Hyperspectral sounder performance for cold scenes

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ABSTRACT

We investigate the use of 200K scenes as a valuable "stress test" for the evaluation of the calibration of AIRS and CrIS. Under these conditions both instruments show artifacts much larger than the nominal stated radiometric accuracy of about 0.1-0.2 K. Except for the AIRS shortwave trend, both instruments clearly perform well at the 1 K level even for these extremely low scene temperatures. Unfortunately, changes in extremes, in this case cold extremes, are of great interest to the evaluation of climate change effects, such as changes in the height of the tropopause or the frequency of severe storms. The evaluation of the AIRS performance at extremely low scene temperatures has been key to identifying the need for updating the polarization coefficients in the L1B software Version 7. These changes are expected to eliminate a large fraction of the observed AIRS artifacts. The CrIS instrument teams is also working on refining the calibration.

Keywords: AIRS, CrIS, hyperspectral, infrared sounder, Deep Convective Clouds, cold clouds

1. INTRODUCTION

Hyperspectral infrared sounders Atmospheric Infrared Sounder (AIRS)[1] on EOS Aqua and Cross-track Infrared Sounder (CrIS)[2] on the Suomi NPP spacecraft are in similar 1:30 PM sun-synchronous polar orbits and provide very similar information. A major long-term goal is to produce a continuous record from the two instruments and future versions of CrIS. Their performance has been shown to agree well at the 0.1-K level for some conditions[3,4,5] , but not for global or large regional scales and the wide temperature range of interest for climate applications. The temperature regions which most stress the instruments, i.e. are likely to produce artifacts, depend on the details of the instrument design. For AIRS these regions are extremely cold scenes and the sensitivity to the accuracy and stability of the space view. For CrIS the extreme cold and hot scenes stress the linearity correction equally, since the instrument operates near 280K. In addition, the self-emission of the instrument can essentially cancel the scene signal for certain conditions between 270 and 280K. Resulting instrument artifacts that need to be fully characterized before a merged set can be produced. Different sorts of artifacts dominate in different temperature domains. Here we investigate the application of a novel source to evaluate the performance of both instruments under extremely cold conditions, which are daily available in large numbers: Extremely cold cirrus cloud tops which spread at the tropopause. Clouds colder than 210K at 900 cm^{-1} are found in the tropical zones in about 0.5% of the footprints. With this new tool we identify interesting artifacts for each instrument.

1.1 Data

AIRS spectra come from Level-1B version 5 available from the GES DISC DAAC at http://disc.gsfc.nasa.gov/datacollection/AIRIBRAD_005.html. This calibration uses the coefficients and equations developed during the pre-launch calibration. (Version 5 changes some formatting and added some parameters in support of quality control.) To collect the cold cloud cases conveniently, we use the AIRS calibration subset product, known variously as "CalSub", "AIRXBCAL", or "AIRS Calibration Data Subset (ACDS). It is available from the GES DISC DAAC at http://disc.gsfc.nasa.gov/datacollection/AIRXBCAL_005.html. We use the current latest product there, version 5. Each daily file of this product includes several targeted subsets of the spectra, including all spectra within latitudes 50N to 50S from a day where the brightness temperature at 1231 cm^{-1} is less than 210 K. For AIRS we used L1b V5 calibrated radiances for all data where the radiance of the channel was not set to -9999. This is 99.99 % of the all data. AIRS has 2378 spectra channels. Individual AIRS channels with high noise levels (0.8 K or 2x nominal) or other known problems flagged with A/B state > 3 in the channel properties files are excluded. This leaves 2250 spectral channels. AIRS uses A/B redundancy, i.e. for each AIRS channel there is a radiometrically independent A-side and a B-side. For most AIRS channels A and B-sides are functioning. Because AIRS has a complete record of over 14 years, it is possible to look for subtle trends.

For CrIS we used the IDPS calibration. CrIS spectra are screened for quality in all bands using the imaginary components according to the recommendation in Han 2013 [6] and are Hamming apodized. Guard channels are not used and the spectral range from 1700-1755 cm^{-1} is not displayed because it is affected by a known issue from light reflecting off of baffles, which was corrected in the 2016 data but not in the 2013 data. The data were quality filtered using a threshold on the magnitude of the imaginary component defined by the CrIS instrument team[6]. The Sounder SIPS has a preliminary versions of a CrIS Calibration data subset starting in May of 2012, which largely mirrors the AIRS calibration subset. Cold clouds are defined as cases where brightness temperature at 900 cm^{-1} is less than 225 K and latitude is within 50 degrees of the equator. We do have nearly full data for 2013 and 2016, so these two years are used in the figures below. Some differences may come from differences in the production IDPS algorithm between 2013 in 2016, however. For 2013 N_Algorithm_Verision is set to "1.O.000.005" to "1.O.000.007". For all of 2016 it is "1.O.000.012".

1.2 Methodology

To get comparable spectra to explore the shapes of spectra we subset from the larger set of cold clouds only those where the brightness temperature at a key frequency is in the narrow range of 200.0 ± 1.0 K. 200 K is warm enough to give us a large sample to work with but cold enough that cold effects dominate. We make full-year averages of all spectra meeting the criteria. We can then investigate changes with time in the detectors, day/night differences, CrIS FOV differences, and differences between cold clouds seen in the first and last parts of a scan.

The key frequency for AIRS was chosen as 939.04 cm^{-1}, because this is a high-quality channel that has minimal atmospheric sensitivity and has not changed characteristics over the 14 years. For CrIS we use the nearby 938.75. These brightness temperatures are called BT939 below. This is different from the frequencies used for either the AIRS or CrIS subsets, but the BTs at the 3 temperatures are very close and the 201 K threshold used here is well below the 210 & 225 K thresholds used in the original subsets so all possible BT939-200K clouds should be present in both subsets.

Choosing the comparison subset according a fixed brightness temperature hides biases at this frequency, so we explore only relative differences.

2. RESULTS

2.1 Cold cloud spectra

Figure 1 shows AIRS and CrIS mean nighttime cold cloud spectra for 2013 and 2016. For much of the frequency range we are essentially viewing a flat cloud spectrum at ~200 K, but with significantly warmer regions where there is stratospheric emission.

The most prominent features in Figure 1 are mostly related to expected differences in spectral coverage and spectral resolution between the two instruments. There is only one evident instrument problem: at the shortwave end (2380-2550 cm^{-1}) AIRS is warmer than CrIS. This is the result of a warming trend in AIRS data which is explored in section 2.4 below.

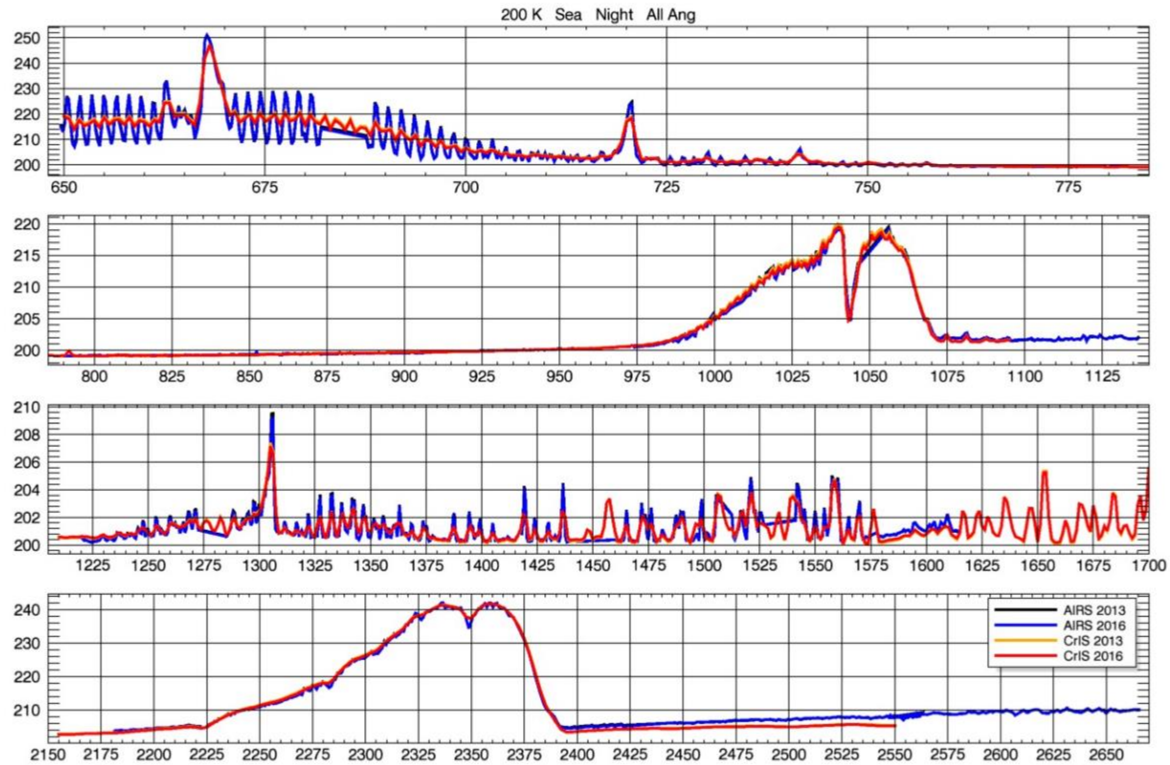

Figure 1. AIRS and CrIS mean 200-K cloud spectra for 2013 and 2016. X axis is frequency in cm^{-1}; Y axis is brightness temperature in K.

We can concentrate on just the "window" regions where we are viewing the clouds by applying the rules in Table 1. Generally, these only exclude broad spectral regions with strong stratospheric signal, but in the midwave band the rule keeps individual cold channels that seem not to have emission.

Table 1. Rules for selecting 200-K "window" channels

Frequency range (cm^{-1})	**Brightness Temperature condition**
760 - 973	None
1076 - 1200	None
1200 - 1700	< 200.6 K
2150 - 2220	None
2395 - 2665	None

Figure 2 shows AIRS and CrIS nighttime cold cloud spectra for 2013 and 2016, as in Figure 1, but now only "window" channels are shown. The difference in 2400-2550 cm^{-1} is now clearly 2-3 K, but other spectral regions all agree well within the ~0.3 K uncertainty from the difference in spectral characteristics.

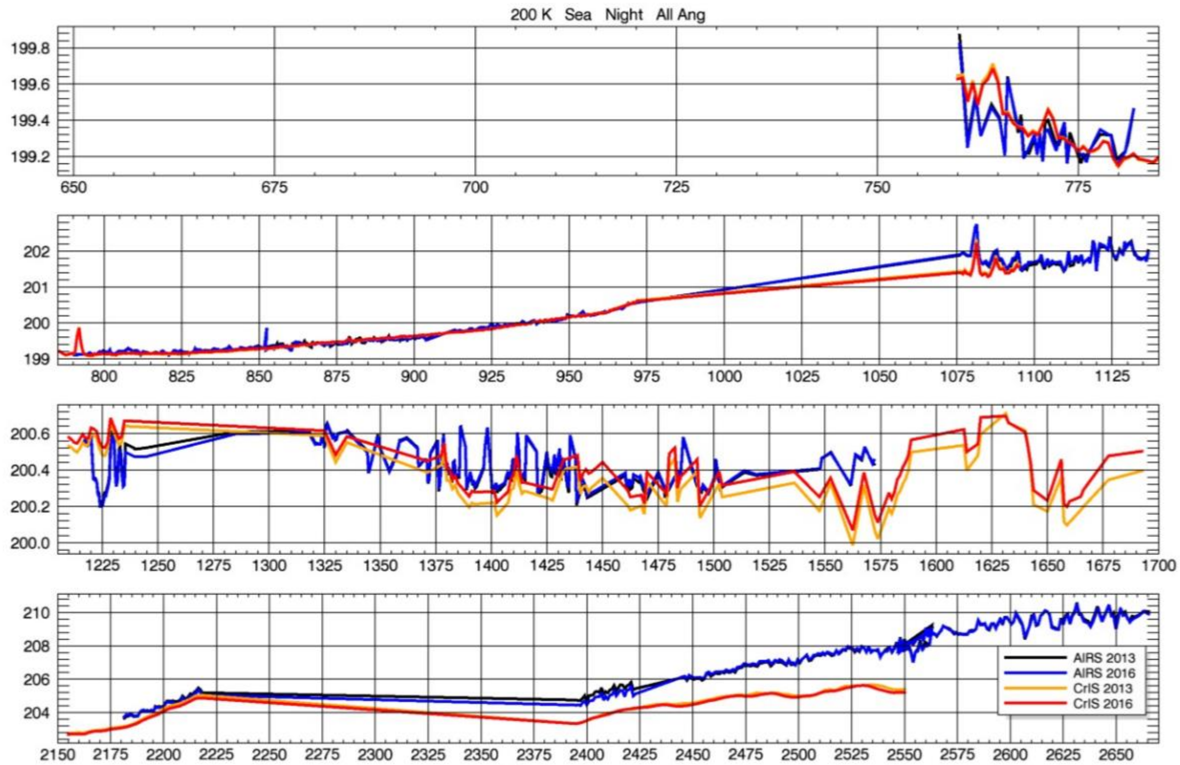

Figure 2. AIRS and CrIS mean 200-K cloud spectra for 2013 and 2016, now excluding channels with significant stratospheric signal. X axis is frequency in cm^{-1}; Y axis is brightness temperature in K.

2.2 Right-left bias

One sensitive test of instrument characteristics is a comparison of cold clouds seen in the right and left 1/3 of each scan. The clouds should be nearly identical. Observation local time on the two sides of the swath differs by ~50 minutes, but for night observations this should result in little difference between the two sides, since the diurnal cycle in the cold clouds over ocean is weak. The polarization of the light entering the instruments will be different. Figure 3 gives right minus left differences for AIRS and CrIS for 2013 and 2016.

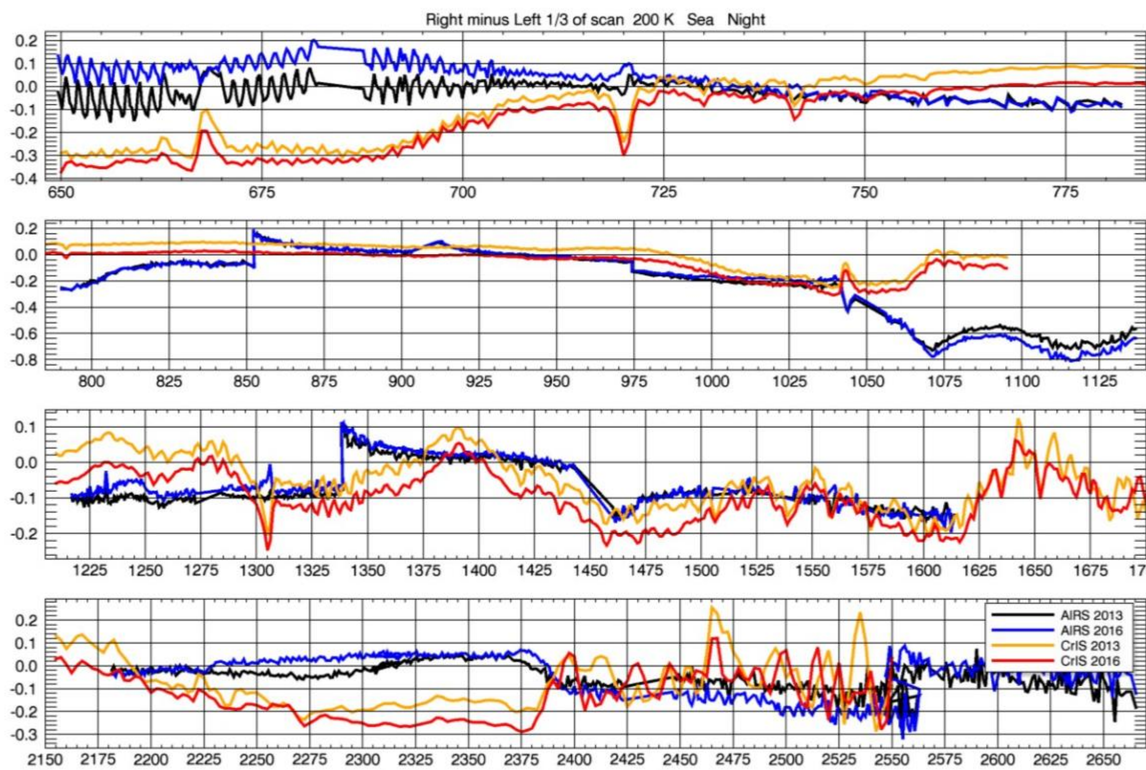

Figure 3. Difference between right and left 1/3 of scan for AIRS and CrIS 200K cloud spectra for 2013 and 2016. X axis is frequency in cm^{-1}; Y axis is brightness temperature difference in K.

While the two instruments perform similarly in the two years, there are noticeable differences between the instruments, including:

1) AIRS shows significant left-right bias in the 1070-1135 cm^{-1} region.
2) AIRS has discontinuities at boundaries between detector modules, including 852, 905, 975, 1070, 1340, 1450, and 2555 cm^{-1}, and has some curvature within the modules.
3) CrIS has some wavy structure 1220-1700 cm^{-1} with a period of ~125 cm^{-1} and an amplitude of ~0.15 K.
4) Both instruments show temperature dependence in right-left bias.

The AIRS bias in 1070-1135 cm^{-1} is linked to the trends discussed in section 2.4 below. It is notable that this is the only AIRS trend which has a significant right/left component. The larger shortwave trends do not show up here because the entire scan seems to be changing together.

AIRS module discontinuities and most other structure seem to be linked to the different sensitivities to polarized signals in the different parts of the instrument. The version 7 of the of AIRS L1b s will use new polarization coefficients derived from the differences among the four space views. This is expected to reduce these effects considerably.

The wavy structure seen in CrIS right minus left 1220-1700 cm^{-1} is probably a sort of ringing in the Fourier transform.

The right minus left spectra for both instruments show echoes of the basic spectra shown in Figure 1. For the warmer broad parts of the original spectra (650-700, 1000-1070, 2225-2380 cm^{-1}), CrIS in particular is ~0.2 to 0.3 K cooler for these scenes on the right than on the left but AIRS shows no clear systematic effect. Where there are relatively narrow spectral peaks in the original spectra (720, 1043, 1305 cm^{-1}), AIRS right minus left has small peaks in the same sign as the original spectrum and CrIS has ~3x larger peaks in the opposite sign.

2.3 Day-Night differences

Another sensitive test for instrument effects is to compare results for day minus night. The diurnal cycle in the cold clouds over ocean is weak. The key is whether the two instruments see the same differences.

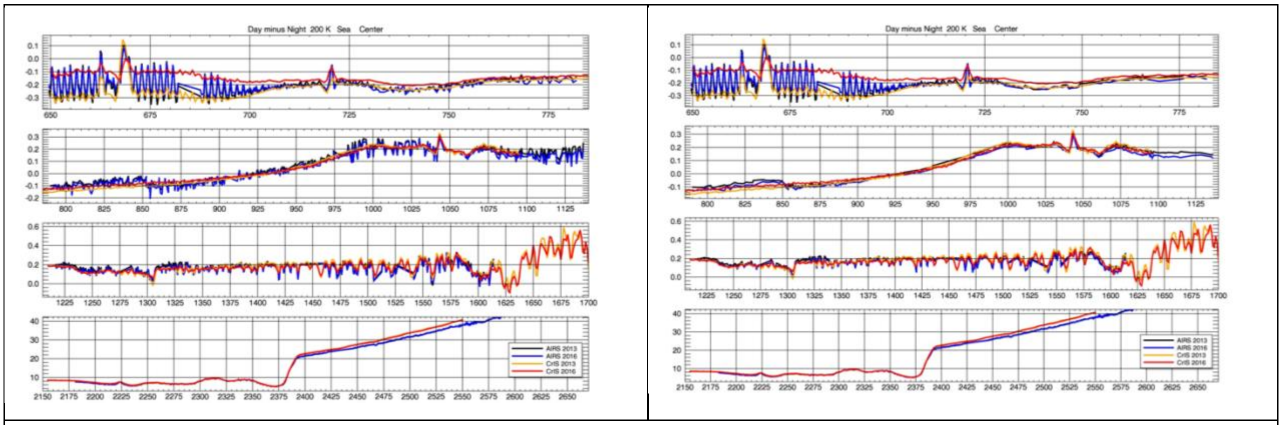

Figure 4. Difference between day and night for AIRS and CrIS 200-K cloud spectra for 2013 and 2016. X axis is frequency in cm^{-1}; Y axis is brightness temperature difference in K. a) includes all good AIRS channels; b) includes only channels where both detector elements are used.

In Figure 4a all good AIRS channels are included and there is obvious 0.05 K "hash" associated with A vs B channels (section 2.4). The presence of this signal indicates that this effect has a significant orbital component.

Figure 4b includes only AIRS channels where both A and B sides are used. The agreement is very good through most of the spectrum. At the shortwave end (2380+ cm^{-1}), AIRS sees smaller day-night differences because it is too warm at night (section 2.4). At the longwave end (up to ~720 cm^{-1}) there are significant differences. Both instruments show day colder than night and both show that the difference is larger in 2013 than 2016. But for AIRS the change is <~ 0.1 K while for CrIS it is ~0.2 K. This may just be an artifact because different versions of the IDPS software were used for 2013 and 2016.

2.4 AIRS trends

Because we have 14 years of AIRS data we can look for patterns in the changes. Figure 5a shows annual means of AIRS nighttime ocean 200K cloud cases for even-numbered years. Because cases are selected based on BT939, no trends are seen at this frequency, so changes are only relative to this reference.

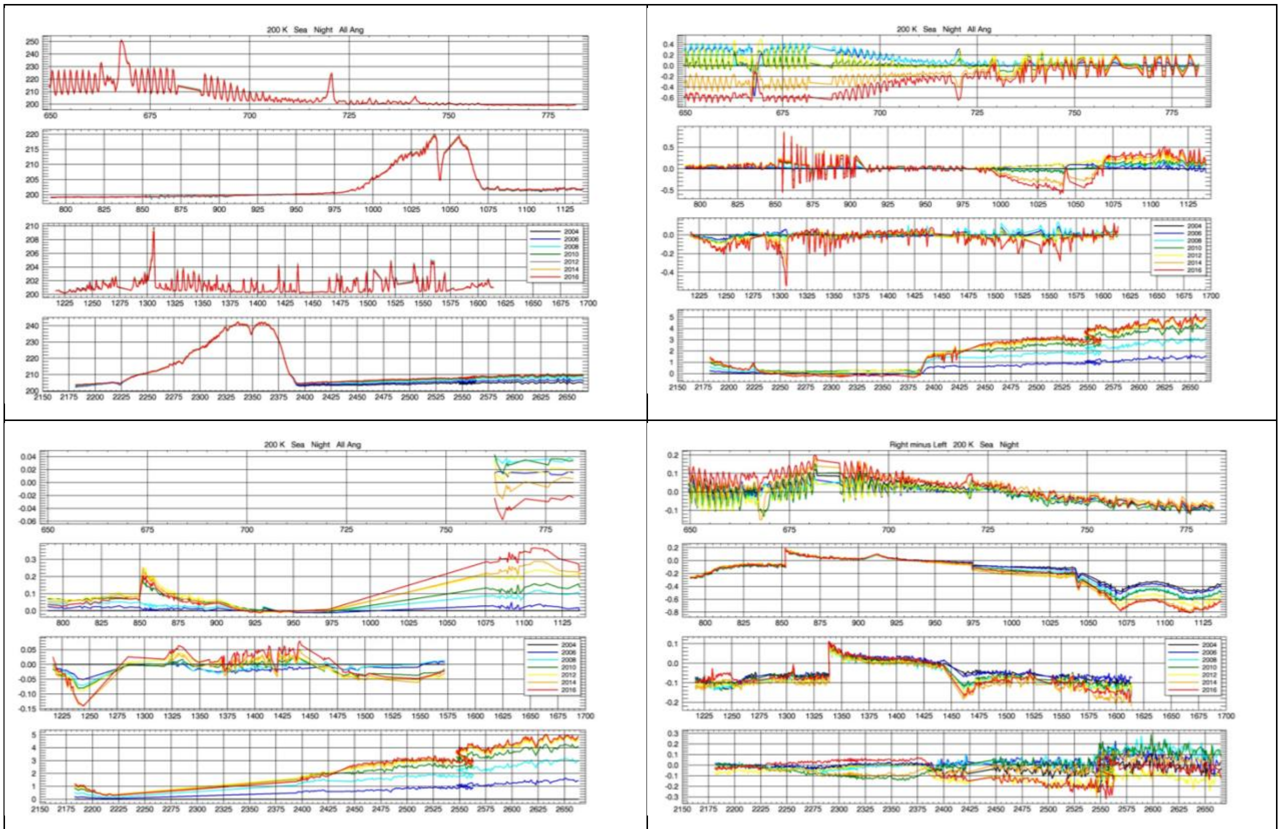

Figure 5. AIRS sea night 200-K cloud spectra for 2004 to 2016. X axis is frequency in cm^{-1}; Y axis is BT or BT difference in K. a) Raw mean spectra by year. b) yearly difference from 2004; c) yearly difference from 2004 using only window channels with both detectors; d) right/left difference by year.

Figure 5b shows the same values as differences from the 2004 values. There are biases where the product is using only one or the other of the two redundant detector elements. This is important in the range of 850-910 cm^{-1} and also in some other ranges. Note that while these changes seem to be increasing when 2004 is used as a baseline, they in fact have been decreasing over AIRS mission and are quite small since 2012. This problem is being addressed in the AIRS V7 release.

We also see large changes in the areas that view stratospheric emission instead of the actual clouds. These are caused by changes in the stratosphere including increasing CO2 and stratospheric cooling instead of by instrument effects.

Figure 5c removes both the A or B side only detectors and the stratospheric channels so that we can concentrate on cold radiometric effects. There are small changes throughout, but 3 spectral regions stand out with changes of over 0.1 K over the mission:

1) The shortwave end from 2400-2665 cm^{-1} has warmed by up to 5 K over the mission but is now stabilizing. Probably the values from around 2004 were correct and would match CrIS.
2) 1075-1140 cm^{-1} has increased fairly steadily, and is now up to 0.3 K warmer than in 2004.
3) 850-910 cm^{-1} increased by up to 0.2 K, with most of the change between 2008 and 2010.

Figure 5d shows right minus left biases by year. The only significant systematic change is in 975-1140 cm^{-1}, where only the left (start) of the scan has been warming.

The AIRS instrument team believes these changes reflect increasing light reaching the detectors when viewing Earth, perhaps by baffles becoming less black. The effects are much smaller at typical scene temperatures and should be corrected in the next version of the AIRS Level-1B or Level-1C products.

2.5 CrIS Field-of-View differences

Where AIRS has different detectors for different frequencies, and the A/B redundancy provides two radiometrical independent measurements, CrIS has different detectors per Field-of-View (FOV) and band. Figure 6 shows the difference from mean for each FOV at 200K. As before, spectra are selected to guarantee a match at 938.75 cm^{-1}. In this case 938.75 cm^{-1} seems to correspond to a small spectral feature with different magnitudes per FOV, so this gives a possibly misleading bias among the FOVs of up to 0.05 K in the longwave band. True biases must be evaluated with a different methodology. (See presentation by Aumann in this session.)

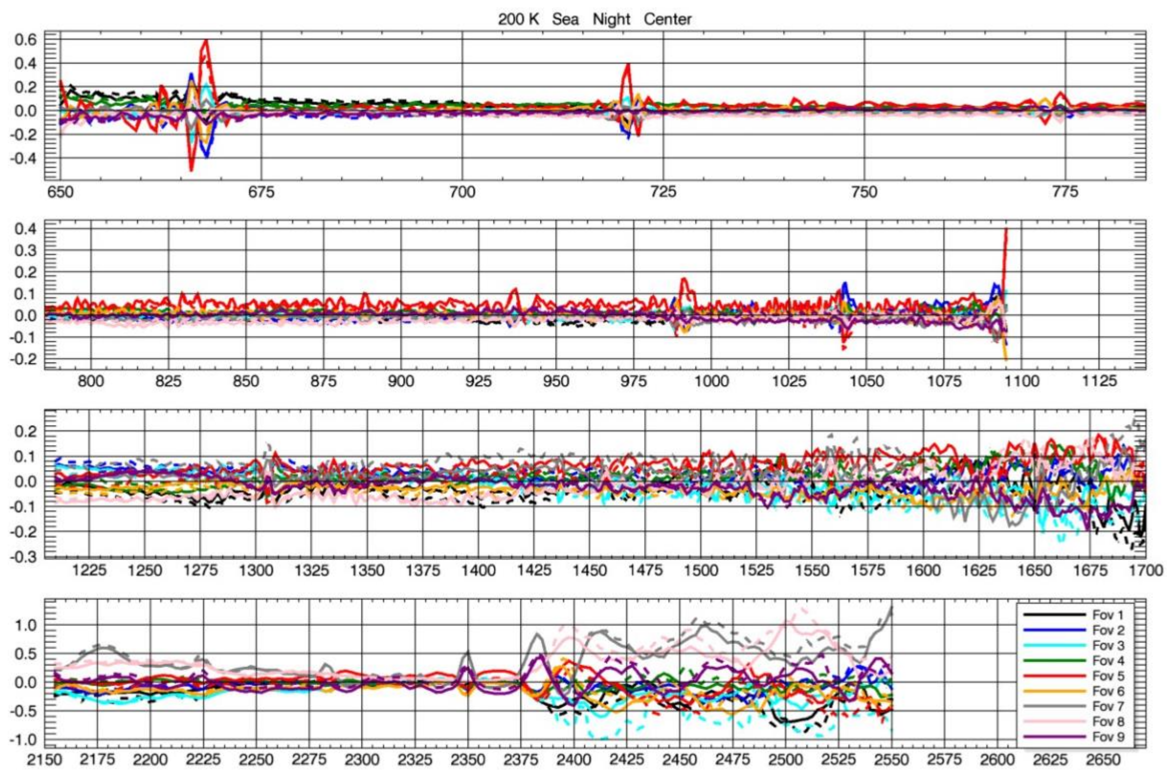

Figure 6. Difference from mean for CrIS FOVs for 200-K cloud spectra. Data from 2016 is shown with solid lines; Data from 2013 is dashed. X axis is frequency in cm^{-1}; Y axis is brightness temperature difference in K.

Discounting the broad biases, the main features in the longwave band (650-1100 cm^{-1}) are isolated areas where the FOVs diverge by up to 1 K, with consistent patterns in both years. These include the areas near 667, 720, 774, 990, and 1043 cm^{-1}. Figure 6 zooms in on these 5 spectral features and also includes the corresponding AIRS data. These patterns are partly dipoles, an expected pattern if there is a spectral shift among FOVs at a spectral line, but they also show that FOV 5 has slightly sharper features, implying a narrower spectral response function (SRF). There are spectral lines at 667, 720, and 1043 cm^{-1}, but the features at 774 and 990 cm^{-1} occur at generally geophysically featureless spectral regions.

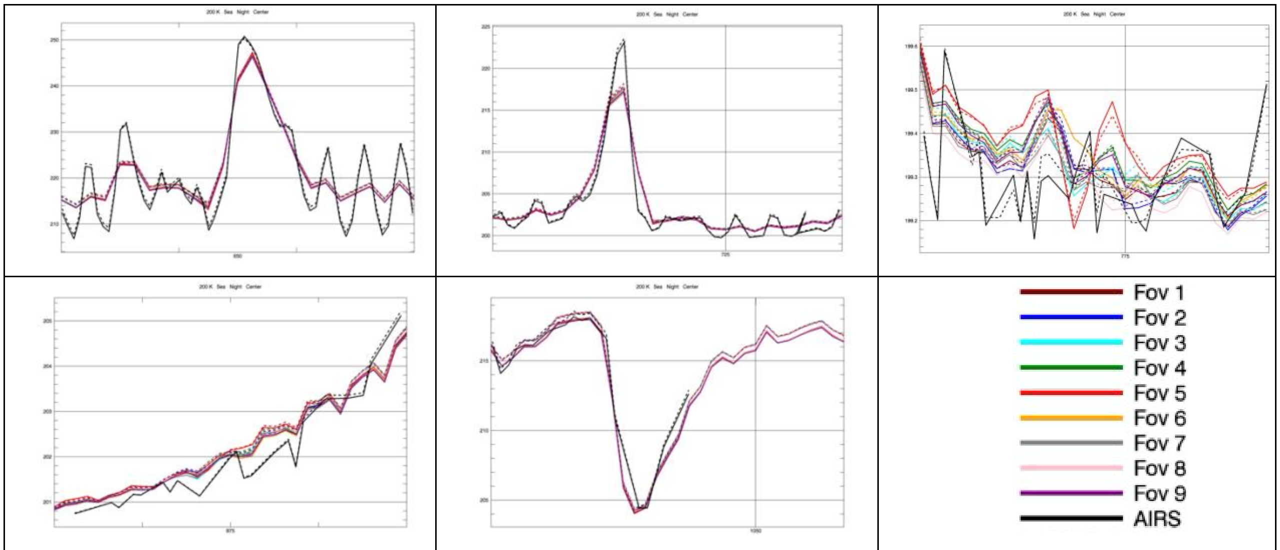

Figure 7. The same 200-K scene data as in Figure6, now close-up images of parts of the shortwave band where the FOVs diverge, with AIRS superimposed. A) 667 cm^{-1}; B) 720 cm^{-1}; C) 774 cm^{-1}; D) 990 cm^{-1}; E) 1043 cm^{-1}; F) color key

At the shortwave end of the longwave band there also seems to be an artifact. The two guard channels at 1096.25 and 1095.625 cm^{-1} are not displayed, but still there appears to be a problem with the next channel, 1095.0 cm^{-1}, and possibly beyond that.

In the midwave band (1210-1700+ cm^{-1}), biases between FOVs are somewhat larger than in the longwave band. This is probably because the longwave band is used to select the included spectra, and the midwave band is using a separate set of detectors. Still, the biases are generally under 0.1, gradually increasing toward the shortwave end.

Biases among the FOVs are largest in the shortwave band, especially the cold parts on the ends. They can be up to 0.5 K and do not match the ordering of the biases is the other bands.

3. SUMMARY AND CONCLUSIONS

Investigation of very cold scenes provides a valuable "stress test" for hyperspectral infrared sounders. We have seen a variety of artifacts for both instruments, summarized in Table 2.

Table 2. Largest suspected artifacts at 200 K per instrument and spectral band, with references to section numbers above.

Band Name	Band Frequency range (cm^{-1})	Largest suspected artifact AIRS (K)	Largest suspected artifact CrIS (K)
Longwave	650-1150	0.7 (§2.2, 2.4)	0.5 (§2.5)
Midwave	1200-1700	0.1 (§2.2)	0.2 (§2.2)
Shortwave	2150-2670	5.0 (§2.4)	0.7 (§2.5)

Some of these numbers are large relative to the nominal stated radiometric accuracy of about 0.1-0.2 K, but it is important to remember that we are dealing with extremely cold scenes, where the shape of the Planck function increases the impact of small radiance changes when expressed in units of brightness temperature, especially for the shortest wavelengths. However, 0.1-0.2K accuracies are large for climate research, where changes of 0.1K per decade are expected.

Except for the AIRS shortwave trend, both instruments clearly perform well at the 1 K level even for these extremely low scene temperatures. Unfortunately, changes in extremes, in this case cold extremes, are of great interest to the evaluation of climate change effects, such as the height of the tropopause or the frequency of severe storms. The evaluation of the AIRS performance at extremely low scene temperatures has been key to identifying the need for updating the polarization coefficients in the L1B software Version 7. These changes are expected to eliminate a large fraction of the observed artifacts. The CrIS instrument teams is also working on refining the calibration.

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