AIRS radiometric calibration validation for climate research

H. H. Aumann, Tom Pagano, Denis Elliott, Steve Gaiser, Dave Gregorich and Steve Broberg

Jet Propulsion Laboratory, California Institute of Technology

Pasadena, California 91109, USA

aumann@jpl.nasa.gov 818-354-6865

ABSTRACT

Climate research using data from satellite based radiometers makes extreme demands on the traceability and stability of the radiometric calibration. The selection of a cooled grating array spectrometer for the Atmospheric Infrared Sounder, AIRS, is key, but does not ensured that AIRS data will be of climate quality. Additional design features, plus additional pre-launch testing, and extensive on-orbit calibration subsystem monitoring beyond what would suffice for application of the data to weather forecasting were required to ensure the radiometric data quality required for climate research. Validation that climate data quality are being generated makes use of the sea surface skin temperatures (SST and (obs-calc). The SST is deduced from first principles from the Atmospheric Infrared Sounder (AIRS) window channel at 2616 cm^{-1} for cloud-free night ocean observations between +/- 30 degree latitude and compared with the NCEP produced Real-Time Global Sea Surface Temperature (RTGSST). The agreement is within 100 mK absolute and better than 14 mK/year stability for the past two years. The sst comparison ties down the calibration at 2616cm-1 and validates the accuracy and stability of the onboard blackbody. In principle this suffices to validate the calibration of all channels. The validation of the calibration at 2616cm-1 is extended to almost all AIRS channels by analyzing the difference between the observed brightness temperatures and the calculated brightness temperatures using the ECMWF analysis. The bias of (obs-calc) for those channels where the ECMWF profiles are reliable is within 0.2K of zero.

AIRS was launched into a 705 km altitude polar orbit on the EOS Aqua spacecraft on May 4, 2002. AIRS covers the 3.7 to 15.4 micron region of the thermal infrared spectrum with spectral resolution of $\nu/\Delta\nu=1200$ and has returned 3.7 million spectra of the radiance each day since the start of routine data gathering in September 2002.

INTRODUCTION

The use of satellite data for climate research, where temperature changes at the 15 mK/year level are significant, makes extreme demands on the radiometric calibration. In principle, the calibration of an infrared radiometer using the classical two point calibration with a hot reference source and a cold space view is simple. However, careful attention has to be paid not only to the first order terms but to the second order terms in the radiometric calibration. Ensuring that AIRS data will be usable for climate research required four major steps:

Step 1. was the choice of an inherently “calibration friendly” instrument design from the start. For AIRS, we selected a cooled grating array spectrometer. The key terms are “cooled” and “grating array”. Cooling the AIRS spectrometer to 160 K and controlling that temperature at a milli-Kelvin level suppresses second order terms, such as changes in instrument photon background, which potentially affects the linearity correction. The beauty of the grating array approach is that all channels act like independent radiometers, sharing the same blackbody and space views for the two-point radiometric calibration and the same grating for the spectral calibration without moving parts in the light path. This means that validating the accuracy and stability of the blackbody at one frequency in principle suffices to validate the calibration of all channels.

Step 2. The "calibration friendly" design has to be supplemented by additional design features, such as a full aperture black-body calibration reference source, and attention to elimination of contamination of key surfaces by water ice or molecular deposition from outgassing.

Step 3. Additional pre-launch testing is required to ensure traceability of the calibration over the full operating range of the instrument. For example, the temperature which a radiometer achieves in space is modulated by the orbital and seasonal changes in the solar heating. The prelaunch calibration has to cover this instrument temperature range in order to provide coefficients for the second order terms of the calibration equation.

Step 4. Careful attention has to be paid to on-orbit calibration subsystem monitoring, beyond what would suffice for application of the data to weather forecasting. If the radiometric calibration was routinely dynamically adjusted by aligning the observed radiances to radiances expected based on operational radiosonde data, its value for climate research would be severely diminished. This dynamic adjustment is known as "tuning" and is routinely applied in the assimilation of satellite data for numerical weather forecasting.

Details of the AIRS design, the prelaunch test setup and results are found in Aumann et al.(1), Pagano et al.(2) and references therein. In the following we focus on the validation that climate data quality is being achieved. For this, we make use of the fact that for a grating array design all channels act like independent radiometers which share the same blackbody and space views for the two-point radiometric calibration. The calibration of all channels is in principle as accurate and stable as it can be demonstrated for one channel using the two point radiometric calibration. The reference for the absolute calibration is the sea surface skin temperatures (SST).

Routine AIRS Calibration Monitoring

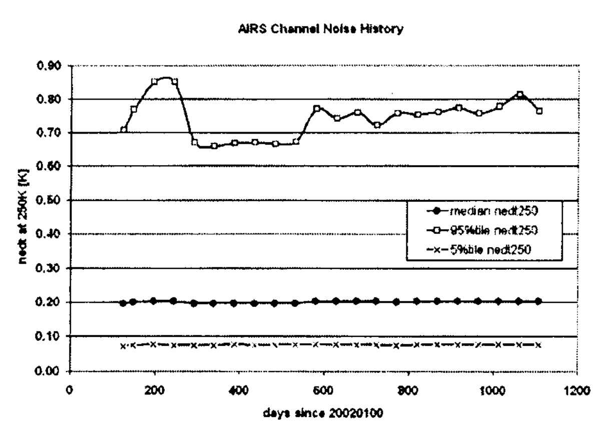

Figure 1. The noise equivalent temperature difference (NeDT) of the AIRS channels has been very stable for the three years in orbit.

The climate quality of the AIRS data is established and continuously evaluated by routinely monitoring: 1. The internal calibration parameters. 2. The SST derived from AIRS under cloud-free conditions relative to the NCEP SST, and 3. (obs-calc).

1. Monitoring of internal calibration parameters: AIRS has 2378 channels. The performance of these channels is routinely monitored relative to internal indicators, such as responsivity and noise. The responsivity is measured using the On-board Calibration source (OBC). The noise for a 250K scene is inferred from the standard deviation of the responsivity and the standard deviation of

two adjacent space views. Figure 1 shows that the noise, as measured by the Noise Equivalent Delta Temperature at 250 K (nedt250), in terms of the 5%tile, the 50%tile (median) and the 95%tile of the 2378 channels as a function of time since September 2002, the start of the operational data taking phase. The median noise is 0.2 K and has been very stable since September 2002. The steps in the 95%tile value in January 2003 and November 2003 are due to loading of a new electronic gain table for the AIRS on-board data system. During prelaunch testing only 152 of the 2378 channels were either dead or "noisy, defined as nedt250>1K. The time history since September 2002 is shown in Figure 2. Changes occurred in January 2003 and November 2003, when the electronic gain table were reloaded. In the absence of eternal interference the channel properties have been very stable. The routine monitoring system sets an alarm when the noise exceeds three times the normal amount. This effort by the AIRS instrument operations team is described by Licata et al (2004). Many alarms are due to radiation hits on the electronics, particularly the DC-restore capacitors.

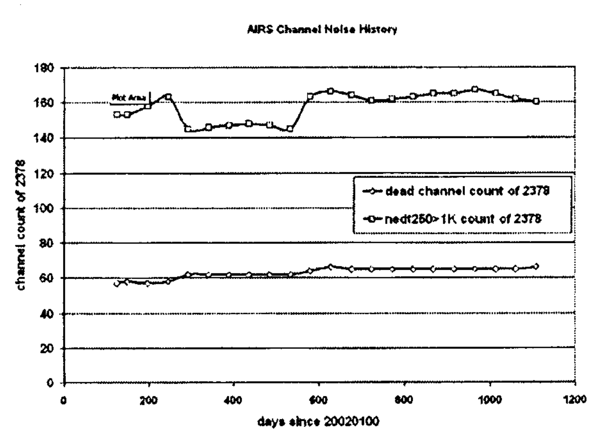

Figure 2. The number of dead or noisy channels of 2378 has increased from 59 to 61 in the three years in orbit.

2. Monitoring the SST relative to NCEP SST: The comparison of the SST generated from AIRS data under cloud-free condition with the sea surface temperature (SST) generated by models is a powerful tool for the evaluation of the calibration accuracy and stability. The reference for the absolute calibration is the Real Time Global SST, RTG.SST, which was developed by the National Centers for Environmental Prediction/Marine Modeling and Analysis Branch (NCEP/MMAB) (Thiebaux et al. 2002) in support of daily weather forecasting, is produced daily on a half-degree (latitude, longitude) grid using a two-dimensional variational interpolation of the most recent 24-hours buoy and ship data and satellite-retrieved SST data. Routine daily validation of the RTGSST shows that it agrees with the drifting buoys within 30 degree from the equator within 50 mK. Figure 3. shows a typical one month time series for April 2003 (11 March – 9 April 2003 adapted from http://polar.ncep.noaa.gov/sst/), typical at least since September 2002, when AIRS operational data gathering started. The RTGSST represents the day/night mean temperature of the buoys at about 2 meter below the surface. At night, this temperature is typically 0.4 K colder than the skin temperature.

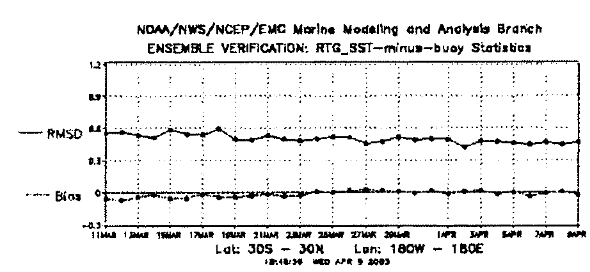

Figure 3. The 30 day time series of tropical ocean rtg.sst-buoy validation for April 2003 shows that the day.night mean rtg.sst fits the buoys to well within 50 mK

The AIRS SST is deduced from first principles from the Atmospheric Infrared Sounder (AIRS) window channel at 2616 cm^{-1} for cloud-free night ocean observations between +/- 30 degree latitude and compared with the NCEP produced Real-Time Global Sea Surface Temperature (RTGSST). Details of the cloud-filtering technique and the algorithm are given in Aumann et al.(3). In principle, any reasonable atmospheric window channel can be used to measure the sst. This has been done from space for many years using a 10 micron "split window" technique, first implemented by McMillin (4) on TOVS, and still used currently for the MODIS sst. This approach uses channels where the atmospheric absorption due to water vapor is several degrees Kelvin, and the coefficients required for converting the observed brightness temperatures to the sst are obtained by regression relative to a training set, usually the drifting buoys. This approach places minimal demands on the absolute radiometric calibration. It also provides no information about the absolute radiometric calibration. The important point to make here is the availability of the 2616cm-1 "super-window" channels and its pivotal role in the validation of the absolute calibration. Chahine (5) was first to point out the extremely low atmospheric absorption at 2616 cm-1, typically 0.2K under tropical conditions due to water continuum plus about 0.1K of nitrogen continuum.

In order to use the sst derived from AIRS to validate the radiometric calibration, the atmospheric correction uncertainty has to be small compared to the desired radiometric calibration accuracy and it has to be derived from first principles. Although the atmospheric transmission correction is small at 2616 cm-1, the formal water vapor correction uses the radiative transfer for a first principles water absorption correction. The amount of water vapor in the slant path is obtained from the difference in the brightness temperatures between the 2616cm-1 and 2607 cm-1 channels. Details of the algorithm are found in Aumann et al. (6).

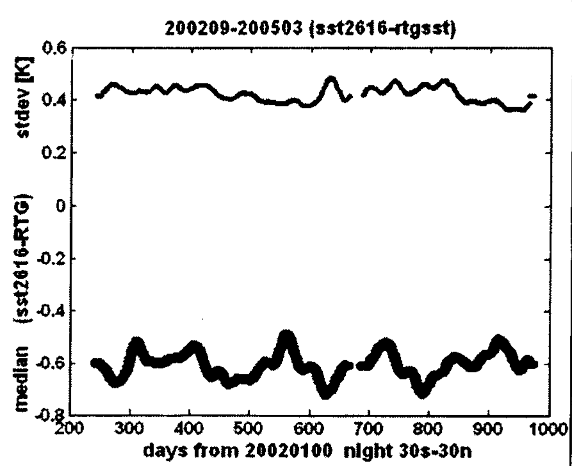

Figure 4. Two years of sst2616 and RTGSST comparison

Since the RTGSST is most reliable in the tropial oceans, we used matchups between the AIRS sst2616 and the RTGSST under "cloud-free" night time +/-30 degree latitude ocean conditions for the evaluation of the radiometric calibration accuracy and stability. This results in about 5000 extremely clear matchups every 24 hours. The radiometric accuracy and stability are evaluated using the daily median difference and standard deviation of (sst2616-RTGSST). Figure 4. shows the median daily difference and standard deviation of sst2616-RTGSST, smoothed by a 16 day triangular sliding average. The 16 day period smoothes out the 16 day orbit repeat cycle of the EOS Aqua spacecraft. The median difference, shown Figure 4, is very stable, with what appears to be a 100 mK p-p seasonal cycle, with a two year mean (sst2616-RTGSST)=-0.60 K and standard deviation of 0.41K The one week break in data in November 2003, which also required the gain table reload, was due to the preventative shutdown of AIRS due to the very large solar flare.

We used data from September 2002, when the AIRS was placed in the operational mode, through August 2004, for exactly 24 months of data, to minimize the effect of seasonal variations on the long term trend. The nominal trend is +11 mK/year with a formal trend uncertainty of 7 mK/year. The analysis for 11 other window channels (6) shows comparable bias and stability, but with a larger standard deviation due to the need to correct for an order of magnitude larger water absorption.

3. Monitoring of (obs-calc): The validation of the calibration at 2616cm-1 is extended to almost all AIRS channels and temperatures ranging from 300K to 220K by analyzing the difference between the observed brightness temperatures (obs) and the calculated brightness temperatures using the ECMWF temperature and water vapor profiles (calc) for cloud-free night ocean data within 40 degrees of the equator. The surface temperature for the calculation uses sst2616 from AIRS. Figure 5. shows the result of (obs-calc) for two years of cloud-free ocean data (adapted from Strow et al 2005).

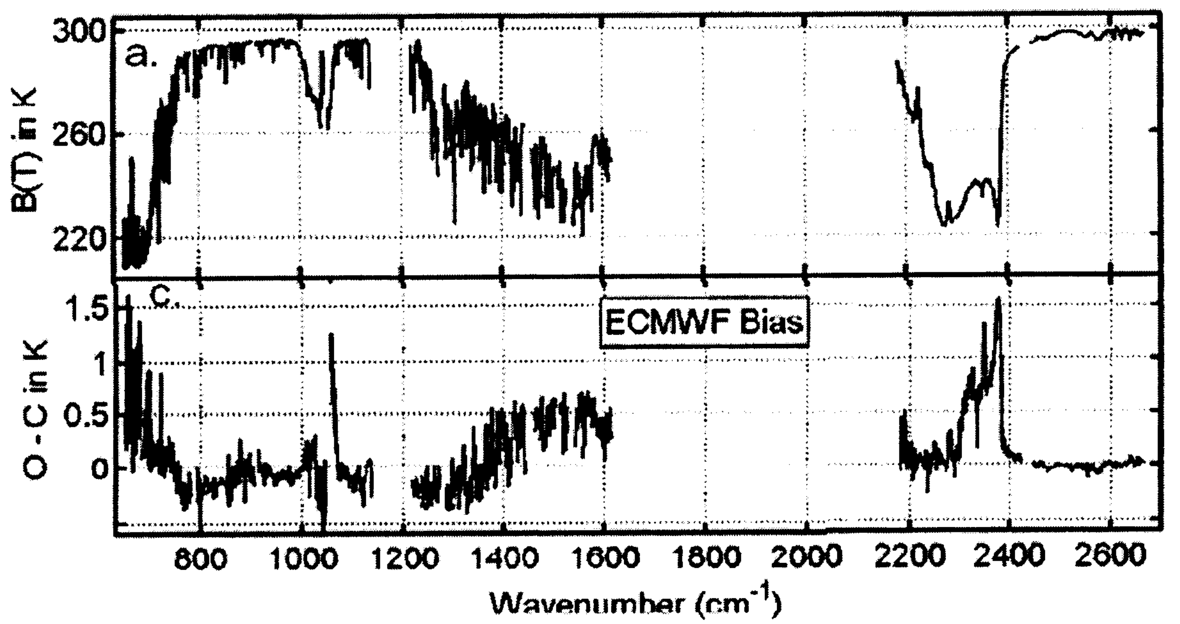

Figure 5. The bias between the observed and the calculated brightness temperatures for two years of cloud-free ocean data is less than 0.2K for the AIRS channels were the ECMWF water and temperature profiles are reliable.

Discussion

A quick glance at Figures 4 and 5 indicate that there are significant biases. Figure 4. shows that (sst2616-rtgsst) is 0.6K cold. In Figure 5 there are regions of the spectrum where the AIRS observations are 0.5K warmer than calculated from the ECMWF analysis.

1. The RTGSST represents a day/night average buoy temperature, which, on average is 0.2K warmer at night than the actual buoy temperature. In addition AIRS measures the skin temperature, which is typically 0.2K colder than the buoy temperature. The combination of the

two effects explains 0.4K of the observed 0.6K cold bias. This is confirmed by the analysis of day-night difference in the sst1231, (day(sst1231-rtgsst) – night(sst1231-rtgsst)).

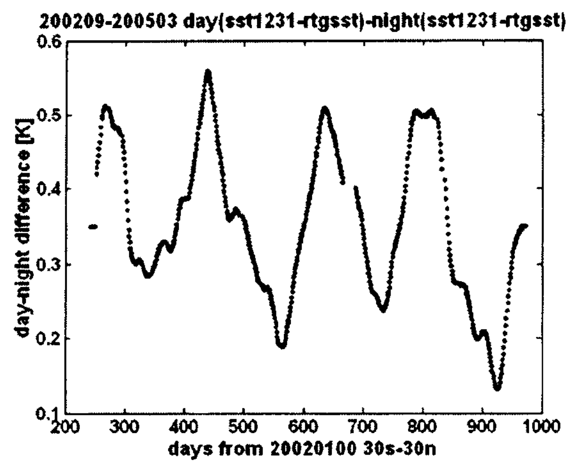

Figure 6. The mean day-night difference in the sst1231 is 0.35K, but there is considerable seasonal variability.

The result is shown in Figure 6. The sst1231 was derived using the 1231 cm-1 window channel, with bt1231-bt1227 used for the water vapor correction and regression training at night on sst2616 (4).

The two year mean day-night difference of 0.35K is very close to the expected 0.4K difference between the day and night. There is considerable variability in the day-night difference, with a clear seasonal cycle. The unexplained cold bias in (sst2616-rtgsst) is thus between 0.2 and 0.25K. Aumann (3) argued using analysis of light reflected from "cloud-free" ocean footprints, that about 0.1K of the unexplained cold bias is due to cloud-contamination in the :cloud-free" footprints. This means that the AIRS absolute calibration at 2616 cm-1 is validated at the 0.1K level. This agrees with spot-checks of the AIRS radiometric calibration in November 2002 using SHIS underflights over the Gulf of Mexico (10). Calibration at the 0.1K level was expected based on the repeatability of the pre-launch calibration (2).

The 7 mK/year trend uncertainty in (sst2616-rtgsst) indicates that the nominal trend of +11 mK/year is not likely to be real. We consider the trend in (sst2616-rtgsst) after two years to be less than 14 mK/year. Since the tropical ocean temperature are typically about 300K, i.e. close to the temperature of the AIRS OBC at 308K, the upper limit of 14mK/year stability of (sst2616-rtgsst) is essentially an estimate of the stability of the AIRS OBC of 0.05% per year.

The 1231 cm-1 window channel derived sst1231 produces good surface temperatures when trained on the sst2616, even though the atmospheric correction at 1231 cm-1 is about 2-2.3K for typical ocean nadir viewing conditions. This correction is a function of total amount and vertical distribution of water continuum. Uncertainty in this distribution limits the usefulness of this or any channel significantly effected by water vapor for the evaluation of the absolute calibration.

2. For most AIRS channels of the spectrum (obs-calc) is less than 0.1K. This is particularly true for channels which are not sensitive to water vapor and channels below the tropopause. For the water vapor channels (1400-1600 cm-1) AIRS is consistently 0.5K warmer than ECMWF. The lower stratospheric channels (640-680 cm-1 and 2300 -2385 cm-1) have a warm bias of up to 1K. The Ozone channels around 1050 cm-1 have a warm bias of up to 1K. All three effects are correlated with known deficiencies in the ECMWF model. Evaluation of the time dependence of (obs-calc) shows no trend in the water and surface channels, but show the expected increase in the bias in the CO_2 sensitive channels duo to the 2 ppm/year increase in the CO_2 column abundance (11).

Summary

The on-orbit verification of the AIRS radiometric performance at the 100 mK absolute level, and stability at the better than 14 mK/year level establishes the state of art of for thermal infrared measurements of the Earth from polar orbit and establishes the level of performance which is expected of future hyperspectral sounders. This high performance shows that the choice of the AIRS grating array spectrometer design, in combination with a meticulous pre-launch calibration and on-orbit monitoring pays off in a climate research quality radiometric product. The expectation that establishing the radiometric performance for one channel establishes the level of performance for all channels has been validated using (obs-calc).

The radiometric accuracy and stability demonstrated by AIRS opens the way to trend analysis of mid-tropospheric temperatures, water vapor and CO_2 abundance using the AIRS atmospheric sounding channels, where stability at the mK level leads to results of significance for climate research. The first result from AIRS, which shows that the global CO_2 abundance is increasing slightly faster than the popularly accepted 1.5 ppmv/year has just appeared in the literature (11).

Acknowledgments

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