THE CALIBRATION OF BROAD BAND INFRARED SENSORS: TIME VARIABLE BIASES AND OTHER ISSUES

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Abstract

Broad band infrared sensors have been utilized by the remote sensing community for over 30 years but recently have been shown to have significant calibration problems, at least when using their operational calibrations. With the current drive towards datasets that can be used for climate studies there is now an imperative for fixing such calibration problems. In particular, it of the utmost importance to remove any time-variable biases from the data records, but the operational calibration of many broad band infrared sensors still show strong evidence for such biases in both polar and geostationary sensors.

Here we report on the latest work on resolving some of the calibration issues seen in such sensors. This includes the progress on a recalibration project for the Advanced Very High Resolution Radiometer AVHRR that is attempting to recalibrate the historic AVHRR data record. We also report on efforts to recalibrate geostationary sensors such as the GOES Imager, an instrument which is known to have significant time-dependent biases, including a strong diurnally varying component, and propose possible solutions. Remaining problems and issues with both polar and geostationary sensors are also discussed.

INTRODUCTION

A crucial step towards generating accurate and stable geophysical parameters from satellite data is to understand and improve instrumental calibration. In particular, ensuring temporal stability is extremely important as climate studies require that instrumental trends must be removed from the signal. Unfortunately, in terms of broad band infrared sensors, many of the commonly used instruments have been shown to have time-variable biases, including the AVHRR (see for example Mittaz & Harris 2011b) as well as the GOES Imager, which has a known problem around local midnight (e.g. Yu et al. 2013). Many sensors also show significant temperature-dependent biases, which should also be removed in order to ensure retrieval of the most accurate geophysical parameters.

In this paper we discuss continuing efforts in recalibrating the AVHRR sensors and in particular the AVHRR/3 (in this case NOAA-16 through MetOp-A) sensors. We also discuss a new algorithm to correct the midnight blackbody effect in the GOES Imager. We show that, with an improved parameterization for both the AVHRR and GOES Imager sensors, a significant portion of their time dependent biases may be removed, as well as (for the AVHRR) reduce any spectrally-dependent bias.

A RECALIBRATION OF THE AVHRR/3 SENSORS

As part of a project funded through the NOAA Climate Data Record Program (see http://www.ncdc.noaa.gov/cdr/index.html) we have been working on recalibrating the AVHRR historic data record with the aim of providing a Fundamental Climate Data Record (FCDR) to be used in creating climate data records. To begin with we have concentrated on the AVHRR/3 group of sensors since these overlap with a range of potential top-of-atmosphere radiance sources such as the hyperspectral sounders AIRS and IASI, as well as the Advanced Along Track Scanning Radiometer
The Level 1B data format for the AVHRR/3 also contains more complete information regarding the sensor including a larger range of measured temperatures and currents that are not standardly available for the older sensor series, at least in the Level 1B format.

The AATSR as a top-of-atmosphere reference

For the FCDR recalibration project we have chosen to concentrate on the (A)ATSR series (the ATSR-1, ATSR-2 and AATSR) as our reference sources. This is because while more detailed information regarding the AVHRR calibration may be available using hyperspectral sounders, they did not exist before 2000 and therefore do not overlap with the older AVHRR/2 sensors. By concentrating on the (A)ATSR sensors we can ensure that any FCDR we develop will have a consistent reference for the largest time overlap possible, from 1991 to 2012, and can link the AVHRR/2 and AVHRR/3 sensors using the same reference.

The (A)ATSR series of sensors also has the added advantage that it was designed for climate applications with on-board blackbodies that have been referenced to an SI-traceable standard. It is important to realize, though, that while the (A)ATSR series are going to be very stable due to the design of their blackbodies, this does not necessarily mean that the calibrated radiances are similarly traceable if there are biases in the calibration procedures themselves. Problems with the calibration are certainly apparent for the AATSR sensor. To begin with the pre-launch analysis (e.g. Smith et al. 2012) shows that the calibration methodology used does not remove all biases relative to traceable standards, with residuals of up to 0.1K apparent at the coldest temperatures. While this may not seem like a large error, it is larger than the quoted accuracy of the AATSR (0.05K) and is also larger than the desired accuracy for fundamental climate data records (e.g. Ohring et al. 2005). Post-launch problems have also been identified with the 12 $\mu$m channel (e.g. Nightingale et al. 2004) where, in the sea surface temperature (SST) radiance regime, a bias of approximately -0.2K offset has been discerned.

More recent work (e.g. Bali & Mittaz, 2012) has undertaken a more detailed analysis of the AATSR radiances by comparing AATSR 11 and 12$\mu$m channel radiances with IASI. This work has shown that the radiance bias in the 12$\mu$m channel is more complex than a simple offset and shows a strong temperature-dependent bias between +0.4K to -0.2K over the 200-300K temperature regime. In terms of the 11$\mu$m channel it has also been shown that, apart from a small offset (~0.06K), the IASI radiances are close (within a few hundredths of a degree) to the pre-launch references. We have therefore created polynomial functions of the 11 and 12$\mu$m channel biases that have been normalized to try and match the zero line in the pre-launch data and hence should be close to a traceable reference. Once the AATSR radiances are corrected, they are collocated with the AVHRR data to enable the recalibration to proceed. We then correct for spectral response function (SRF) differences using an radiative transfer model for the 3.7$\mu$m channel, and a lookup table derived from IASI spectra (which includes cloudy pixels) for the 11 and 12$\mu$m channels.

A recalibration of the AVHRR/3 series

Previous work has shown that the current operational calibration for the AVHRR/3 series of sensors is sub-optimal both from a pre-launch analysis point of view (Mittaz, Harris & Sullivan 2009) and from an in-orbit point of view (e.g. Wang & Cao 2008, Mittaz & Harris 2011a). The reason for the biases seen in the operational calibration arise from a combination of a non-physical calibration equation, as well as change in the thermal environment between the pre-launch test chamber and the orbital conditions. Further work has shown that there is also a time-dependent bias, particularly for the AVHRR sensor on the NOAA-16 satellite, which can contribute up to a -0.5K bias (e.g. Mittaz & Harris 2011b).

Time dependent biases in the AVHRR

The time-dependent bias has been linked to the AVHRR instrument temperature and almost certainly is related to variations in the thermal environment and hence in internal thermal gradients that are reflected in variations in the radiance bias terms in the calibration equation. In its simplest form, the calibration equation can be written as
\[ R_{Earth} = \alpha + \frac{(1+\varepsilon)R_{BB} - \gamma(C_S - C_{Earth})^2}{(C_S - C_{BB})} + \gamma(C_S - C_{Earth})^2 \]

where we have assumed that the bias term in the gain part of the equation is close to zero, as implied by the detailed study of the AVHRR flown on the MetOp-A satellite (Mittaz & Harris 2011a). While in truth there will be a small gain bias term that may even have a small time dependent component, there is also a potential uniqueness issue between the blackbody emissivity term \((1 + \varepsilon)\) and the gain radiance bias term that can be difficult to resolve, especially when dealing with collocations between different satellites where the orbital coverage can be poor.

As shown in Mittaz, Harris & Sullivan (2009) the \(\alpha\) term can be decomposed into components related to changes in the so-called configuration factors between looking at the Earth scene and looking at the space view. Essentially, this bias term is related to subtle changes in the instrument self-emission when looking in different directions and hence at different parts of the instrument body. Because it is related to the instrument itself, it is a function of the instrument temperature, as well as thermal gradients within the instrument. As an example, Mittaz & Harris (2011b) showed a strong relationship between the average orbital instrument temperature and a bias seen in the Pathfinder v6.0 SST data record for NOAA-16 that can be directly related to an instrument temperature dependent radiance bias.

![Figure 1: The average orbital instrument temperature for the AVHRR/3 sensors flown on NOAA satellites. It shows that a strong time dependent bias is expected for NOAA-15 and NOAA-16. In the case of NOAA-17, while there would be an observable time dependent bias, from 2010 the scan motor was failing, rendering the data unusable.](image)

In order to understand the impact of such time- & instrument temperature-dependent biases on the calibration of the AVHRR we need to understand the instrument temperature variations for the AVHRR/3 sensors. Figure 1 shows the average orbital instrument temperature for the NOAA AVHRR sensors and indicates that a temperature-dependent bias will be large for the AVHRRs flown on-board NOAA-15 and NOAA-16. NOAA-17 would also show a strong time dependent bias from 2010, apart from the fact that at that point the scan mirror motor was failing, making the data unusable. For the other AVHRR sensors, the variation in the orbital temperature is small, e.g. at the level reported for MetOp-A it gives rise to a very small temperature dependent bias of less than a few hundredths of a degree (Mittaz & Harris 2011a). For the present such small biases will be ignored, though it will be included in a revised calibration at a later date.

For NOAA-15 and NOAA-16 a time-dependent bias needs to be addressed. Fortunately, in the case of NOAA-16 there is a period of time (pre-2004) where the time-dependent bias is very small and can be used to define the baseline calibration. Subsequent time-dependent bias can then be based off this calibration by defining a simple correlation between instrument temperature and bias. Such correlations are shown in Figure 2, and show the need for an extra level of complexity. It is clear that
there are at least two separate regimes that correspond to times when the instrument temperature variation was slowly varying (before the end of 2007) and when the variation was more rapid (2008 onward). While this implies that the true underlying bias is more complex than the simple model defined above, Figure 2 also shows that the bias correction can correct the time dependent bias to much better than 0.1K and overall removes the significant trends. Unfortunately in the case of NOAA-15, a period with only a small time-dependent bias regime does not exist and it has proved to be difficult to derive a reliable baseline calibration, so we do not have a new calibration for NOAA-15 as yet.

Figure 2: Correlations between the average orbital instrument temperature and the bias for NOAA-16. Shown are two sets of correlations, the points in black for the period where the instrument temperature varied slowly (up to late 2007) and the points in red for when the instrument temperature varied rapidly (post late 2007).

Figure 3: Top two panels shows the 11 and 12µm channels over an 8 year period for NOAA-16 showing the time-dependent bias relative to the AATSR. The lower panels show the same data where the calibration has an instrument temperature dependent bias included.

A new calibration for the AHVRR/3 sensors

We have therefore taken the collocation data between the AVHRR and AATSR and, together with the time-dependent bias defined above, have fitted new calibration coefficients for the AVHRRs on-board NOAA-16 through MetOp-A. Figure 3 illustrates the removal of the time-dependent bias for NOAA-16.
discussed above for the \(11\) and \(12\)\(\mu\)m channels, and shows that significant trends in the data are removed - a key requirement for an FCDR.

Other important effects in the operational calibration include simple radiance biases, some of which have been reported by other of authors. Starting with the linear channel, the left-hand part of Figure 4 shows the difference between the operational and recalibrated radiances for the \(3.7\)\(\mu\)m channels where we only show radiances where the SRF differences can be reliably corrected using a radiative transfer model. The new calibration improves the result, though the difference is quite small. On the other hand, the right-hand panel of Figure 4 shows the \(3.7\)\(\mu\)m difference over a wide range of scene temperatures where we have simply compared the new and operational calibrations and shows that at cold temperatures the difference can be large, at least in brightness temperature space. Of course, much of this is because of the effect of the Planck function in the \(3.7\)\(\mu\)m channel, but it is also in part due to the fact that, in the new calibration, we are using a more realistic estimate of the blackbody emissivity, which is assumed to be unity in the operational calibration.

Figure 4: The left hand panels shows the difference between the operational and new calibration for the \(3.7\)\(\mu\)m channels (black = operational, red=new). Note that the scene temperature range is small due to the use of radiative transfer modelling to correct the SRFs. The right hand panel shows the difference for a single AVHRR (NOAA-18) over a wider range of scene temperatures showing quite large differences.

For the non-linear channels, Figure 5 shows the difference between the operational and new calibration for the \(11\) and \(12\)\(\mu\)m channels. There are a few important things to note from Figure 5. First, in every case the new calibration is better than the operational calibration and the effect of the time dependent bias for NOAA-16 is obvious. Second is the strong scene temperature-dependent bias for NOAA-17 and MetOp-A. Such biases have been discussed in the literature before. It is interesting to note, however, that two other AVHRR sensors (NOAA-18 and NOAA-19) show a much smaller operational bias, which implies that, the thermal environment for NOAA-18 and NOAA-19 must be similar to the pre-launch environment (presumably very uniform). Since NOAA-18 and -19 are afternoon satellites, and NOAA-17 and MetOp-A are morning satellites, this implies a distinct difference in the thermal environment between morning and afternoon orbits that the new calibration takes into account but the operational calibration does not.

THE GOES IMAGER MIDNIGHT BLACKBODY CALIBRATION CORRECTION

The time-dependent bias seen in the AVHRR is not the only time-variable bias seen in broadband infrared sensors. One other sensor which has a known time-variable bias in the calibration is the GOES Imager, where a so-called Midnight Blackbody Calibration Correction (MBCC) has to be applied to radiance to try and remove a strong diurnal calibration bias. The underlying cause is thought to be extraneous radiation from a heated part of the instrument/satellite body (probably the sun shield) being reflected off the GOES Imager blackbody and contaminating the calibration counts, thereby corrupting the gain calculation. The current algorithm (Weinreb & Han 2003) uses a model of the gain that correlates the responsivity (defined as \((m + 2qC_{BB})^{-1}\) where \(m\) is the
Figure 5: Bias of the AVHRR relative to the AATSR for NOAA-16 through MetOp-A. The left two columns show the operational (first) and recalibrated (second) biases for the 11µm channel, and the right two columns show the operational and recalibrated biases for the 12µm channel. Taking each sensor in turn from the top to bottom we have NOAA-16 with large operational biases caused by the time dependent bias discussed above. Second row shows NOAA-17, which shows the ‘standard’ linear bias of order ±0.5K discussed by previous authors that is removed by the new calibration. The next two rows (NOAA-18 and -19) show the operational calibration is close to (though not quite as good as) the new calibration, and the last row (MetOp-A) is similar to NOAA-17.

uncontaminated gain, \( g \) is the non-linearity and \( C_{BB} \) is the blackbody counts) against the primary mirror temperature. For those times when the gain is contaminated, the primary mirror/responsivity correlation is used to estimate what the gain should have been, which is then used to calibrate the radiances.
It was originally thought that the MBCC would only be significant for the 3.9\(\mu\)m channel but more recent work has shown that a strong diurnal bias also exists in the longwave channels of up to 0.7K (Yu et al. 2013), and it has been suggested that the MBCC may need to be applied more frequently to improve the calibration. Here, however, we suggest that the problem may be more fundamental and may instead lie with the use of the responsivity in the algorithm. In Mittaz, Harris & Sullivan (2009) a different form of the calibration equation was derived which related the gain directly to the instrument self emission

\[
R_{Earth} = a_0 + (a_1 + 4qR_{Self}(T))^2(C_S - C_{Earth}) + q(C_S - C_{Earth})^2
\]

where \(R_{Self}\) is the instrument self-emission radiance. Since the self-emission is the fundamental parameter that drives the gain variations, a more sensible model for the gain would directly relate the self-emission to a parameter such as the primary mirror temperature (emission from the primary mirror emission is thought to dominate the self-emission radiance). A different algorithm for the MBCC would therefore be

\[
(a_1 + 4qR_{Self}) = m^2 = \left( \frac{\epsilon_{BB}R_{BB} - q(C_S - C_{BB})}{(C_S - C_{BB})} \right)^2 = b_0 + b_1T_{Prim} + b_2T_{Prim}^2
\]

Including the effect of the variable scan mirror emissivity would then lead to

\[
\left[ \frac{\epsilon_{BB}R_{BB} - q(C_S - C_{BB})}{(C_S - C_{BB})} \right]^2 - 4q\epsilon_{scan}R_{Scan} = b_0 + b_1T_{Prim} + b_2T_{Prim}^2
\]

where \(\epsilon_{scan}\) is the scan mirror emissivity and \(R_{Scan}\) is the scan mirror radiance. Figure 6 shows the difference between the operational calibration and the new algorithm in the case of the 11\(\mu\)m channel for GOES-11 when compared to AIRS. The black points show the midnight effect with a time-dependent bias centred around local midnight. The red points show the application of the new algorithm which effectively removes most, if not all, of the bias. While these results are preliminary, the fact that a more physical approach to the MBCC, together with the example shown above, would seem to indicate that the new algorithm works better than the operational one, and may indeed fix the problem, though more work needs to be done on other channels and examining the MBCC behaviour over different seasons.
CONCLUSION

A new calibration has been derived for the AVHRR/3 sensors from NOAA-16 through MetOp-A including a correction for a time-dependent bias for NOAA-16. Results show that the new calibration removes both scene temperature-dependent biases and time-dependent biases to better than 0.1K. It has also been shown that the calibration biases are orbit-dependent, with the afternoon satellites having smaller calibration errors than the morning satellites, apart from the case for NOAA-16 which has strong time dependent biases. It is intended that this new calibration will be made available to the community via the NOAA NCDC Climate Data Program (http://www.ncdc.noaa.gov/cdr/index.html).

A new calibration has also been derived for the GOES Imager to provide an improvement to the MBCC, as the operational configuration is introducing a diurnally varying calibration bias of up to 0.7K in the longwave IR channels. This new calibration has been shown to provide a substantial improvement over the operational MBCC, at least for the 11\(\mu\)m channel on GOES-11, and implies that the error in the current MBCC may be due to a sub-optimal parameterization of the instrument self-emission.

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