Tropical SNO comparisons of AIRS and CrIS calibration for windows

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ABSTRACT

AIRS on EOS-Aqua and CrIS on Suomi NPP are two hyperspectral infrared sounders with similar capabilities and orbits, so there is a great opportunity to compare their absolute calibration while they are both in orbit. This insures that long-term climate record can be created by concatenating the two instrument records. There are significant differences in instrument architecture which may lead to subtle differences and complicate attempts to combine the records.

We use Tropical Simultaneous Nadir Observations (TSNOs), cases where both instruments are looking nearly at the same place at the same time, to explore the differences. Due to the presence of cold clouds and clear hot desert surface, the data cover a brightness temperature range from 190 K to 340 K. We concentrate on the differences between the mean of the two instruments using atmospheric window channels as function of brightness temperature in 20-K wide bins.

With the currently available AIRS and CrIS official calibrated data, radiometric differences as large as 0.3 K are seen at the extreme temperatures. These differences may be reduced in future releases of the AIRS and CrIS calibration.

Keywords: AIRS, CrIS, hyperspectral, infrared sounder

1. INTRODUCTION

There are currently two similar hyperspectral IR sounders covering a spectral range from 3.7 µm to 15.4 µm in similar 1:30 PM sun-synchronous polar orbits. Spectra from both instruments are used by Level-2 processes to measure many atmospheric and surface properties including temperature and water vapor profiles; abundance of trace gases (including ozone, methane carbon monoxide, carbon dioxide); cloud properties; dust; and surface temperature and IR emissivity.

The Atmospheric Infrared Sounder (AIRS)[1] launched on EOS Aqua in May 2002. It observes 2378-channel thermal IR spectra for each scene. AIRS now provides an unprecedented record since September 2002 of over 13 years of high-quality data.

The Cross-track Infrared Sounder (CrIS)[2] on Suomi NPP was launched in October 2011 with a primary mission to support forecasting. High quality data have been available since May 2012. Further CrIS instruments are to be launched into similar orbits every 5 years on the JPSS series of spacecraft, eventually providing a climate record spanning decades.

Though the spectra from both instruments are used to retrieve the same geophysical quantities with similar algorithms, subtle differences in the orbits, footprint sizes and spectral resolution make it likely that the results will differ. For weather forecasting and for some climate process studies this is not critical, but long-term climate studies will require combining the records from individual instruments to make a continuous time series. To track expected climate signals on the order of 0.1 K/decade, differences as small as 0.01 K must be understood. This extremely demanding level cannot be achieved by comparing the retrieved geophysical products, but requires a direct comparisons of calibrated radiances while two instruments are flying in similar orbits at the same time.

Table 1 gives some key parameters for AIRS and the first CrIS.

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Table 1: Key instrument parameters for AIRS and CrIS

Platform	**Instrument**	**Instrument Type**	**Scan Rate (s)**	**Scan Range (°)**	**Scan Pattern**	**IFOV Diameter (km, nadir)**	**Scan type**	**Spectral Channels**
Suomi NPP	CrIS	IR (FTS)	8	±50	30 x 3 x 3	14	Stare and scan	1305 (NSR)
EOS Aqua	AIRS	IR (Grating)	8/3	±50	90	13.5	Continuous scan	2378

Comparisons of AIRS and CrIS can use many types of data. Some comparisons are based on global or large regional statistics, with the assumption that since both instruments are observing the same planet, they should on average see the same signal. Or statistics can be local, separately comparing observations from each instrument to "ground truth." Because of differences in the retrieval algorithms there are no exactly corresponding domain subsets and these types of comparisons are not very helpful at tracking down the causes when differences are found.

The most direct comparison of two instruments is the comparison of calibrated radiances where AIRS and CrIS observe nearly the same scene at the same scan angle at the same time. Unfortunately, the FOVs can never match exactly in time and space, however, the mean radiance difference should approach zero for a sufficiently large data set. The key is to create sufficiently large sets of pairs of observations. As the number of pairs increases, the probable error in the mean decreases and, at some point the mean may be statistically significantly different from zero, i.e. instrument differences emerge. There is a tradeoff between very tight spatial and temporal coincidence requirements, which yields almost no data, and looser coincidence requirements which yield a large amount of data with a large scatter.

The most common type of simultaneous observations is the Simultaneous Nadir Observation (SNO)[3]. Sounder SIPS at JPL for example collects AIRS/CrIS SNOs where:

1) FOV centers are within 8 km
2) observations are within 10 minutes
3) both instruments observe within +/- 1 FOR (1 AMSU FOV; 3.3 degrees) of nadir

The different 1:30 PM orbits sun-synchronous orbits of the two platforms give a 2.667-day repeating pattern in how close together the satellite tracks are and how close observations of the same location are in time. Many matches are seen near the poles and excellent agreement has been shown between AIRS and CrIS under the uniform cold dry conditions which dominate these cold, polar-condition biased SNO sets. However, these sets represent less than 6% of the area of the globe and the results are not globally representative. There are instrumental difference which make the calibration for different seasons (sun angle) and under warmer and less homogeneous conditions challenging. Agreement in the polar zone is a necessary but not sufficient condition to expect agreement in the tropical zone, which covers 50% of the globe, and is key to weather and climate. The classic SNOs are of limited help. As example the entire month of April 2014 produces only 40,000 SNO observation pairs in the tropical zone. In order to make the analysis with the desired 100 mK accuracy for a wide range of conditions, about 1 million spectra are required. Unfortunately combining several years of data blurs the analysis of trends. The task is to find a data set with 1 million samples in one month.

Table 2: Key orbital parameters for EOS Aqua and Suomi NPP

	EOS Aqua Orbit (AIRS)	Suomi NPP Orbit (CrIS)
Period	99 minutes	101 minutes
Altitude	710 km	835 km
Inclination	98.12 degrees	98.63 degrees
Repeat cycle	233 orbits per 16-days	228 orbits per 16 days

2. APPROACH

For TSNOs (Tropical SNOs) we collect spectra where:

1) FOV centers are within 8 km
2) observations are within 10 minutes
3) both instruments observe within +/- 3 FOR (3 AMSU FOV; 9.9 degrees) of nadir
4) latitude is within 30 degrees of the equator

The first two conditions are identical to the older SNO methodology. The difference is that TSNOs allow each instrument to look farther from nadir, and that we now collect only tropical spectra. Manning 2015 showed that the impacts from this were always small.

The next issue is how to compare two instruments when they have different spectral spacing and each has multiple versions of products available.

For AIRS data we selected AIRS Level-1C version 6[4]. This provides continuous coverage in three bands, replacing problem detectors and filling gaps in the observed level-1B spectrum.

For CrIS data we use the official product from CLASS at normal spectral resolution (NSR). While there are various experimental versions available, including some at full spectral resolution, this remains the only official version. Hamming apodization was applied. We deal with the differences between AIRS and CrIS spectral response functions and sampling by resampling both spectra to a common grid and then smoothing both with a common trapezoidal filter. Essentially we reduce the AIRS spectral resolution to the CrIS resolution. Characteristics of the filter are in Table 3. This approach allows some conclusions to be reached across the spectrum.

Table 3: Smoothing filter characteristics for this comparison

Band	Limits (cm^{-1})	# channels AIRS	# channels CrIS	# samples	Oversampled interval (cm^{-1})	Smoothing trapezoid FWHM (cm^{-1})
Longwave a	649.6 784.9	469	219	2000	.068	20.25
Longwave b	785.2 1096.2	942	499	5000	.062	18.7
Midwave	1207.5 1613.9	751	331	3000	.135	40.7
Shortwave	2181.5 2555.0	482	153	4004	.075	28.0

Figure 1 shows the mean tropical night ocean AIRS spectrum before and after this smoothing. All spectral detail is smoothed away, leaving only broad features.

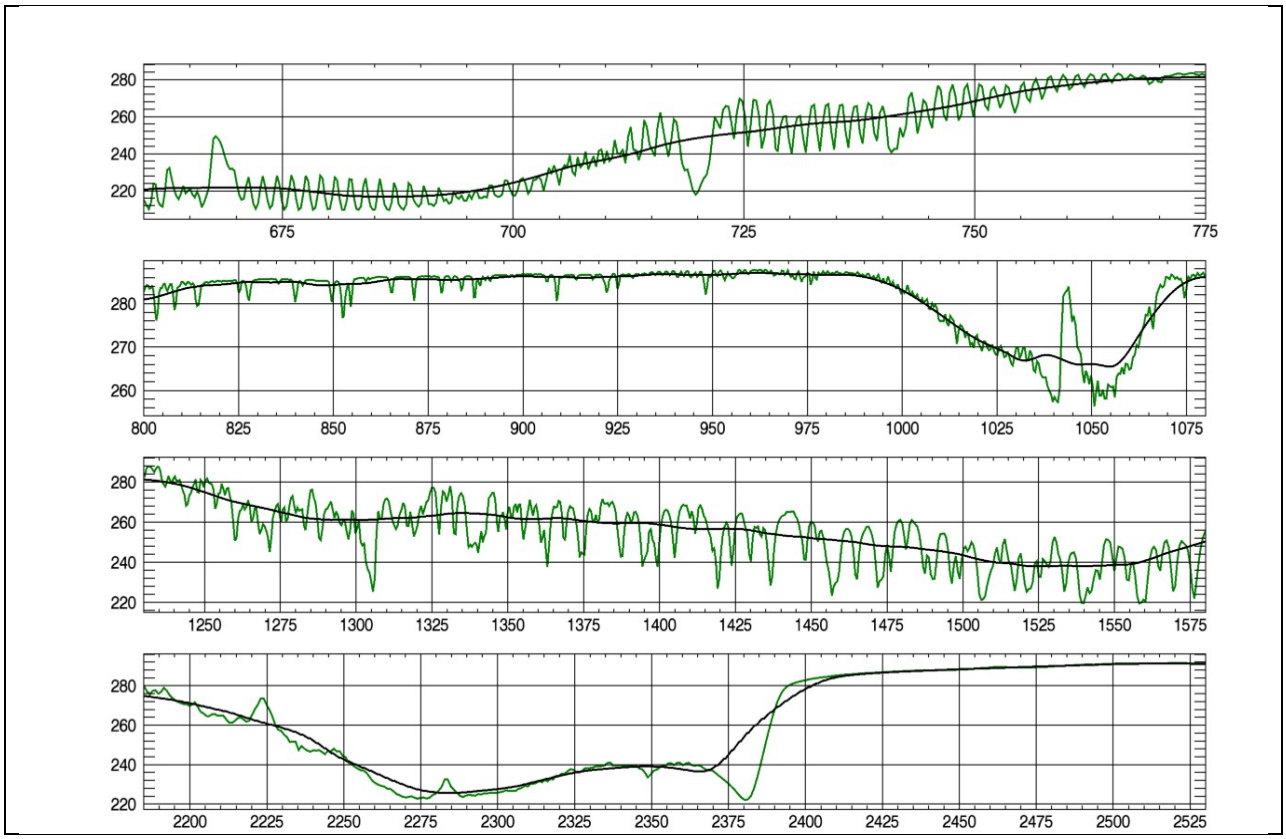

Figure 1: mean tropical ocean night spectrum from AIRS before and after smoothing. Smoothing leaves only the broadest features, which is ideal for radiometric comparisons.

3. DATA SET

TSNOs were produced for May – December 2015 and February 2016. For analysis, any observation with a mismatch of over 5 K in brightness temperature at 900 cm^{-1} (BT900) was excluded and observations were analyzed in 20-K bins of mean AIRS/CrIS BT900. For some analyses we further included only scenes where the AIRS Level-1C inhomogeneity indicator Inhomo850 showed relatively uniform scenes.

Although a primary purpose of the TSNO approach is to go beyond average conditions and sample a range of brightness temperature conditions, the overwhelming majority of observations remains in the "mostly clear" 290 K bin, where mean BT900 is in [280, 300] K. Still, there are so many observations over 9 months that statistically significant results can be seen for other scene brightness temperatures. Table 4 gives the number of observations for each brightness temperature bin, along with statistics on AIRS-CrIS BT900 illustrating the statistical power of this data set.

Table 4: Statistics for AIRS/CrIS TSNO data set by BT900 bin

Central BT900 (K)	BT900 range (K)	# observations (all/uniform)	AIRS-CrIS BT900 mean (K) (all/uniform)	AIRS-CrIS BT900 standard deviation (K) (all/uniform)	AIRS-CrIS BT900 probable error (K) (all/uniform)
210	200-220	32656 / 9803	.11 / .05	1.9 / 1.8	.011 / .018
230	220-240	60591 / 20822	.20 / .15	2.3 / 2.1	.009 / .014
250	240-260	104114 / 39500	.16 / .13	2.4 / 2.1	.007 / .011
270	260-280	285730 / 118573	.08 / .07	2.1 / 1.7	.004 / .005
290	280-300	1842440 / 651902	.00 / .04	1.2 / 0.9	.001 / .001
310	300-320	72649 / 25189	-.20 / -.16	1.2 / 0.9	.004 / .006
330	320-340	14124 / 4285	-.26 / -.23	0.9 / 0.7	.007 / .011

The probable error for all BT900 bins when all observations are used is below the key 0.01 K level needed for climate trend applications. If we can also exclude systematic errors in the comparisons at this level then we will be able to form a robust combined record.

Restricting to the most uniform ~1/3 of cases decreases the standard deviations, but it also increases the probable error because of the decrease in number of observations. The values for BT900 in this table are for individual channels, not for the band averages shown below, so they do not agree precisely.

Biases in table 4 are generally smaller in magnitude for uniform scenes, often by statistically significant amounts. The reason for this will be discussed in section 4.1.

The mean smoothed spectrum for each 20-K BT900 bin of tropical night ocean cases is shown in Figure 2. Window regions scale closely with BT900; stratospheric regions are nearly constant in temperature; and ozone and water bands decrease the scaling.

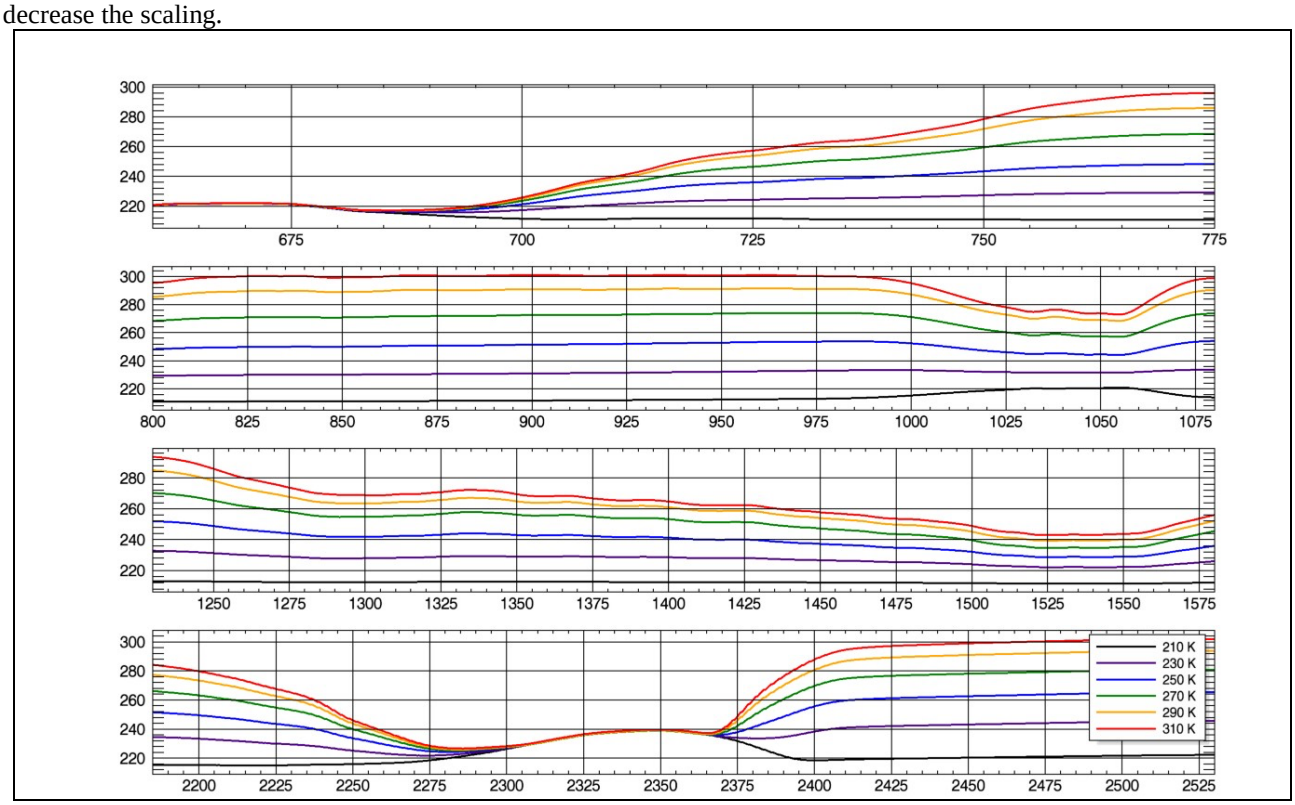

Figure 2: Smoothed AIRS night ocean spectra for each 20-K BT900 bin. At this scale AIRS and CrIS are indistinguishable. Differences reduce for the water and ozone bands and disappear for stratospheric regions.

To further characterize the data set we can look at log-scale histograms of number of observations as a function of BT900.

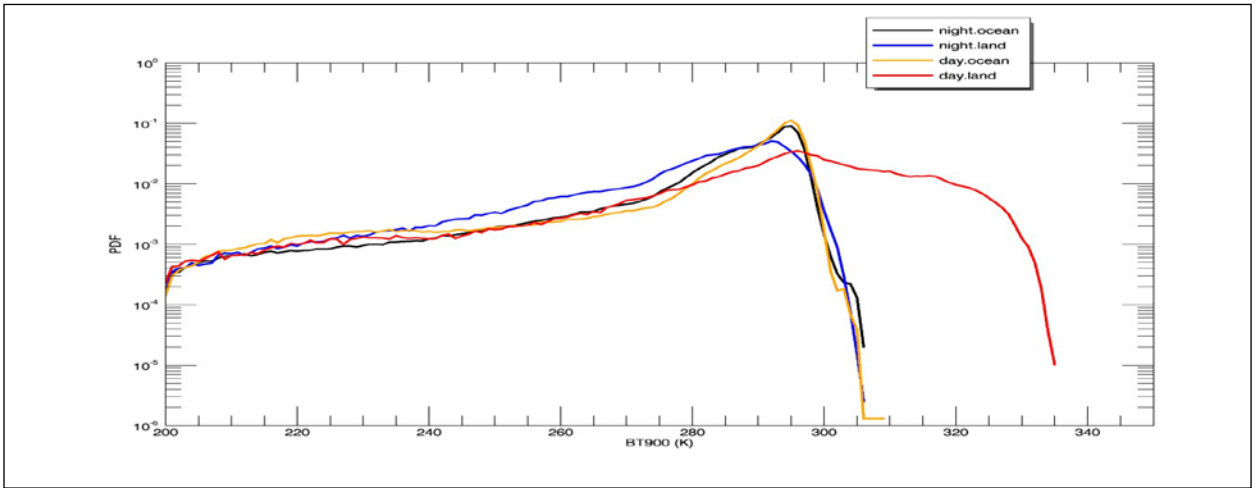

Figure 3: PDFs of BT900 for different subsets of TSNOs. Temperatures above 307 K only occur for day land. Temperatures below 290 represent cloudy cases.

4. RESULTS

Figure 4 shows the smoothed results of TSNO comparison. Small-scale ripple comes from residual resolution differences and should be ignored. BT differences are almost always within +/- 0.1 K.

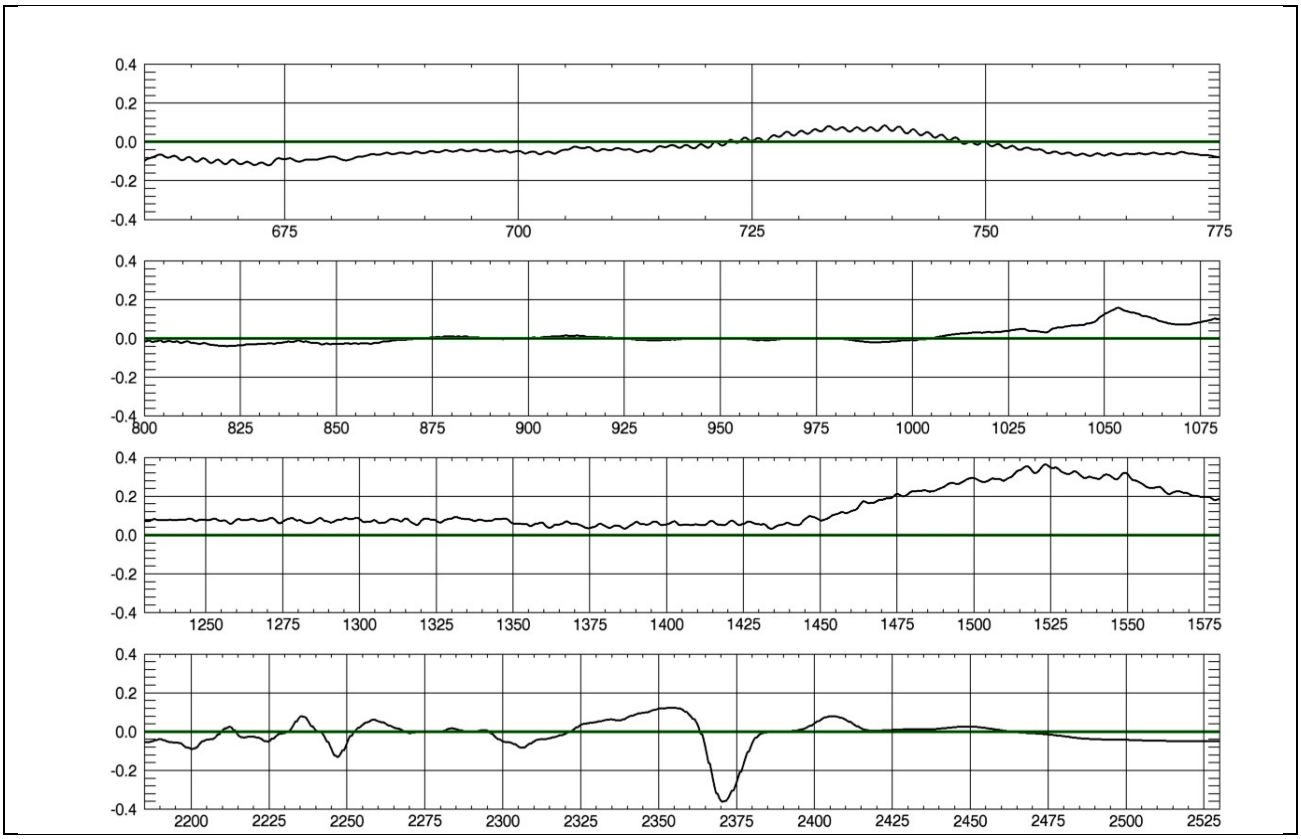

Figure 4: Mean smoothed BT differences (K) for AIRS-CrIS tropical night.

The most prominent feature is a dip near the tropopause at 2375 cm^{-1}. This resembles what might result from differences in spectral resolution or SRF shape between the instruments, but these effects should produce zero-mean biases overall, so more investigation is needed. Manning[6] showed similar patterns in differences among CrIS FOVs, so CrIS is suspected.

There are two regions with biases where AIRS is warmer than CrIS for intervals which seem to match AIRS detector modules, and so could reflect calibration problems with those modules. AIRS is about 0.2 K warmer 1460-1600 cm^{-1}, for AIRS detector modules M-04a and M-04b, and about 0.1 K warmer for 1050-1130 cm^{-1}, which is detector module M-05.

Below the 0.1 K level there are more biases which must eventually also be addressed to achieve climate quality.

Exploiting the power of the TSNO data set to probe instrument effects more thoroughly, Figure 5 shows results for tropical night ocean scenes separated using 20-K bins of BT900. Since this is an atmospheric window region and tropical ocean surface is almost always in [295, 300] K, the coldest bins represent the cloudiest scene conditions.

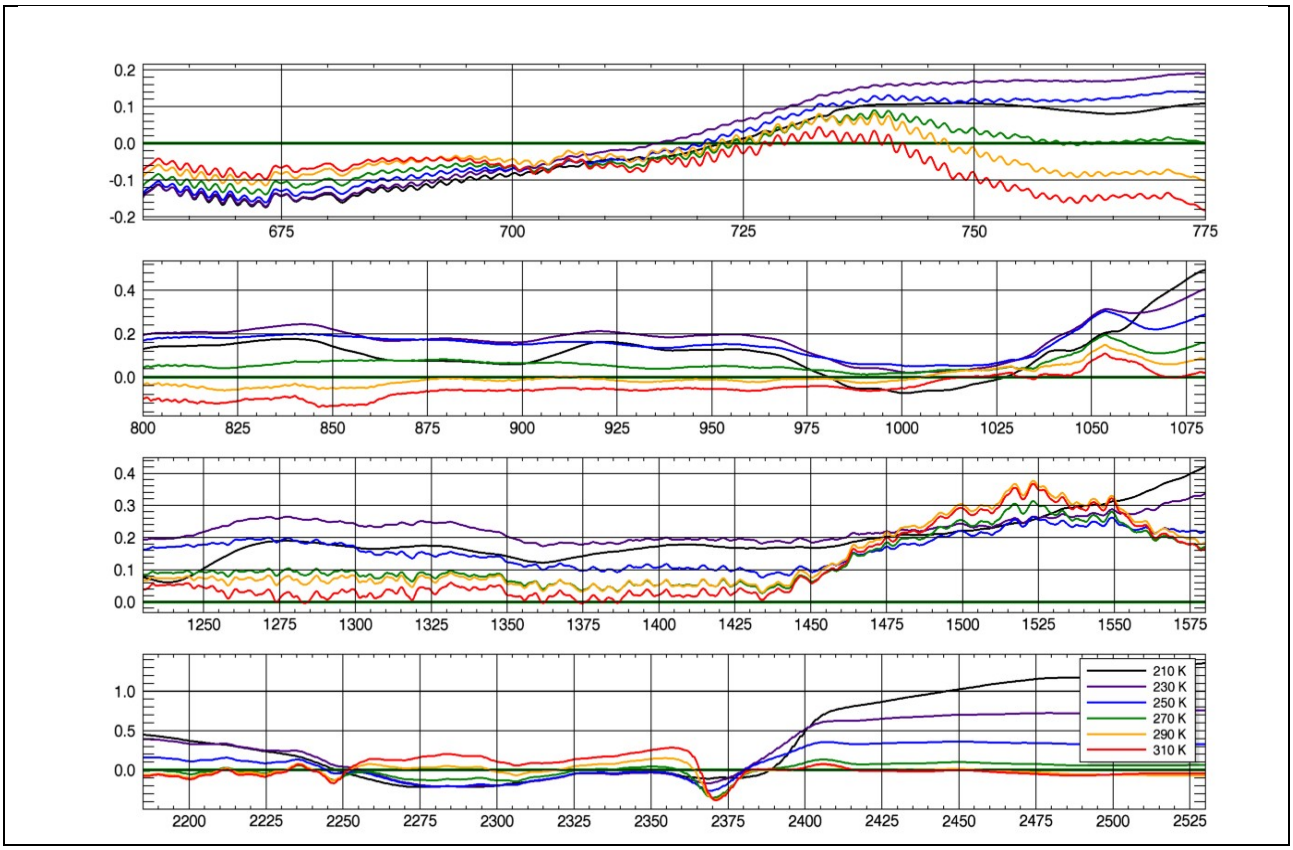

Figure 5: Tropical night ocean BT (K) AIRS-CrIS differences broken out by BT900 bin.

There is relatively little scene temperature dependence in the stratospheric regions 660-700 cm^{-1} and 2250-2375 cm^{-1}. But in most of the tropospheric portions of the spectrum the coldest scenes have AIRS warmer by about 0.1 K, while warm scenes have the opposite sign. This suggests a significant temperature-dependent calibration difference between the two instruments, but systematic effects must first be examined.

The coldest scene temperature regimes, 210 K and 230 K depart from this pattern, with reduced differences. See the discussion in section 4.3 below.

One effect which might cause a similar temperature-dependent difference in this analysis is instrument noise. Because there is a sharply peaked distribution of temperatures, the instrument with the higher effective noise will have a wider distribution of temperatures, seeming colder at cold BTs and warmer at warm BTs. The smoothing applied here will tend to greatly reduce AIRS noise, which is almost uncorrelated among individual channels. But CrIS noise is more correlated, perhaps leaving CrIS effectively the noisier instrument after smoothing. The sign at least of this effect seems to agree with the observations, but unsmoothed noise levels themselves are of order 0.1 K, so any such effect on radiances would be much smaller.

Another effect is FOV size. Because AIRS has a larger effective FOV size, it should see more scenes near the average temperature and fewer extremes. This also fits the observations. But Aumann has shown that the FOV size effect is small.

Both effects should disappear for uniform cold stratospheric spectral regions, and indeed the differences do decrease there.

We conclude that the effect is real. For most of the spectrum AIRS is warmer than CrIS in cold scenes and colder in warm scenes – AIRS has lower sensitivity than CrIS by ~0.2 K/80 K ~= 0.25%. This could mean AIRS is not sensitive enough to scene variation or CrIS is too sensitive.

The spectral region from 1460-1600 cm^{-1} flips the general pattern of temperature dependence. Assuming it is an AIRS instrument problem with modules M-04a/b, the pattern suggests the problem is with the blackbody views because it is at the hottest scene temperatures that this region departs furthest from expectations. The M-05 region 1050-1130 cm^{-1} does not have the same pattern.

The stratospheric regions also show a temperature dependence in the AIRS-CrIS signal, though with the reverse sign and with a smaller magnitude. It is interesting that each band contains some regions with each sign, suggesting an effect spreading signal over bands. This is likely related to the effects of phase correction errors in an FTS, which show up as broad radiance differences.

5. DISCUSSION

5.1 Scene inhomogeneity

To study the effects of scene inhomogeneity we plot AIRS–CrIS BT900 as a function of Inhomo850, separately for each bin of BT900.

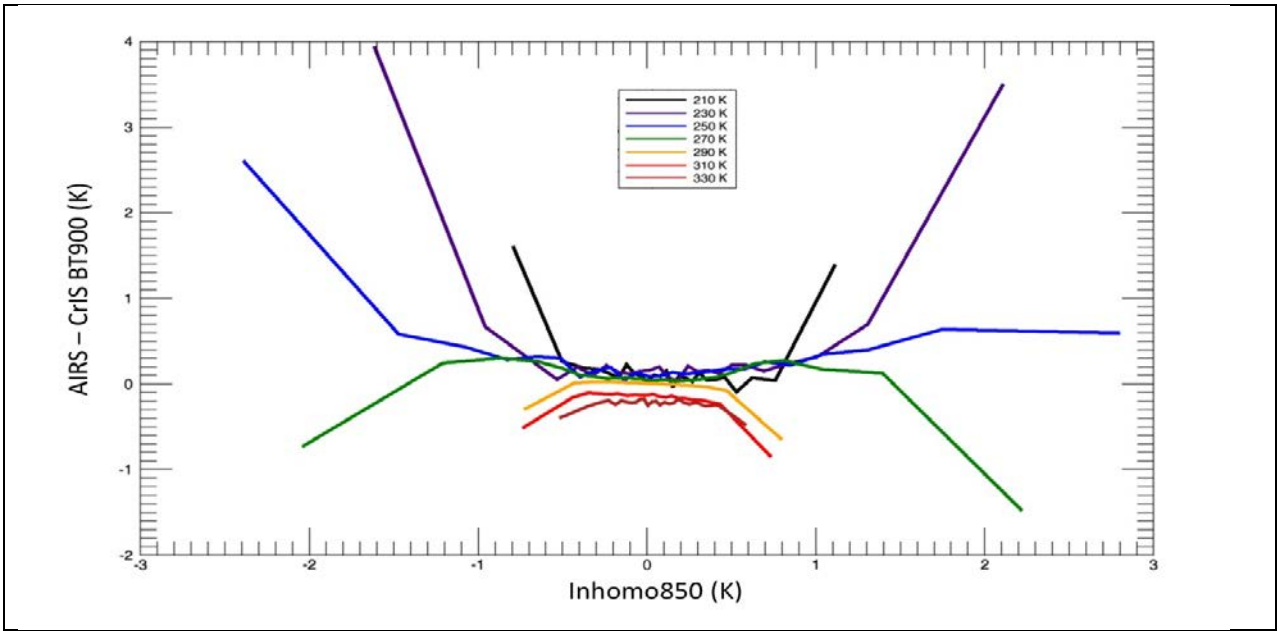

Figure 6: Variation of AIRS-CrIS BT900 as a function of scene inhomogeneity metric Inhomo850

Clearly there is a strong effect, with more inhomogeneous scenes (those with greater |Inhomo850|) having temperature-dependent systematic change in the AIRS-CrIS difference. These differences correspond with the differences observed in figures 4 and 5 and also with the differences between all scenes and homogeneous scenes in Table 4.

Figure 6 shows residual differences when Inhomo850 is zero. This is may show that inhomogeneity is not the only effect separating the curves, but it may simply indicate that Inhomo850 is an inadequate measure of scene inhomogeneity. Inhomo850 is an AIRS measure of inhomogeneity as measured by the brightness temperature differences between two sets of detectors on either side of 850 cm^{-1}. It is quite sensitive to inhomogeneity within the AIRS FOV in one dimension, less sensitive in the other direction, and not at all sensitive to variation in the part of the CrIS FOV that does not overlap the AIRS FOV.

Identifying the contribution of scene inhomogeneity to AIRS/CrIS differences doesn't explain the phenomenon. Part of the effect is clearly related to effective FOV size. CrIS has a smaller FOV size, so it sees more extremely hot and extremely cold scenes, because more of a CrIS FOV can fit in a small hot or cold area. But there is also the possibility that one or the other instrument reacts to inhomogeneous scenes in a way that creates a bias.

Whatever the cause, the effect can be reduced by using a more powerful metric of homogeneity and applying stricter limits. Cx1231, the variance among the surrounding field of regard of window channel near 1231 cm^{-1}, has will be used as a data filter in a future analysis.

5.2 Comparison with other results

Wang et al[5] conducted a similar analysis using SNOs from the two poles and the tropics. Instead of a sliding band filter they reported values for 25 specific bands. They did not break out their results in 20-K BT900 bins as we do here; they just give averages for North pole SNOs, South pole SNOS, and tropical SNOs. Assuming the mean BT900 for these sets are near 250 K, 230 K, and 290 K, we display them in Figure 7 in similar colors with our results for these BT900 categories.

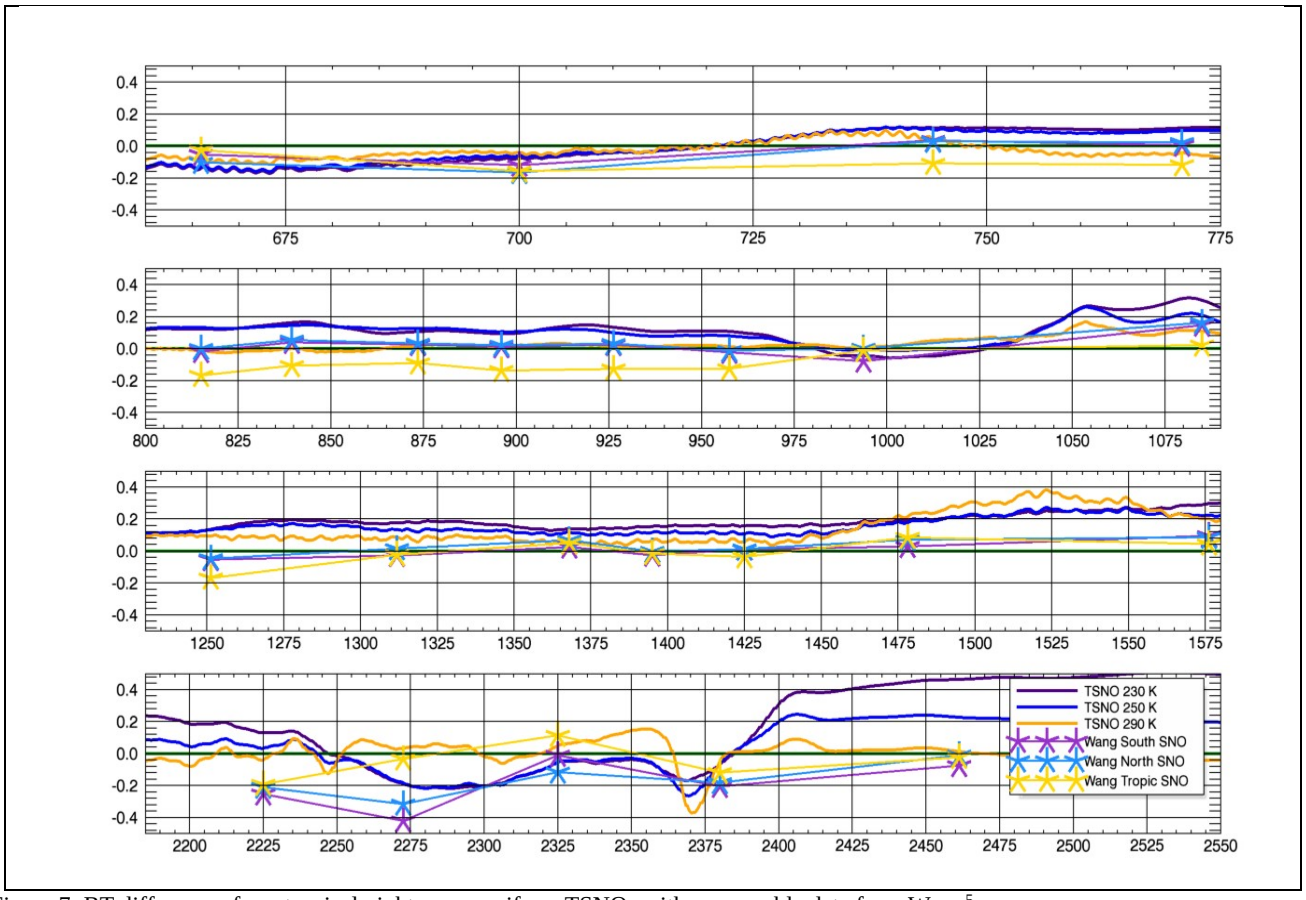

Figure 7: BT differences from tropical night ocean uniform TSNOs with comparable data from Wang[5]

Because the Wang statistics do not break out the coldest and hottest cases, the curves here do not show the extremes of dBT seen in Figure 5.

There is broad agreement at the 0.2 K level except in the shortwave band. In the shortwave band solar effects probably make polar SNOS not comparable to cold tropical night spectra, but for warm tropical cases they agree. Generally the two agree well in finding very similar biases for both cold bins and in the sign and magnitude of the difference between the bias for the colder cases and the bias for the warm set.

Despite the smoothing, this approach shows interesting structure in areas the Wang paper skips over including the spectral region near 1525 and 2350 cm^{-1}, which are available in the AIRS L1C product.

5.3 Differences as a function of scene radiance

Differences in radiance units as a function of scene radiance can help show likely underlying causes. Figure 8 shows AIRS-CrIS radiance for some key bands.

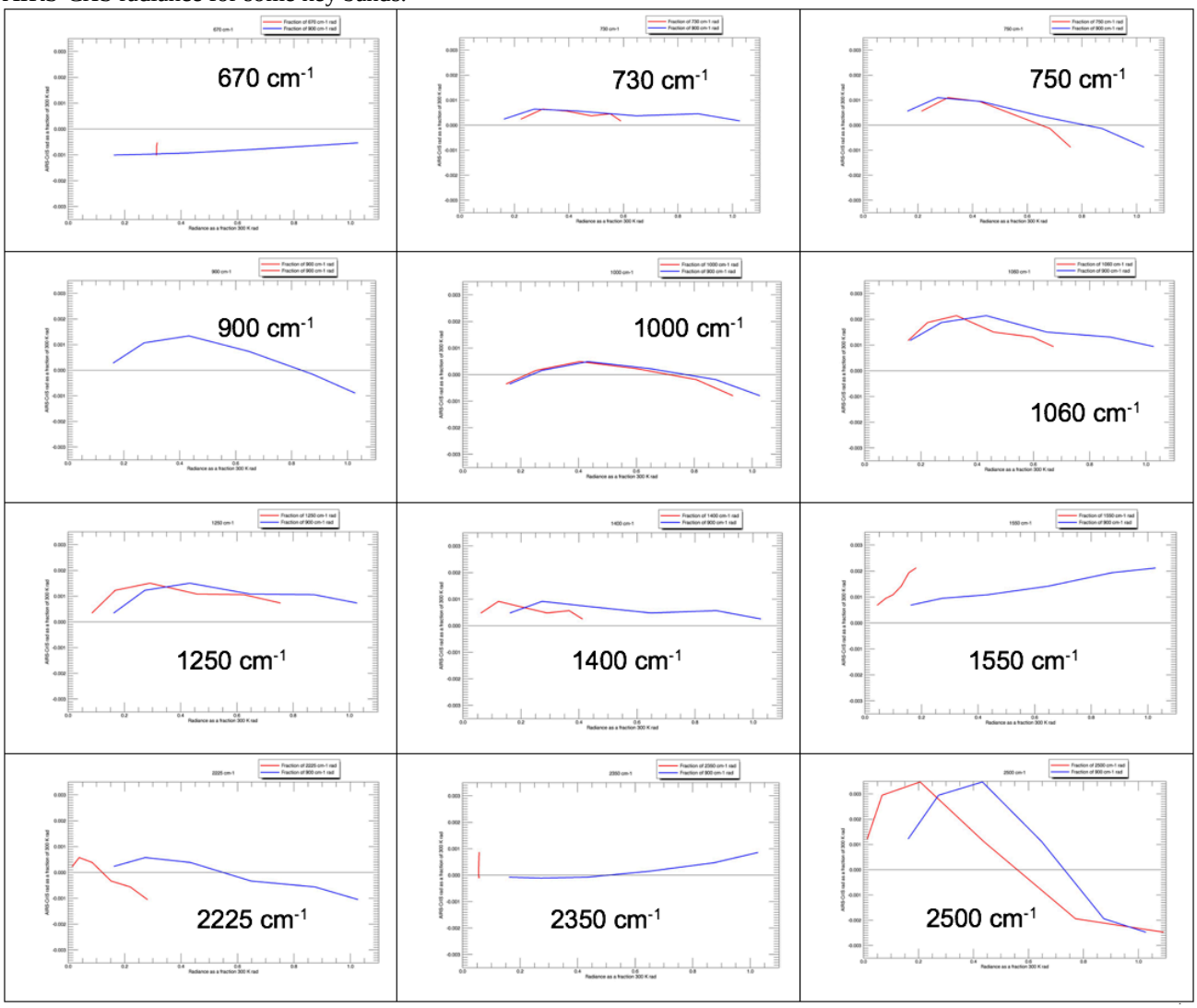

Figure 8: radiance differences at key frequency bands. All parts use a common scale: x runs from 0 to 1.1 x the radiance of a 300 k scene; y runs +/- 0.0035 x the radiance of a 300 K scene, which very roughly corresponds to +/- 1 K.

Radiance differences for each spectral region is plotted twice: in red as a function of radiances at its own frequency and in blue as a function of radiance at 900 cm^{-1}. All radiances and radiance differences are scaled as a fraction of 300 K radiance. Radiance differences as a function of same-frequency 300 K radiance can point to classic calibration issues: errors at the cold or hot extremes or nonlinearity problems that peak in the middle. Radiance differences as a function of 300 K radiance highlight situations where stray signals or phase correction errors may contribute.

At 670 cm^{-1} there is very little variation in scene radiance, but the AIRS-CrIS radiance difference scales with 900 cm^{-1}, suggesting the error is linked to signal from warmer spectral regions.

At 730 cm^{-1} we have a positive bias with little variation.

By 750 cm^{-1} there is clear curvature in the bias, which continues through the window region. The bias is flattened or compressed towards 1000 cm^{-1} and biased in the ozone band at 1060 cm^{-1}. The curvature suggests the primary problem here is nonlinearity.

Through the start of the midwave band we have a similar curved pattern with an overall positive bias. This changes by 1550 cm^{-1}, to a steep upward slope suggesting a problem with the hot calibration or leakage of signal from warmer regions.

The shortwave starts with a familiar curved pattern.

In the stratospheric region of the shortwave at 2350 cm^{-1} there is again a dependence on general scene temperature. In the far shortwave at 2500 cm^{-1} there is a large signal with strong temperature dependence, suggesting problems with both warm calibration and nonlinearity.

6. CONCLUSIONS

TSNO is a powerful tool for comparing AIRS and CrIS in the 50% of the area of the globe that is most critical for weather and climate. It has demonstrated statistical power at the 0.01 K level over the full range of observed brightness temperatures for these instruments. It already has helped to diagnose temperature-dependent differences between the two instruments in selected spectral ranges. With more powerful metrics and statistical approaches, it will be possible to isolate the effects of scene inhomogeneity and gain better insight into both instruments. We show that the two instruments generally agree at the better than 0.3 K level. From an instrument specification viewpoint this is an excellent agreement. However, from a climate change viewpoint an 0.1K difference is the equivalent of one decades of global warming. The agreement between AIRS and CrIS may impove with the release of an improved CrIS or AIRS calibration algorithm.

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