CGMS

CGMS-36, NOAA-WP-12
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Discussed in WG II

NOAA Report on Satellite Calibration Anomalies: Characterization and Correction of Significant Discrepancy in Satellite Inter-Calibration

In response to CGMS Recommendation 35.04 (Satellite operators to explain significant discrepancies in satellite inter-calibration as part of their contribution to GSICS)

Summary of the Working Paper

NOAA WP-12 states that assessing the consistency among satellite instruments is a necessary but only the first step of the Global Space-based Inter-calibration System (GSICS). A critical next step is to explain any significant discrepancy if found, thus to improve the use of space-based global observations for weather, climate and environmental applications and to establish stable fundamental climate data records (FCDR). The GSICS algorithm has been carefully designed to characterize the discrepancy, investigate the root cause, and correct for the bias. One example is detailed in this paper; others are forthcoming. The CGMS member agencies are encouraged to explain the discrepancy among satellite instruments if found, using the GSICS tools, and to share their discoveries among the CGMS members. This will greatly contribute to the improved accuracy in numerical weather prediction and climate monitoring.

Introduction

The National Oceanic and Atmospheric Administration (NOAA) added a new channel to the Imager instrument of its Geostationary Operational Environmental Satellite (GOES) since GOES-12. During the GOES-13 Post Launch Science Test, it was found (Schmit and Gunshor 2007) that this relatively new channel, centered at 13.3 m (Fig. 2), has a cold bias of ~2 K. Similar bias was also found for GOES-12 when compared with both a traditional High-resolution Infrared Radiometer (HIRS, onboard NOAA-16) and the hyperspectral Atmospheric Infrared Sounder (AIRS). These results, summarized in the first two rows of Table 1, are consistent with evaluation of selected products, including sea surface temperature (SST), satellite derived wind speed, and numerical weather prediction (NWP) models. The analysis of GOES-13 data (Row 3 of Table 1), with smaller sample size due to the short duration of the Science Test, is generally in agreement with that of GOES-12.

Table 1: Comparison of GOES Imager 13.3 μm band measurements with other space-based measurements, compiled from Schmitt and Gunshot (2007). GOES-13 comparisons with AIRS for other Imager bands are reported in the last three rows.

Comparison	Sample Size	Bias (K)	Standard Deviation
G12-HIRS	217	-2.2	1.2
G12-AIRS	52	-1.4	0.5
G13-AIRS	19	-2.4	0.6
G13-AIRS, shifted SRF	19	+0.0	0.7
G13-AIRS, Imager Band 2	19	+0.2	0.6
G13-AIRS, Imager Band 3	19	-0.4	0.3
G13-AIRS, Imager Band 4	19	-0.1	0.4

To corroborate these early findings, initial results from the Global Space-based Inter-Calibration System (GSICS) indicate that the difference between AIRS and GOES-11/12 long wave infrared channels are generally small, except for the GOES-12 13.3 m channel (Fig. 1). For reference, also plotted are GOES-13 bias for this channel that was estimated as -2.4 K and -1.8 K by different researchers, and the GOES-12 bias in February 2007. Note that for this channel both bias and variation are larger than other channels.

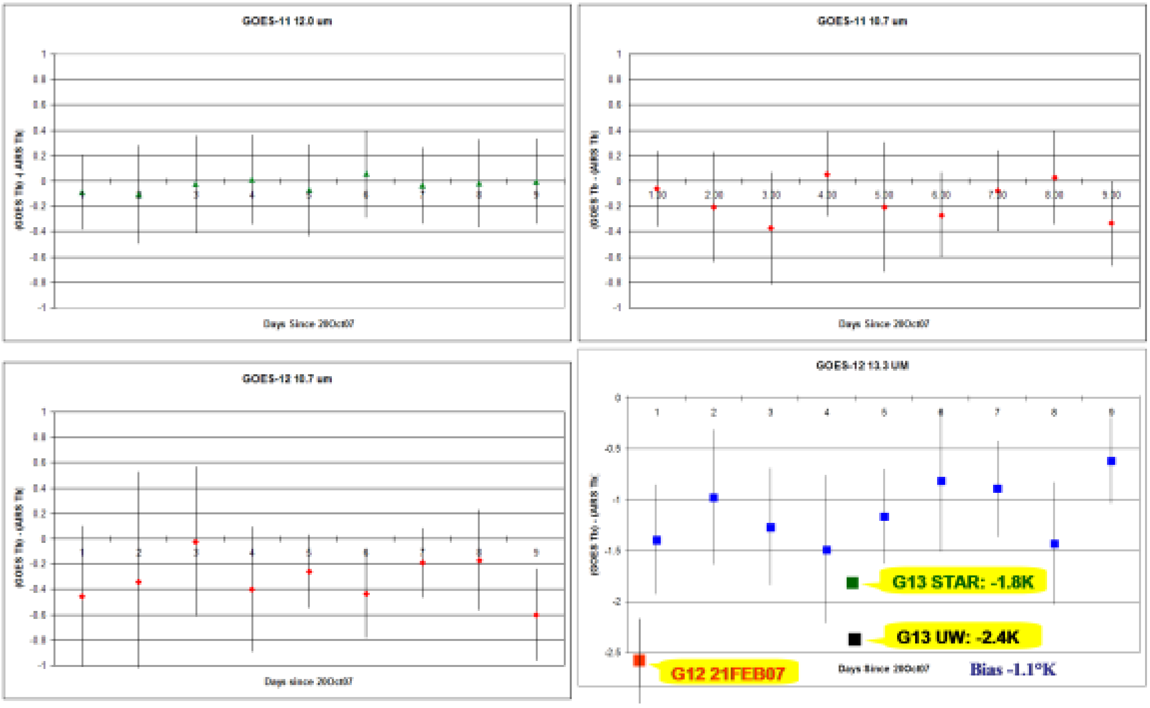

Figure 1: Mean and standard deviation of difference between GOES and AIRS during a ten-day period in October 2007. The bias is -0.03 K for GOES-11 12.0 m channel (upper left panel), -0.16 K for GOES-11 10.7 m channel (upper right panel), -0.32 K for GOES-12 10.7 m channel (lower left panel), and -1.1 K for GOES-12 13.3 m (lower right panel). Also plotted in the lower right panel are bias for GOES-13 13.3 m channel.

Based on these analyses, it was recommended (Schmitt and Gunshot 2007) that the relative spectral response (RSR) for this band be shifted by -4.7 cm^{-1} (Fig. 2). Such a shift would practically eliminate the bias as compared with AIRS (Row 4 in Table 1).

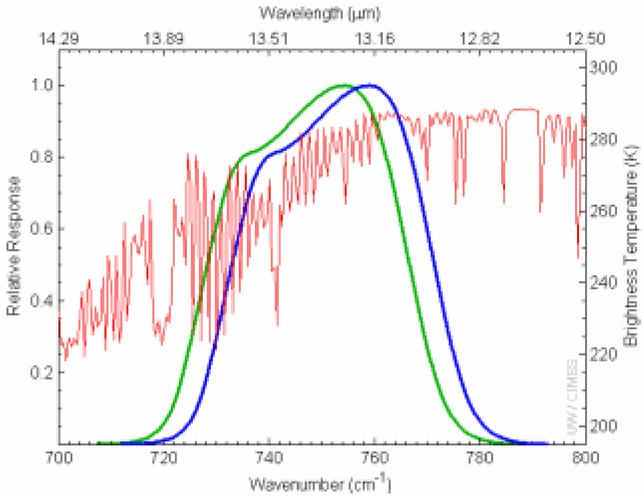

Figure 2: GOES-13 Imager Band 6 spectral response functions, original (blue) and with a -4.7 cm^{-1} shift (green), superimposed on spectral radiance for the U. S. Standard Atmosphere (red).

While an RSR shift could eliminate the bias, it remains a question whether the RSR from pre-launch tests can have that much uncertainty and whether that is the root cause of the bias. These are important questions because bias can be caused by any number of deficiencies. If a problem is "corrected" for wrong reasons in one situation, it likely will cause other problems elsewhere.

Unlikely Causes of the Bias

In the analysis above, the AIRS and GOES measurements may not be collocated perfectly in time and space. This, however, could increase the uncertainty that is random in nature, not necessarily the systematic bias one way or another. Also, impact due to collocation uncertainty should not be limited to one particular channel, in fact it should have more impact on the more transparent window channels.

The GOES onboard calibration has caused bias in the past, due to angular dependence of scan mirror emissivity (Weinreb et al 1997) or the midnight blackbody calibration anomaly. However, corrective measures have been taken to minimize those biases, and preliminary analysis indicates that the cold bias is independent of scan angle and thermal variation of satellite operating environment.

The onboard blackbody could cause the cold bias, for example the platinum resistance thermometers (PRT) embedded in the blackbody could report wrong readings, although that uncertainty is extremely small and, should it exist, it would affect all IR channels. We also note that the blackbody emissivity displays no special feature in the spectral region of interest (Fig. 3). While the emissivity may change after many years in space, it must be larger than the assumed value of unity, should it be the sole cause of a cold bias. Since the blackbody emissivity is neither expected to increase over time not to exceed unity, this is unlikely the cause.

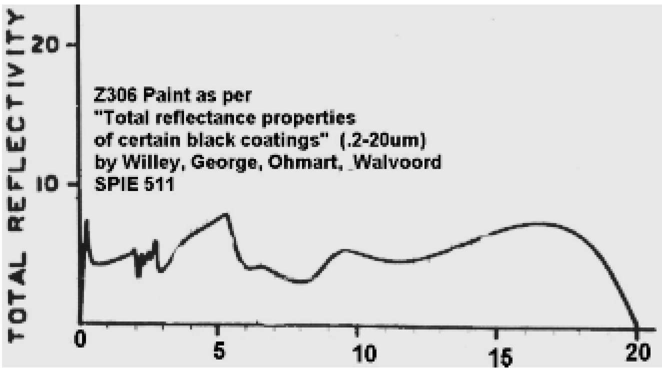

Figure 3: Spectral reflectivity of the Z306 paint used for GOES blackbody (Willey et al)

The Mercury-Cadmium-Telluride (HgCdTe) detectors used for the long wave IR channels respond nonlinearly to radiance (Fig. 4), therefore it is reasonable to suspect that the nonlinearity could be responsible for the cold bias. However, the nonlinearity is small (~0.2 K) and has been largely corrected; the signature of nonlinearity (small in some middle range, large and in opposite sign for very hot and cold scenes) is absent; and this particular cold bias is found only in one channel. These eliminate nonlinearity as the major contributor to the cold bias.

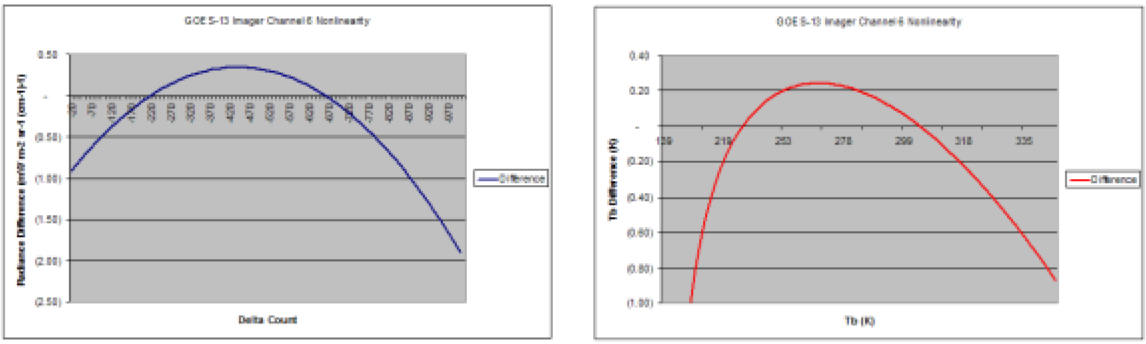

Figure 4: GOES-13 Imager 13.3 m channel nonlinearity, plotted in unit of radiance (left) and brightness temperature (right) as a function of count.

Cause of the Bias

The only remaining mechanism capable of causing the observed cold bias is error in the instrument spectral response. To confirm that this is indeed the dominant factor, it is noticed that the GOES Imager 13.3 m channel is located at a wing of a CO_2 absorption band (Fig. 2) such that the spectral radiance is highly structured. If the spectral response function is in error, the bias, or the difference between the measured and expected radiance, would be present when the radiation from a surface is subject to the modulation of CO_2 on its way to the radiometer (Fig. 5). By the same argument, if there are less CO_2 between the radiating surface (such as clouds) and the radiometer, the bias would be smaller. In the limiting case when there is no CO_2 between the source of radiation and the measuring radiometer, the bias would be entirely due to the wavelength dependence of Planck's function, which is nearly an order of magnitude smaller than observed (Galvin 2007).

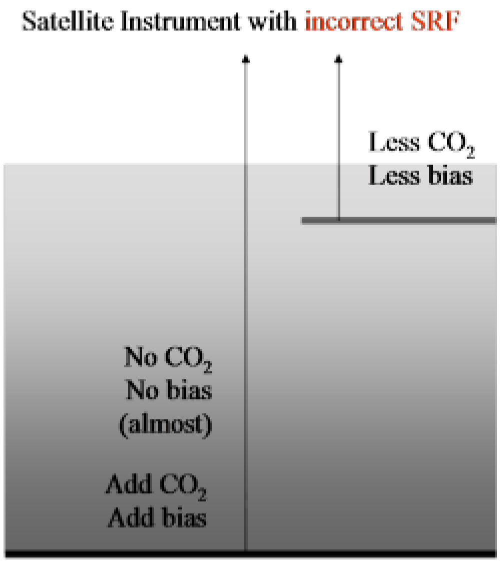

Figure 5: Illustration that the bias due to SRF error should depend on scene temperature.

One indication of CO_2 modulation is the difference between AIRS measurements at 900 cm^{-1}, where the atmosphere is largely independent of CO_2, and at 675 cm^{-1}, where CO_2 absorption is strong. As shown in Fig. 6, the bias is indeed large (3-4 K) where the CO_2 modulation is strong, and vice versa. When the SRF is shifted by an appropriate amount, the bias is not only reduced to zero in mean but also becomes independent of the T_b difference (Fig. 6).

The speculation so far has been implicitly based on the assumption that the atmospheric lapse rate is nearly constant, which is acceptable in the tropical and mid-latitude troposphere. In rare cases, deep convective clouds penetrate into the lower stratosphere, where the lapse rate is neutral or negative. For such cases, bias caused by SRF error should reverse the sign. Fig. 6 showed that this again is the case. Furthermore, the correction by the shifted SRF also reverses the sign for these cases. This lends further support to the hypothesis that the bias is caused by SRF error. In a final note, the thin dashed line in Fig. 6 shows that a constant bias correction would under-correct the bias for warm scenes and over-correct the bias for cold scene, stressing the importance of finding and correcting the root cause of a problem instead of the symptom.

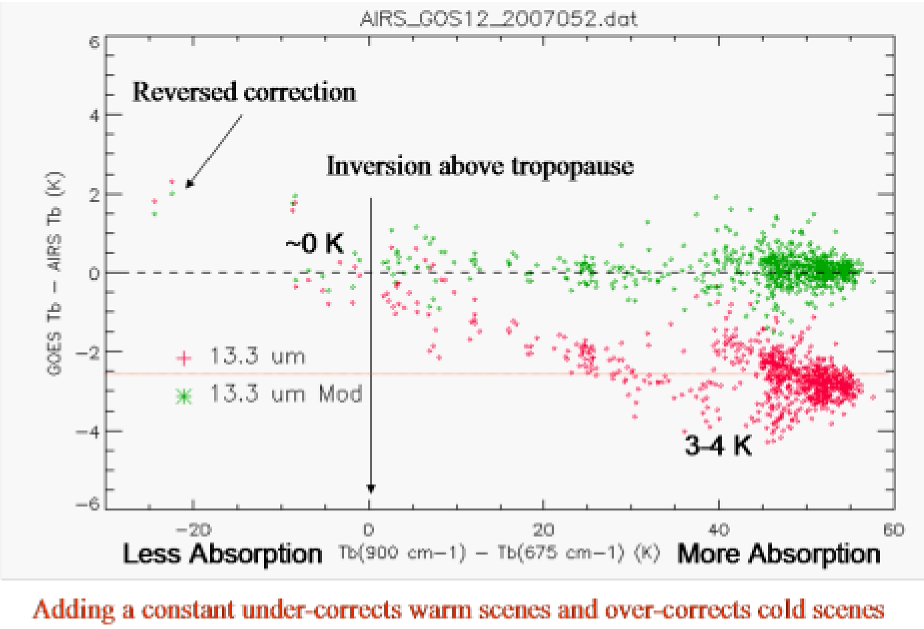

Figure 6 : The observed GOES-12 Imager Band 6 bias on February 21, 2007, as evaluated by AIRS using the original (red +) and shifted (green *) spectral response function, plotted as a function of the difference of brightness temperature (T_b) at 900 cm^{-1}, where the atmosphere is quite transparent, and T_b at 675 cm^{-1}, where CO_2 absorption is strong.

Causes of the RSR Error

If the SRF error caused the observed cold bias, then what caused the SRF error? To answer this question, the pre-launch measurement and derivation of the spectral response for GOES-13 Imager have been thoroughly reviewed by ITT, the instrument vendor (Galvin 2007). The review covered the calibration and alignment of the test equipment; the transfer of the witness sample characteristics to the flight part (the latter was not tested cryogenically and there was a small f-number shift); possible shift of the filter spectral response due to Gibbs ringing, shape change with temperature, wavelength vs. wavenumber conversion, among others; and the possible shift of the detector spectral response with temperature. In the end, it was found that the witness sample was tested at 84 K, however the operating temperature was later lowered to 81 K. For the detector, the test results for 101 K were used without correction to 81 K. These two errors effectively shifted the RSR by 1.2 cm^{-1}, as shown in Fig. 7. It was also found that the combined uncertainty of RSR could reach 4-5 cm^{-1}. Nevertheless, the instrument remains in compliance with specifications, including the pre-launch characterization that is based on radiance uncertainty when viewing a blackbody source.

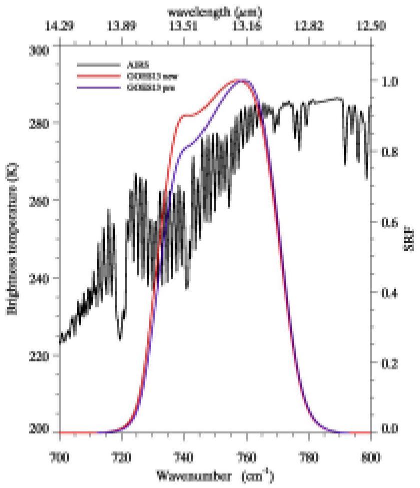

Figure 7: GOES-13 Imager 13.3 m channel spectral response functions, original (blue) and revised (red), superimposed on AIRS spectral radiance for the U. S. Standard Atmosphere (black).

In search for other causes for the SRF error, it is noted that the bias for GOES-12 was considerably larger on February 21, 2007 (-2.6 K, see Fig. 1). Hewison and König (2008) showed that the bias for the 13.4 m channel of Spinning Enhanced Visible and Infrared Imager (SEVIRI) on METEOSAT-9 changed after a decontamination maneuver in December 2007. Examination of the impact of the GOES-12 decontamination in July 2007 (Fig. 8) shows a sudden change in 13.3 m channel bias such that the bias before and after the decontamination is consistent with those in Fig. 1.

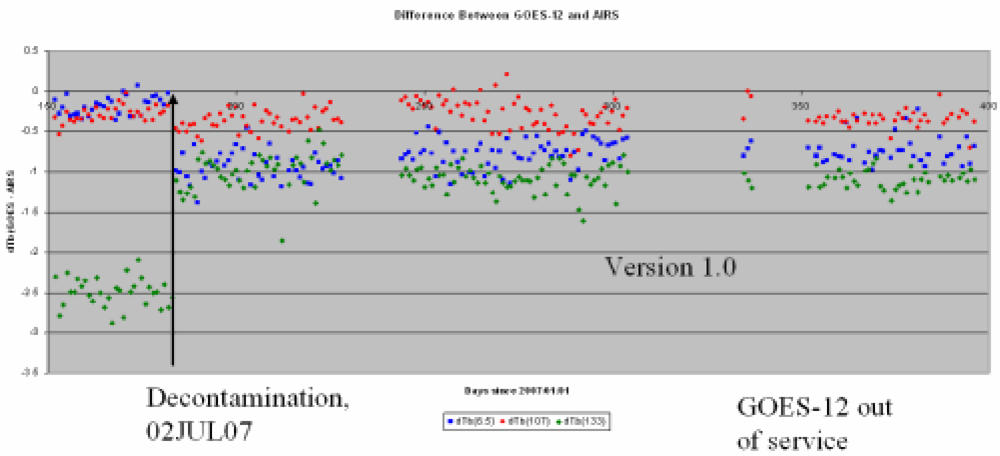

Figure 8: Time series of GOES-12 Imager Band 3 (6.5 m), Band 4 (10.7 m), and Band 6 (13.3 m) biases from June to December 2007. Note the sudden change of bias, particularly for Band 6, after decontamination that started on July 2, 2007.

In addition to the change for 13.3 m channel, Fig. 8 also shows an opposite change in the 6.5 m channel bias. To explain this phenomenon, we examined the spectral transmission of thin water ice that has been verified with the Infrared Atmospheric Sounding Interferometer (IASI). It was found that the spectral gain loss prior to the July 2007 GOES-12 decontamination is consistent with the effect of spectral transmission of 2.1 m water ice. Using that information, we calculated the spectral response with 2.1 m ice (Fig. 10); the results are consistent with those in Fig. 8.

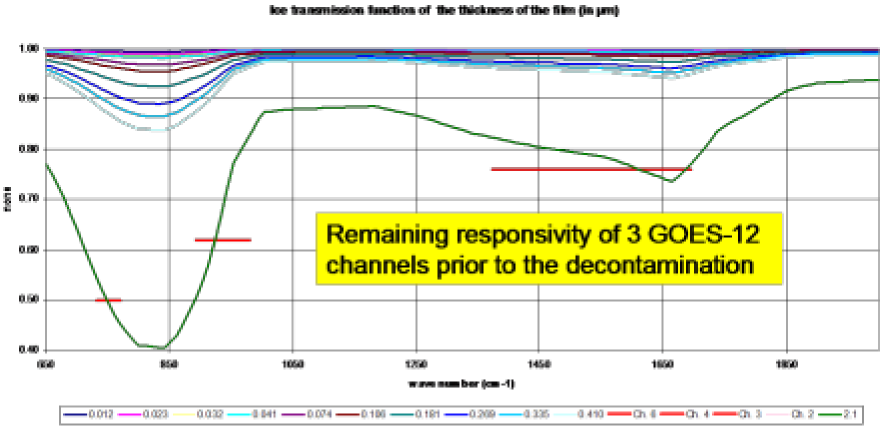

Figure 9: Spectral transmission of H_2O ice of various thickness, modeled by CNES and verified with IASI. The red horizontal lines mark the gain loss of three GOES-12 channels before the July 2007 decontamination. The thick green curve shows that the spectral gain loss is consistent with the spectral transmission of 2.1 m H_2O ice.

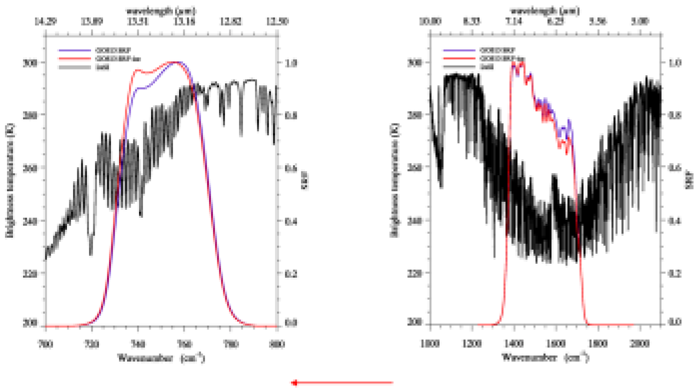

Figure 10: Impact of 2.1 m H_2O ice on instrument spectral response, which effectively shifted the 13.3 m channel (left) to more opaque spectral region and the 6.5 m channel to more transparent spectral region.

Correction for GOES-13 Imager 13.3 m Channel Cold Bias

The GOES-13 Imager 13.3 m channel bias is -1.8 K using the original SRF and -1.3 K using the revised SRF. The latter number is consistent with the -1.1 K bias for GOES-12 after its July 2007 decontamination. Assuming the decontamination completely removed the ice, it can be concluded that the pre-launch characterization of the instrument spectral response contains uncertainty that leads to a cold bias on the order of -1 K. This remaining bias can be removed empirically by incrementally shifting the spectral response function until the bias is minimized, both in terms of mean and its dependence on scene T_b difference, as illustrated in Fig. 11. The mean bias is minimized when the SRF is shifted by -2.3 cm^{-1} (upper right panel), whereas the dependence of bias on T_b difference is minimized when the SRF is shifted by -3.0 cm^{-1} (middle panel). This analysis was repeated for a few more cases; the results were similar. While any SRF shift between these two values should be acceptable, -3 cm^{-1} is recommended. This is partly in anticipation of slow contamination in future, and partly because the SRF shift for minimum slope is relatively stable around -3 cm^{-1} whereas the SRF shift for minimum bias varies depending on the relative composition of clear and cloudy scenes (as can be expected from Fig. 6).

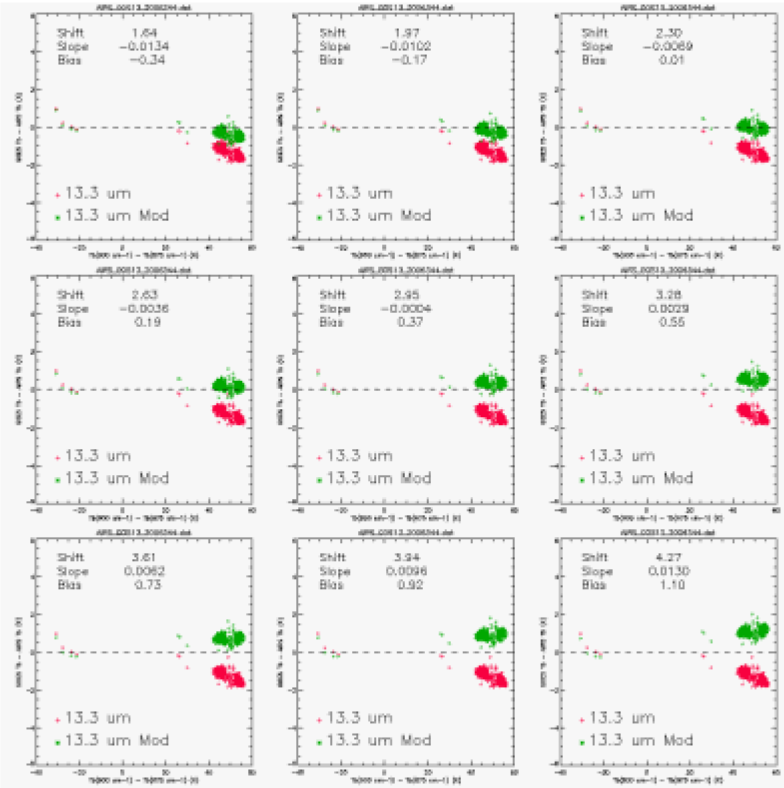

Figure 11: Determination of optimal shift from ITT revised spectral response function. Each of the nine panels is similar to that in Fig. 6, except with various SRF shift and the resulted bias. "Slope" is that of regression of bias on T_b difference, which should be close to zero when the bias is independent of CO_2 absorption.

Conclusions

Using the Global Space-based Inter-Calibration System (GSICS) tools for GOES-AIRS inter-calibration, we confirms the cold bias for GOES-12/13 Imager 13.3 m channel that was first reported by Schmit and Gunshot (2007). Exhaustive search leaves a single factor as the possible root cause for the bias, namely the error in the instrument spectral response. All known characteristics of the bias are subsequently verified to be consistent with this assessment. Analysis of pre-launch characterization of instrument spectral response revealed a bias of -1.2 cm^{-1} for GOES-13. Substantial bias can be caused by on-orbit contamination that, in one case for GOES-12, effectively altered the SRF by -2.5 cm^{-1}. For both GOES-12 and GOES-13, there is an unexplained bias on the order of -2 cm^{-1} to -3 cm^{-1} in the instrument spectral response, which agrees with the analysis of pre-launch characterization that allows uncertainty up to 4-5 cm^{-1}.

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