASA and NCEP. The data types include satellite measurements, *in situ* measurements, weather prediction products, and ancillary data used as part of the algorithm validation process. The ability of the testbed to analyze retrievals globally on a daily basis provides an excellent platform for on-going algorithm testing and verification.

Currently, on a continuous basis, we obtain and process surface observations, radiosonde soundings, analyses and forecasts from the NOAA Global Forecast System (GFS), data from the NOAA-16 Advanced Microwave Sounding Unit (AMSU) and from the east and west Geostationary Operational Environmental Satellite (GOES) imagers. In addition, data from the NASA Earth Observing System (EOS) Terra and Aqua satellites are processed on an intermittent basis, and will begin continuous processing of the data in the near-term. From Aqua, our processing includes radiances and retrieval products from the Atmospheric Infrared Sounder (AIRS), Advanced Microwave Scanning Radiometer -EOS (AMSR-E), and the Moderate Resolution Imaging Spectroradiometer (MODIS). These real-time data are used for long-term analyses of sensor products and algorithms.

4. ONGOING VALIDATION ACTIVITIES

Extensive testing of the CrIMSS algorithm has been performed on simulated data. However, the best test of an algorithm is its ability to work with real data. To this end the CrIMSS algorithm has been applied to data from the AMSU and AIRS sensors on the EOS-Aqua satellite. AIRS is an infrared sounder with similar spectral coverage and spectral resolution, spatial resolution, and viewing geometry as CrIS. AMSU is a microwave sounder with similar channels as ATMS (a subtle difference is that AMSU and AIRS have a co-located scan pattern while footprint matching is required to map ATMS to the CrIS scan pattern). Data from AMSU/AIRS provides an excellent opportunity to understand the retrieval abilities of the CrIMSS algorithm.

The AMSU data from NOAA-16 are processed daily along with a post-processing procedure that co-locates the AMSU retrievals with radiosondes. The radiosonde data is used as a measure of the true atmospheric profile and provides a basis for evaluating the retrieval algorithm performance. As part of the co-location process, the AMSU retrievals found to have very low amounts of cloud liquid water are flagged as “clear”.

The same procedure that we apply daily to the NOAA-16 AMSU data was also applied to the EOS AMSU data. One specific AMSU/radiosonde match up region was chosen to illustrate the AMSU/AIRS retrievals: AIRS Granule 008 collected on 4 October 2003. Examination of the brightness temperatures around 11 microns indicates the presence of thick clouds within the scene (Figure 1). Auxiliary data from MODIS (not shown here) indicated patchy low clouds over the entire scene, though there are a number of spots that appear to be nearly clear. The scene is much more uniform after cloud-clearing has been applied to mitigate the impact of clouds (Figure 2, note the scale change from Figure 1).

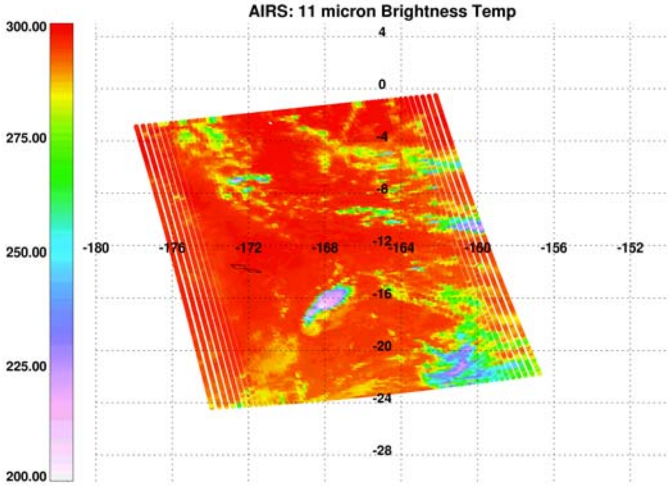

Figure 1: Observed scene radiance (given in brightness temperature) for channels around 900 cm^{-1} indicates the presence of clouds within the scene.

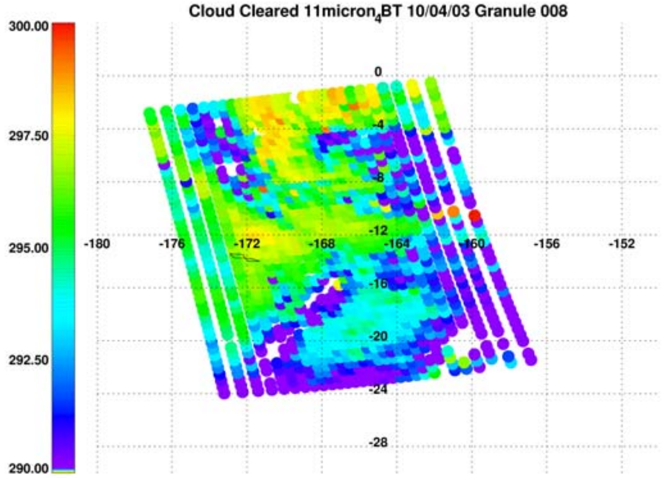

Figure 2: Observed scene radiance (given in brightness temperature) for channels around 900 cm^{-1} after the application of cloud-clearing.

As stated above, this particular granule was chosen because a co-location was found between the AMSU retrieval and a radiosonde. The co-location algorithm does a time and space match up; the match up chosen here was also a case for which the AMSU retrieval indicated no cloud within the FOV. Of course a MW retrieval indicating no cloud within the FOV does not translate into no cloud observed by the IR, but the co-located IR FOR was very warm and exhibited little variability between the FOVs within the FOR. The scene classification algorithm labeled the FOR clear and thus the FOVs were averaged and a retrieval performed on this averaged measurement. Figure 3 shows a comparison of the radiosonde, microwave-only retrieval, and final retrieval product for temperature and water vapor. Note the excellent agreement, particularly for the water vapor profile. It should also be noted that the radiosonde measurement is not exactly co-located with the AIRS measurement, so some differences due to spatial inhomogeneity are to be expected.

The measured spectrum from AIRS is given in the top panel of Figure 4. Note that because of sun glint data shortward of 1600 cm^{-1} was not used in the retrieval. The bottom part of the figure shows the radiance residual between the averaged radiance and the radiance computed from the final retrieved profile. Note that in general the residuals are well within the sensor noise level (shown as the lighter, near-horizontal lines in the figure).

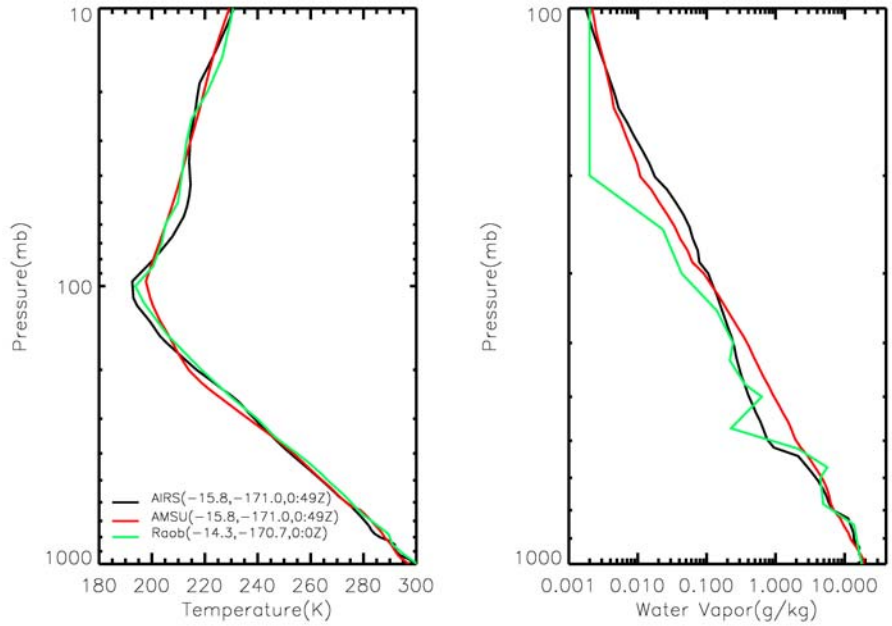

Figure 3: Comparison of radiosonde, microwave-only, and final retrieval product for both temperature and water vapor.

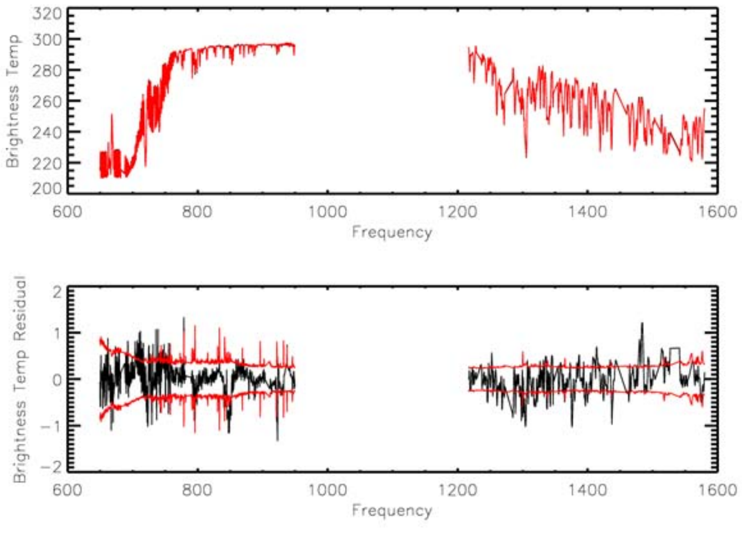

Figure 4: Measured AIRS spectrum (top) and radiance residuals.

5. CONCLUSIONS

The NPP and NPOESS spacecraft represent a significant improvement to the current measurement of environmental parameters necessary for day-to-day weather operations. The CrIMSS algorithm, developed at AER, has been chosen as the operational algorithm for these platforms. The algorithm is fast, efficient and designed to meet the NPOESS requirements. The microwave component of the algorithm has been running operationally on NOAA-16 AMSU data for the last two years. We have tested the algorithm on AMSU/AIRS measurements with very promising results. Although not shown here, the algorithms have also been tested using data from the NPOESS Testbed Airborne Simulator Infrared (NAST-I) instrument. The results also showed the ability to generate retrievals that matched both local radiosondes and even more co-located dropsondes (see the CrIMSS ATBD for more information). The algorithm structure has been designed such that switching from one instrument to another only requires input files to be changed, particularly the OSS forward model parameters.

6. ACKNOWLEDGEMENTS

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