Radiometric Stability in 16 years of AIRS hyperspectral infrared data (SPIE OP-431-20)

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ABSTRACT

With global warming at the rate of 10 mK/yr, it is important to at least characterize any trend in the AIRS data, which may impact the use of AIRS data for climate change research. We evaluated the stability of the AIRS v5 calibration for seven atmospheric window channels between 2002 and 2018 under tropical ocean clear conditions. Trends for the channels between 961, 1128 and 1231 cm^{-1} channels are typically +3 mK/yr; for 790 and 901 cm^{-1} the trend is 6 mK/yr, i.e. the observations are increasingly getting warmer than expected. The trends are day/night consistent. The trend for the 2508 and 2616 cm^{-1} channels is close to 10 mK/yr at night, but closer to 6 mK/yr during the day. On an absolute scale these trends are small, but not when viewed in the context of global warming at a 10 mK/yr rate. While the warming trends are consistent with increased scattering from the scan mirrors, which create an error in reading the Onboard Blackbody Calibration, the resulting changes in the gain are a factor of about five larger than observed changes in the gain. The effects of scattering due to scan mirror contamination are evident at extremely cold temperatures, but scattering does not produce the observed warming at warm temperatures. It is possible that much of the observed warming in the AIRS window channels is a geophysical effect related to the warming of the oceans, resulting in a shift in the diurnal cycle and skin effect correction. This requires more careful evaluation.

Keywords: hyperspectral, infrared sounder, climate, Deep Convective Clouds, Dome Concordia

1. INTRODUCTION

Global warming at the Earth surface at the nominal rate of 10 mK/year has been observed for many decades. Less observed but of equal interest is how this warming is globally distributed and how it changes with altitude. The current crop of hyperspectral sounders, starting with AIRS, (Aumann et al. 2003), in 2002, continuing with IASI in 2007 (Blumstein et al. 2004) and CrIS (Glumb et al., 2003) into for the next decade, have the potential to collectively make these measurements, provide the instruments make stable measurements. The objective of our paper is to estimate the stability of AIRS L1b calibrated radiances.

AIRS (Aumann et al., 2003), like all other infrared radiometers, uses a two-point calibration with a cold space view (SV) and a view of the onboard black body (OBC). Unlike CrIS and IASI, the AIRS OBC is actively controlled at a temperature of 308.3 K. The SV measures the instrument background. The basic assumption in the two-point calibration equation is that a) the measurements at SV position of the scan mirror is identical to the background in the OBC and the scene view positions b) That the view of the OBC during the pre-launch calibration is identical to the view in orbit. At some level neither assumption is exact. Even if the OBC is perfect, scan angle dependent difference in the contamination of surfaces seen in the side-lobes of the optical beam may change or changes in the electronic linearity may create artificial trends in the calibrated radiances. One way to evaluate the instrument radiometric stability is to use the upwelling radiances from accurately known scenes as references. We use the Sea Surface Temperature (SST) of the non-frozen oceans under clear conditions as this reference. It is tied to a large number of floating buoys. The SST is available daily as a day/night average on a 0.5-degree grid based on floating buoys (Thiébaux et al., 2003) at about 2 meters below the surface and referred to as the Real Time Global SST (RTGSST). In order to relate the RTGSST to AIRS skin temperature measurements we have to make two corrections, which were derived before 2002 (Aumann et al. 2006): 1) The skin temperature is 0.2 K cooler than the bulk temperature and 2) the temperature for the 1:30 PM overpasses are 0.4 K warmer than for the night overpasses. The combination of the two effects means that the SST at night is 0.4 K colder than the RTGSST.

2. METHODOLOGY

For the evaluation of the radiometric stability we used AIRS Level-1B version 5 data available from the GES DISC DAAC at http://disc.gsfc.nasa.gov/datacollection/AIRIBRAD_005.html. For the evaluation of the stability we used the difference between the observations (obs) and the calculated spectra (calc) based on knowing the SST. AIRS is a grating array spectrometer. There are 2378 independent spectral channels, arranged in 17 detector modules. Listed in Table 1 column #1 are the seven atmospheric window channels, representing 7 detector modules, used for the evaluation of the radiometric stability. The surface emissivity of salt water is known and the water vapor absorption correction is based on the total water column derived from the AIRS radiances (Aumann et al 2006) under clear conditions. The water vapor correction was based on regression training of spectra calculated using the latest spectroscopy (HITRAN2012 and CKD25) and LBLRTM calculations for 1800 non-frozen ocean night model spectra (Aumann et al 2017). Under ideal conditions the mean of (obs-calc) is zero. Imperfections in the spectroscopy, or the accuracy of the spectral response functions may produce a small bias in (obs-calc).

Each day AIRS makes 3 million observations. From these observations we randomly selected 45,000 observations each day. Of the selected data typically 9000 are from the non-frozen oceans for the day overpasses, and an equal number from the night overpasses. These data are screened for clouds using a Spatial Coherence (SC) threshold and a total water vapor test (Aumann et al 2006). The SC, cx1231, is the sum of the absolute difference between the pixel under evaluation and its four nearest neighbors using the 1231 cm^{-1} channel. The lowest usable threshold for SC is limited by the Noise Equivalent Difference Temperature, NEDT, of the 1231 channel. NEDT=0.08 K for the 1231 channel. The SC threshold test has an ambiguity in that it passes some very uniform cloud fields, e.g. low stratus and mesoscale convection. The water vapor column above these clouds is typically very small. The water vapor test, q3=bt1231-bt1228 > 0.1, where bt1231 and bt1228 are the brightness temperatures at 1231 and 1228 cm^{-1}, allows us to eliminate the uniform cloud ambiguity of the SC test.

3. RESULTS

We used cx1231 < 0.5 and cx1231 < 1. Typically 500 spectra from the day overpasses, 300 from the night overpasses pass the cx1231 < 0.5 K clear test. The relaxation of the cloud filter to cx1231 < 1 K triples the yield of "clear" spectra. We use the daily mean of (obs-calc) for the evaluation of the radiometric stability. While the mean(obs-calc) under perfectly clear conditions is zero, (obs-calc) may have a small cold bias due to residual cloud contamination. If the number of observations used for the calculation of the mean were to have a trend, the mean(obs-calc) may also show a trend, which would then be mistaken for an instrument trend. It is therefore important to verify that the number of observations used for the calculation of mean(obs-calc) does not have a trend.

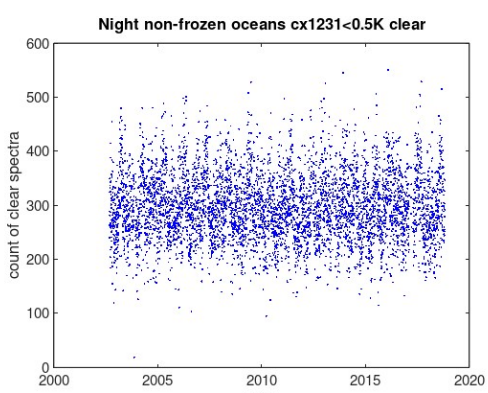

Figure 1. Time series of the night clear count.

Figure 1 shows the time series of the cx1231 < 0.5 K night clear count. Each dot in Figure 1 represents the count of "clear" spectra from one day. A faint seasonal variability can be detected, but no obvious trends. Quantitatively, the mean is 286 counts with an anomaly trend of -0.16 counts per year, with a one sigma (bootstrap) uncertainty of +0.19 counts per year. Expressed as percentage of the mean the trend in the clear count is -0.065±0.063 %/year. For day overpasses we find a mean of 507 counts per day with a trend of -0.028 ±0.047 %/year. The cx1231 < 0.5 K threshold is extremely tight. Had we selected cx1231 < 1 K we would find 851 clear night cases with a trend of +0.033±0.047 %/year, 1328 day cases with a trend of +0.053±0.039 %/year.

We conclude that the daily count of clear spectra has been extremely stable since 2002.

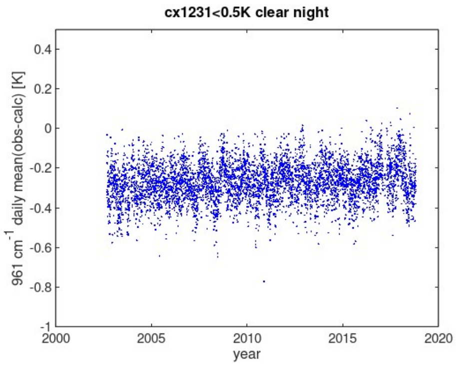

Figure 2 shows the time series of (obs-calc) for the 961 cm^{-1} channel.

Figure 2 shows the time series of (obs-calc) for the 961 cm^{-1} channel for night data with cx1231 < 0.5 K. A cold bias of -0.27 K and a trend of +6.0±0.2 mK/year are apparent. Tables 1 and 2 summarize the bias and trends for the seven channels used in our analysis for cx1231 < 0.5 K, cx1231 < 1 K and day and night. The number following the +/- sign is the one sigma trend uncertainty calculated using the bootstrap method.

Channel wavenumber (cm^{-1})	Mean (obs-calc) [K] cx1231 < 0.5 K	Trend K/yr +/- uncertainty cx1231 < 0.5 K	Mean (obs-calc) [K] cx1231 < 1 K	Trend K/yr +/- uncertainty cx1231 < 1 K
2616	-0.3682	0.0093 +/- 0.0003	-0.4810	0.0090 +/- 0.0002
2508	-0.2153	0.0111 +/- 0.0003	-0.3381	0.0109 +/- 0.0002
1231	-0.5559	0.0027 +/- 0.0003	-0.6580	0.0025 +/- 0.0002
1128	-0.2972	0.0032 +/- 0.0003	-0.3876	0.0033 +/- 0.0002
961	-0.2695	0.0036 +/- 0.0003	-0.3709	0.0035 +/- 0.0002
900	-0.2497	0.0060 +/- 0.0002	-0.3706	0.0059 +/- 0.0002
790	-0.2744	0.0054 +/- 0.0003	-0.4150	0.0052 +/- 0.0003

Table 1. Summary of night results with cx1231 < 0.5 K and cx1231 < 1 K thresholds

Channel wavenumber (cm^{-1})	Mean (obs-calc) [K] cx1231 < 0.5 K	Trend K/yr +/- uncertainty cx1231 < 0.5 K	Mean (obs-calc) [K] cx1231 < 1 K	Trend K/yr +/- uncertainty cx1231 < 1 K
2616	3.3267	0.0022 +/- 0.0016	3.5028	0.0017 +/- 0.0016
2508	2.4080	0.0061 +/- 0.0013	2.4885	0.0058 +/- 0.0011
1231	-0.5415	0.0024 +/- 0.0002	-0.6072	0.0023 +/- 0.0002
1128	-0.2852	0.0029 +/- 0.0002	-0.3453	0.0030 +/- 0.0002
961	-0.2698	0.0035 +/- 0.0003	-0.3324	0.0034 +/- 0.0002
900	-0.2483	0.0059 +/- 0.0002	-0.3268	0.0060 +/- 0.0002
790	-0.2575	0.0046 +/- 0.0002	-0.3560	0.0045 +/- 0.0002

Table 2. Summary of day results with cx1231 < 0.5 K and cx1231 < 1 K thresholds

From Table 1 Column #2 we can see that all channels have a cold bias of typically -0.25 K or more. In Column #4 we show the bias when the cloud filter is relaxed to cx1231 < 1 K. This relaxation triples the yield of "clear", but at the expense of a slightly larger cloud leak, resulting in a slightly colder bias. In all cases the cold bias gets colder by about 0.1 K. A bias could be the result of an error in the Radiative Transfer Model (RTM) used for the regression training. However, for an RTM error the cold bias would not be a function of tightness of the cloud filter. The 1231 channel shows evidence of an RTM related 0.2 K cold bias.

Table 1 Columns #3 and #5 list the trend and one sigma trend uncertainty. We note that in all cases the trend is slightly positive and not an obvious function of cx1231. We also note that the trends in the channels at 790 and 901 cm^{-1} are about + 6 mK/yr; 961; 1128 and 1231 cm^{-1} are about +3 mK/yr. For the 2616 and 2508 cm^{-1} channels the trends are 10 mK/yr.

For the 790, 900, 961, 1128 and 1231 channels the day results are almost identical to the night results. For the 2508 and 2616 channels the bias is dominated by the reflected solar component, which was not included in the calculations. We note that the daytime trend in 2508 and 2616 is consistent with a change from cx1231 < 0.5 K to cx1231 < 1 K, and now agrees better with the other channels. Trends in the AIRS shortwave channels have been reported previously (Manning and Aumann, 2017), but not explained.

4. DISCUSSION

Any trend in the AIRS observed radiances has to be considered when making measurement of any geophysically interesting parameters. We do see a trend which for some channels approaches the 10 mK/yr global warming. Of the effects which may produce the observed positive trend a spectral shift can be rejected, since we are dealing with window channels. However, changes in the electronics non-linearity and changes in the contamination of key surfaces are currently being evaluated. The brightness temperatures for the clear night cases are typically 300 K. For the day cases the reflected sunlight increases this to 305 K, approaching the OBC temperature. For brightness temperatures near that of the OBC (308.3 K) non-linearity is irrelevant.

Where is the observed warming trend at warm scene temperatures coming from? A change in the contamination of the scan mirror is potential source of the observed slight warming. There are two effects: 1) related to the OBC and 2) related to the scene viewing.

1. OBC view effect. The calibration equation assumes that the OBC view is unchanged from the pre-launch calibration and radiates at an effective temperature of a 308.3 K blackbody. Assume the scan mirror is contaminated and due to the resulting scattering the OBC view sees only 99% of the OBC and 1% from the surroundings of the OBC at the scanner housing temperature of about 275 K. At 1231 cm^{-1} the effective OBC temperature would now be 308.03. The calibration software would counter this effect by increasing the gain by 0.5%. Table 3 shows the effect of 1% scattering of the scan mirror on a uniform 300 K scene and under uniform and non-uniform 210 K scenes.

Channel wavenumber (cm^{-1})	Uniform 300 K scene	Uniform 210 K scene	210 K scene surrounded by 235 K	210 K scene surrounded by 275 K	210 K scene surrounded by 300 K
2616	300.18	210.09	210.75	216.37	224.48
2508	300.19	210.09	210.72	215.76	223.10
1231	300.25	210.12	210.48	211.67	212.89
1128	300.26	210.13	210.47	211.52	212.54
961	300.27	210.13	210.46	211.32	212.09
900	300.27	210.14	210.45	211.26	211.95
790	300.28	210.14	210.44	211.15	211.73

Table 3. Effect of a 1% out-of-field scattering for 300 K and 210 K scenes.

At 1231 cm^{-1} we observed a trend of 2 mK/yr under uniform clear observation (Tables 1 and 2). If we assume that the effect of the contamination at 1231 cm^{-1} increased steadily from 0 to 0.1% in 10 years, the trend is +0.25*0.1/10 = 2.5 mK/yr for uniform 300 K scenes. For the 1231 channel this is in reasonable agreement with observations. At 2508 and 2616 a 1% scattering would create a 0.18 K shift, i.e. a trend of 0.18*0.1/10=1.8 mK/yr. Since the observed trend is close to 10 mK/yr, the effect of scan mirror contamination at 2508 and 2616 appears to be 5 times larger than at 1231. The problem with this model is change in the gain: For the 1231 cm^{-1} channel we see an increase in the gain of only 0.1% between 2004 and 2016, not 0.5%.

2. Scene view effect. The accuracy of the radiometric calibration is always stated under uniform scene conditions, i.e. the instrument views a blackbody of infinite extent. In real life, the scene will seldom be uniform and scattering by the scan mirror has a more complicated effect. If a 300 K scene is surrounded by 275 K clouds, then an increase in scattering will

cause the scene to appear increasingly colder. But the warm scenes are warming for all window channels. However, if the scenes consist of 210 K cloud embedded in a 275 K cloud field, then 1% of the radiance attributed to the cold cloud would actually originate from the warmer surroundings. A 210 K cold cloud identified at 900 cm^{-1} would actually be 211.26 K, but it would appear to be 215.76 K at 2508. Assuming no other calibration errors, a 0.1% scattering would cause the 900 channels to read 210.13 K for a 210 K cloud, the 1231 channel would read 210.16 K. With the 0.5% scattering effect in the 2508 channel, it would read 212.7 K, 2.7 K warmer than in 2002.

The result of observation of clouds colder than 210 K identified in the night tropical oceans by the 900 cm^{-1} channel are shown in Figure 3. Since the clouds are selected using the 900 channel, a trend in the 900 channel would not be detected. The results from the 961 and 1231 channels are almost exact overlays.

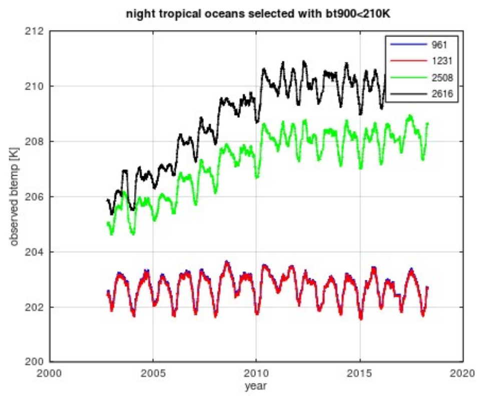

Figure 3. Overlay of observations of cold clouds seen at 961, 1231, 2508 and 2616 channels.

It can be seen that the signal from the 2508 and 2616 channels increased steadily between 2002 and 2011, then leveled off. By 2011 the 2508 channel read 5 K warmer and the 2616 channel read 7 K warmer than the 900 channel. Assuming the 0.1% effect deduced from the 300 K observations at the 900 channel, the 210 K scenes at the start would be identified as 210.12 K clouds with 10 years of contamination. This is a small effect compared to the changes seen in the 2508 and 2616 channels

Based on the 0.5% effect deduced from the 300 K observations we would expect 2508 to be 2.3 K warmer and 2616 to be 2.5 K warmer. The results shown in Figure 3 indicate that we need to assume that the 210 K clouds are embedded into much warmer scenes. For tropical oceans this is very likely, and the scattered radiation may originate from as far as 50 degrees from the boresight.

We used the observations with the 2508 and 2616 channels at extremely low temperatures, but likely highly nonuniform scenes as key evidence for the scan mirror contamination. One could argue that at extremely cold temperature the 2508 and 2616 measurement are not reliable. We counter this argument using data from Dome Concordia (DomeC) in the Antarctic. The scene at DomeC is extremely cold, but much more uniform than cold clouds similar temperatures surrounded by clear ocean. For every day since 2002 we collected AIRS data from the 14 daily overpasses of DomeC within 100 km of the DomeC location. This creates a data set with typically 250 observations each day.

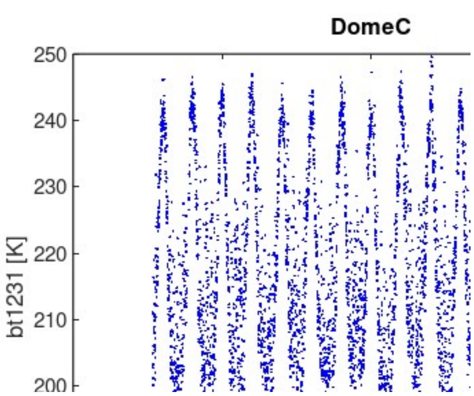

Figure 4. Temperatures measured by the 1231

Figure 4 shows the daily mean of these data for the 1231 channel. The temperatures swing between 200 K and 240 K. We divided these data into day and night observations and define day as solar zenith angles less than 90, night as solar zenith angles larger than 90 degrees. The results are summarized in Table 4. At night the typically 207 K temperatures agree to within 1 K for all window channels. (Results for the day are included in Table 4, but the 2508 and 2616 channels are impacted by reflected solar radiation. The other channels agree within 0.5 K at 225 K for the day time observations.)

channel for DomeC in the Antarctic.

The extremely cold temperatures are accurately measured by the shortwave channels and the trends seen at DomeC agree for all window channels. This supports a model that increased scattering from the scan mirrors creates a warming trend for extremely cold scenes surrounded by much warmer scenes. Whatever caused the contamination, it stopped in 2011.

On the EOS spacecraft with AIRS and MODIS and CERES is the AMSR-E. The AMSR-E scan mirror motor current motor steadily increased between 2002 and 2011, until the drive current exceeded the limit and the scan mirror was stopped. This suggests that the bearing lost lubricant, which resulted in increased friction and created a cloud of contaminants. One would expect that the MODIS and CERES may see a similar steady degradation of some observations. As of 2018, nobody has looked for or reported such a degradation.

Channel wavenumber (cm^{-1})	Mean [K] night	Trend (night)	Mean [K] day	Trend (day)
2616	208.10	-0.004 +/- 0.0351/yr	234.834	0.071 +/-0.0210/yr
2508	208.89	-0.138 +/- 0.0353/yr	230.383	0.034 +/- 0.0183/yr
1231	206.97	-0.110 +/- 0.0363/yr	225.506	0.025 +/-0.0186/yr
1128	207.31	-0.082 +/- 0.0355/yr	226.112	0.039 +/-0.0179/yr
961	207.10	-0.112 +/- 0.0364/yr	225.706	0.027 +/-0.0186/yr
901	206.80	-0.109 +/- 0.0359/yr	225.392	0.029 +/-0.0186/yr
790	206.41	-0.109 +/- 0.0357/yr	224.854	0.025 +/- 0.0185/yr

Table 4. DomeC night and day observations.

It is apparent that there is increased scattering from scan mirror contamination, but the observation that that 300 K clear scenes in all window channels have gotten slightly warmer is apparently unrelated to a scan mirror degradation. This leads us to look at the SST. Between 2002 and 2018 the RTGSST for the tropical oceans increased by about 15 mK/yr. The SST was corrected for the diurnal cycle and the skin effect based on statistical offsets derived before 2002. It is possible that much of the observed warming in the AIRS window channels is related to a shift in the diurnal cycle and skin effect correction.

5. SUMMARY AND CONCLUSIONS

The objective of our paper was to estimate the stability of AIRS L1b calibrated radiances. We evaluate the stability of the AIRS v5 calibration in seven atmospheric window channels between 2002 and 2018 under tropical ocean clear conditions. Trends for the channels between 961, 1128 and 1231 cm^{-1} channels are typically +3 mK/yr, 790 and 901 cm^{-1} the trend is 6 mK/yr, i.e. the observation are increasingly getting warmer than expected. The trends are day/night consistent. The trend for the 2508 and 2616 cm^{-1} channels is close to 10 mK/yr at night, but closer to 6 mK/yr during the day. On an absolute scale these trends are small, but not when viewed in the context of global warming at a 10 mK/yr rate. The effects of scattering due to scan mirror contamination are evident at extremely cold temperatures, but scattering does not produce the observed warming at warm temperatures. It is possible that much of the observed warming in the AIRS window channels relative to RTGSST is a geophysical effect related to the warming of the oceans, resulting in a shift in the diurnal cycle and skin effect correction. This requires more careful evaluation.

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