# Performance Status of the Atmospheric Infrared Sounder Ten Years after Launch

Thomas S. Pagano*[a], Steve Broberg[a], Hartmut H. Aumann[a], Denis Elliott[a], Evan Manning[a]
Larrabee Strow[b]

[a]Jet Propulsion Laboratory,
California Institute of Technology, Pasadena, CA 91109

[b]University of Maryland Baltimore County (UMBC), Baltimore MD.

## ABSTRACT

The Atmospheric Infrared Sounder (AIRS) is a hyperspectral infrared instrument on the EOS Aqua Spacecraft, launched on May 4, 2002. AIRS has 2378 infrared channels ranging from 3.7 µm to 15.4 µm and a 13.5 km footprint at nadir. 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. 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 $CH_4$. AIRS data are used for weather forecasting, climate process studies and validating climate models. The AIRS instrument has far exceeded its required design life of 5 years, with over 10 years of operations as of September 2012. While the instrument has performed exceptionally well, with little signs of wear, the AIRS Project continues to monitor and maintain the health of AIRS, characterize its behavior and improve performance where possible. Radiometric stability has been monitored and trending shows better than 16 mK/year stability. Spectral calibration stability is better than 1 ppm/year, and a new gain table was recently uploaded to recover 100 significantly degraded or dead channels by switching to their redundant counterpart. At this time we expect the AIRS to continue to perform well for the next decade.

Keywords: EOS, AIRS, infrared, sounder, calibration

## 1. BACKGROUND

The Atmospheric Infrared Sounder (AIRS) shown in Figure 1 is the first hyperspectral infrared sounder developed by the National Aeronautics and Space Administration (NASA) in support of operational weather forecasting by the National Oceanic and Atmospheric Administration (NOAA). Integration of the fully tested and calibrated AIRS flight unit with the EOS-Aqua satellite was completed in 2001 with the launch of AIRS on May 4, 2002.

The AIRS Instrument provides spectral coverage in the 3.74-4.61 µm, 6.20-8.22 µm, and 8.8-15.4 µm infrared wavebands at a nominal spectral resolution $\lambda/\Delta\lambda$ = 1200, with 2378 spectral samples. Key to the spatial coverage and the calibration is the scan head assembly, containing the scan mirror and the calibrators.

.

Figure 1. The Atmospheric Infrared Sounder (AIRS).

*Correspondance: E-Mail: tpagano@jpl.nasa.gov; Telephone: +1-818-393-3917; Fax: +1-181-393-4918

A cross section of the scan head assembly is shown in Figure 2. A 360 degree rotation of the scan mirror generates a scan line of IR data every 2.667 seconds. The scan mirror motor has two speeds: During the first 2 seconds it rotates at 49.5 degrees/second, generating a scan line with 90 footprints of the earth scene, each with a 1.1 degree diameter IFOV. During the remaining 0.667 seconds the scan mirror completes one revolution with four independent views of cold space (SV), one view into a 310 K radiometric calibrator, called the On-Board Calibrator (OBC) Blackbody, one view into a spectral reference source (Parylene), and one view into a photometric calibrator. The VIS/NIR photometer, with a 0.185 degree IFOV, is boresighted to the IR spectrometer to allow simultaneous visible and infrared scene measurements.

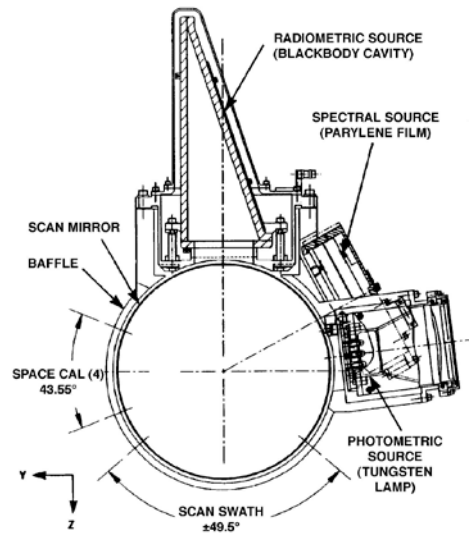

Figure 2. AIRS Scan Assembly

The diffraction grating in the IR spectrometer disperses the radiation onto 17 linear arrays of HgCdTe detectors (Figure 3) in grating orders 3 through 11. Cooling of the IR optics and detectors is necessary to achieve the required instrument sensitivity. The IR spectrometer is cooled to 156.5 K by a two stage radiative cooler. The IR focal plane is cooled to 58.1 K by a Stirling/pulse tube cryocooler. The scan mirror is cooled to about 260.5 K by radiative coupling to the Earth, space and IR spectrometer. The VIS/NIR photometer uses optical filters to define four spectral bands in the 400 nm to 1000 nm region. The VIS/NIR detectors are not cooled and operate at the temperature of the instrument housing at 271K. Signals from both the IR spectrometer and the VIS/NIR photometer are passed through onboard signal and data processing electronics, which perform functions of radiation circumvention, gain and offset subtraction, signal integration, and output formatting and buffering to the high rate science data bus. In addition, the AIRS instrument contains command and control electronics whose functions include communications with the satellite platform, instrument redundancy reconfiguration, the generation of timing and control signals necessary for instrument operation, and collection of instrument engineering and housekeeping data. The Stirling/pulse tube cryocoolers are driven by separate electronics which control the phase and amplitude of the compressor moving elements to minimize vibration and to accurately control the temperature. Heat from the electronics is removed through coldplates connected to the spacecraft's heat rejection system.

Full use of the high measurement sensitivity and accuracy capability of AIRS required very careful prelaunch calibration. The extensive prelaunch spectral, spatial, and radiometric calibration of AIRS was made using a test facility especially designed for AIRS located at the former Lockheed Martin Sanders facility in Lexington, Massachusetts[1] (now BAE Systems). We have previously described the AIRS hardware and provided a summary of the performance as measured pre-launch and shortly after launch[2,3]. The AIRS Calibration Plan required a special set of tests using only internal calibration sources to be performed during spacecraft thermal vacuum and for the first time in orbit as soon as the optics were cooled[4]. A subset of the tests are performed periodically throughout the life of the mission to obtain trending information on critical performance parameters. Spatial and polarimetric performance has not been updated since before launch since no methods exist at this time for updating these performance estimates. Radiometric and spectral performance is monitored in orbit using these special tests and using upwelling spectral radiances as discussed below. Finally, we have developed a Level 1C product to fill noisy or dead channels and gaps in the spectrum, and resample to a common frequency grid, making AIRS radiances easier to compare with radiances from other instruments.

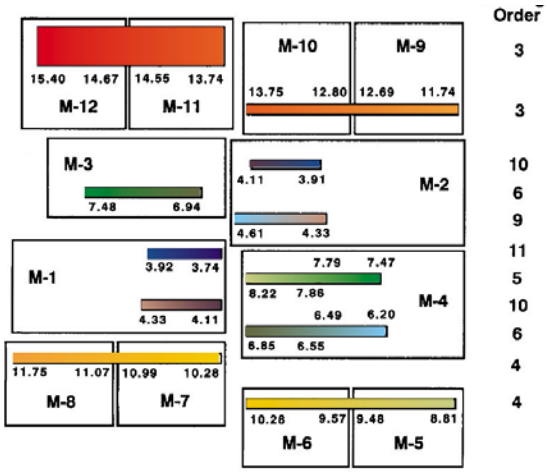

Figure 3. AIRS FPA Layout. Numbers represent wavelength for that module. Module names identified bv "M-X".

## 2. INSTRUMENT TELEMETRY TRENDING

Instrument telemetry is tracked automatically on a daily basis to detect changes in subsystem performance. Instrument telemetry includes numerous temperatures, voltages and currents for a variety of subsystems. Figure 4 shows a sample of the key subsystems monitored on a regular basis from September 2002, when AIRS became operational through

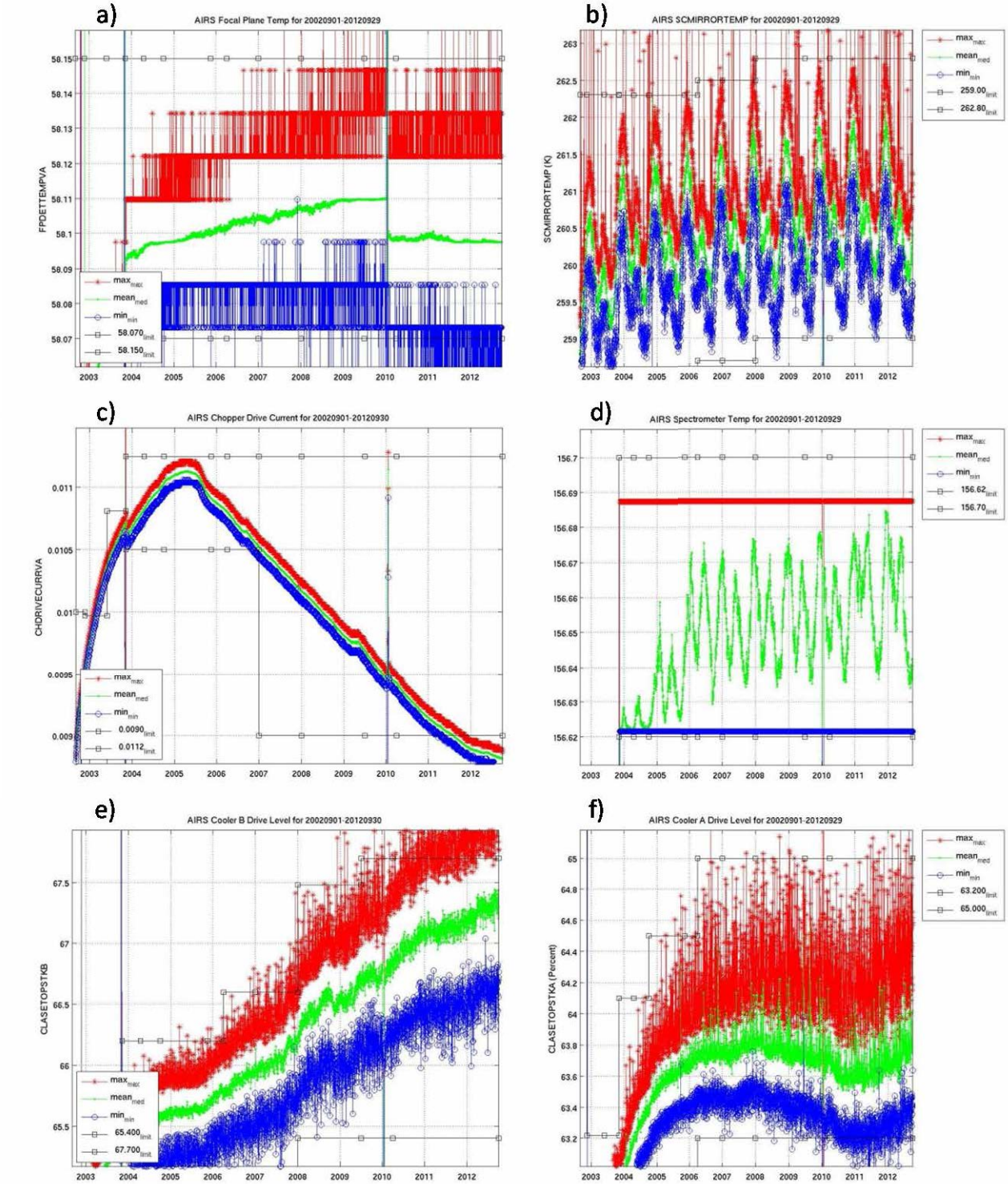


Figure 4. Instrument Telemetry as measured from September 2002 through April 2012. a) FPA Temperature, b) Scan Mirror Temperature, c) Chopper Drive Current, d) Spectrometer Temperature, e) B-Side Cooler Stroke, f) A-Side Cooler Stroke. Red and blue represent max and min of all values in the day, while green represents the mean.

September 2012, a period of 10 years. Figure 4a shows the mean focal plane temperature readout with daily maxima and minima. The average temperature is stable to 20 mK. Limits of 58.07K and 58.15K are not critical and are set to detect long-term changes. Changes in FPA temperature can influence the radiometric response of the instrument if large enough, however the regular view of the OBC blackbody and space remove first order fluctuations longer than 2 sec. Figure 4b shows the scan mirror temperature. The scan mirror temperature contributes to the radiometric calibration in the offset correction. A 5 K uncertainty in the knowledge of the scan mirror will only impact the radiometry to 5 mK[5], but better than 0.5K in stability of the temperature is achieved from the subsystem. Figure 4c shows the current of the chopper used to modulate the signal on the PC detectors. The cause of the early increase then decrease later in the mission is unknown but phase is well within limits. Temperature control of the optical bench is critical for maintaining the alignment of the spectrometer to the FPA and impacts spectral calibration. Figure 4d shows the spectrometer temperature which has been controlled to better than 70mK over the life of the mission. Finally, figures 4e and 4f show the stroke of the B and A side coolers respectively. The A side cooler stroke has remained stable showing no increase, and only a small increase is seen in the B side. The rate of increase is low enough to indicate that the coolers will be operating at safe levels through the anticipated life of the mission. All data sets show the response of the instrument to the shutdown of January 9, 2010 after the 28V power supply shut down due to a Single Event Upset (SEU). The instrument was returned to operate mode January 26, 2010 with mostly no change to the instrument telemetry.

## 3. RADIOMETRIC PERFORMANCE

The AIRS radiometric performance can be divided into three categories: a) sensitivity (SNR, NEdT) b) accuracy and c) stability. To date, the NEdT performance of AIRS has not been an issue for the majority of users, despite the higher NEdT's in the longwave and shortwave and ends of the arrays. With a large degree of redundancy in the atmospheric spectrum, and the large number of AIRS channels, the loss of specific channels in the spectrum due to the use of a grating spectrometer and multiple linear arrays of detectors has not been an issue. Nevertheless, 100 channels have been recovered or improved with a change to the redundant detector. Radiometric accuracy is excellent and discussed in a prior writing[5], with an update in process. Of more importance is the stability of the radiometry and the relative uniformity in the spectrum. We see excellent stability in AIRS, but a small drift is detectable in the shortwave at low scene temperatures. Some overlap channels show small differences in radiometric bias that have been improved using new calibration coefficients, but we are rapidly approaching the limits of accuracy and precision of the pre-flight testing and characterization. Vicarious calibration using clear radiances and correlation with Sea Surface Temperature (SST) and Deep Convective Clouds (DCC's) have provided insights into the instrument radiometric and spectral response over the past ten years of the mission. We discuss these issues and methods in this section.

### 3.1 Radiometric Sensitivity

Radiometric sensitivity was measured pre-flight and directly after launch using the "space view noise test". In this test, the noise is measured (in digital number) while viewing space. The resultant digital number is converted to NEdN using the instrument gain (using the OBC signal) and finally to NEdT at 250K using the calculated radiance and gradient with respect to temperature at this temperature[6]. These early results showed negligible difference between pre-launch and in-orbit noise performance.

Radiometric sensitivity is also determined during the normal science operations of the AIRS. In the Level 1B software (converts counts to radiances), the instrument radiometric gain is calculated. The gain is the first order responsivity of the AIRS in terms of radiance units (mW/m$^2$-sr-cm$^{-1}$) per digital number (dn) measured from the instrument. We calculate the gain as follows[7].

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

where

$a_{1,i}$ = Gain of the AIRS per scan in units of Radiance per digital number, (N/dn).

$N_{OBC,i}$ = Radiance of the on-board calibrator blackbody (OBC BB) as calculated below.
$p_r p_t$ = Product of the polarization factor of the scan mirror and spectrometer respectively.
$\delta$ = Phase of the polarization of the AIRS spectrometer.
$a_o(\theta_{OBC})$ = Radiometric offset evaluated at the angle of the scan mirror while viewing the Units of Radiance, N.
$a_2$ = Second order coefficient as obtained from pre-flight testing ($N/dn^2$)
$dn_{obc,i}$ = OBC blackbody digital number for the $i^{th}$ scan
$dn_{sv,i}$ = Space View digital number for the $i^{th}$ scan

The mean and standard deviation of the gain over all 135 scans in the granule are used to compute the instrument SNR. Noise Equivalent Radiance (NEN) is calculated from the SNR assuming a 250K scene and reported in the Level 1B file on a per-granule basis. We calculate the NEdT from the NEN using the radiance and radiance gradient at 250K. Figure 5 gives the daily average NEdT of the instrument separated by 10 years. Those channels that were declared bad either prior to launch or later in orbit are not plotted and discussed below. For the vast majority of channels we see excellent stability in the noise performance.

$$SNR = \langle a_{1i} \rangle / Std(a_{1i})$$

$$NEN_{scene} = N_{scene} / SNR$$

$$NE\Delta T_{scene} = \frac{NEN_{scene}}{\partial N / \partial T|_{T=Tscene}}$$

where

*$DN_{obc}$ = Noise while viewing the OBC (dn)*
*$DN_{sv}$ = Noise while viewing space (dn)*
*$N_{obc}$ = Radiance of the OBC Blackbody ($W/m^2$-sr-$cm^{-1}$)*
*Gain = Instrument Linear Response ($W/m^2$-sr-$cm^{-1}$)/dn)*
*$N_{scene}$ = Radiance of the scene ($W/m^2$-sr-$cm^{-1}$)*
*$NEN_{scene}$ = Noise Equivalent Radiance of the Scene ($W/m^2$-sr-$cm^{-1}$) in the L1B Granule.*
*$NE\Delta T_{scene}$ = Noise Equivalent Temperature of the Scene (K)*
*$T_{scene}$ = Temperature of the Scene (K) = 250K for Evaluation*

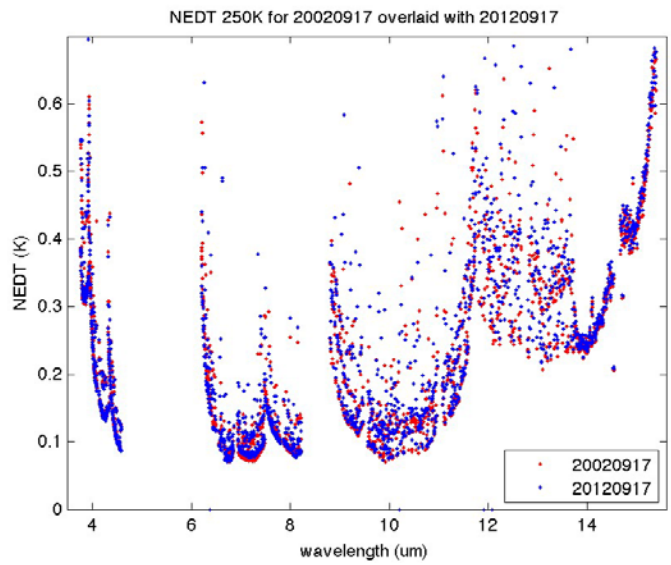

Figure 5. NEΔTs for AIRS at 250K measured when AIRS became operational haven't changed in 10 years

### 3.2 Channel Failure and Recovery

The AIRS PV HgCdTe detector material is affected by radiation in orbit. An "AB State" is assigned to each channel to reflect the detector redundancy configuration (A, B or A+B) and the noise performance. The numbers 0 to 6 were assigned for AB_State as follows: 0 (A+B, both Good), 1(A Good), 2(B Good), 3 (A+B, both Poor) 4 (A Poor: B Bad), 5 (B Poor: A Bad), 6 (A+B, Both Bad). "Poor" indicates the detector is operating but not as good as its peers, and "Bad" indicates the channel is not responsive or severely degraded. With 2104 PV channels in the instrument, 1856 were identified to be good pre-launch (State 0,1,2), 180 were poor (3,4,5), and 68 were bad.

We regularly (approximately once per month) use the "guard" test to measure the instrumental noise of the redundant detectors for each channel. The test exercises the A, B, and A/B optimum gain and circumvention tables and acquires 1 Granule (135 scans) of data in each case. For each gain table, the instrument acquires several scans of the SV and OBC view. These views are used to compute noise levels as discussed above, for the A and B detectors independently.

Figure 6 shows the number of channels flagged by the automated limit detection system in the AIRS Level 1B software. Limits were set at launch for all the 2378 channels. We see that 80-100 channels increased in noise or pop characteristics over the life of the mission enough to exceed the limits in the software. We can see the characteristics of the FPA's change for the 2010 shutdown (although the FPA's were kept cool). On January 21, 2012, the AIRS team uploaded a new gain table changing the state for 100 channels. We can see the drop in pop count when we loaded the new gain table but do not see a drop in high noise flags in the figure. This is due to the gain table emphasizing changes primarily to channels that were dead or that exhibited non-Gaussian noise (e.g. popping). In some cases, the AIRS science team felt that it is better to keep a detector operating in its current state, even if it is noisy, rather than change its bias and spectral characteristics by switching to the redundant detector. However, dead detectors or popping detectors cannot be used for climate studies and were changed where possible.

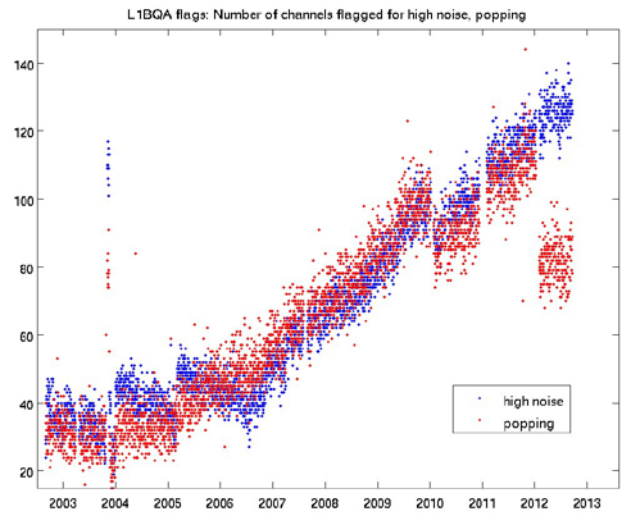

Figure 6. Number of channels flagged for high noise or pops by the automated noise detection system in L1B.

Figure 7 shows an example case for a change of state for channel 758 occurring in late 2004. In this example both A and B were combined in the gain table, but the A side suffered significant noise degradation most likely due to a radiation hit while the spacecraft was passing through the South Atlantic Anomaly (SAA).

Near the right hand side of the figure, we see a reduction of noise corresponding to the time the new gain table was uploaded switching to the redundant B-side detector. The NEdT for this channel is nearly fully recovered having only lost the √2 improvement gained by combining detectors.

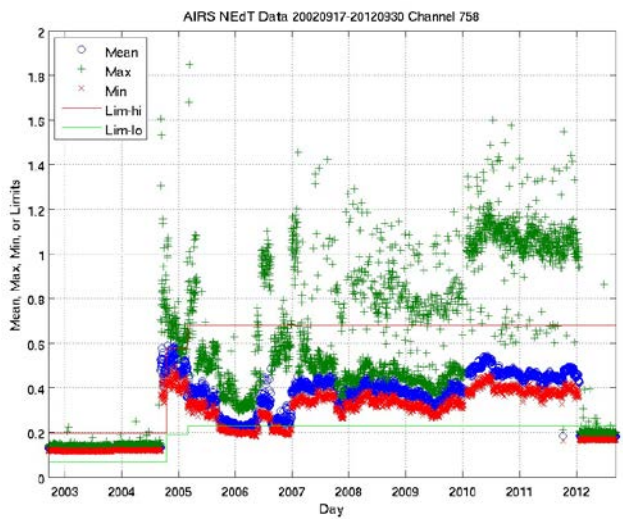

Figure 7. Channel 758 suffered a radiation hit on the A-side, causing increased noise. Changing from A+B to B recovered

### 3.3 Radiance Stability

The two point radiometric calibration every scan line (OBC and SV) corrects for degradation in the instrument response over time. It is well known that optical systems degrade in orbit and in fact we can see the impact in the AIRS by looking at the gain in the system. The gain is measured in radiance per counts. Lower transmission will result in smaller signal (counts) and a larger gain. We plot the ratio of the inverse of the gains as a measure of transmission from 2002 and 2011 in Figure 8. We see a significant reduction in the gains over the life of the mission that can be predominantly attributed to icing or contamination that occurred during the first week after the instrument cooldown before going operational, but also misalignments and electronics degradation. The gain loss does not significantly impact the NEdT's as shown earlier, but verification that the instrument radiometric response is stable requires comparison with ground based reference targets.

AIRS radiances have undergone extensive checks for stability based on (obs-calc), where "obs" is the observed brightness temperature in an AIRS channel, and "calc" is the brightness temperature expected to be observed. In general "calc" requires the independent knowledge of the surface temperature and emissivity, and temperature and water vapor profiles, which can be obtained from the ECMWF or NCEP analysis. For the window channels available to a hyperspectral sounder only the Sea Surface Temperature needs to be known for the daily evaluation of (obs-calc) under

clear conditions. Based on the first three years of data the AIRS radiances have been demonstrated to be stable to better than 16 mK/year using the 2616 $cm^{-1}$ AIRS superwindow channel[8]. This early result is confirmed by results from ten years of data and zonal day/night analysis.

Figure 9 shows the anomaly of (obs-calc) for the 1231 $cm^{-1}$ window channel. We show the 1231 $cm^{-1}$ channel results since this channel is available to IASI and CRIS. Each point in Figure 8 represents the anomaly of the mean(obs-calc) from typically 5000 clear night spectra from the non-frozen oceans. The red trace is a sliding 32 day mean. The ten year trend in the anomaly is +4 ± 1 mK/yr, where the trend uncertainty is 2 sigma[9]. The analysis of trends in window channels at 2616 $cm^{-1}$, 2508 $cm^{-1}$, 1128 $cm^{-1}$, 961 $cm^{-1}$, 900 $cm^{-1}$, 790 $cm^{-1}$ and 781 $cm^{-1}$, day/night and 20 degree wide ocean latitude zones produce similar results.

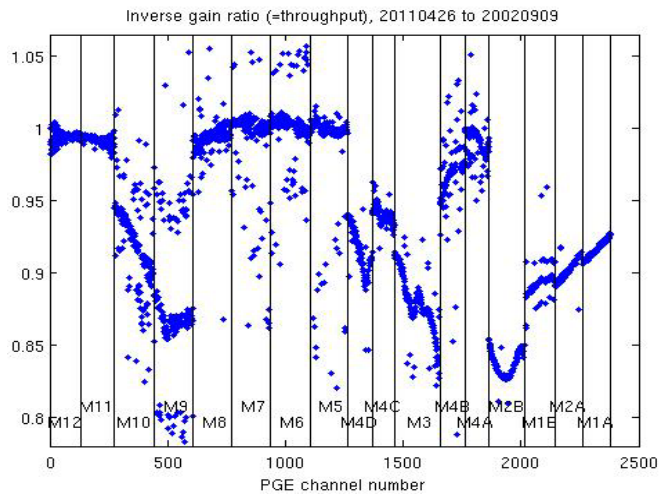


Figure 8. Normalized inverse of gain ratio for 2002 to 2011. The reduction is predominantly due to icing on the optical elements occurring during instrument activation.

## 4. SPECTRAL PERFORMANCE

The AIRS achieves spectral channel definition using a grating spectrometer. As the temperature of the instrument changes, small alignment changes occur between the spectrometer and focal plane that will shift the frequencies of the instrument. The upwelling spectrum provides a wealth of atmospheric absorption lines that have been used to calibrate the spectral shift. The shift as a function of time is performed by correlating the AIRS spectra and spectra computed based on ECMWF model fields[10]. The correlations are performed separately for each AIRS module, with sufficient spectral structure. The final frequency shift is derived from a single module with very high-quality spectral features (a water vapor module) that correlates extremely well with modules only sensitive to carbon dioxide line emission, for example. Shifts represent a lateral shift of the focal plane in the spectral direction and are expressed in microns, however since the pixel size for one resolution element is 100 μm, the value also represents a percentage of the width of the Spectral Response Function (SRF). Results from the model are shown in Figure 10. The ordinate represents the relative position of the FPA (in microns) for each of the 17 modules, and the abscissa represents time in years. We see a steady shift in the position of the FPA, covering about 1 μm (or 1% of the width, or about 10 ppm of the center frequency) over the life of the mission, or about 0.5% of the width since the first major shutdown in late 2003. In the last five years the system has been extremely stable showing less than 0.25% of the width shift of the centroids. Not shown, but also corrected by the model is an orbital shift and Doppler effect due to the satellite velocity. Frequencies are available at the UMBC Atmospheric Spectroscopy Laboratory website: http://asl.umbc.edu/pub/airs/srf/. The files are used in the V6 processing to account for drift in the channel center frequencies as a function of time, and also for the shift in the relative positions of interference fringes pre/post the November 2003 shutdown of AIRS.

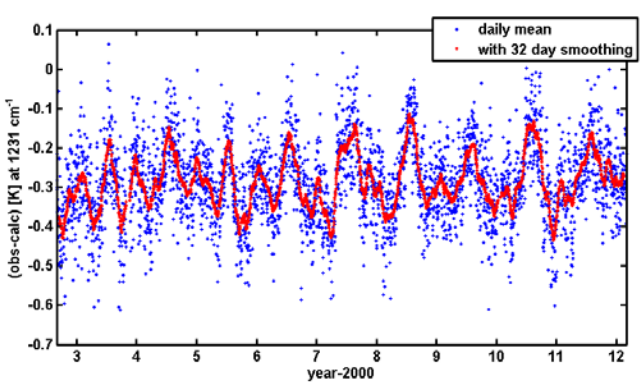


Figure 9. Difference in observed and calculated radiances for channel 1231 $cm^{-1}$ for AIRS show stability to 4mK/yr.

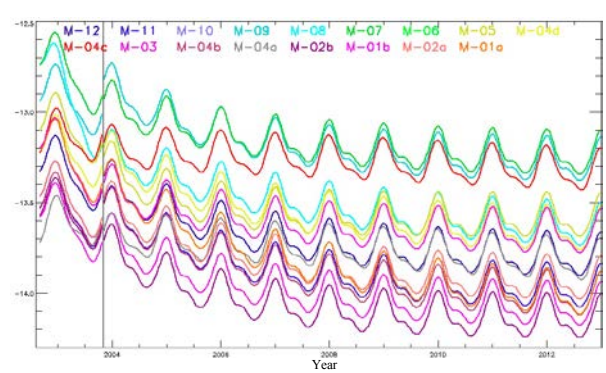


Figure 10. Modeled AIRS Band Positions for life of mission based on observed shift in absorption peaks.

## LEVEL 1C PRODUCT

The AIRS team has developed a beta product that cleans up a few of the artifacts in the Level 1B product[11]. The product, called "Level 1C", is designed to simplify inter-comparisons of AIRS data with other instruments for cross calibration purposes. The major corrections that can be applied to the Level 1B are as follows:

1. Noisy Channel Replacement
2. Resampling to a common frequency grid
3. Gap filling

Figure 11 shows an example spectrum cleaned using the L1C channel replacement algorithm and gap filled in the region where no AIRS data exist. Only channels with non-Gaussian noise performance or non operational channels are replaced in Level 1C, leaving most channels untouched. Replaced and gap-filled channels are flagged accordingly and care should be taken when using them in scientific investigations.

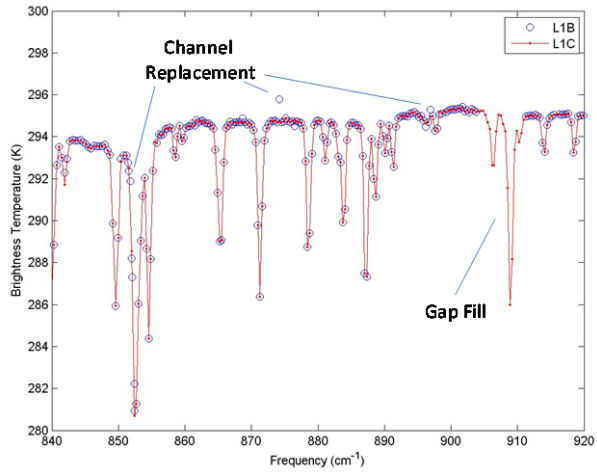


Figure 11. Level 1B Spectrum and Level 1C with gap fill and bad channel replacement.

The process of channel replacement starts with identifying known noisy channels based on their NEdT or pop characteristics. Buddy channels are selected based on simulated spectra that have statistical properties similar to the channel to be replaced. The brightness temperature of the channel to be filled or replaced is the average of the four best correlated of the useable channels weighted by the deviations from the filled or replaced channel. Once a spectrum has been cleaned by the "buddy-system" replacement, the principal component analysis (PCA) is used in order to further detect and correct the cleaned spectrum. All channels replaced are appropriately flagged in the L1C data set.

Spectral resampling and gap filling are also performed in the Level 1C product if desired. Spectral resampling adjusts the reconstructed spectrum using a cubic spline interpolation. The input frequencies are those based on the model for the given timeframe, while the output frequencies are a fixed set corresponding to the frequencies when AIRS became operational in September 2002. Gap filling provides proxy data in the spectral regions where there is no AIRS data (e.g. 903-910 $cm^{-1}$) and is performed in a similar way to the bad channel replacement but without the PCA reconstruction. Gap filling enables comparison with other broadband instruments allowing more accurate integration over the spectrum.

Level 1C at this time is actually a set of tools (executable programs) which converts the Level 1B into Level 1C, rather than a pre-processed product. This allows users to use the existing Level 1B files they already have and apply only the tools corresponding to those corrections desired. Alternatively the user will be able to request the Level 1C directly from the GES/DISC where the AIRS data are distributed. Level 1C should be available in early 2013.

## SUMMARY AND CONCLUSIONS

The Atmospheric Infrared Sounder (AIRS) is a hyperspectral infrared grating spectrometer with over 2378 infrared channels. The large majority of channels in the AIRS are well behaved and operating with minimal change over the ten years of life of the mission to date. Scores of detectors have failed over the course of the mission, but the AIRS includes a set of redundant detectors. Gain tables were uploaded in January 2012 to recover 100 channels with degraded noise behavior. Instrument stability is better than 16 mK/year in all channels with spectral drift of less than 10 ppm over the life of the mission. A new Level 1C product is available to simplify intercomparisons with other instruments, yet preserves most channels unchanged. Minimal change has been seen in the AIRS instrument telemetry and the instrument is expected to operate with exceptional performance and stability over the next decade.

## ACKNOWLEDGMENTS

The AIRS instrument was designed, built and tested by BAE Systems of Nashua New Hampshire, under a systems contract with the Jet Propulsion Laboratory, Pasadena, CA. The Jet Propulsion Laboratory, California Institute of Technology, operates under contract with the National Aeronautics and Space Administration.

## REFERENCES

1. P. Morse, J. Bates, C. Miller, "Development and test of the Atmospheric Infrared Sounder (AIRS) for the NASA Earth Observing System (EOS).", SPIE 3759-27, July 1999.
2. Pagano, T. S., H. Aumann, D. Hagan, K. Overoye, "Pre-Launch and In-flight Radiometric Calibration of the Atmospheric Infrared Sounder (AIRS)", IEEE TGRS-00136-2002, February 2002
3. T. Pagano et al., "Pre-launch Performance Characteristics of the Atmospheric Infrared Sounder (AIRS)", SPIE 4169-41, September 2000.
4. Pagano, T. S., et. al., "On-board Calibration Techniques and Test Results for the Atmospheric Infrared Sounder (AIRS)", SPIE 4814-38, July 2002
5. 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
6. T. Pagano et al., "Operational Readiness for the Atmospheric Infrared Sounder (AIRS) on the Earth Observing System Aqua spacecraft", SPIE 4483-04, August 2001
7. Pagano, T. S., H. Aumann, D. Hagan, K. Overoye, "Pre-Launch and In-flight Radiometric Calibration of the Atmospheric Infrared Sounder (AIRS)", IEEE TGRS-00136-2002, February 2002
8. H.H. Aumann, et al., Three years of Atmospheric Infrared Sounder radiometric calibration validation using sea surface temperatures, Journal of Geophysical Review, VOL. 111, D16S90, doi:10.1029/2005JD006822, 2006
9. Aumann, H. H., D. Elliott, S. Strow, "Validation of the Radiometric Stability of the Atmospheric Infrared Sounder." Proc. SPIE 8510-28, August, 2012
10. Strow, L. L., S. E. Hannon, S. De-Souza Machado, H. E. Motteler, and D. C. Tobin (2006), Validation of the Atmospheric Infrared Sounder radiative transfer algorithm, J. Geophys. Res., 111, D09S06, doi:10.1029/2005JD006146
11. Manning, E. M., Y. Jiang, H. Aumann, D. Elliott, S. Hannon, "Level-1C Product from AIRS: Principal Component Filtering", Proc SPIE 8510-30, August 2012.