Level 1B Products from the Atmospheric Infrared Sounder (AIRS) on the EOS Aqua Spacecraft

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Abstract

The Atmospheric Infrared Sounder (AIRS) was launched May 4, 2002 on the EOS Aqua Spacecraft. A discussion is given of the objectives of the AIRS experiment, including requirements on the data products. We summarize the instrument characteristics, including sensitivity, noise, and spectral response, and preflight calibration results leading to the estimate of the calibration accuracy. The Level 1B calibration algorithm is presented as well as the results of in-flight stability and sensitivity measurements.

Keywords: Atmosphere, Sounding, Calibration, Stability

Introduction

The Atmospheric Infrared Sounder (AIRS, shown in Fig. 1) is a hyperspectral infrared sensor on the Earth Observation Satellite (EOS)-Aqua Spacecraft. AIRS is designed to measure atmospheric temperature and water vapor profiles with greater 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 1. This paper focuses on the AIRS IR Radiance product. The 3% accuracy requirement is met easily as shown here. A description of the project status one year after launch can be found in the literature (Pagano et al., SPIE 2003).

Table 1: AIRS/AMSU Data Products and Accuracies

	RMS Uncertainty
Radiance Products (Level 1B)	
AIRS IR Radiance	3%
AIRS VIS/NIR Radiance	20%
AMSU Radiance	.25 – 1.2 K
Standard Core Products (Level 2)	
Cloud-Clear IR Radiance	1.0 K
Sea Surface Temperature	0.5 K
Land Surface Temperature	1.0 K
Temperature Profile	1 K
Humidity Profile	15%
Total Precipitable Water	5%
Fractional Cloud Cover	5%
Cloud Top Height	0.5 km
Cloud Top Temperature	1.0 K

Fig. 1: The AIRS Instrument Prior to Delivery to the Aqua Spacecraft

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AIRS Instrument

The AIRS instrument, developed by BAE SYSTEMS, incorporates numerous advances in infrared sensing technology to achieve a high level of measurement sensitivity, precision, and accuracy (Morse et al., 1999). This includes a temperature-controlled spectrometer (158K ± 0.1K) 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 Focal Plane Assembly (FPA) contains 17 individual line arrays of detectors in a 2 x N element array where N ranges from 94 to 192. The AIRS acquires 2378 spectral samples at resolutions, $\lambda/\Delta\lambda$, ranging from 1086 to 1570, in three bands: 3.74 µm to 4.61 µm, 6.20 µm to 8.22 µm, and 8.8 µm to 15.4 µm. AIRS scans the earth scene up to ±49.5° 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 visible/near infrared (VIS/NIR) photometer, which contains four spectral bands with a spatial resolution of 2.3 km.

Pre-Flight Instrument Characterization

Accurate characterization of the instrument response is critical to climate observations. Results from the pre-flight calibration are presented in the literature (Pagano et al., 2000). They show very good characterization of the radiometric, spectral, and spatial response of the AIRS. Here we highlight the stability of the results indicating a stable instrument and Level 1B data product.

Radiometric Calibration Equations and L1B

The radiometric transfer equations are derived from the design of the AIRS instrument and the measurement approach as discussed in the literature (Pagano et al., IEEE 2003). These radiometric transfer equations form the basis of the Level 1B calibration for AIRS. The scene radiance is derived from the signal counts as follows:

$$N_{sc,i,j} = \frac{a_o(\theta_j) + a_{1,i}(dn_{i,j} - dn_{sv,i}) + a_2(dn_{i,j} - dn_{sv,i})^2}{1 + p_r p_t \cos 2(\theta_j - \delta)} \qquad (1)$$

and

$$a_o(\theta_j) = P_{sm} p_r p_t [\cos 2(\theta_j - \delta) + \cos 2\delta] \qquad (2)$$

The second part of the gain and offset correction every scan is to perform a gain correction using the On-Board Calibrator (OBC) blackbody. We discuss calibration of the OBC blackbody below. Once achieved, the gain used in flight in the radiometric transfer equation is obtained using the first radiometric transfer equation solving for the a_1 term while viewing the OBC blackbody.

$$a_{1,i} = \frac{N_{OBC,i}(1 + p_r p_t \cos 2\delta) - a_o(\theta_{OBC}) - a_2(dn_{obc,i} - dn_{sv,i})^2}{(dn_{obc,i} - dn_{sv,i})} \qquad (3)$$

Explicitly defining the terms in the radiometric transfer equations, we have:

$N_{sc,i,j}$ = Scene radiance of the i^{th} scan and j^{th} footprint (mW/m^2-sr-cm^{-1})
P_{sm} = Plank radiation function evaluated at the temperature of the scan mirror
$N_{OBC,i}$ = Radiance of the On-Board Calibrator (mW/m^2-sr-cm^{-1})
i = Scan Index
j = Footprint Index (1 to 90)
θ = Scan Angle. θ = 0 is nadir.
$dn_{i,j}$ = Raw Digital Number in the Earth View for the i^{th} scan and j^{th} footprint

$dn_{sv,i}$ = Space view counts offset. This is an algorithmic combination of eight AIRS raw space view digital numbers.

a_o = Radiometric offset. This is nonzero due to polarization and is scan angle dependent.

$a_{1,i}$ = Radiometric gain. This term converts dn to radiance based on the radiometric gain as determined using the OBC blackbody.

a_2 = Nonlinearity Correction

$p_r p_t$ = Polarization Product. This is the product of the polarization factor from the scan mirror and the spectrometer.

δ = Phase of the polarization of the AIRS spectrometer

Radiometric Sensitivity and Noise

Radiometric sensitivity is expressed as the Noise Equivalent Temperature Difference (NEdT) for a scene temperature of 250K. The NEdT for AIRS is measured by interpolating the noise while viewing cold space and the OBC at 308K as published in the literature (Pagano, IEEE 2003). The NEdTs for AIRS are shown in Fig. 2 pre-flight and in-orbit as calculated using equation 5.

Noise characterization is performed by acquiring instrument digital output while viewing a known calibration target temperature. In this test, the AIRS scan mirror is locked at the calibration target for 20 minutes while data are collected. For AIRS, data were acquired while viewing the Space View Blackbody (SVBB), and the Large Area Blackbody (LABB). Fig. 3 shows the noise amplitude (1 sigma) in counts while viewing the space view. Also shown in the figure is the amplitude of the noise that is correlated among all the channels in a module. Correlated noise does exist in some AIRS modules, with M1, M2, M4, and M8 showing the greatest levels. Worst case, these levels are about 2x lower than the nominal noise and are not surprising since all detectors in a readout share common circuitry. These levels are very low since the AIRS noise is very low in the shortwave channels, and the random noise will be higher at non-zero scene radiances.

Calibration Coefficients

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 LABB, is stepped in temperature, and the instrument response is recorded. The resulting nonlinearity from two separate measurements is plotted in Fig. 4. We see less than 1.5% nonlinearity with better than 0.2% repeatability of the measurement for

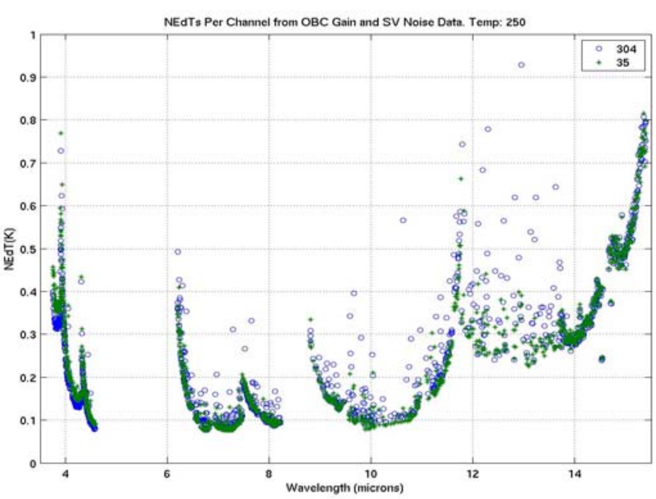

Fig. 2: NEdTs for AIRS at 250K measured pre-launch and in orbit

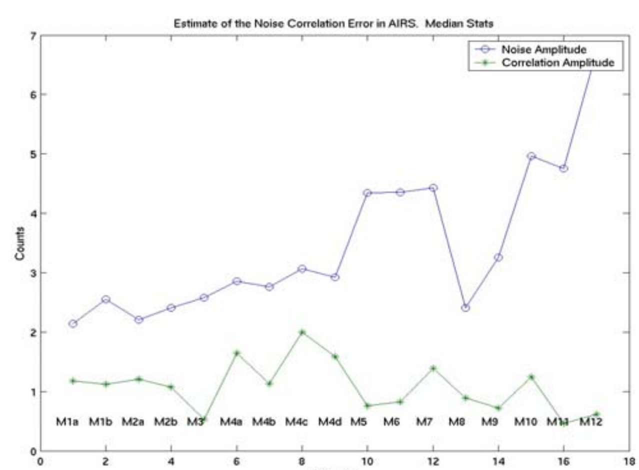

Fig. 3: Amplitudes of the random noise and the correlated noise in the 17 airs modules.

tests taken four days apart and at different scan angles.

Fig. 5 shows the polarization term, $p_r p_t$, calculated using three different methods. The first uses the offset from the linearity tests and equation 2 to solve for the polarization term. Data from two different tests are shown in the figure. We also plot the polarization obtained from the bottoms-up component model and from the subsystem-level test, which measured the polarization of the spectrometer. The worst-case difference is $\pm$ 0.4K. The Level 1B uses the average of the “component” and “measured” polarization products.

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.

Radiometric Uncertainty

We can determine the uncertainty in the radiometry by applying variance analysis on the radiometric transfer equations (1, 2, and 3). This will give us only those errors that are directly attributable to the calibration equation. We can add to this the uncertainty of the AIRS transfer standard, the Large Area Blackbody (LABB), to arrive at an overall measurement uncertainty.

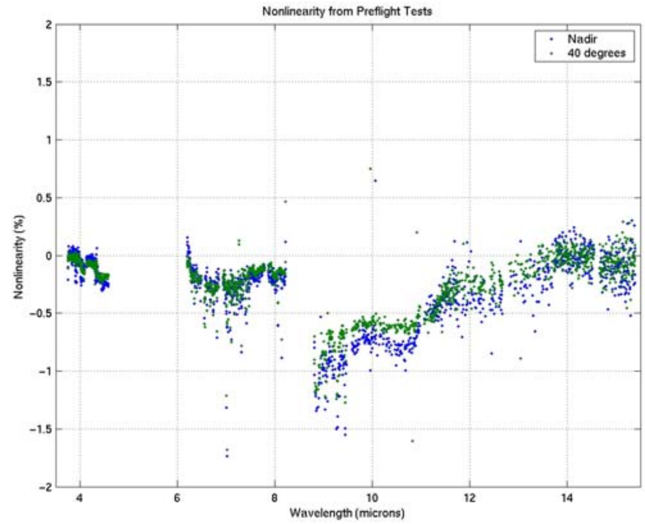

Fig. 4: Instrument stability is evident in the nonlinear term obtained from tests separated by 4 days.

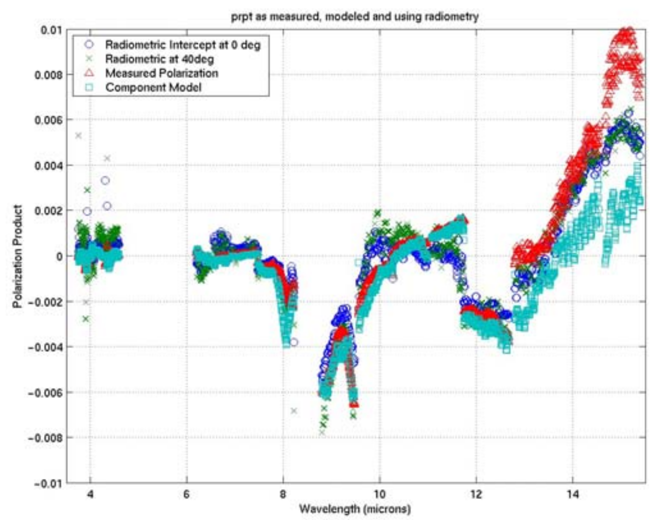

Fig. 5: Product of spectrometer and scanner polarization factors obtained from three methods.

$$\partial N_{SC}^2 = \left(\frac{\partial N_{SC}}{\partial p_r p_t}\Delta p_r p_t\right)^2 + \left(\frac{\partial N_{SC}}{\partial T_{sm}}\Delta T_{sm}\right)^2 + \left(\frac{\partial N_{SC}}{\partial \varepsilon_{sm}}\Delta \varepsilon_{sm}\right)^2 + \left(\frac{\partial N_{SC}}{\partial \varepsilon_{OBC}}\Delta \varepsilon_{OBC}\right)^2 + \left(\frac{\partial N_{SC}}{\partial T_{OBC}}\Delta T_{OBC}\right)^2 + \left(\frac{\partial N_{SC}}{\partial a_2}\Delta a_2\right)^2 + \left(\frac{\partial N_{SC}}{\partial dn}\Delta dn\right)^2 \quad (4)$$

Rather than solve for the equation analytically, we can apply the variance directly to the radiometric equation and calculate the change in radiance. This was performed in a computer model with the following assumptions for the error terms.

Error Terms

Pol: $p_r p_t$: The first primary error term is the uncertainty in the product of the polarization factors of the scan mirror and spectrometer. We cannot explain the differences in Fig. 5 between the various approaches, and carry the difference between the radiometric offset term at nadir and the average of the modeled and component offset terms as the radiometric error.

Scan Mirror Temperature and Emissivity: ΔT_{sm}, $\Delta\varepsilon_{sm}$: The AIRS scan mirror temperature is monitored using a non-contacting temperature sensor located at the base of the rotating shaft. The uncertainty in the scan mirror temperature is estimated to be less than 0.5K by design. Models executed by the instrument contractor estimate the uncertainty to be less than 1K. The scan mirror emissivity uncertainty at launch is carried in the polarization term; the degradation effects are not included in this model so the results represent at-launch expectations.

OBC Temperature Uncertainty: ΔT_{OBC}: The temperature of the OBC Blackbody is monitored by four temperature sensors located in and around the OBC. We have seen fluctuations on the order of ±0.05K in the blackbody temperature, but we believe the noise on this circuit to be on the order of ±0.01K. All other biases on this term come out of the emissivity calibration of the OBC.

OBC Gain Correction Term: $\Delta\varepsilon_{OBC}$: A 0.3K offset was applied during the calibration to match the radiances of the OBC and the external LABB. The residuals are contained in the gain correction term, ε_{OBC}. It is possible that the observed gain corrections are due to how we view the OBC and the LABB and are not well understood. We therefore have included all of the gain correction as an error; i.e. $\Delta\varepsilon_2 = 1-\varepsilon_{OBC}$. We obtain this term during the pre-flight testing (Pagano et. al IEEE 2000) during the radiometric calibration while viewing the LABB.

Nonlinearity: Δa_2: The uncertainty in the nonlinear term is taken to be the difference in the values obtained for this term for the nadir and 40 degree tests as shown in Fig. 4.

Non-Random Instrumental Noise: Δdn: This term represents the instrumental noise while viewing the target. By convention, we do not include the random noise terms in the absolute radiometric uncertainty estimate. This is most likely because the retrieval process minimizes the impact of random noise on most products. We present the random noise separately as in Fig. 2. We include here the non-random, correlated instrumental noise component as a full radiometric error. It is not know what effect correlated noise has in the Level 2 retrieval processing; further simulation is planned.

Error Results

Fig. 6 shows the results of predicting the radiometric errors based on the assumptions in the previous section. The major contributors are the correlated noise, the polarization term, and the gain. The correlated noise is the highest of these yet is the most uncertain in its contribution on the radiometry. For all channels, we see the radiometric error to be less than 0.18K. These errors will later be combined with the predicted LABB radiometric accuracy to arrive at an estimate of the AIRS radiometric accuracy.

Overlaid on the prediction is the error resulting from an independent measurement of the LABB. Data from a 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 Fig. 3. The error is the difference between the derived temperature of the LABB using the calibration coefficients and the true temperature obtained from the LABB temperature sensors.

Preflight Radiometric Accuracy Estimate

The LABB is a wedge cavity design, considerably larger, but otherwise similar in its basic design to the OBC, but with selectable temperature between 190K and 360K. During TVAC testing it was located at a distance of 11.5” from the scan mirror. At this position its entrance aperture is large enough to fully contain four consecutive AIRS footprints. The walls of the LABB are coated with Aerogalze Z-302, which has a reflectivity of less than 0.11. For the wedge angle of 27.25 degrees and the AIRS geometry more than 6 specular reflections are required before the beam exits the cavity. The LABB emissivity is

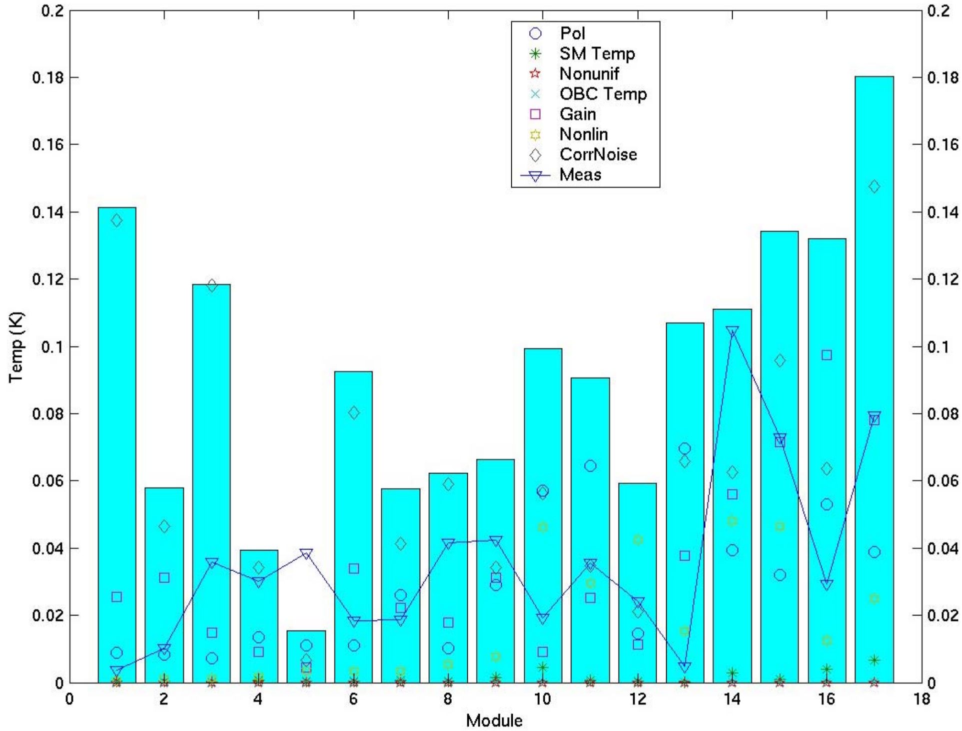

Fig. 6: Modeled radiometric error and measured repeatability pre-launch.

theoretically better than (1-(0.11)^6), i.e. better than 0.9999. The LABB output is given directly by the Planck function corresponding to its temperature. The Platinum Resistance Thermometers (PRT) were NIST calibrated. The LABB output is thus NIST traceable through contact thermometry, but not through actual radiance measurements.

The absolute radiometric accuracy of the AIRS depends on the traceability of the AIRS calibration standard, the LABB, and the Space View Blackbody (SVBB) to National Institute of Standards and Technology (NIST) Standards. The LABB and SVBB have an identical cavity structure (Fig. 7). The first bounce surface is inclined at 45 degrees relative to the incident beam. It is constructed of a specular black paint with specified reflectance of less than 13.5% for wavelengths below 6 um and less than 17.5% below 15.4 um. The effective emissivity is expected to be 0.9999 for the cavity with a temperature precision of 0.01K, stability of 0.01K. The uncertainty of the first surface is specified to be less than 0.03K with all other surfaces less than 0.1K. With more than 90% contribution from the first surface, we expect the radiometric uncertainty to be better than 0.05K.

Our estimate of the absolute uncertainty of the LABB and SVBB of better than 0.05K combined, with the better than 0.18K radiometric errors gives us a total radiometric uncertainty of better than 0.2K. The radiometric accuracy of the AIRS measurements is better than 0.2K on average. Any single measurement is accurate to the 0.2K root sum squared with the NEdT values at the scene temperature as shown in Fig. 2 for a scene temperature of 250K.

Spectral Response

The Spectral Response calibration is not part of the Level 1B algorithm, but it is discussed briefly here for completeness. 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.

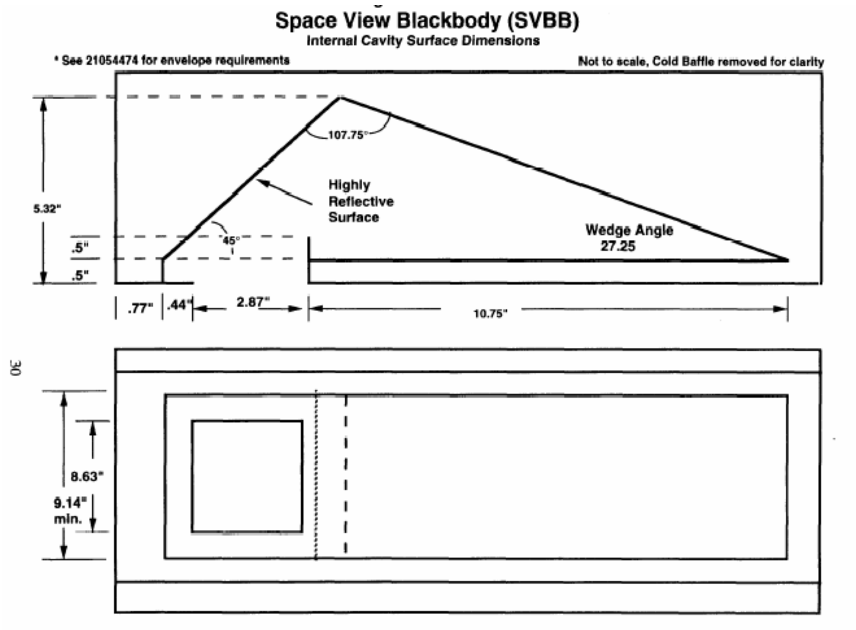

Fig. 7: AIRS SVBB and LABB internal Geometry.

Measurements were made at three different temperatures and resulted in no change to the spectral response shape (Pagano et al., 2000). Absolute knowledge of the spectral response centroids prior to flight has been demonstrated to be better than 5 ppm (Gaiser et al., 2003).

In-Flight Accuracy and Stability

Accuracy Comparison with ECMWF

The accuracy of the Level 1 products looks exceptional at this time. Comparison of the AIRS observed (O) radiances (in terms of brightness temperature) to calculations (C) based on the European Center for Medium-Range Weather Forecast (ECMWF) using the AIRS Radiative Transfer Algorithm (RTA) have shown (Pagano et. al SPIE 2003) less 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. Comparison with Scanning HIS (Revercomb et. al 2002), MODIS and GOES (Tobin et. al, 2003) also show better than 0.2K agreement.

Stability Comparison with Buoy Network

Comparisons of AIRS channel 2616 cm^{-1} with the Real-Time Global Sea Surface Temperature (RTG SST) (based on buoy measurements) between 1 September 2002, when routine data from AIRS became available, and 31 March 2003 show extremely good AIRS radiometric stability (Aumann et. al SPIE 2003).

Spectral Stability

Spectral centroids of the SRFs are determined in orbit by correlating observed upwelling radiance spectra with pre-calculated, modeled radiance spectra. Results of using this technique to determine the spectral stability of the AIRS have shown (Gaiser et al., 2003) less than 0.2 microns of FPA shift. 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 approximately 2 ppm of the center frequency. This far exceeds our stability requirement of 10 ppm.

Summary and Conclusions

The AIRS instrument allows for a simple and straightforward radiometric calibration. Since the design is solid state, accurate characterization of the spectral response functions pre-flight combined with thermal control results in good knowledge of the spectral frequencies, without continuous on-board calibration correction. The Level 1B calibration algorithms, therefore, only include radiometric terms. The radiometric calibration is straightforward and relatively simple as demonstrated in this paper. The resulting calibration accuracy has been predicted to be better than 0.2K. These predictions agree well with repeatability measurements that show better than 0.1K repeatability. The noise levels are higher than this for many channels and must be considered for any single measurement from the AIRS using only a single channel. Level 2 algorithms, however, mitigate the noise in the instrument through retrievals that involve use of many channels. A small amount of correlated noise in the AIRS instrument is present at a fraction of less than ½ the random noise. These have been included in the radiometric accuracy estimates, which leave us with better than 0.2K RMS uncertainty.

Independent validation has demonstrated better than 0.2K agreement with other in-situ, spaceborne, and airborne instruments. Stability is better than 0.1K when viewing a single channel at 2616 cm^{-1} over oceans. The AIRS Level 1B product has been very stable and accurate since the instrument was declared operational. This long stable well-calibrated data product will be a useful climate data record for scientists for years to come.

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