Checking AIRS Nonlinearity in Flight

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ABSTRACT

Radiances from the Atmospheric Infrared Sounder (AIRS) show excellent stability and are traceable to SI standards through the On-Board Calibrator (OBC) blackbody. The OBC can be used to check the nonlinearity by turning off the heater and letting the target float from 308K to roughly 261K while acquiring data. The OBC Float test was performed once prior to launch, and again shortly after launch. However, the OBC Float test did not produce accurate nonlinearity results because the temperature sensors became inaccurate below 290K. This paper summarizes a technique using a reference channel that is highly linear to measure the apparent temperature of the OBC, then using that temperature to determine the nonlinearity of the other channels. This method works well, and we are able to confirm the nonlinearity derived pre-flight for most of the channels. The AIRS has A side and B side channels that have different gain and nonlinearities, but the OBC float test was performed with an A/B optimum data set. We recommend repeating the test with A side and B side only gains selected for the channels.

Keywords: AIRS, hyperspectral infrared, radiometric, calibration, nonlinearity

1. INTRODUCTION

The Atmospheric Infrared Sounder (AIRS) on the EOS Aqua Spacecraft was launched on May 4, 2002 and is currently fully operational. 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]. AIRS acquires hyperspectral infrared radiances in 2378 channels ranging in wavelength from 3.7-15.4 µm 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. AIRS L1 and L2 products are widely used for studying critical climate processes related to water vapor feedback, atmospheric transport, atmospheric composition and cloud properties.

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[2]. Extensive testing was performed pre-flight including a calibration nonlinearity of the instrument response. Key to an accurate calibration is the accurate non-linearity correction for all channels. In order to check the AIRS instrument non-linearity in orbit, a test was devised whereby the temperature of the On-Board Calibrator (OBC) blackbody is changed to provide a varying radiance. In this test the OBC heater is turned off and the OBC temperature is allowed to float towards the ambient temperature in the scan cavity. The test, called the OBC float test, was performed once pre-flight and once shortly after launch. The temperature range for the pre-flight OBC float test was limited from 308K-287K, while the test performed in-flight covered the range 308K-261K. In this analysis we look only at the in-flight OBC float data set. We compare the nonlinearity obtained from the OBC float test to the data acquired pre-flight in the stepped Large Area Blackbody (LABB) test.

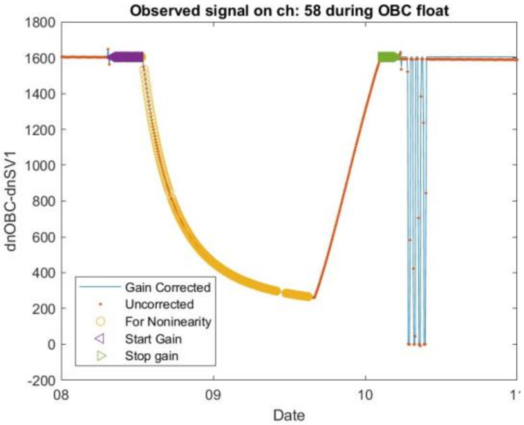

Figure 1. Signals on channel 58 while viewing the OBC during the obc_float test.

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The stepped LABB test measures the AIRS response at a set of discrete temperatures from 205K to 310K[3]. The nonlinearity from the LABB test is considered to be the most accurate as confirmed by the good precision between the multiple tests performed and the low residual offset errors.

2. METHODOLOGY

We define here the methodology for determining the nonlinearity from the OBC Float Test acquired in-orbit in 2002 and possible future tests. The signals from the test performed in 2002 (shown in Figure 1 for channel 58) are fit to a second order polynomial in signal counts and the 2nd order coefficient (or nonlinearity) derived. The overall approach to determining nonlinearity from the OBC differs from the approach using the stepped LABB and also differs from the method used to analyze the OBC Float Test shortly after launch[4]. The OBC temperature sensors become increasingly inaccurate below 290K. To get around this problem we pick a "reference channel" that we assume to be purely linear and use this channel to determine the OBC temperature. From the apparent OBC temperature derived using the reference channel, and the emissivity from the stepped LABB test, we compute the radiance for all channels and fit the AIRS response to a second order polynomial to get the second order coefficient. The process is a little more involved as we need to apply a gain correction to the signals while viewing the OBC to correct for instrument responsivity drift, during the time of the test. We also apply a correction to the apparent temperature of the OBC derived from the reference channel to correct for apparent gradients seen by the other channels. Finally, we apply a correction to the nonlinearity we calculate to account for the different gains during the pre-flight stepped LABB test and the OBC Float test.

2.1 Gain Correction for all Channels

Before we process the signals obtained during the OBC float test, we need to correct for instability in the gain. To achieve this, we perform a fit to the gains prior to and after the OBC float test and interpolate to the values in between. The gain as a function of time can be written as

$$b_1(t) = b_{10} + b_{11}t + b_{12}cos\omega t + b_{13}sin\omega t \qquad [1]$$

We fit the above equation to the gain at the start and end of the OBC float test (see Figure 1). The gain at the start and stop of the OBC float test is determined using the emissivity determined pre-flight in the stepped linearity test and the telemetered temperature (corrected for 0.3K offset) of the OBC. The gain, b_1, at the start and end the test for each channel is given by

$$b_1(t_{1,end}) = \left[\frac{\epsilon_{obc}P(T_{obc}(t_{1,end}),\lambda)[1+2p_rp_tcos2\delta]-c_2dn_{obc}{}^2(t_{1,end})-c_o}{dn_{obc}(t_{1,end})}\right] \qquad [2]$$

where ε_{obc}, p_rp_t, δ, c_o and c_2, are obtained pre-flight during the stepped LABB test, and we use the short notation

$$dn_{obc}(t_i) - dn_{sv}(t_i) \rightarrow dn_{obc}(t_i) \qquad [3]$$

The temperature, T_{OBC}, is derived from the on-board temperature sensors which operate well at this temperature[1]. The gain correction was applied to the signals obtained while viewing the OBC during the test for all channels.

$$dn'_{obc}(t_i) = dn_{obc}(t_i)\frac{b_1(t_i)}{b_1(t_1)} \qquad [4]$$

An example correction to the gain is shown in Figure 2 for channel 58 during 8 orbits. Prior to correcting the gain we see a trend and orbital oscillation. After gain correction, the trend and oscillation are reduced. While we have corrected both the trend and oscillation, the correction for the oscillation results in little change to the overall nonlinearity result.

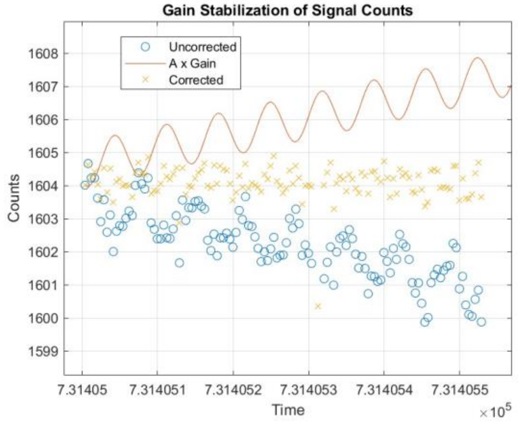

Figure 2. Signals on channel 58 prior to and after gain correction

2.2 Apparent OBC Temperature

2.2.1 Reference Channel Selection

In this analysis, a reference channel is used to measure the OBC temperature vs time. The reference channel must be sufficiently linear to allow us to neglect the nonlinearity when converting the observed radiance of the OBC to temperature. We define the figure of merit for the nonlinearity of the channel as the ratio of the signal at the OBC from nonlinearity (c_2dn^2), to the linear signal (c_1dn) with $c_1 = L_{obc} / dn$

$$F = \frac{c_2 L_{obc}}{c_1^2} \qquad [5]$$

Figure 3 shows the Figure of Merit for nonlinearity for all the AIRS channels based on the coefficients obtained pre-flight[5]. There are several channels with low nonlinearity in the 4 µm and 14 µm regions. We choose channel 2108 (LMID+1) at 13.74 µm as the reference channel since this channel has the lowest nonlinearity.

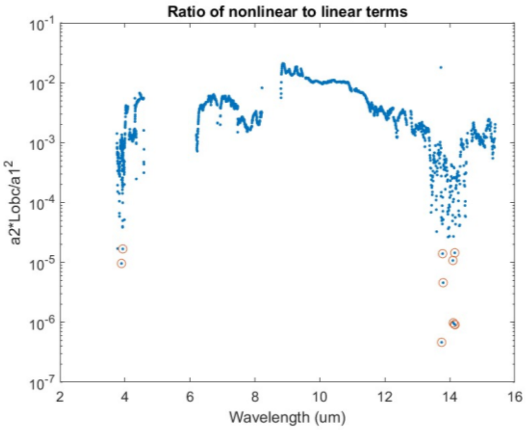

Figure 3. Nonlinearity figure of merit, F, for AIRS channels based on the stepped LABB linearity test.

2.2.2 Reference Channel Apparent Temperature

We can now use the reference channel to infer the temperature of the OBC during the test. Using the AIRS radiometric calibration equation, we first compute the radiance observed by the reference channel

$$L_{obc,r1}(t) = L_o(\theta) + \frac{c_0 + b_1'(t)dn_{obc,r1} + c_2(dn_{obc,r1})^2}{[1+p_r p_t cos2\delta]} \qquad [6]$$

Where $L_o(\theta)$, $p_r p_t$, δ, c_o and c_2, are obtained pre-flight, and $b_1'(t)$ is derived above for the reference channels. The radiance is converted to an apparent temperature using the inverse Planck function.

$$T_{obc,r1}(t) = P^{-1}\left[\left(\frac{L_{obc,r1}(t)}{\epsilon_{obc,r1}}\right), \lambda_{r1}\right] \qquad [7]$$

Figure 4 shows the temperature as measured by the 4 on-board temperature sensors and the apparent temperature by the reference channel. 3 of the 4 on-board temperature sensors saturate at about 278K. The fourth on-board sensor appears to go out of calibration below 290K as compared to the temperature derived from the reference channel.

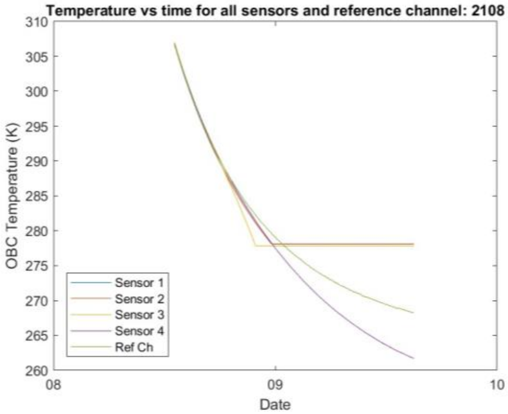

Figure 4. Temperature during OBC Float as measured by the 4 on-board temperature sensors and as derived from the reference channel 2108.

2.2.3 All Channels Apparent Temperature

Since the different AIRS modules view slightly different parts of the blackbody, there could be temperature gradients between the location viewed by the reference channel, and the rest of the channels. We tested this by computing the apparent temperature for all the channels using the same technique for computing the apparent temperature for the reference channel. We found that there is a gradient that varies linearly with temperature approaching 200mK for the worst case modules, M5 and M6. This gradient was removed on a module by module basis by subtracting a linear fit to the module average temperature difference relative to the reference channel vs blackbody temperature. The temperature for the ith channel is the temperature of the reference channel, r_1, minus the module average temperature difference relative to r_1.

$$T_{obc,i}(t) = T_{obc,r1}(t) - \overline{\Delta T_{obc,mod}}(t) \qquad [8]$$

2.3 Determination of Nonlinearity for all channels

We can now determine the coefficients of the radiometry for all channels by the fitting OBC radiance to a second order polynomial in counts measured as the temperature drops during the Float Test

$$L_{obc,i} = \epsilon_{obc,i} P\left(T_{obc,i}, \lambda_i\right) = a_0 + a_{1,i} dn_{obc} + a_{2,i} dn_{obc}^2 \qquad [9]$$

The second order term from the fit of the OBC, a_2 should be very close to the corresponding term determined from the stepped LABB test, c_2. But before we can compare the nonlinear terms, we must apply a correction for the gain differences during LABB tests pre-flight and the OBC float test in orbit.

2.3.1 Gain Correction to Nonlinearity

The instrument gain measured as radiance units per dn, is measured every 8/3 seconds using the OBC. The gain can change from ground to orbit in AIRS. This can occur due to several factors including radiation exposure, contamination, or a change in the detector illumination within the optics. Assuming a simple gain change,

$$dn'_{obc,i} = \frac{a_{1,i}}{a_{1,i'}} dn_{obc} \qquad [10]$$

Solving for dn_{obc} and substituting into equation 9, we get

$$L_{obc,i} = a_0 + a_{1,i}' dn'_{obc} + a_{2,i}' dn'^2_{obc} \qquad [11]$$

where,

$$a_{2,i}' = \left(\frac{a_{1,i'}}{a_{1,i}}\right)^2 a_{2,i} \qquad [12]$$

Any time the gain changes on the instrument, we must apply a gain correction to the nonlinear term to ensure the correct 2nd order term is applied.

3. TEST DATA

Data for the OBC_Float Test analyzed here was obtained on July 8, 9, 10, 2002, shortly after launch. The raw Level 0 data are unpacketized and converted to Level 1a counts and engineering telemetry by the AIRS project Product Generation Executables (PGE's). From this data we extract the counts while viewing the OBC and Space, the temperature of the OBC and the scan mirror, and the date. The data for the entire period is aggregated into a single file of temperature and counts containing 705 values for each variable (from 240 granules for July 8, and July 10, and 225 granules from July 9)

From the aggregated data set, we extract the tests corresponding to the time before and the time after the OBC Float Test, during the time when the OBC is stable at 308K, to fit the gain vs time across the period of the OBC Float Test. Data prior to the test corresponds to granules 80-125, and after the test corresponds to granules 490-515. The test includes a cooldown period (granules 131-171, 174-304, and granules 308-375), and a warmup period (granules 385-510). The missing tests correspond to periods when a guard test may have been performed (upload of tables to switch A and B sides) and have been avoided. Only the cooldown results are shown here.

The OBC temperatures for the gain correction is obtained using the standard formula for the OBC temperature, which is a weighted sum of the four temperature sensors with weights 0.45, 0.45, 0.09, 0.01 respectively. The OBC signal is obtained by subtracting the space view counts from the OBC counts for every scan in the granule and averaging them per granule. The gain correction is applied to the OBC signals prior to fitting them to derive the coefficients.

4. RESULTS

A second order polynomial (equation 9) in OBC signal counts is fit to the OBC radiance determined from the apparent temperature of the channel (equation 8) and the emissivity from pre-flight testing. The resulting zeroth, first and second order coefficients obtained during the OBC Float Test are compared to the same coefficients obtained pre-flight. The uncorrected coefficients are shown in Figure 5. Figure 5 shows the results for the OBC cooldown period, but we also have results for the warmup period. The first thing we notice is that the zeroth order term, a_o is not zero in the OBC Float test for some channels. This is probably due to the fact that there are uncorrected gradients in the OBC Float test at cold temperatures. The gain term (Figure 5 center) shows the average of A and B sides, but we indeed see a difference pre-flight and during the OBC float test that needs to be corrected. The uncorrected nonlinearity, a_2, is shown in Figure 5 right. We see a significant variability in the nonlinear term that is largely due to the variability in the gain.

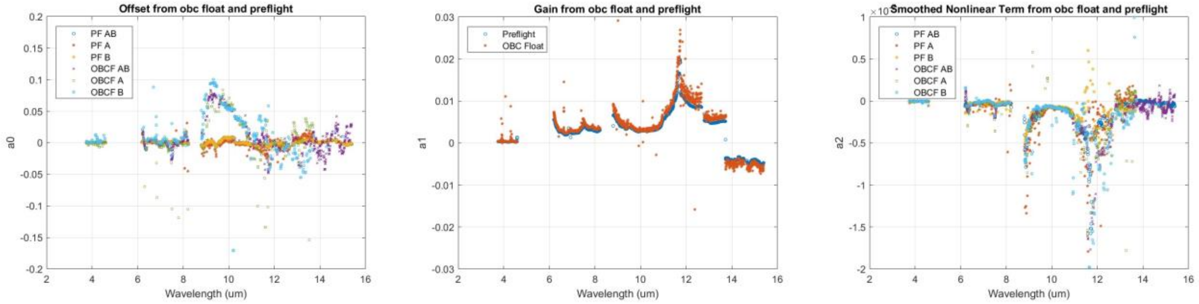

Figure 5. left) Zeroth order Term, a_o, center) 1st order term, a_1, and right) 2nd order term obtained pre-flight and during the OBC Float Test cooldown period.

Both the pre-flight nonlinear term, c_2, and the nonlinear term obtained during the OBC Float, a_2 were gain corrected to the module average gain obtained pre-flight. Figure 6 (left) shows the nonlinear coefficient obtained pre-flight before and after correction to the module average gain for Module 8. We see that the gain variability across a module can contribute to variations in the nonlinear term and when normalized to the average module gain, that the nonlinearity remains nearly constant across the module for both the A and B sides. This argues for applying the gain correction to data obtained in-orbit.

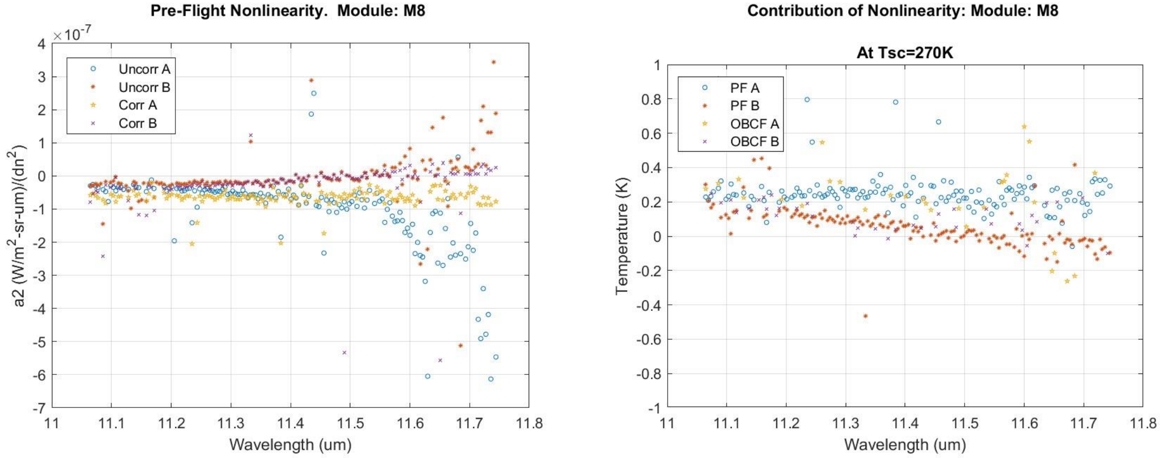

Figure 6 (left). Pre-Flight Nonlinearity, c_2, before and after gain correction to the module average gain. (Right) Contribution after gain correction of the pre-flight and OBC Float nonlinearity.

A better way to interpret the nonlinearity is to examine its contribution to the signal we see at a given temperature. This process corrects for the gain variability and gives us a measure of the size of the difference in terms of the measurement. The contribution of the nonlinear term to the scene temperature measured for a given channel can be shown to be

$$\Delta T_{a2} = a_{2,i} dn_{sc}(dn_{sc} - dn_{obc}) / \left[\frac{\partial L}{\partial T}\right]_{T_{sc}} \quad [13]$$

This equation highlights the point that the nonlinearity contribution goes to zero at the OBC temperature. Figure 6 (right) shows the gain corrected contribution for both the pre-flight and OBC float data sets for Module 8. The preflight contribution is still different for A and B sides. The results from the OBC-Float test follow well the pre-flight test despite the few points in on-board OBC Float data set.

We can now look at the nonlinearity obtained for all modules during the OBC Float Test and compare that to the pre-flight data. We choose to look at module median values since the OBC Float test as configured in 2002 does not have sufficient samples to accurately compute a single channel non-linear coefficient and the uncertainty is high since we are not covering the full temperature range. Figure 7 shows the nonlinearity contribution for each of the 17 modules of AIRS using the pre-flight and On-Board gain corrected nonlinearity. In this figure, the module mean gain corrected a_2 and c_2 terms are expressed as a temperature contribution at 270K. The error bars represent the standard deviation of the c_2 term obtained Pre-Flight to give us a reference of the accuracy we believe to have on the Pre-Flight data set. The overall results show the proper trends and confirm the nonlinearity observed to within 100mK in most cases. We consider this test to be a success in that it confirms the nonlinearity we obtained pre-flight. The test was never intended to provide an accurate calibration. For that reason, we will not change the nonlinearity measured pre-flight, but now know that it may be necessary to adjust the nonlinearity based on changes to the gain observed between Pre-Flight and In-Orbit.

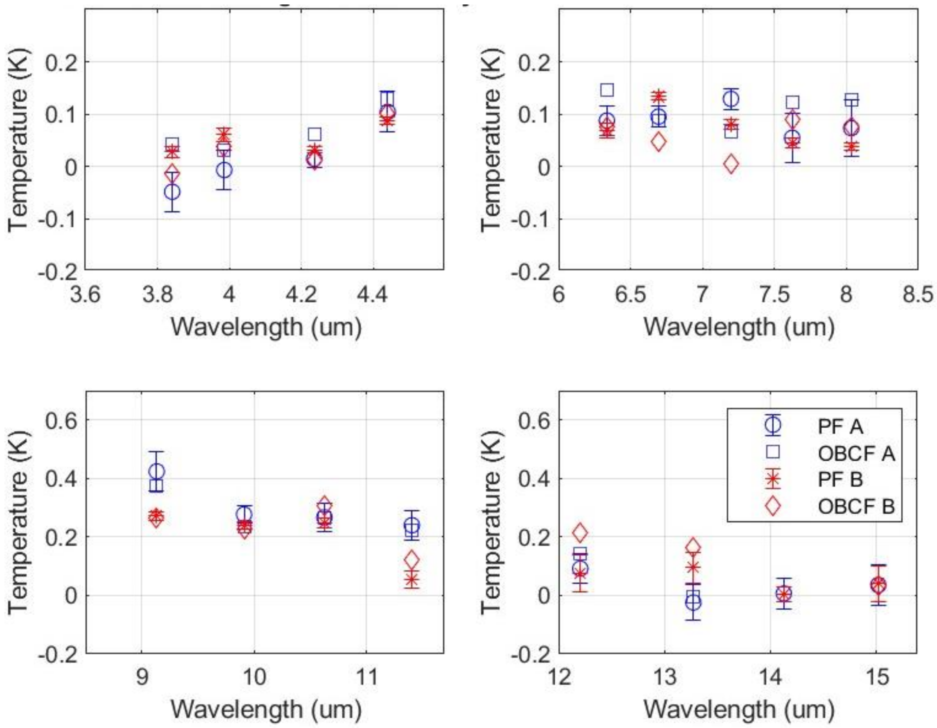

Figure 7. Contribution of nonlinearity Pre-Flight and during the OBC Float Test for A side and B side. Error bars represent 1-sigma uncertainty in Pre-Flight c_2.

5. SUMMARY AND CONCLUSIONS

The nonlinearity in the AIRS instrument was measured during pre-flight testing. The OBC Float Test allows us to check the nonlinearity by turning off the OBC heater and letting the temperature of the OBC float to a colder temperature. This test was performed once in orbit in July of 2002. We also analyzed results during the warm-up, and those results are similar but are not shown here. Since the temperature sensors on the OBC are not useful for this test, a highly linear reference channel was used to measure the radiance of the OBC that was then converted to an apparent temperature as the temperature dropped. This apparent temperature was transferred to the other channels after removing a bias as a function of temperature for each module. The resulting apparent temperature was fit to a second order polynomial to determine the instrument response in orbit.

In the process of comparing the non-linearity pre-flight to that from the OBC float test, we found that a gain correction must be applied to the nonlinear terms to account for the change in gain of the first order term. After applying the gain correction, we found that the variability of the nonlinearity within a module decreases substantially. This confirmed our hypothesis that the nonlinear term is dependent on the linear term. We then compared the pre-flight nonlinearity to the OBC float test nonlinearity after normalizing both to a common gain, the module average gain obtained pre-flight. The module average contribution for A and B sides obtained during the OBC Float test match well the values obtained pre-flight.

In general, the new analysis of the OBC Float test confirms:

1. The nonlinear term depends on the linear term. This implies a correction should be made to the nonlinear term to account for gain changes from ground to orbit, and possibly during the life of the mission.
2. Separate coefficients for A side and B side are warranted for many channels, but is not necessary for all channels, provided a separate A side and B side gain correction is applied.
3. The test performed in 2002 did not have sufficient separation between A side and B side tests to provide a good measure of the nonlinearity for each of the sides. If the test is to be repeated, we recommend changing the A/B weight table to have every other channel as A or B side accounting for if there is an A side or B side channel already in place.

Uncertainty in the nonlinearity is the largest contributor to the radiometric accuracy uncertainty of the AIRS instrument.[6] Re-analysis of the OBC Float test confirms our suspicions that A side and B side nonlinearity should be held separately. It also allows us to understand how the nonlinearity should be adjusted as the gain changes. A repeat of the OBC Float test will improve the statistics with respect to the A side and B side differences and may allow us to see if there are any changes in the nonlinearity over the course of the mission.

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