Application of Atmospheric Infrared Sounder (AIRS) Data to Climate Research

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ABSTRACT

The application of hyper spectral radiometric data to climate research requires very high absolute radiometric accuracy and stability. We use cloud-free tropical ocean data from the Atmospheric InfraRed Sounder (AIRS) Calibration Data Subset (ADCS) to show that the radiometric precision and stability required climate applications has been achieved. The sea surface skin temperatures derived from the AIRS 2616cm-1 super window channel are stable relative to the RTG.SST at the better than 8 mK/year level, and the spectral calibration is stable at the 1 ppm/year level. The excellent stability and accuracy are the result of the implementation of AIRS as a grating array spectrometer, which is cooled and stabilized within 10 mK at 155 K. Analysis of daily measurements of the temperature gradient between the surface and 7 km altitude show that the AIRS Calibration Data Subset has applications which extend its original intent for calibration support to climate research.

The Atmospheric Infrared Sounder (AIRS) on the EOS Aqua satellite was launched into polar orbit in May 2002. AIRS covers the spectral region from 640 to 2700 cm-1 with 2378 independent channels and represents the first of a new generation of hyper spectral resolution sounders in support of global sounding data for weather forecasting and climate research.

Key Words: Infrared, temperature retrieval, hyper spectral , remote sensing, climate

1. INTRODUCTION

Temperature sounders on early polar weather satellites were designed to support weather forecasting. The instruments were designed to be replaced on an 18 months cycle, with little consideration for the extreme calibration stability and traceability required to allow the data (twenty years later) to be analyzed for climate signals. The Atmospheric Infrared Sounder (AIRS) is a grating spectrometer on the EOS Aqua satellite, which was designed from the start with a five year lifetime to support climate research and weather forecasting (Aumann et al. 2003). AIRS covers the spectral region from 640 to 2700 cm-1 with 2378 independent channels and is the first of a new generation of hyper-spectral resolution sounders gathering global sounding data for weather forecasting and climate research. AIRS was launched in May 2002 and has produced 4 million spectra of the globe each day since September 2002.

Near real-time data from AIRS have been distributed to the major numerical weather forecasting centers since October 2002 and have been part of the operational forecast since May 2004. The requirements for absolute radiometric accuracy and stability for weather forecasting applications are greatly relaxed by the fact that the Numerical Weather Prediction (NWP) centers dynamically tune all data from satellites to match the temperature and moisture profiles measured by routinely launched radiosondes (RAOBs). The tuning procedure applies corrections to the data from the satellite sensors to assure that there is no bias between the data and the RAOBs. This assumes that the RAOBs are unbiased and have a higher and more reliable information content and calibration accuracy than the satellite data. This assumption is in general not correct for the new generation of hyper spectral sounders, which are designed to support weather forecasting and climate research.

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The application of hyper spectral radiometric data to climate research requires high absolute radiometric accuracy and very high stability. With the discussion of global temperatures at the 100mK absolute level and changes at 15 mK/year level (ICCP 2001), the absolute accuracy and long term stability required from a climate data set can not be any less. Radiometric accuracy and stability of any instrument designed to create a climate quality data record has to be demonstrated at this level using routine on-orbit measurements. In the following we discuss the approach which has been taken in the design of AIRS and results from routine on-orbit measurements from the first two years of AIRS data, which demonstrate that the level required for climate quality is being achieved.

2. APPROACH

In order to verify the radiometric and spectral stability of the AIRS data , the data are routinely analyzed relative to two relatively undisputable standards: The temperature of the ocean surface, which is routinely measured by the global network of drifting buoys, and the spectral features due to atmospheric constituents in the upwelling radiance spectrum.

a) AIRS Radiometric Calibration.

AIRS uses the classical two point method radiometric calibration: The electrical offset is eliminated with regular observations of cold space, and the radiometric gains are calculated using regular observations of an on-board blackbody source. Non-linearity of the electronics is calibrated pre-launch. Instruments in polar sun-synchronous orbit are exposed to temperature changes due to the change in the sun angle. The classical two point calibration cancels these effects to first order, but not to second order. Second order effects appear as diurnal and/or seasonal variability or secular trends in the data, which mimic climate signals. The AIRS design suppresses the second order effects through active thermal control: The entire AIRS spectrometer temperature is cooled to 155K and maintained at this temperature to within 10mK. The onboard calibration source, a full aperture wedge cavity, is actively controlled at 308K to within 10mK. The AIRS detectors are mounted on a single focal plane which is cooled by a pulse tube refrigerator to 55K. The temperature at the cold head is maintained within 1 mK. The calibration sequence using the blackbody and four cold space views is repeated every 2.67 seconds (every scan line). The absolute radiometric accuracy was verified for scenes at temperatures between 220K and 340K and for a number of scan angles during pre-launch testing at the 0.2K level (Pagano et al. 2003).

AIRS covers the spectral region from 640 to 2700 cm-1 with 2378 independent channels, each of which is calibrated independently using the classical two point calibration. Since the calibration for all 2378 channels shares the same blackbody and space views, verification of the absolute calibration and stability for one channel in principle provides verification for all channels. The validation of the radiometric calibration makes use of the Global Real Time Sea Surface Temperature (RTG.SST) provided by NOAA/NCEP on a 0.5 degree grid for the daily GCM forecast (Thiebaux et al. 2002). The RTG.SST is verified daily relative to the floating buoy network. The floating buoys, which are calibrated at the 0.1K level relative to a secondary standard before they are released, serve effectively as radiometric transfer standards for AIRS. AIRS measures the temperature of the skin using the extremely transparent 2616 cm-1 channel at night, based strictly on first principles (Aumann et al. 2003). The temperature at the buoy level is slightly warmer during the day than at night. In addition, the skin temperature is on average slightly cooler than the buoys. The combination of the two effects causes the RTG.SST, which is a day night average of the buoy temperatures interpolated on a global 0.5 degree grid, to report a temperature about 0.35K warmer than the true skin temperature at night.

b) **AIRS Spectral Calibration.**

The AIRS spectral calibration combines pre-launch measurements with on-orbit measurements. The shapes of the spectral response function (SRF) of all 2378 channel and the focal plane map of their locations were measured pre-launch (Strow et al. 2003) with an absolute accuracy of 4 ppm and are frozen into the AIRS design. All that is required to know the frequencies of the SRF centroids on-orbit are routine measurements of the translation of the entire focal plane in the dispersed direction (Gaiser et al. 2003). The nominal requirement for AIRS is knowledge of the SRF frequencies at the +/-4 ppm level throughout the 7 year nominal mission lifetime and frequency stability within +/- 4 ppm during any 24 hour period.

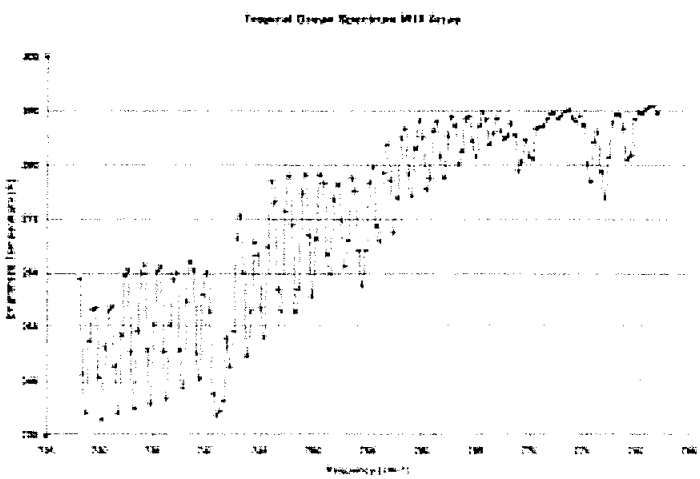

Figure 1. shows the 725 to 795 cm-1 region of a calculated tropical spectrum. The strong spectral features due to mid-tropospheric co2 are ideal for spectral calibration.

The on-orbit calibration is performed once per granule, using typically 400 cloud-free spectra near nadir from most of the 135 scan line in the granule. Figure 1. shows the 725 to 795 cm-1 region of a calculated spectrum based on tropical ocean temperature and moisture conditions. The high spectral contrast features due to resolved lines of co2 in the mid-troposphere are ideal for frequency calibration. Each dot represents one AIRS channel. The spectral calibration consists of determining the shift required to align observed spectra with the a pre-calculated model spectrum, which is based on a static tropical climatology and over-samples the AIRS frequency spacing by a factor of twelve. The absolute positions of the resolved spectral features in the calculated spectrum are known with the precision of laboratory spectroscopy to better than 1 ppm.

c) **AIRS Calibration Data Subset**

No matter how well an instrument is designed or "meets specifications", all claims to accuracy and stability on the basis of first principles of a data set intended for climate applications need to be verified by an aggressive on-orbit program of validation and performance monitoring while the instrument is still in orbit. A product called the AIRS Calibration Data Subset (ACDS) was created to provide the data for this validation. The ADCS contains data from three types of footprints: "cloud-free" ocean footprints, footprints from fixed ground locations of potential interest to calibration, such as Dome Concordia in the Antarctic, and footprints from the tops of deep convective cloud systems. For a typical day the ACDS collects data from about 100,000 of the 4 million spectra observed by AIRS. Details of the cloud-filtering method are found in Aumann et al. (2004). Saved in the ACDS are 84 key channels from the 2378 channel spectrum, the fifteen AMSU channels , data from the three AIRS visible light channels, all mapped on the AIRS 13 km footprint scale, and associated time and geolocation data . The RTG.SST is also included for convenience. The ACDS condenses 721 AIRS files totaling 36 Gbytes into a single 30 Mbyte file daily. The factor-of-1200 reduction in data volume makes the ACDS an efficient tool for calibration and climate data trend analysis. One year of data can be read from disk and re-analyzed in just one hour.

3. RESULTS

Carefully screened cloud-free nighttime (descending orbits) tropical ocean (+/- 20 degree latitude) footprints were taken from the ACDS. This corresponds to typically about 3000 clear spectra for any 24 hour period. Figure 2.

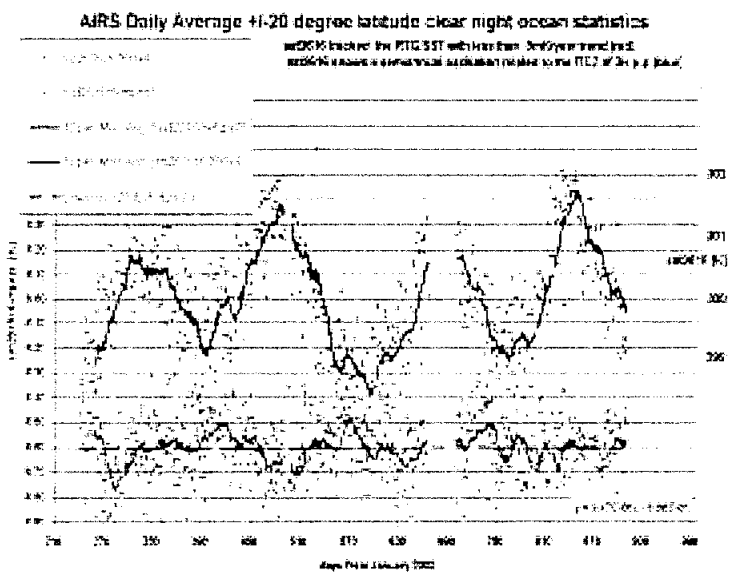

Figure 2. The upper curve is sst2616 (scale on the right), the lower curve (scale on the left) is sst2616-RTG.SST. The results track with 3 mK/year stability. Of the observed 600 mK cold bias, 350 mK is expected and the remaining 250 mK is due to a small, but stable residual cloud contamination.

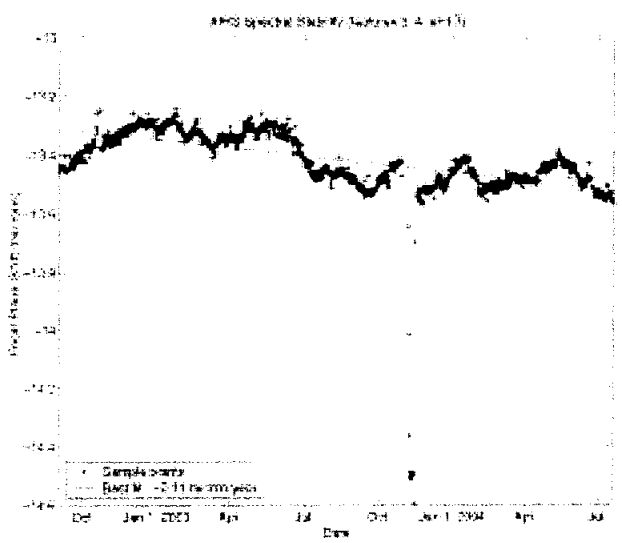

Figure 3. shows a potential 1 ppm shift in the SRF centroids towards higher frequencies and a possible seasonal modulation of about the same magnitude.

shows the result of AIRS sea surface temperature measurements. Each point on the graph represents the median of the measurements from the descending parts of the fourteen orbits each day. The blue points (scale on the right) are sst2616 measurements, which oscillate with a 3 K peak-to-peak amplitude between 299.5K and 302.5K with the 6 month period characteristic of the Inter-tropical Convergence Zone (ITCZ). The 15 day gap near day 690 (counting from January 2002) is due the intentional shut-down of AIRS during the major solar flare in November 2003. The solid (blue) line is a 16 day sliding average intended to smooth out spatial coverage inhomogeneities related to the 16 day ground track repeat cycle of the EOS Aqua orbit. The red points (scale on the left) show the difference between sst2616 and the RTG.SST. The solid (red) curve is the 16 day sliding average. A linear fit through these data (dashed line, equation in the lower right corner), shows that the slope is 9E-6 K/day, i.e. 3mK/year. The uncertainty in this slope is 8mK/year, i.e. the calculated slope is statistically not significant. The sst2616 tracks the rtg.sst with great stability, but with a bias of -0.6K. As discussed above, a nighttime cold bias of about 0.35K was expected. The remaining 0.25K offset can be seen for night and day data (not shown) . Analysis of the surface temperature measurements during the day (using the 1231 cm-1 window channel) using the AIRS 0.7-0.9 micron VIS/NIR channel shows that the 0.25K bias is due to low cloud, which are not identified by the day/night cloud filter (Aumann et al. 2004). The 0.25K radiometric offset decreases to less than 50 mK, if the day time data are re-screened using the VIS/NIR channel, but at the expense of yield in "cloud-free" data. The key for climate record evaluation is the demonstrated stability at the few mK/year level , which applies in the case of AIRS to all channels.

Figure 3. shows the results of the spectral calibration using the upwelling radiance. The units are absolute microns relative to a reference mark in the focal plane in the direction of dispersion. One micron in focal plane coordinates corresponds to 1% of the width of the spectral response function (SRF). Since the spectral resolving power $\nu/\Delta\nu=1200$, one micron in focal plane coordinates is equivalent to 8 ppm in frequency. The two week gap in the data in November 2003 is due to the protective shutdown of AIRS during the solar flare, when the spectrometer and the detectors were allowed to warm to ambient spacecraft conditions of about 280K. The data points which are low by as much as one micron were taken while the spectrometer temperature re-stabilized after AIRS was restarted.

Inspection of Figure 3. leads to two observations:

1) The best linear fit to the data from September 2002 through July 2004 has a slope of -0.11 micron/year. This corresponds to a 1 ppm shift per year of the nominal SRF frequencies to higher frequencies. An equally good fit to the data could be obtained by assuming that the SRF centroids were stable between September 2002 and October 2003, and shifted 0.1 micron (to higher frequencies) when the AIRS resumed operations, and continue to be stable between mid November 2003 and the present. Another six months of data will be required to distinguish between these two possibilities.

2) There appears to be a small seasonal modulation in the apparent SRF centroid of +/- 0.1 micron in focal plane coordinates, i.e. +/- 1 ppm in frequency. Further analysis is required to determine if this seasonal modulation is an artifact of the spectral calibration algorithm, or if it is a real effect. While the spectrometer temperature is thermostatically controlled at the 10mK rms level at the second stage radiator, there is a 20 mK peak-to-peak seasonal variation in the temperature sensor attached to the grating. Based on the pre-launch calibration under thermal equilibrium conditions, a 20mK shift in the spectrometer temperature would only produce a 0.04 micron apparent shift in the SRF centroids, i.e. a factor of 2.5 less than observed. This discrepancy is under evaluation.

The requirement for AIRS is knowledge of the SRF frequencies and 24 hour stability at the +/- 4 ppm level, which suffices for weather forecasting applications. The reason for the interest in shifts in the SRF centroid at the 1 ppm level, real or calibration algorithm induced, is their potential impact on the radiometric interpretation of the data. Any real shift in the SRF centroid frequency from the nominal frequency, $\Delta\nu$, could be included in the radiative transfer calculation, or it could be recorded in the data records as a component of the radiometric measurement uncertainty. A frequency shift of $\Delta\nu$ which is not accounted for cause the radiometric interpretation to be in error by

$$DT(\nu) = (dT/d\nu)*\Delta\nu,$$

where $dT/d\nu$ is the slope of the brightness temperature at frequency ν. Since the median absolute value of $dT/d\nu$ for a typical spectrum is 2mK/ppm, the radiometric impact of a 1 ppm seasonal frequency shift for most channels is 2 mK or less. This includes virtually all retrieval channels, which are located either at the peak of lines (high in the atmosphere) or between lines (low in the atmosphere and window channels). The steepest slope of any channel is 35 mK/ ppm. The sensitivity of the spectral frequency calibration depends on these channels, but their use for retrievals has to be weighted on a case by case basis relative to the availability of equivalent other channels.

The sounding channels in the 4.3 micron co2 R-branch channels are unique in the AIRS spectrum, because they are pure temperature sounding channels with essentially no sensitivity to water vapor. At 2388 cm-1, $dT/d\nu$=10mK per ppm in frequency. In the following example we use the 2388 cm-1 channel, where this correction needs to be taken into account.

4. APPLICATION TO CLIMATE

With the radiometric stability of AIRS established at the 3 mK/year or better level, we illustrate the potential of the AIRS Calibration Data Subset for climate applications with one example. In Figure 2. we showed that the surface temperature in the equatorial ocean has a 3 K peak-to-peak modulation with a 6 months repeat cycle. Figure 4. shows the difference between the surface temperature, sst1231, and the temperature sensed by the 2388 cm-1 channel at about 7 km altitude. Unlike sst2616, which can be used only at night, sst1231, which is derived from the 1231 cm-1 window channel, can be used for day and night time measurements. The opacity at 2388 cm-1 is due to co2, with essentially no sensitivity to water vapor. Data from daytime and nighttime are shown separately. There is some overlap in the spatial coverage for descending and ascending orbits, but cloud-free spectra on one orbit and on the ground-track crossing twelve hours later have little correlation, other than seasonal. Although the two data sets are essentially independent, the day and night measurements track each other within a small fraction of a degree. There is a small, but statistically significant increase in the gradient during the last two years of 212 +/-42 mK/year. This gradient has to be corrected for the effect of the increase in the co2 abundance, nominally 2.6 ppmv/year, on the 2388 cm-1 channel, corresponding to 107 mK/year, and 10mK/year for the previously discussed spectral shift. This correction decreases the gradient to 115mK +/-42 mK. Taken at face value the increase in the gradient corresponds to slight cooling trend in the mid-troposphere. A longer time record than that presently available is required to reliably discern the relationship of this gradient to multi-annual cycles or long term trends.

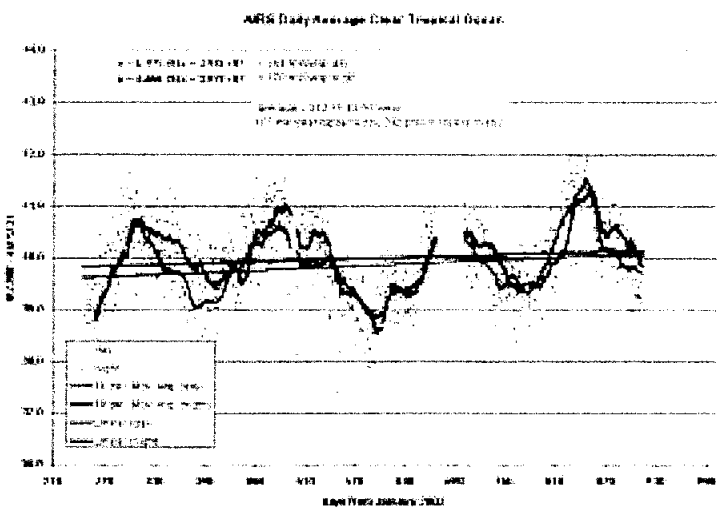

Figure 4. The gradient between the surface temperature (sst1231) and the temperature at 7 km altitude (bt2388) appears to be increasing significantly faster than expected from the increase in co2 alone.

5. SUMMARY AND CONCLUSION

Radiometric accuracy and stability are key requirements for a data set in support of climate research. We use the AIRS Calibration Data Subset to analyze trends of the first two years of AIRS data: The AIRS radiometric stability is better than 8 mK/year relative to the RTG.SST, which can be treated as a defacto transfer standard from the drifting buoys. The spectral stability is 1 ppm/year. This stability and accuracy is the result of the implementation of AIRS as a grating array spectrometer which is cooled and temperature stabilized within 10 mK rms at 155 K. The example showing the slight cooling trend in the mid troposphere shows that the AIRS Calibration Data Subset has applications which extend its original intent for calibration support to climate research.

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