Recent checks on the radiometric and spatial calibration of AIRS in-orbit

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ABSTRACT

The Atmospheric Infrared Sounder (AIRS) on the EOS Aqua Spacecraft was launched on May 4, 2002 and is currently fully operational. AIRS acquires hyperspectral infrared radiances in 2378 channels ranging in wavelength from 3.7-15.4 um with spectral resolution of better than 1200, and spatial resolution of 13.5 km with global daily coverage. The AIRS was designed to measure temperature and water vapor profiles for improvement in weather forecast and improved parameterization of climate processes. Currently the AIRS Level 1B Radiance Products are assimilated by NWP centers worldwide and have shown considerable forecast improvement. Although the calibration of AIRS (< 200 mK 3 sigma) is sufficient for data assimilation into Numerical Weather Prediction (NWP) models, long term trends of Earth's climate require radiances with stability approaching 10 mK/year, and absolute accuracies better than 100 mK. This investigation uses views of space during roll maneuvers of the Aqua spacecraft to calibrate the mirror emission (one of the largest error sources for AIRS) and reduce the residual errors in cold scenes. We also present results of a secondary study that uses MODIS data to determine the alignment of the AIRS boresight. In this study we match AIRS and MODIS data and iterate on the assumed boresight to find the minimum difference in signal. In this way we are able to confirm the boresight projections determined shortly after launch.

Keywords: Atmosphere, Infrared, Sounder, AIRS, Calibration

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] 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. For more information see http://airs.jpl.nasa.gov.

2. RADIOMETRIC CALIBRATION

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, used in version 5 (V5) of the AIRS L1B product, 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 which allowed for the solution of the offset, b_o, gain, b_1, and nonlinear coefficients, b_2. The offset term in the fit, b_o, was not used, instead it was calculated from 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[2].

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[3]. 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 for the version currently in use, V5, the differences were not yet significant enough to warrant changing the Level 1B. We also needed to better understand the limiting factors contributing to the uncertainty of the test and characterize them more accurately.

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In 2013, it was discovered that there is sufficient view of space in the Earth viewport during a Lunar Roll maneuver that one can use these data to derive the polarization emission of the scan mirror for that particular angle.[4] These data can then be used at all scan angles assuming our functional dependence of the mirror emission with scan angle is correct. Polarization results from the roll test were compared to other methods of deriving the terms and residual errors in the approach were estimated.

In this paper, we revisit the derivation of the coefficients from the roll data and provide a new estimate of the residual errors in the V5 coefficients and the new roll coefficients.

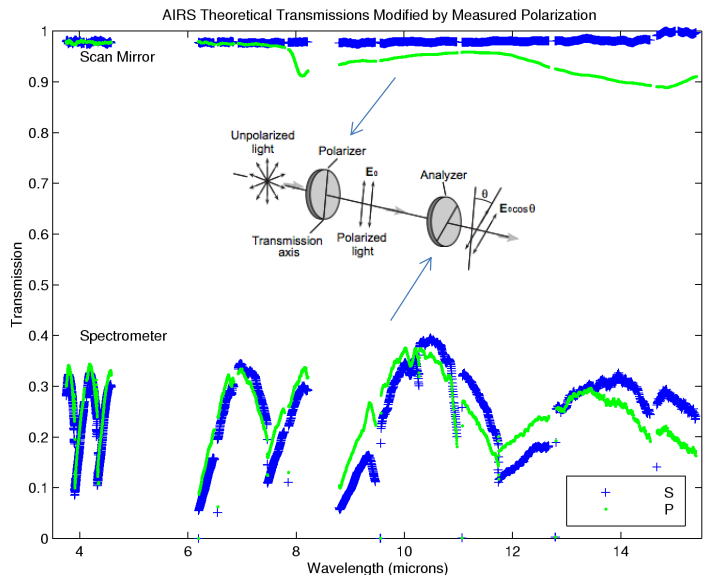

Figure 1. AIRS Scan mirror and spectrometer polarization couple to act like a polarizer/analyzer that modulates the emitted radiation from the scan mirror with scan angle.

2.1 Methodology

The overall method for determining the radiometric calibration coefficients for AIRS has not changed and is described in detail in the literature[5]. We review it again here for completeness and to identify where we get the terms for the original V5 calibration, and the new calibration proposed for V7. Note, there has been no calibration update since V5, and the next PGE release is V7.

The radiance difference at the focal plane between the Earth view and Space view is given by

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

The data acquired during linearity testing gives us a second order polynomial vs radiance at the sensor aperture

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

$b_i(\theta)$= 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)
θ = Scan angle from the mirror encoder (radians)
δ = Phase of spectrometer polarization (radians)
P_{ev} = Spectral Radiance at the Aperture 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)

In this test, an external Large Area Blackbody (LABB) is stepped through a set of temperatures enabling a fit of the three coefficients, b_0, b_1, and b_2 to the resulting transfer curve.

Equating the RHS of equation 1 to the LHS of equation 2 (assuming RT = 1 since we are referring to the radiance at the aperture rather than the focal plane), we find the AIRS radiative transfer equation as

$$P_{ev} = \frac{b_o(\theta)+b_1(dn_{ev}-dn_{sv})+b_2(dn_{ev}-dn_{sv})^2}{[1+p_r p_t cos2(\theta-\delta)]} \quad (3)$$

Where the offset term, b_o, is related to the product of the polarization diattenuation of the scan mirror and the spectrometer, $p_r p_t$.

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

The gain term, b_1 is used to derive the on-board blackbody temperature and emissivity calibration. The gain is then recalculated on-orbit for every granule using the on-board blackbody.

$$b_1 = \frac{\varepsilon_{OBC} P_{OBC}[1+p_r p_t cos2\delta] - b_o(180°) - b_2(dn_{OBC} - dn_{sv})^2}{(dn_{OBC} - dn_{sv})} \quad (5)$$

2.2 Data

We have four pre-flight and one post-flight test that allow us to derive the coefficients of the radiometric calibration. We mention these in the introduction and have discussed this in prior publications, but summarize here for completeness. The tests and their use is as follows:

1. **Pre-flight Stepped Blackbody**. This test allows us to derive the coefficients b_0, b_1, and b_2. From the radiometric offset, b_o we can derive $p_r p_t$, but the phase, δ, is ambiguous in this data set. For V5 we assumed the phase is zero. From the b_1 in this test we also derive the blackbody emissivity, ε_{obc}, and the correction for the temperature of the blackbody. We update the gain in flight using the blackbody emissivity, temperature and measured signal (dn_{OBC}-dn_{sv}). Finally, this test provides the only measure of the nonlinearity coefficient b_2. This is discussed in more detail in prior writings[3].
2. **Pre-flight Response vs Scan (RVS) Angle**. The RVS test involved viewing the LABB and rotating the AIRS instrument, collecting signals at each angle[2]. The test was performed at two fixed LABB temperatures (200K, 308K). We can derive the polarization product, $p_r p_t$, and the phase, δ from this test.
3. **Pre-flight Polarization Measurements**. In this test, an off-axis section of a paraboloidal mirror is used to project the image of a target aperture onto the field stop of the AIRS instrument[2]. The target aperture at the focus of the collimator is back illuminated with a blackbody source reflected from a spherical condenser mirror. The polarization of the optical beam entering the AIRS entrance pupil is selectable by a choice of one of four positions of a filter wheel containing wire grid polarizers in three different orientations, plus one open position. The polarization product $p_r p_t$ and phase, δ, (the orientation of the polarization ellipse) are computed from the data.
4. **Component Model**. Measurements of the polarization of the component piece parts of the AIRS were used in a model of the system polarization. This is also discussed in prior writings[2].
5. **In-flight Lunar Roll**. Lunar roll tests allow us to view space in the Earth Viewport. Under these conditions, the AIRS is essentially viewing the difference in mirror emission between the Earth view and the Space view. From this data we can calculate the polarization product, if we know the phase (e.g. from RVS test), from equation 4. The initial look at this data was discussed in a prior writing[4] and refinements are given below.

Figure 2 (left) show the polarization product, $p_r p_t$, for methods 1, 3, and 4 above, and phase from method 2. Version 5, the at-launch and currently operational version of the AIRS Level 1B product, uses the average of the Polarization Measurements and Component Model for the $p_r p_t$ to balance the difference between the estimates observed in the LWIR, and avoid the difference in the stepped blackbody test seen in the 10 µm data. V5 also assumed zero phase. All other

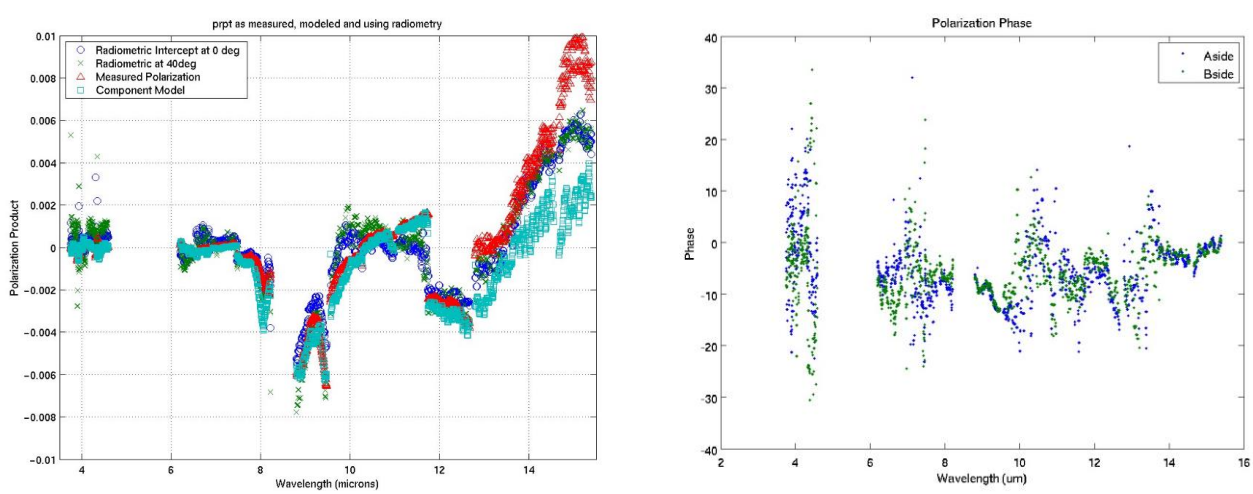

Figure 2. Left: Polarization product, $p_r p_t$ derived using three methods. Right: Polarization Phase from the RVS test. V5 uses the average of Measured and Component Modeled $p_r p_t$ and zero phase.

parameters (ε_{OBC}, T_{OBC}, b_2) were derived from the Stepped Blackbody test. Figure 2 (right) shows the polarization phase derived from the RVS test. Zero phase was used since we were not confident in the phase measurements and the potential error in use of zero phase was low. While this seems to be working fine for AIRS, as our calibration is good to better than 200 mK, the Lunar Roll test data set allows us to verify the V5 calibration and potentially re-calibrate the system and remove small errors in the polarization term.

Figure 3 (left) shows a diagram of the AIRS scan head assembly with an arrow showing the roll direction during the Lunar Roll test. When the spacecraft rolls to view the moon in the space viewport (for MODIS), it results in a view of space in the Earth viewport for AIRS. Figure 3 (right) shows the resulting brightness temperature (BT) image obtained from AIRS in channel 2333 at 2616 cm^{-1}. At the bottom of the image, the dark blue band is a view of space in the last few footprints. We have carefully selected the footprints which are uncontaminated with the earth limb[4]. There have been numerous roll maneuvers over the life of the Aqua spacecraft, however not all of them are sufficient in roll angle to allow the AIRS to view space without limb contamination.

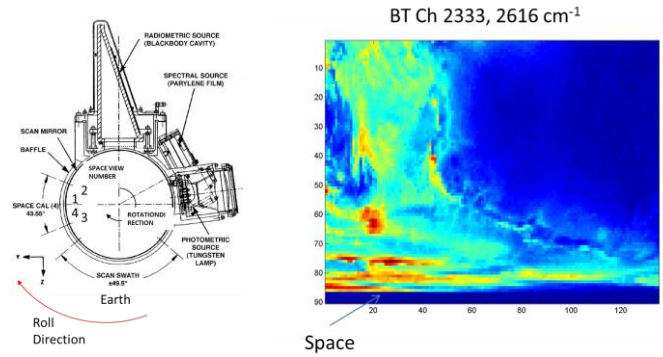

Figure 3. The lunar roll maneuver is designed to view the moon in the space viewport, but can result in a space look in the Earth viewport as shown above for 07/18/13.

Table 1 shows the roll test with the largest angles. The data from 6 of these roll test (1, 2, 4, 6, 9, and 10) were used to compute the polarization product assuming phase from the RVS test. Figure 4 (left) shows the raw polarization product derived from 6 tests selected for optimum roll angle and data quality. The derived polarization product is nearly the same as those derived from the other methods, and the repeatability is good. We can clean up the results by eliminating bad channels in AIRS as shown in Figure 4 (right) for one test used as an example. Since these polarization coefficients are derived from the space view data in the Earth viewport, we can expect that the polarization effect from the mirror is representative and should produce zero residual radiances in the on-orbit configuration rather than assuming everything measured on the ground matches in orbit. In this work we compute an "average" polarization product from the roll test that we can compare with the other methods.

Table 1. Key parameters for the Lunar Roll test ranked by roll angle.

Aqua MODIS Lunar Calibration Roll (MLC) History									
Roll rank	Date (mm/dd/yy)	DOY	Slew Out Start Time (hh:mm:ss)	Slew Complete (hh:mm:ss)	Roll Angle (degrees)	Slew Return Start Time (hh:mm:ss)	Slew Complete (hh:mm:ss)	Calibration Time (mm:ss)	NOTES
1	10/16/02	289	14:11:38	14:21:28	-20.0510	14:29:58	14:39:48	08:30	G144 complete
2	07/10/11	191	21:12:52	21:23:41	-20.0000	21:32:11	21:43:00	08:30	Scan profile test during this slew
3	07/06/06	187	13:35:43	13:46:30	-19.9065	13:55:00	14:05:47	08:30	G138 complete
4	08/17/13	229	0:30:29	0:41:15	-19.8433	0:49:45	1:00:31	08:30	G007 complete
5	07/02/09	183	5:02:47	5:13:32	-19.7496	5:22:02	5:32:47	08:30	G053 return slew last 1:23
6	10/13/05	286	16:06:53	16:17:36	-19.6645	16:26:06	16:36:49	08:30	G163 slew stops 11 sec in
7	09/18/10	261	9:32:54	9:43:32	-19.3639	9:52:02	10:02:40	08:30	G97 3:53 min in slew. G98 4:37
8	07/19/02	200	21:00:24	21:10:02	-19.3540	21:18:32	21:28:10	08:30	G212 complete
9	08/06/14	218	20:04:13	20:14:50	-19.2678	20:23:20	20:33:57	08:30	G203 return slew starts last 5 sec
10	07/18/13	199	20:04:45	20:15:20	-19.1540	20:23:50	20:34:25	08:30	G203 complete
11	08/13/16	226	21:30:02	21:40:33	-18.9155	21:49:02	21:59:33	08:29	G217 Complete
12	08/25/15	237	16:46:15	16:56:41	-18.6407	17:05:11	17:15:37	08:30	G170 complete

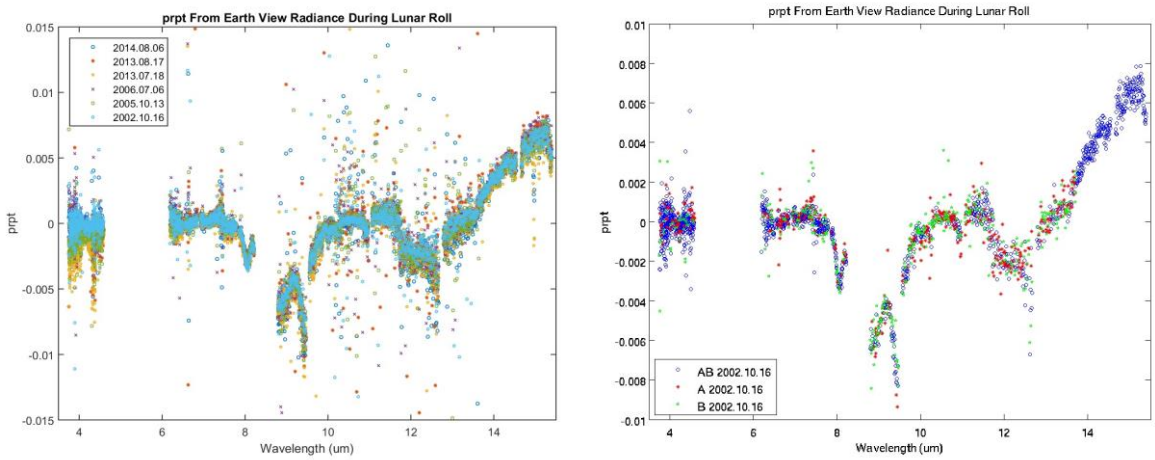

Figure 4. Left: Polarization product derived from several roll tests before channel filtering. Right: Polarization product after removing bad channels for one test and using different colors for A, B, and A/B side detectors.

2.3 Results

We compute the residual radiance error (converted to equivalent temperature at 220K using the gradient of the Plank function at this temperature and each wavelength) in the Earth view using the different polarization coefficients averaged over the 6 test. The results are shown in Figure 5 (left). The uncorrected result shows the magnitude of the error we are trying to correct. V5 shows the residual error we are currently experiencing in the Version 5 product. The "N40rab" shows the errors we would get if we used the stepped blackbody test (not used operationally), and "Roll" shows the residuals we would get if we used the coefficients derived from roll test itself. This last case is really a consistency check because we use the data from these tests to derive the coefficients. Finally, Figure 5 (right) shows the residual errors for each roll test after applying the average polarization product from the roll test. We see a consistent error for most wavelengths, however there is a hint of instability or trend in the shortest wavelength channels. We need to recognize that at the shortest wavelengths at this temperature that the radiance residuals are extremely small and what we might be viewing is noise.

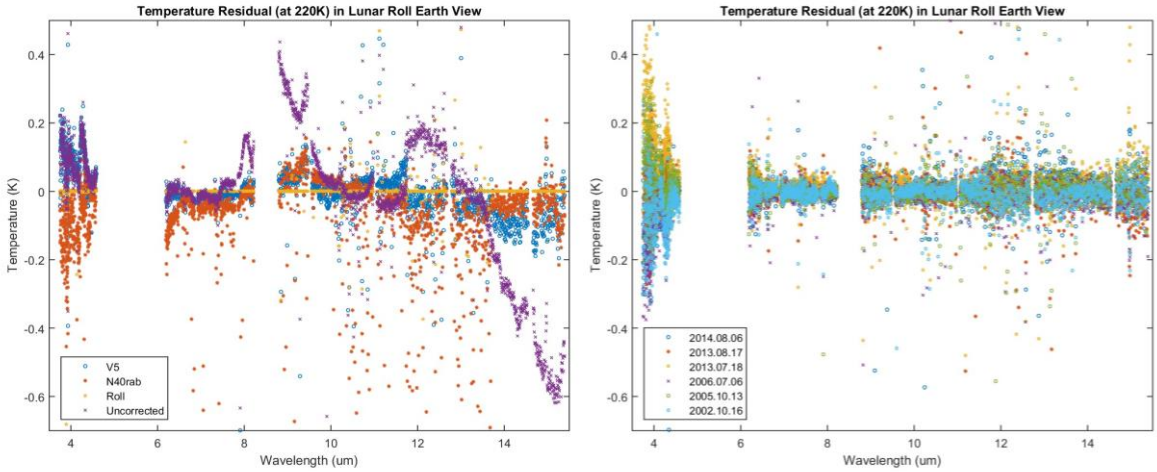

Figure 5. Left: Residual radiometric error for AIRS while viewing space in the Earth viewport averaged over 6 roll tests expressed at 220K uncorrected vs those when using polarization and phase coefficients for the current operational radiance product (V5), those obtained from the stepped linearity test, (N40rab), and those derived from the Lunar Roll test (Roll) itself. Right: Residual error in the earth viewport while viewing space using the average coefficients derived from the roll test for each test from which the coefficients are derived.

2.4 Radiometric Conclusions

The AIRS instrument is operating well and the radiance product derived with the currently operational version (V5) is having high impact to operational forecast and is used widely for long term climate studies. The residual errors in V5 due to the polarization effect are less than 200 mK, as shown in Figure 5 (left). We have found several ways to measure the polarization product, $p_r p_t$ pre-flight but only recently have found that the lunar roll test data provide a consistent measure of the polarization product with the instrument in the operational flight configuration. We initially recognized this data as useful for evaluating the V5 calibration, but now recognize that these data can be used to "re-calibrate" the AIRS and remove the small residual errors due to this effect seen in V5. We can expect to see the polarization product derived from the roll test to be implemented in the next operational version of the AIRS radiance product (Level 1B).

3. AIRS SPATIAL CALIBRATION CHECK

Boresight knowledge of the AIRS instrument relative to earth geocentric coordinates was evaluated shortly after launch using coastline detection[6,7]. At that time, it was determined that the AIRS boresight knowledge met specifications. Table 2 gives the results at that time. Results are sorted in columns by predominantly "scan" direction coastline crossing and "track" direction coastline crossings. The latitude and longitude difference for each group is given in the table. Since the scan direction is primarily in the longitude direction, the best numbers for longitude error are in the 2nd column, and show +0.84 km. Similarly for the track direction, we would use the 3rd column with a result of -0.38 km. Again, these results meet the AIRS specification of 2 km with margin.

Table 2. Results of AIRS geolocation analysis post-launch shows better than 1km geolocation knowledge.

	Lat diff s (km)	Lon diff s (km)	Lat diff t (km)	Lon diff t (km)
Mean	0.5918	0.8431	-0.3804	0.5072
Std. Dev	2.7515	3.6836	2.3950	4.2506

3.1 Methodology

In this analysis, we examine the results of perturbing the geolocation of AIRS while comparing MODIS and AIRS radiances. MODIS resolution is 1km while AIRS is 13.5 km in the infrared. First we compute the spatially integrated MODIS radiance in a window channel, band 31, weighted by the AIRS Point Spread Function (PSF)[8]. We also compute a corrected AIRS radiance that uses MODIS band 31 data and the AIRS PSF to correct for non-uniform scene effects. The improvement depends on the reduction in the variability between MODIS and AIRS. It is expressed as a temperature improvement, ΔT, as follows:

$$\Delta T = \sigma\left[BT(L_{AIRS}) - BT(L'_{MODIS})\right] - \sigma\left[BT(L'_{AIRS}) - BT(L'_{MODIS})\right]$$

The temperature improvement, if positive, represents less variability between the corrected AIRS radiances, L'_{AIRS}, and MODIS.

ΔT is calculated as a function of the boresight perturbation for selected channels. Channels examined give either the best "improvement" (highest ΔT) (channels: 770-786), vs those that show no improvement or are slightly degraded (channels 472 543 558 564 820 825 930). For each channel and for 6 footprints (1 22 36 45 67 and 90), the boresight of AIRS is adjusted relative to MODIS, and ΔT is calculated. The range of adjustment is -0.038° to 0.038° in earth geocentric coordinates in 20 equal steps of 0.004° in both latitude and longitude (400 grid points tested). The location of the greatest improvement (maximum ΔT) is a measure of the geolocation error between AIRS and MODIS.

3.2 Results

The results of the analysis are shown in Figure 6. This figure shows the optimal latitude and longitude with the biggest improvement, ΔT. The top figure shows the channels that show no improvement or a slightly degraded corrected radiance. In this figure it is seen that the optimal latitude and longitude is highly uncertain with a mean value of less than ±0.01° for all footprints with high statistical uncertainty. Basically the channels that are not improved with the AIRS PSF and MODIS

correction (most uniform PSF) do not get any better with boresight adjustment. The bottom figure shows the channels with the highest improvement (most asymmetric PSF), ΔT. We see a definite optimum (lower errors) latitude and longitude for these channels that is scan angle dependent.

Focusing our attention on the lower half of figure 6 for the channels with biggest improvement, ΔT, the longitude error appears to be about than -0.0025° at nadir and can be considered statistically insignificant. The error grows with scan angle (footprint number away from 45), becoming more positive at the beginning of scan and more negative at the end of scan. The magnitude of the error is about ±0.04° or about 4km. This difference is significant enough to warrant further investigation. The latitude error appears to be about +0.025° at nadir and has a nonlinear functional dependence with scan angle, returning to the value near nadir at the end of scan.

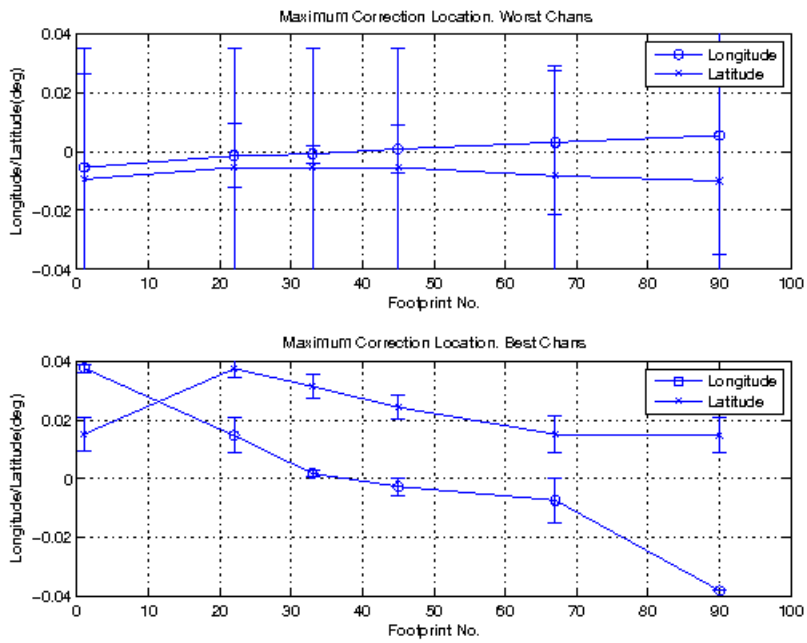

Figure 6. Latitude and Longitude where the biggest improvement is seen for the corrected AIRS radiances. (Top) Channels that are not improved by the AIRS PSF and MODIS correction are not improved by displacing the boresight. (Bottom) Channels that improve with the AIRS PSF and MODIS correction are further improved with a small boresight correction

3.3 Spatial Conclusions

The preliminary results here would indicate there could be a small pointing difference between the AIRS and MODIS of about +0.025° at nadir, but nearly zero error in the cross-track or scan direction. The differences off nadir grow significantly in both directions and warrants further investigation. The differences could be related to the selection of channels used.

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REFERENCES

[1] Chahine, M. T., et al., “The Atmospheric Infrared Sounder (AIRS): improving weather forecasting and providing new insights into climate,” Bulletin of the American Meteorological Society 87, 911–926, doi:10.1175/BAMS-87-7-911, (2006).

[2] Pagano, T. S., H. Auman, K. Overoye, G. Gigioli, “Scan Angle Dependent Radiometric Modulation due to Polarization for the Atmospheric Infrared Sounder (AIRS)”, SPIE 4135-14, August 2000

[3] Pagano, T. S., H. Aumann, R. Schindler, D. Elliott, S. Broberg , K. Overoye, M. Weiler, “Absolute Radiometric Calibration Accuracy of the Atmospheric Infrared Sounder”, Proc SPIE, 7081-46, San Diego, Ca, August 2008

[4] Pagano, T.S., Aumann, H., Weiler, M., “Lessons learned from the AIRS pre-flight radiometric calibration”, Proc. SPIE 8866-30, San Diego, CA (2013).

[5] Pagano, T. S.; Aumann, H.; Hagan, D. & Overoye, K. R. (2003), “Prelaunch and in-flight radiometric calibration of the Atmospheric Infrared Sounder (AIRS)”, IEEE T. Geoscience and Remote Sensing 41 (2) , 265-273

[6] Pagano, T. S., H. Aumann, S. Gaiser, D. Gregorich, “Early Calibration Results from the Atmospheric Infrared Sounder (AIRS) on Aqua”, SPIE 4891-09, (2002)

[7] Gregorich, David T., and Hartmut H. Aumann. "Verification of AIRS boresight accuracy using coastline detection." Geoscience and Remote Sensing, IEEE Transactions, 41(2), 298-302 (2003).

[8] T.S. Pagano, H. Aumann, D. Elliott,, E. Manning, “Improving AIRS radiance spectra in cloudy scenes using MODIS’, Proc. SPIE 9607-19, San Diego, CA (2015)