Lessons learned from the AIRS pre-flight radiometric calibration

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ABSTRACT

The Atmospheric Infrared Sounder (AIRS) instrument flies on the NASA Aqua satellite and measures the upwelling hyperspectral earth radiance in the spectral range of 3.7-15.4 μm with a nominal ground resolution at nadir of 13.5 km. The AIRS spectra are achieved using a temperature controlled grating spectrometer and HgCdTe infrared linear arrays providing 2378 channels with a nominal spectral resolution of approximately 1200. The AIRS pre-flight tests that impact the radiometric calibration include a full system radiometric response (linearity), polarization response, and response vs scan angle (RVS). We re-derive the AIRS instrument radiometric calibration coefficients from the pre-flight polarization measurements, the response vs scan (RVS) angle tests as well as the linearity tests, and a recent lunar roll test that allowed the AIRS to view the moon. The data and method for deriving the coefficients is discussed in detail and the resulting values compared amongst the different tests. Finally, we examine the residual errors in the reconstruction of the external calibrator blackbody radiances and the efficacy of a new radiometric uncertainty model. Results show the radiometric calibration of AIRS to be excellent and the radiometric uncertainty model does a reasonable job of characterizing the errors.

Keywords: Atmospheric, Infrared, Sounder, Radiometric, Calibration, Uncertainty

1. INTRODUCTION

The Atmospheric Infrared Sounder (AIRS) is a hyperspectral infrared instrument on the EOS Aqua Spacecraft, launched on May 4, 2002. The AIRS has 2378 infrared channels ranging from 3.7 μm to 15.4 μm and a 13.5 km footprint. The AIRS is a "facility" instrument developed by NASA as an experimental demonstration of advanced technology for remote sensing and the benefits of high resolution infrared spectra to science investigations.[1,2] The AIRS, in conjunction with the Advanced Microwave Sounding Unit (AMSU), produces temperature profiles with 1K/km accuracy on a global scale, as well as water vapor profiles and trace gas amounts for CO_2, CO, SO_2, O_3 and CH_4. The AIRS data are used for weather forecasting, climate process studies and validating climate models[2]. For more information see http://airs.jpl.nasa.gov.

Radiometric calibration of the AIRS instrument was performed pre-launch in a thermal vacuum chamber using SI traceable calibration standards and with the AIRS mounted on a rotary table that allows viewing the external blackbody at multiple angles of incidence. The calibration coefficients derived pre-launch, V5, are still in use today with no modifications. The method used to calibrate the AIRS was to step the external blackbody over a range of temperatures over an extended period of time (approximately 18 hours) to achieve a radiometric transfer curve solving for the offset, b_o, gain, b_1, and nonlinear coefficients, b_2.[3] The offset term in the fit, b_o, was not used, instead it was calculated from a theoretical estimate of the polarized emission difference when viewing the mirror in the earth view and the space view. The polarization used in the theoretical calculation was an average of a component level polarization model and a measurement of the instrument polarization made in the laboratory after repair of the internal field stop.

Later, in 2008, a new method was introduced where the polarization coefficients were calculated from the offset term from the intercept of the radiometric fit, b_o[4]. This resulted in a significant reduction in the residual differences between the fit and the original data, giving approximately 50-100 mK residuals at nadir and 100-200 mK residuals at the end of scan for most temperatures. While the residuals were smaller than currently in use, V5, the differences are not yet significant enough to warrant changing the Level 1B. We also would like to better understand the limiting factors contributing to the uncertainty of the test and characterize them more accurately.

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2. METHODOLOGY

In this section we discuss three independent methods for obtaining the instrument polarization coefficients. First we revisit the "linearity test" where the AIRS response is calibrated relative to an external Large Area Blackbody (LABB) that is stepped in temperature. This produces offset, gain and nonlinearity coefficients[4]. We next make use of an independent data set where the instrument Response vs Scan-Angle (RVS) was measured pre-flight. This test provides polarization parameters directly from the response of the AIRS. Finally we examine the AIRS response to a space look in the earth viewport during a lunar roll maneuver. This provides a direct measure of the instrument offset in flight.

2.1 Coefficients from Linearity Test

The AIRS radiometric response is calibrated pre-flight by allowing the AIRS to view an external LABB. The response of the AIRS in counts, *dn*, at the FPA is can be written as a second order polynomial

$$L_{ev} - L_{sv} = b_1(\theta)(dn_{ev}(\theta) - dn_{sv}) + b_2(\theta)(dn_{ev}(\theta) - dn_{sv})^2 \tag{1}$$

Where

$L_{ev,\,sv}$ = Spectral Radiance at the FPA(W/m^2-sr-μm)
θ = Scan Angle measured from nadir (radians)
dn = AIRS digital number (counts)

Note there is no offset term in this equation since all signals except from the LHS of the equation at the detector should cancel when taking the difference between earth view and space view. However, we have shown that the radiance difference at the detector is modulated by the instrument polarization causing an artificial offset term[3]

$$L_{ev} - L_{sv} = P_{ev}RT[1 + p_r p_t cos2(\theta - \delta)] - P_{sm}RTp_r p_t[cos2(\theta - \delta) + cos2\delta] \tag{2}$$

Equating equation (2) to equation (1) we get the radiance at the aperture in the radiometric transfer equations

$$P_{ev} = b_o(\theta) + b_1(dn_{ev} - dn_{sv}) + b_2(dn_{ev} - dn_{sv})^2 \tag{3}$$

$$b_o(\theta) = P_{sm}p_r p_t \frac{[cos2(\theta-\delta)+cos2\delta]}{[1+p_r p_t cos2(\theta-\delta)]} \tag{4}$$

$$b_1(\theta) = \frac{\xi P_{obc} - b_0(180°) - b_2(dn_{OBC} - dn_{sv})^2}{(dn_{OBC} - dn_{sv})} \frac{[1 + prpt\ cos2\delta]}{[1 + prpt\ cos2(\theta-\delta)]} \tag{5}$$

where

$b_i(\theta)$= Coefficients of polynomial fit to radiometric response of AIRS during pre-flight testing. i=0, 1, 2
RT = Product of the total AIRS reflection and transmission (unitless)
P_{sm} = Spectral Radiance of the Scan Mirror for Unity Emissivity at T_{sm} (W/m^2-sr-μm)
$p_r p_t$ =Product of scan mirror and spectrometer polarization diattenuation (unitless)
δ = Phase of spectrometer polarization (radians)
P_{ev} = Spectral Radiance in the Earth Viewport (W/m2-sr-μm)
ξ = Effective Emissivity of the On Board Calibrator (OBC) blackbody
P_{obc} = Spectral Radiance of the OBC for Unity Emissivity at T_{obc} (W/m^2-sr-μm)

The set of LABB and instrument signals collected during pre-flight linearity testing {P_{ev}, (dn_{ev} – dn_{sv})} at nadir (0°) and 40° can be fit to the polynomial equation 3 to arrive at a set of coefficients b_o, b_1, and b_2 for each scan angle. The gain is determined in-flight from the signal on the OBC (at 180°), and correcting for all scan angles. The nonlinear term, b_2, is preserved from the fit, and from b_o, we can determine the phase and polarization product

$$\delta_{calc} = \frac{1}{2} tan^{-1}\left\{\frac{b_o(\theta) + \frac{2P_{sm}b_o(\theta)}{b_o(0°)} + P_{sm}}{[b_o(\theta) - P_{sm}]sin2\theta} - \frac{1}{tan2\theta}\right\} \tag{6}$$

$$[p_r p_t]_{calc} = \frac{b_o(\theta)}{P_{sm}[cos2(\theta-\delta)+cos2\delta] - b_o(\theta)cos2(\theta-\delta)} \tag{7}$$

The effective emissivity, ξ, is calculated using the radiometric transfer equation, the signals while viewing the on-board calibrator (OBC) blackbody and the coefficients, b_i, to compute the radiance. The emissivity is this radiance divided by the radiance calculated using the thermistors and unity emissivity, P_{OBC}.

$$\xi = \frac{b_0(0°)+b_1(0°)(dn_{OBC}-dn_{sv})+b_2(dn_{OBC}-dn_{sv})^2}{P_{OBC}} \tag{8}$$

Note: The radiometric transfer equations are similar to those from a prior study[4], with a slight modification, pulling the signal polarization modulation term, $1+p_r\, p_t\, cos2(\theta-\delta)$, into the coefficients.

2.2 Polarization Response from RVS Test

The RVS test involved viewing the LABB and rotating the AIRS instrument collecting signals at each angle. The test was performed at two fixed LABB temperatures (200K, and 308K). Our model predicts we should see a scan angle dependence due to the coupling of the polarization of the scan mirror and the spectrometer. This will cause a signal change at the FPA due to the different radiances

$$dn_{ev} - dn_{sv} = a_1(L_{ev} - L_{sv}) + a_2(L_{ev} - L_{sv})^2 \tag{9}$$

Substituting our model for the change in radiance (2), ignoring 2nd order terms, and a little algebra, we can write the signal change as

$$dn_{ev} - dn_{sv} = a + b\, cos2\theta + c\, sin2\theta \tag{10}$$

where

$$a = P_{sm}RT(1 - p_r p_t cos2\delta) \tag{11}$$
$$b = (P_{ev} - P_{sm})RTp_r p_t cos2\delta \tag{12}$$
$$c = (P_{ev} - P_{sm})RTp_r p_t sin2\delta \tag{13}$$

To find the coefficients a, b, and c, we regress against the RVS data set $\{(dn_{ev}-dn_{sv})_i, \theta_i\}$. We can then solve for the coefficients, δ and $p_r p_t$

$$\frac{c}{b} = tan2\delta; \quad \delta_{rvs} = \frac{1}{2}tan^{-1}\left(c/_b\right) \tag{14}$$

$$[p_r p_t]_{rvs} = \frac{\sqrt{b^2+c^2}}{RT(P_{ev}-P_{sm})} \tag{15}$$

2.3 Polarization Response from Lunar Roll Test

This test occurs during a roll maneuver designed to allow the MODIS instrument to view the moon through the space viewport. During the lunar roll maneuver, the spacecraft is rolled towards the space side of the spacecraft. This brings a view to space in the Earth viewport. The nearest earth view to space occurs at the end of scan, θ_{eos}.

The scene radiance should be zero while we view space through the earth viewport. Since we expect no signal, (dn_{ev}-dn_{sv}), we expect no gain or nonlinearity errors. Any radiance observed can be expressed as a difference between the calculated offset term, $b_o(\theta)$, as defined in equation 4, and the offset observed in the roll, $b_{o_roll}(\theta)$.

$$db_o(\theta) = b_o(\theta) - b_{o_roll}(\theta) = P_{ev_obs}(\theta_{eos}) \tag{16}$$

We can derive from this test a polarization product that would zero out the residuals by adjusting the polarization product used in the initial retrieval of radiances from this test.

$$[p_r p_t]_{roll} = [p_r p_t]_{calc}\frac{b_o(\theta)-db_o(\theta)}{b_o(\theta)} \tag{17}$$

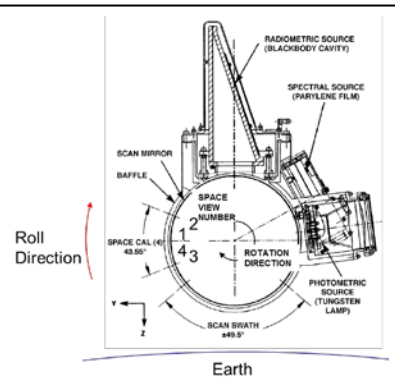

Figure 1. Schematic of AIRS Viewfactors and On-board Calibration Devices. Lunar roll in the direction of scan rotation enabled viewing space in the Earth Viewport.

2.4 Radiance Uncertainty

Then the uncertainty in the radiance, P_{sc}, can be related to the uncertainty in the calibration coefficients, ζ_i, and other terms in the radiometric transfer equation.

$$\Delta P_{sc} = \sqrt{\sum_i \left[\frac{\partial P_{sc}}{\partial \zeta_i} \Delta \zeta_i\right]^2} \tag{18}$$

A radiometric accuracy analysis using this technique was performed in a prior study[4] and is expected to still be valid. Here we present an alternate method for calculating uncertainty in the radiances based on observed variance in the coefficients, b_i.

$$\Delta P_{sc} = \sqrt{\sum_i \left[\frac{\partial P_{sc}}{\partial b_i} \Delta b_i\right]^2} / \sqrt{n} \;\; = \sqrt{\Delta b_o^2 + \left(P_{sc} \frac{\Delta b_1}{b_1}\right)^2 + \left(P_{sc}^2 \frac{\Delta b_2}{b_1^2}\right)^2} / \sqrt{3} \tag{19}$$

Uncertainties in the coefficients are obtained from the fit to the linearity test using the MATLAB *regress* function. The *regress* function returns the ±95 percentile confidence interval (±2σ) for the coefficients. We take the difference of the values returned from *regress* and divide the result by 4 to get 1 σ values. We divide by the square root of the number of degrees of freedom to convert the uncertainty in the coefficients to a standard error in the result.

3. DATA

3.1 Linearity Tests

Thermal vacuum (T/V) testing at BAE Systems was performed in late October and early November 1999. Fortunately, all data from pre-flight testing, are still available and have been recently migrated to a more permanent storage system at the AIRS Team Leader Computing Facility (TLSCF) at NASA JPL. During T/V testing, the AIRS viewed the LABB and a Space View Source (SVS). These provided a two point radiometric gain and offset calibration for the AIRS. The LABB was transitioned from 205K to 310K to calibrate the AIRS response linearity. The test was performed with the LABB at nadir (0° scan angle) and at 40° scan angle. The AIRS pupil rotates with scan angle placing the center footprint at different points along the scan line. The center footprint can be identified using the following algorithm with the coefficients derived empirically from the observed center footprint in the field.

$$j_i = round[j_0 + \theta/1.1° + \alpha(x_i - x_o) sin\theta] \tag{20}$$

where
j = Footprint index
i = Spectral channel index
j_o *= Center pixel = 45.5*
$\propto$ *= Coefficient converting FPA position to footprint index. Derived empirically = 1.5 fp/mm.*
$x_i - x_o$ *= Difference in position on the FPA for the* i^{th} *spectral channel (mm)*

Table 1 gives the test IDs used in the analysis. Some tests were not useful due to data problems, and they were omitted from the analysis. The question remains as to the stability of the instrument and external calibration targets during the almost 18 hour test. Nadir tests were performed first with A, B and AB detector redundancy configurations performed at each temperature. The LABB was then transitioned and allowed to stabilize before proceeding with the next set of tests. The AB side data used a redundancy configuration unique to the pre-flight configuration so coefficients are computed for A side and B side independently so they can be combined for any gain table configuration.

Table 1. Tests used for determining the AIRS radiometric calibration coefficients.

Temp(K)	205	220	230	240	250	265	280	295	310
A Side	1687	1692	1693	1698*	1704	1710	1718	1719	1727
B Side	1688	1689	1696	1697	1705	1706	1715	1720	1726
AB Sides	1686	1690	1694	1700	1703	1709	1716	1722	1725
1698: Saturated M4. This test not used in the analysis									
A Side: 40deg	1830	1841	1844	1849	1852	1857	1860	1865*	1872
B Side: 40deg	1829	1842	1843	1850	1851*	1858	1859	1866	1871
AB Side: 40deg	1832	1840	1846	1848	1854	1856	1862	1864	1870
*1865: Anomalous, 1851 Scan Dropout. These two test not used in analysis									

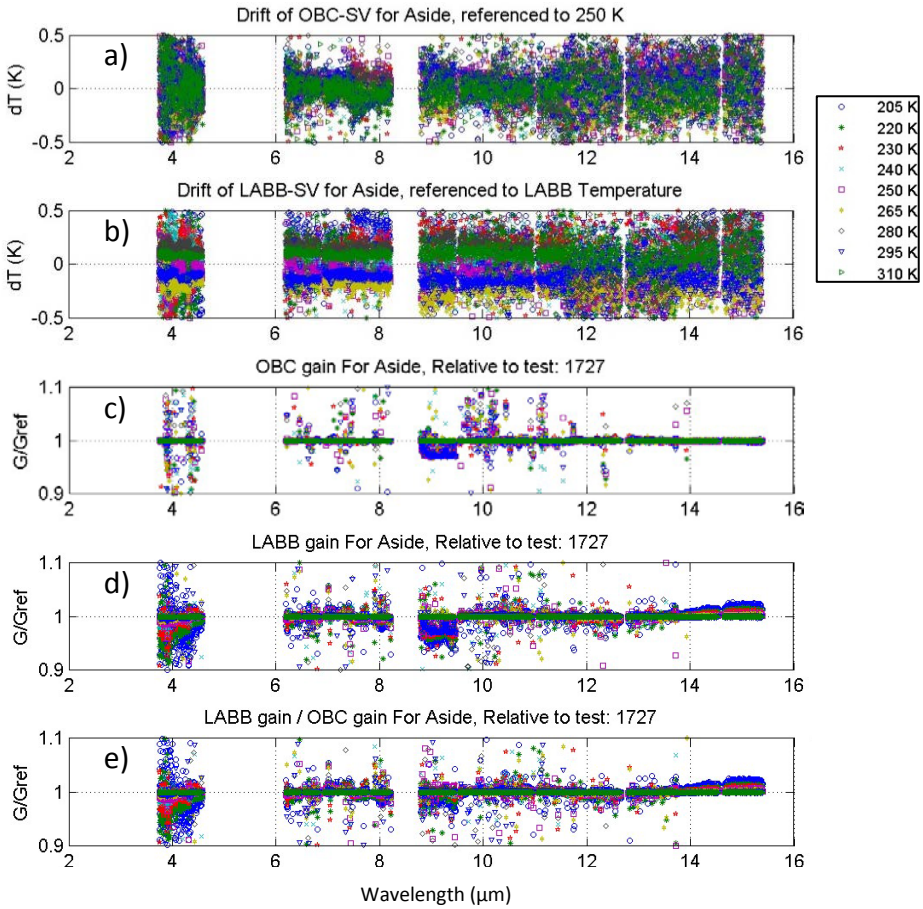

Figure 2. Drift and gain variability for linearity testing on the A side. Drift represented as temperature differential at 250K. a) Drift in Blackbody Calibrator signal is small. b) Drift in LABB signal is as much as 0.2K. c) OBC gain relative to test 1727 (310K) is stable except at 9 μm, d) LABB gain similar to OBC e) LABB/OBC gain is stable to < 5%.

In this recent study we examine the drift in the instrument offset and gain to see if we have stability issues. Figure 2 shows the results for the A-side linearity tests. The top panel, a) shows the "drift" of signal-space view temperature for the OBC. This was calculated by taking the difference in counts from the first 10 and last 10 scans and multiplying by the gain as determined using the OBC. Other than instrumental noise, the OBC appears relatively stable. Similar results are seen in the other tests. Panel b) shows the stability in the LABB signal. The results show that there could be up to 0.2-0.3K of drift in the LABB signal during the test. This indeed will contribute to the uncertainty. Panel c) shows the change in gain as viewed by the OBC relative to the test at 310K (last in the sequence). The gain is very stable except for M5. This gain instability is also reflected in the LABB gain, panel d). We also see an instability in the gain in the longest wavelengths. This could contribute to higher errors in this part of the spectrum. To mitigate the impact on the derived coefficients, the drift in the gain is removed prior to fitting the instrument response by multiplying the LABB signal times the ratio of the OBC gain for the reference test (310K) to the OBC signal at the test in question. This gain correction factor simulated how AIRS works during normal operations and indeed stabilized the data, in particular, with respect to M5 A-side at 9 μm. Impact to the other bands was not particularly noticeable in the results.

3.2 RVS Tests

During thermal vacuum testing at BAE systems, the AIRS was mounted on a rotary fixture as shown in Figure 3. The rotary fixture, also known as the Instrument Handling Fixture (IHF) allowed the AIRS to rotate to view a constant temperature LABB at angles ranging from -48.3º to 35.2º while preserving the view to the cold space view blackbody. Data were obtained at roughly 10º steps over the course of 23 hours for the 300K tests and 13 hours for the 200K test. Test ID's, angles and temperatures are given in Table 2.

Table 2. Test ID's for the Response Vs Scan (RVS) test. IHF=Instrument Handling Fixture. Scan angle measured relative to nadir. Test performed at two LABB temperatures, 300K and 200K.

IHF Angle (deg)		-24	-15.38	-5.48	4.42	14.32	24.13	24.13	35.22	47.32	59.42
Scan Angle (deg)		-48.3	-39.68	-29.78	-19.88	-9.98	-0.17	-0.17	10.92	23.02	35.12
Side	T_LABB (K)	Test ID	Test ID	Test ID	Test ID	Test ID	Test ID	Test ID	Test ID	Test ID	Test ID
A	308	1760	1756	1753	1750	1763	1739	n/a	1743	1767	1778
B	308	1761	1757	1752	1751	1762	1740	n/a	1744	1768	1779
AB	308	1759	1758	1754	1749	1764	1765	n/a	1742	1766	1771
A	200	1805	1802	1809	1812	1799	1790	1827	1820	1793	1796
B	200	1804	1803	1810	1811	1798	1791	1828	1821	1792	1797
AB	200	1806	1801	1807	1813	1800	1789	1822	1816	1794	1795

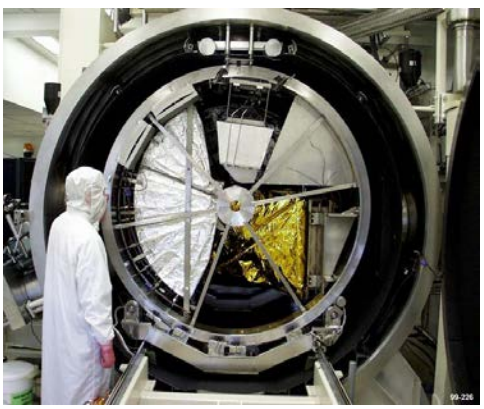

Figure 3. AIRS mounted in rotary fixture during thermal vacuum testing at BAE Systems, Lexington Ma. This fixture allowed the AIRS to view the LABB at a range of scan angles during testing to characterize the RVS.

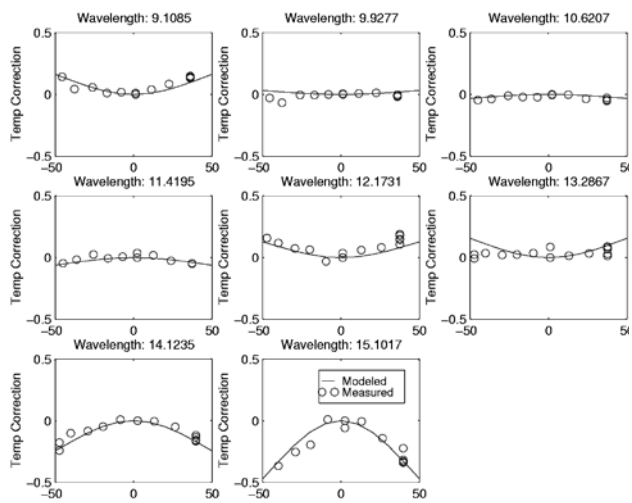

Figure 4. AIRS Response Vs Scan Angle for sample channels, along with the modeled response.

The RVS data showed higher instabilities in the gain over the test period, so the gain correction method used for the linearity testing was applied to this data as well. The 308K data showed less instability than the 200K test and was therefore used in the analysis to retrieve polarization parameters. Test data at -48.3º were not used since it was difficult to get a good view for all channels at this angle.

Figure 4 shows the effective temperature difference between the LABB setpoint temperature and the temperature derived from the AIRS for sample channels. Also shown are the results for a model of the polarization that was developed based on component measurements[5]. The model response match well the predicted response[6]. As will be seen below, the polarization derived from this test is a good match to the polarization measurements made of the instrument pre-flight using wire grid polarizers.

One final consideration for the stability of the linearity and RVS tests is the instrument temperature. According to the test logs, the spectrometer temperature was maintained between 148.4K and 148.6K. Focal plane temperature was also maintained between 57.8K and 58.2K. The spectrometer stability at this temperature matters primarily for the alignment of the entrance slits and the detectors and spectral calibration. We do not expect any influence on the radiometry. The scan mirror temperature does influence the polarized emission, but changes on the order of 5K produce less than 50 mK

worst case and on average only 5 mK impact to the radiometry[4]. Figure 5 shows that the scan mirror temperature does vary during the test but is within the 5K tolerance.

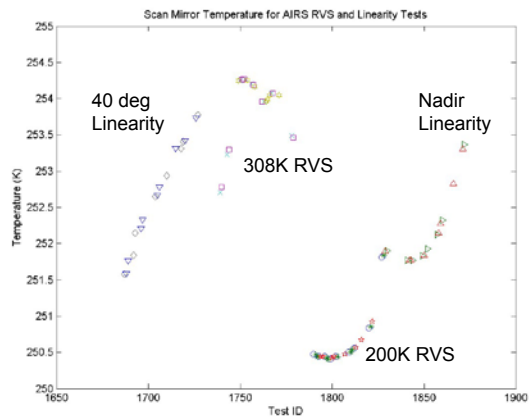

Figure 5. Scan mirror temperature varies during the testing but is within 5K for minimal impact on the radiometry.

3.3 Lunar Roll Test

As described above, during the lunar roll, the AIRS views space in the earth viewport at the end of scan. We use data from the lunar roll maneuver on July 2, 2009 since this provided the largest roll angle of -19.75º. Figure 6a shows an image from this test of one channel at 2616 cm^{-1} in the earth viewport where the horizontal axis is along the track of the spacecraft (scan index), and the vertical axis is footprint number. We see a band of dark blue at the bottom of the image corresponding to the view of space in the last footprints (end of scan). Figure 6b shows the average spectrum over all scans for several footprints in the scan, starting from footprints 1 and 45 that look like normal nadir spectra to footprint 85 where we can see Earth's limb. Footprints 88 through 90 appear to have clear views to space, but for purposes of this analysis, only footprint 90 was

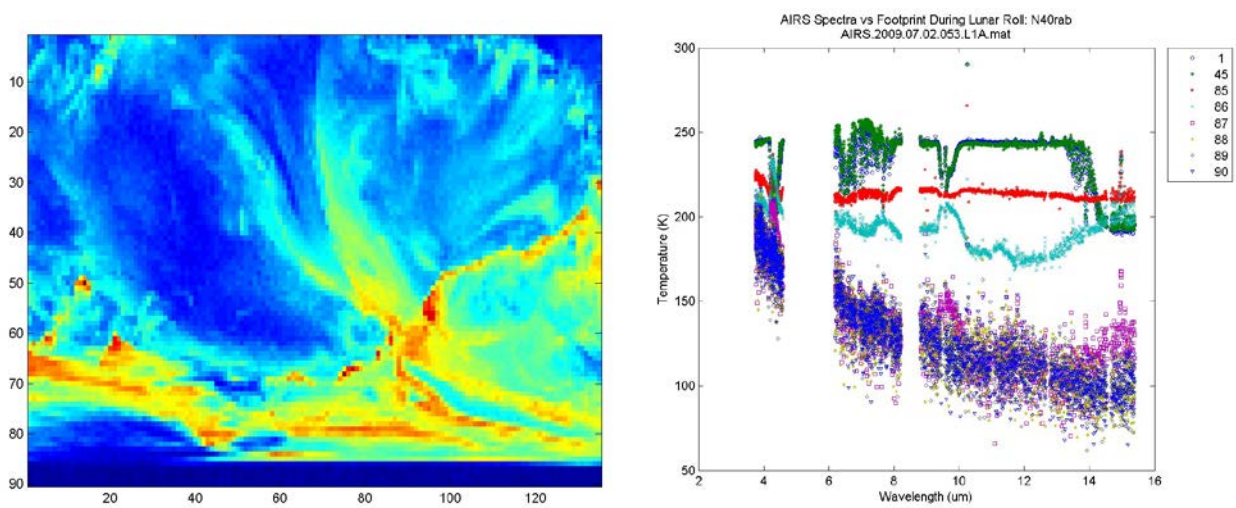

Figure 6a (left). Image from AIRS at 2616 cm^{-1}. Vertical axis is footprint, horizontal axis is scans. The limb can be seen at the end of scan (last footprints). Figure 6b (right) shows the average spectra over all scans vs wavelength for several footprints. The limb is seen in footprints 88-90.

used. Note, that these temperatures are calculated using the AIRS radiometric transfer equations and coefficients from the linearity testing to retrieve the radiance, and using the inverse of the Planck equation to compute temperature. The fact that we do not have colder temperatures in the space viewing footprints is indicative of a small positive radiometric bias in the calibration most likely in the offset term. This is discussed more below. Note that all data in the analyses presented in this paper use spaceview 1. Spaceview 3 is close to the limb and may contain Earth radiance as identified by independent analyses using this same roll test[7].

4. RESULTS

The methods discussed above were used to derive a set of radiometric calibration coefficients. They are compared here to give a sense of the magnitude of the variability. We then examine the residual differences of the retrieved radiances using the radiometric transfer equation compared to the actual LABB. These differences are then compared to a radiometric uncertainty model. Uncertainties of the AIRS radiances are important for error propagation of the radiometric uncertainties into higher level products as well as error characterization in climate science investigations.

4.1 Radiometric Calibration Coefficient Comparison

We start by comparing the coefficients obtained using the various techniques to each other. Not all coefficients are obtained from each of the tests above; this will be explained as we go through the coefficients individually. The coefficients are shown in Figures 7 and 8. We also show the coefficients used in Version 5[3]. Starting with the offset term (7a), the only method that allows an offset other than due to polarization is the RVS method. In this test the polarization phase and amplitude (prpt) are obtained from the RVS test prior to fitting to the linearity tests for the remaining coefficients. This results in a non-zero offset term, discretely different than the offset due to polarization; we call it b_o'. For polarization phase, the only test we get a meaning full phase from is the RVS test. The other methods have insufficient information to retrieve the phase. The linearity and roll tests default to this phase when computing coefficients. Emissivity is obtained from the linearity test; the other tests default to this emissivity except V5. The same is true for nonlinearity.

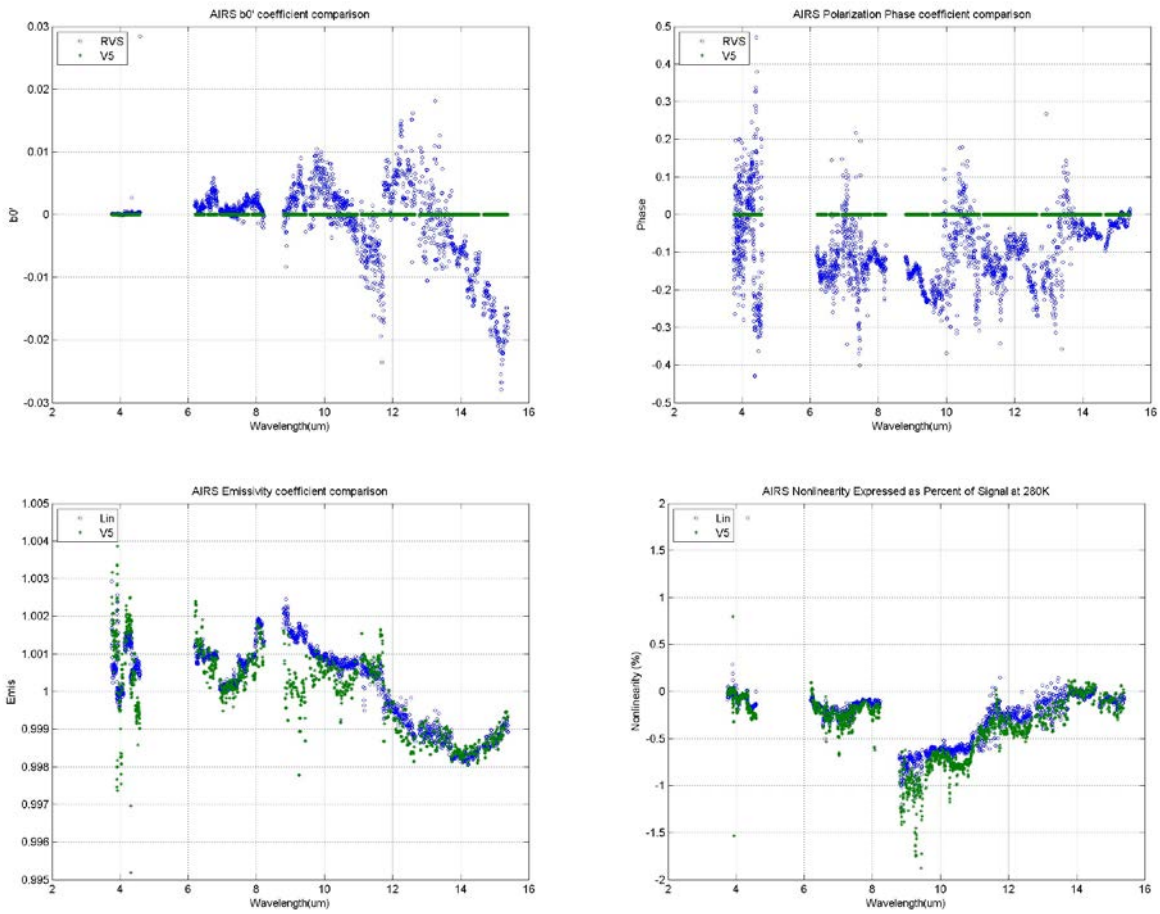

Figure 7. Coefficients in the radiometric calibration as obtained using different methods. a) Offset (W/m^2-sr-µm), b) polarization phase (radians), c) effective emissivity (unitless), d) nonlinearity (%).

Polarization amplitude, p_r,p_t, is obtained independently from the different methods and is shown in Figure 8. Polarization from the linearity tests, "Lin", the RVS tests, "RVS" and the lunar roll test, "Roll" are discussed above in equations 7, 15, and 17 respectively. These tests are essentially independent methods for determining the polarization amplitude. The polarization measured on the instrument using wire grid polarizers, "Meas" is also shown. This method measures the instrument polarization response, PF_{meas}, but relies on the measure of the polarization of the scan mirror to get the term prpt. $PF_{meas} = p_r + p_t$. Knowledge of p_t from component witness samples enables us to solve for p_r and hence $p_r p_t$. The V5 polarization uses an average of the measured polarization and those of a component model[3].

The methods produce very similar results with some primary features including very low polarization in the 3-7 µm region, higher polarization in the 8-10 µm and beyond 12 µm due to the scan mirror. Then we have unique polarization signatures related to filtering in the individual modules scattered throughout. Independent analysis has shown that a change of 0.001 in the $p_r p_t$ term will produce < 50 mK change in the radiometry at 250K. We exceed these uncertainties only slightly at 10 µm, 12 µm and 15 µm, leading to slightly higher uncertainties in these channels. Notice that the polarization product obtained from the RVS test and "measured" are both high in the LWIR. This could be related to fact they are based on the transmitted polarization while the others are based on the emission of the mirror.

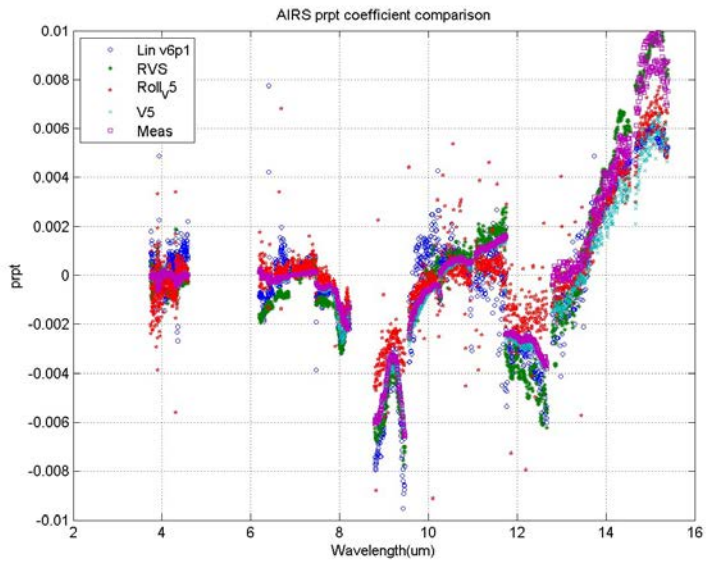

Figure 8. Polarization product as determined from the various test identified in the legend. Agreement is pretty good amongst the various methods, but a better understanding of these differences will lead to reduced residual errors in the calibration.

4.2 Radiance Differences

Reconstructions of the LABB temperatures were performed using the AIRS signal counts while viewing the LABB and polarization coefficients obtained from the linearity test with phase from the RVS test (v6pr). We have several tests to examine: Linearity (A, B, ABopt, nadir and 40 degrees) and RVS (A, B, ABopt, 200K, 308K). Figure 9a shows the residual differences between the reconstruction and the measured temperature of the LABB at a scan angle of 40 degrees in the AB optimum gain configuration. This is a typical result with only slightly poorer results from V5 (not shown). Also shown on this figure in red are the calculated temperature errors from the uncertainty model. There are multiple curves in red corresponding to the calculated temperature error at the various LABB temperatures. We have taken an average and standard deviation of the observed differences between the LABB and the computed AIRS radiances over all the channels in each of the 17 modules of AIRS and plotted them in Figure 9a. The average was performed over all RVS and Linearity tests and for the various polarization coefficients identified in the legend. On average, the calibrated radiances reproduce the observed temperatures of the LABB within 50-200 mK. The the differences are similar amongst all various coefficients, therefore we do not recommend changing the Version 5 (at-launch) coefficients at this time. The standard deviation is much higher and represents the noise and drift in the instrument and test setup during preflight testing.

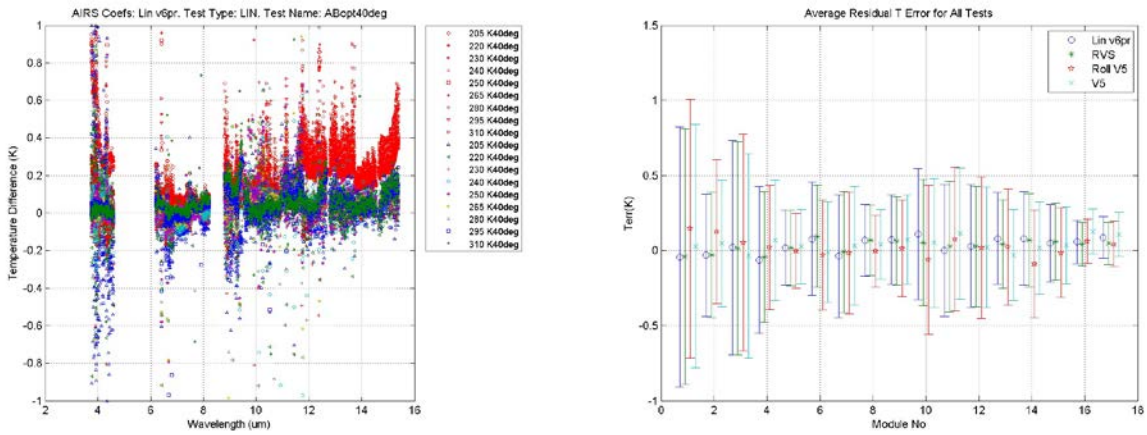

Figure 9a (left). Residual Differences (retrieved vs LABB measured) for ABopt Linearity test at 40 degree scan angle. Red curves are predicted temperature error from the radiometric uncertainty model for each LABB temperature. Figure 9b (right) Average residual error over all tests by module for each of the different polarization coefficient types (legend). Residual errors are similar for most coefficient types.

4.3 Uncertainty Model

Small errors remain in the reconstruction of the pre-flight radiometric test data on the order of 50-200 mK due to a number of factors including temperature drifts of the AIRS and test equipment during testing, uncertainties in the polarization coefficients and the model that uses them, and gain and nonlinearity errors. Here we examine the uncertainty model based on equation 19 where the radiance coefficients, b_i, and the uncertainties, Δb_i, correspond to the v6pr results. We ask the question how well does our radiometric uncertainty model reproduces the observed errors? Figure 10a shows the temperature differences plotted as a function of LABB temperature for the 17 modules. We overlay the model calculated errors. From this figure we see the model over estimates the errors at high temperatures for some modules. This would result from an over estimate of uncertainty in the gain, Δa_1 and Δa_2 most likely due to the instabilities in the test data. For these modules, a better result is obtained setting Δa_1 and Δa_2 to zero.

In order to determine the goodness of our uncertainty model in fitting the observed differences, the chi-squared figure of merit is calculated over all levels (e.g. temperature levels or angles) in a given test (e.g. linearity, RVS) for each channel in the ABopt gain setting

$$\chi_i^2 = \sum_j \frac{\Delta T_{obs,i,j}^2 - \Delta T_{calc,i,j}^2}{\Delta T_{calc,i,j}^2} \tag{20}$$

where

i = channel index
j = temperature level (linearity test), or angle (RVS test) index
$\Delta T_{obs,i,j}$ = the difference between the observed temperature of the LABB as retrieved using the AIRS calibration coefficients and the LABB set point temperature
$\Delta T_{calc,i,j}$ = the calculated temperature error for each test based on the uncertainty model (equation 19)

Figure 10b shows the chi-squared metric for each module and test condition. Again, we use the v6pr coefficients in the calculation of observed (retrieved) temperature. A chi-squared error of about 1 indicates we have identified the errors correctly. Errorbars are (max-ave)/3 and (min-ave)/3.

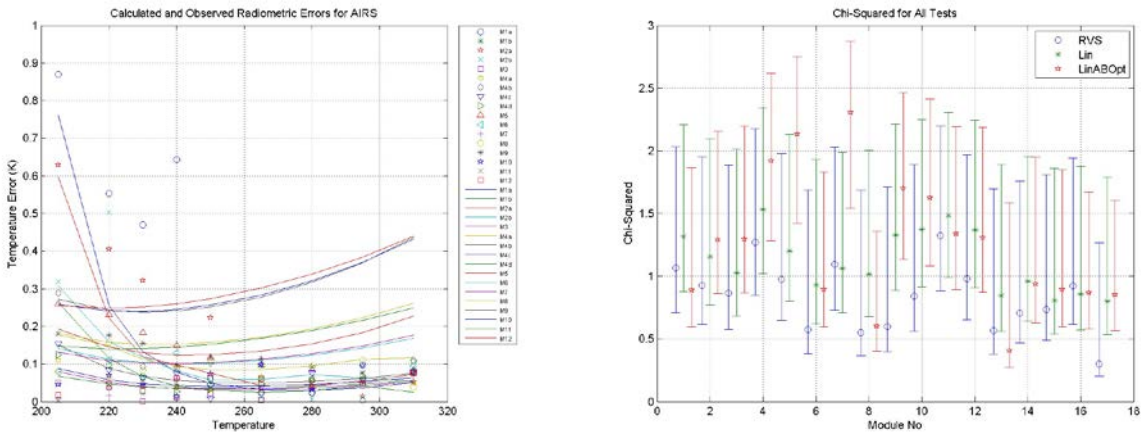

Figure 10a (left). Icons are average error for the 17 modules as a function of temperature for the linearity coefficients, v6pr, applied to the ABopt linearity test. Lines are the computed error from the radiometric uncertainty model. Figure 10b (right) Chi-squared error by module over all levels in test identified in legend.

5. CONCLUSIONS

The AIRS radiometric calibration is based on pre-flight testing through comparison with an external Large Area Blackbody transitioned over a wide range of temperatures. This method of calibration has proven effective as evidenced by agreement with ground-based, airborne, other spaceborne instruments. The radiometric calibration of AIRS has not changed since launch, as it has not been warranted and the need for stability of measurement is critical for climate applications. Residual errors in the calibration are between 50-200 mK as expected. We have identified several possible sources of variability in the residuals including drift in the AIRS instrument and drift in the external calibration blackbody during testing. Several methods for deriving the polarization coefficients for AIRS based on other measurements show good agreement with most difference in the LWIR. We believe a better characterization of the scan mirror polarization including phase retardance and circular polarization could reduce the differences.

A radiometric uncertainty model based on uncertainties in the coefficients of the fit to the linearity data was developed. This can be used with the current (Version 5) release of the Level 1B data product. While the radiometric uncertainty model is consistent with the majority of the pre-flight observations, the observed drifts in the test conditions could lead to an over-estimate of the errors using this model. On-orbit comparisons with in-situ and other spaceborne sounders suggest the differences are indeed lower than shown here.[8] In all cases, the AIRS radiometric accuracy is within required levels and excepetionally good. Continued comparisons of in-situ coupled with improvement of the pre-flight calibration through witness sample retests and model refinement will lead to better accuracy in the instrument as demanded for climate change investigations.

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