The Atmospheric Infrared Sounder (AIRS) on Aqua: Instrument Stability and Data Products for Climate Observations

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Abstract – This paper discusses the stability of the AIRS instrument as measured pre-flight and in-orbit. In order to differentiate instrument related changes with true changes in climate observations, the instrument stability must be demonstrated. The AIRS Level 1B Radiance Products show exceptional radiometric and spectral stability. Comparison of AIRS SST derived from the Level 1B products show better than 0.2K rms variation since launch. Spectral stability is also better than 0.2ppm of the center frequency. This stability is attributable to the instrument design approach and simplicity of the AIRS calibration algorithms. No change to the Level 1B calibration algorithms have been made since launch, making the Level 1B radiances climate data records in themselves.

Keywords: Atmosphere, Sounding, Calibration, Stability

1. INTRODUCTION

The Atmospheric Infrared Sounder (AIRS) is a spaced based infrared sensor on the EOS-Aqua Spacecraft. AIRS is designed to measure atmospheric temperature and water vapor profiles with improved sensitivity and accuracy than prior systems in support of weather forecasting and climate changes studies. When combined with the Advanced Microwave Sounding Unit (AMSU-A), the AIRS/AMSU system produces the data products with accuracies identified in Table A.

Table A. AIRS/AMSU Data Products and Accuracies

<table>
<thead>
<tr>
<th>Radiance Products (Level 1B)</th>
<th>RMS Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIRS IR Radiance</td>
<td>3%</td>
</tr>
<tr>
<td>AIRS VIS/NIR Radiance</td>
<td>20%</td>
</tr>
<tr>
<td>AMSU Radiance</td>
<td>0.25 - 1.2 K</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Standard Core Products (Level 2)</th>
<th>RMS Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloud-Clear IR Radiance</td>
<td>1.0 K</td>
</tr>
<tr>
<td>Sea Surface Temperature</td>
<td>0.5 K</td>
</tr>
<tr>
<td>Land Surface Temperature</td>
<td>1.0 K</td>
</tr>
<tr>
<td>Temperature Profile</td>
<td>1 K</td>
</tr>
<tr>
<td>Humidity Profile</td>
<td>1.5%</td>
</tr>
<tr>
<td>Total Precipitable Water</td>
<td>5%</td>
</tr>
<tr>
<td>Fractional Cloud Cover</td>
<td>5%</td>
</tr>
<tr>
<td>Cloud Top Height</td>
<td>0.5 km</td>
</tr>
<tr>
<td>Cloud Top Temperature</td>
<td>1.0 K</td>
</tr>
</tbody>
</table>

The fundamental climate record produced by the AIRS instrument is the calibrated upwelling radiances produced in the Level 1B data product. They contain the raw information on atmospheric temperature, water vapor and trace gasses that can be derived within the resolution capacity of the instrument. Stability of the Level 1B products is emphasized in this paper since they are fundamental to producing stable higher level products.

2. AIRS INSTRUMENT

The AIRS instrument, developed by BAE SYSTEMS, (shown in Figure 1) incorporates numerous advances in infrared sensing technology to achieve a high level of measurement sensitivity, precision, and accuracy (Morse, 1999). This includes a temperature-controlled grating and long-wavelength cutoff HgCdTe infrared detectors cooled by an active-pulse-tube cryogenic cooler. It is this temperature control that is most likely responsible for the observed stability in the instrument. The AIRS infrared spectrometer acquires 2378 spectral samples at resolutions, \( \lambda/\Delta \lambda \), ranging from 1086 to 1570, in three bands: 3.74 \( \mu m \) to 4.61 \( \mu m \), 6.20 \( \mu m \) to 8.22 \( \mu m \), and 8.8 \( \mu m \) to 15.4 \( \mu m \). AIRS scans the earth scene up to \( \pm 49.5^\circ \) relative to nadir with a spatial resolution of 13.5 km. Each scan provides a full aperture view of space and an on-board blackbody calibration source. AIRS also has a VIS/NIR photometer, which contains four spectral bands with a spatial resolution of 2.3 km.

Figure 1. The AIRS Instrument Prior to Delivery to the Aqua Spacecraft.
3. MEASUREMENT ACCURACY AND STABILITY

3.1 Pre-Flight

Accurate characterization of the instrument response is critical to climate observations. Results from the pre-flight calibration are presented in the literature (Pagano, SPIE, 2000). They show very good characterization of the radiometric, spectral and spatial response of the AIRS. Here we highlight the stability of the measurements as an indicator of the stability of the instrument observed pre-flight.

Spectral calibration was performed using an interferometer as a spectral calibration source. Signals were acquired on every detector simultaneously for each step of the interferometer mirror. The instrument spectral response was obtained by Fourier Transform of the measured response. Measurements were made at three different temperatures and resulted in no change to the spectral response shape. Absolute knowledge of the spectral response centroids prior to flight is expected to be better than 5 ppm (Pagano, SPIE, 2000).

The radiometric calibration equations for AIRS are relatively simple and include an offset, gain, and nonlinearity term and a small polarization correction term (Pagano, IEEE, 2003). The radiance of the scene is given by

\[
N = a_0 + a_1(\Delta n - \Delta n_{pr}) + a_2(\Delta n - \Delta n_{pr})^2
\]

\[
[1 + p_r p_t \cos(\theta - \delta)]
\]

Where \( p_r \) and \( p_t \) are the polarization factors for the scan mirror (t) and the spectrometer (t), and \( \theta \) and \( \delta \) are the angles of the scan mirror and spectrometer polarization orientation respectively. The offset term, \( a_0 \), is due to the modulation of the emission of the scan mirror due to coupling of polarization with the spectrometer and varies with scan angle

\[
a_o(\theta) = N_{str} p_r p_t \cos(2(\theta - \delta)) \cos(2\delta)
\]

The first order term \( a_1 \) is the instrument gain and is calculated in orbit using the \( \Delta n \)'s from the OBC blackbody and space and the OBC radiance and solving the above calibration equation for \( a_1 \) at the angles of the OBC of 180 degrees.

\[
a_1 = \frac{e N_{obc} (1 + p_r p_t \cos(2\delta) - a_o(\theta_{obc}) - a_2(\Delta n_{obc} - \Delta n_{pr})^2)}{(\Delta n_{obc} - \Delta n_{pr})} \]

Coefficients for these terms were derived from a set of linearity tests that took over 12 hours to complete. During this time, a well calibrated external blackbody (the Large Area Blackbody (LABB)) is stepped in temperature and the instrument response is recorded. The resulting nonlinearity from two separate measurements is plotted in Figure 2. These measurements show better than 0.2% repeatability of the nonlinearity measurement for tests taken four days apart and at different scan angles.

Data from the first day were used derive the radiometric calibration coefficients for AIRS Level 1B calibration algorithms. These were then applied to data acquired four days later to observations of the LABB calibration source. The Level 1B faithfully reproduced the LABB temperature to within 0.1K for most bands as shown in Figure 3.
This type of end-to-end testing of the Level 1B calibration prior to flight was very successful for AIRS. The Level 1B radiometric calibration coefficients derived during these tests prior to launch have not been updated one year later in flight since the validation campaign shows good agreement with in-situ, aircraft and spaceborne measurements from other sensors.

3.2 In-Flight

The accuracy of the Level 1 products look exceptional at this time. Figure 4 shows a comparison of the AIRS-measured radiances (in terms of brightness temperature) (O) compared to calculations based on the ECMWF forecast (C) using the AIRS Radiative Transfer Algorithm (RTA). Results show a bias of better than ±1.0 K difference for most of the spectrum with no tuning applied. This comparison tells us that the AIRS radiances are very close to truth, but also that the ECMWF forecast models are very good. These biases are very stable and have not changed by more than 0.1K-0.2K since launch.

Figure 5 shows the results of the comparisons of AIRS channel 2616 cm⁻¹ with the RTG SST (based on buoy measurements) between 1 September 2002, when routine data from AIRS became available, and 31 March 2003. The comparison generates one point per day. Each point corresponds to the comparison of about 8000 clear AIRS footprints over nighttime ocean. The results show excellent stability of 0.1 K RMS. We also believe that a component of this variation is due to natural variability of the scene. Statistics for AIRS SST measurements will improve with the release of cloud cleared Level 2 SST. This may be offset by increased uncertainty introduced by the cloud clearing process.

Figure 6 shows the change that occurred in the instrument transmission due to icing during the timeframe of the SST observations shown in Figure 5. We plot the inverse of αᵢ (the gain term) as a measure of optical throughput. On September 1, 2002, a defrost of the AIRS instrument was completed. After this event, ice re-accumulated on the optics causing a reduction in optical throughput. The ice accumulation stopped in mid-September and has been slowly outgassing ever since. Despite the change in transmission, the self-calibration of the sensor worked well producing stable radiometric response throughout the time frame. Again, there has been no change to the radiometric calibration coefficients since prior to launch.

Spectral centroids of the SRFs are determined in orbit by correlating observed upwelling radiance spectra with pre-calculated, modeled radiance spectra. Because some parts of the spectrum are more suitable than others, this is done for many separate spectral regions (referred to as 'spectral features'), rather
than for the focal plane as a whole. The resultant correlations are fit to, and the location of the maximum correlation is determined. The focal plane shift corresponding to the maximum correlation is the observed shift of the feature. By combining the observed shifts from several different spectral features, the focal plane shift is determined. From that shift, the centroids of each detector can be calculated.

Results of using this technique to determine the stability of the AIRS is shown in Figure 7. The figure shows 7 months of stability data where the shift is expressed in terms of "microns". For AIRS, 1 micron of focal plane shift is 1% of the SRF width. Since the AIRS widths are approximately 1/1000 of the center frequency, the 0.2 micron shift we observe is approximately 2ppm of the center frequency. This far exceeds our stability requirement of 10ppm.

These calibration features of AIRS result in a well calibrated and stable Level 1B product. No changes have been made to the radiometric calibration since prior to launch. Independent validation of the AIRS Level 1B radiances shows good agreement with ocean buoy, aircraft and other instruments. The AIRS radiances are a viable climate data record that will be available for climate changes studies involving atmospheric processes for many years.

ACKNOWLEDGEMENTS

The authors would like to thank Thomas Hearty, Steve Licata, and Rudy Schindler of the AIRS Calibration Team at JPL, Ken Overoye of BAE Systems, Margie Weiler of Swales, and Scott Hannon of UMBC.

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