A NEW PHYSICAL CALIBRATION FOR THE AVHRR INSTRUMENT SERIES

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Abstract

Recently it has become apparent that the calibration of the Advanced Very High Resolution Radiometer (AVHRR) is flawed. Significant problems with the AVHRR calibration have been seen in two separate sources of AVHRR data – problems with the AVHRR pre-launch data used to derive the in-orbit calibration, and observed trends and biases when the AVHRR radiances are compared with other accurate top-of-atmosphere (TOA) radiances sources such as the Infrared Atmospheric Sounding Interferometer (IASI). In this paper we show the results of on-going work to improve the calibration of the AVHRR, and show that for the AVHRR flown on MetOp-A we can derive an in-orbit calibration for the non-linear (11 and 12 µm channels) that agrees with radiances derived from IASI to within 0.1K for nadir observations.

INTRODUCTION

The calibration of the AVHRR is currently based on an algorithm which is derived by fitting a calibration algorithm to pre-launch data. This calibration, based on Walton et al. (1998), fits parameters including a detector non-linearity as well as a 'negative radiance of space' parameter for the 11 and 12 micron channels. The AVHRR is then calibrated in-orbit using the pre-launch calibration without modification and uses measurements of the internal calibration target (ICT) or blackbody to trace both the orbital and long term variations of the instrument response. There is, however, a serious disconnect in this sequence of calibration since the pre-launch calibration was actually derived without reference to the very pre-launch blackbody measurements which are central to the in-orbit calibration. As has been known since at least the early 1990's, the pre-launch ICT radiative temperature derived directly from the measured ICT counts do not seem to match the temperature measured directly by four PRTs attached to the ICT (e.g. Weinreb et al. 1990). Further, issues with the pre-launch calibration such as a non-zero radiance offset and the use of a variable non-linear term (not expected since the AVHRR detector is kept at a constant 105K) have also been identified (Mittaz, Harris & Sullivan 2009). Other problems have also been found including solar contamination effects, particularly when the satellite is coming out of eclipse (e.g. Cao et al 2001), together with the presence of gain loops which can introduce large seemingly latitudinal biases (Trishchenko 2002).

To fully understand the AVHRR we have recently developed a physical model of the instrument with the aim to investigate and improve the calibration (see Mittaz, Harris & Sullivan (2009) for full details). We have found that the pre-launch data for the AVHRR/3 family of sensors was significantly compromised by both stray light problems and temperature drifts. These effects together with the non-physical behavior of the current calibration algorithm have added significant biases and trends into the pre-launch calibrated radiances. For example, an application of the current operational calibration to the pre-launch data from which it was derived yields biases and trends of up to 0.7K. We have therefore refitted the pre-launch AVHRR calibration using our new calibration and can shown that we can remove the trends and biases in the data leaving a scatter consistent with the expected detector noise. We can also show that our new calibration has an accurate predictive power, meaning that when the calibration system is compromised by, for example, solar contamination, we can still derive an accurate estimate of the instrument calibration. Such a prediction was impossible with the current

operational calibration and our ability to do this will provide a significant improvement in providing a gap-free calibrated AVHRR dataset.

In this paper we discuss the new developments in determining the AVHRR calibration. In particular we show that not only was the pre-launch data compromised but the error caused by problems with the pre-launch data has been propagated into the in-orbit calibration as well. We then show that by using IASI as an accurate TOA calibration source we can determine a new in-orbit calibration removing most of the effects introduced by the pre-launch data. We then show that our final calibration can match the IASI radiances to within 0.1K for a nadir observation. We also show that as has been pointed out by other (Wang & Cao 2008, Blumstein et al. 2007) there still remains a significant bias as a function of scan angle which is negligible for surface temperatures but is significant for cold scene temperatures. We then briefly discuss the effect of Earthshine on the 3.7 µm channel and finally discuss future plans.

COMPARING IASI AND AVHRR RADIANCES
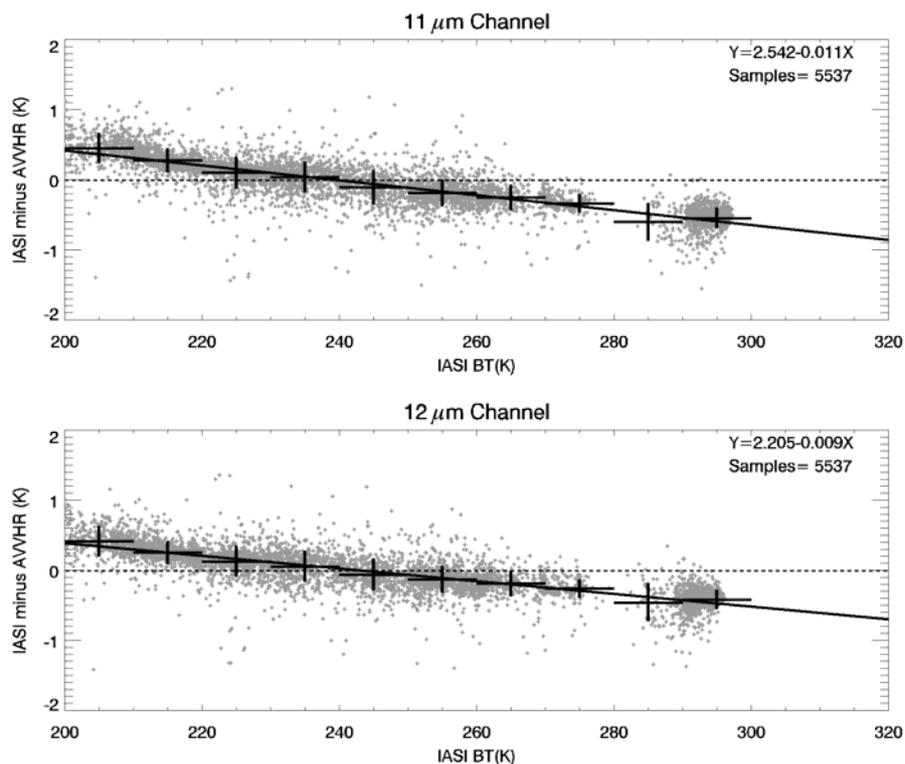
*Figure 1.* A comparison between the IASI and AVHRR integrated radiances for the 1st April 2008 where the AVHRR radiances have been derived using the current operational (Walton et al.) calibration. A strong scene temperature dependent bias can be seen.

In order to re-calibrate the AVHRR we first need an accurate TOA radiance source with which to compare. In this work we will use IASI which has the benefit of being co-located with the AVHRR thereby providing a large number of simultaneous matches as well as providing hyperspectral data enabling us to investigate potential AVHRR spectral response function (SRF) shifts. Then in order to re-do the calibration we therefore create a matchup database where we match IASI footprints with the appropriate AVHRR pixels including all the relevant AVHRR calibration information such as blackbody temperatures and counts together with the observed space counts. Because there are known issues if non-homogeneous scenes are used in any AVHRR/IASI comparison (e.g. Wang & Cao 2008) we have only included fields where the standard deviation of the AVHRR pixels within each IASI footprint has been constrained to be < 1K. For this initial analysis, we have not varied the size of the IASI footprint relative to the AVHRR footprint as a function of instrument scan angle but initial results with an a variable footprint indicates that the difference between what is presented here and a more

accurate matchup is small. Our final dataset consists of 12 days spread over the first six months on 2008 where we have used the 1st and 15th of each month.

Figure 1 shows the bias evident in the AVHRR radiances for the 1st of April 2008 where the AVHRR radiances have been derived using the operational (Walton et al.) calibration. As has been previously shown by Blumstein et al. (2007) and Wang & Cao (2008), there is a large almost linear scene temperature dependent bias in the AVHRR data. Similar scene dependent trends have been reported for the AVHRR on-board NOAA-17 in a comparison with the Advance Along Track Scanning Radiometer (AATSR) which thought to be accurate to 50 mK (see Mittaz & Harris (2008) for details).

Using the IASI/AVHRR matchup data we can also investigate how stable the AVHRR calibration is since our dataset consists of data extracted over a six month period. Figure 2 shows the Walton et al. biases at two different scene temperatures (220-230K and 290-300K) over the six month period of study and shows that the biases, while large, are very stable on this sort of timescale.
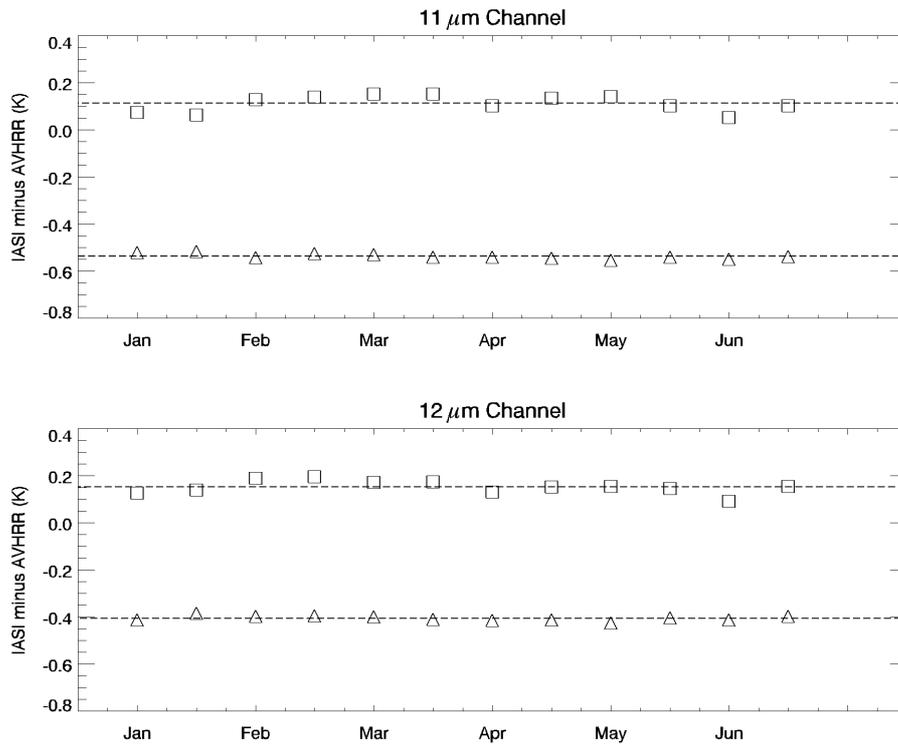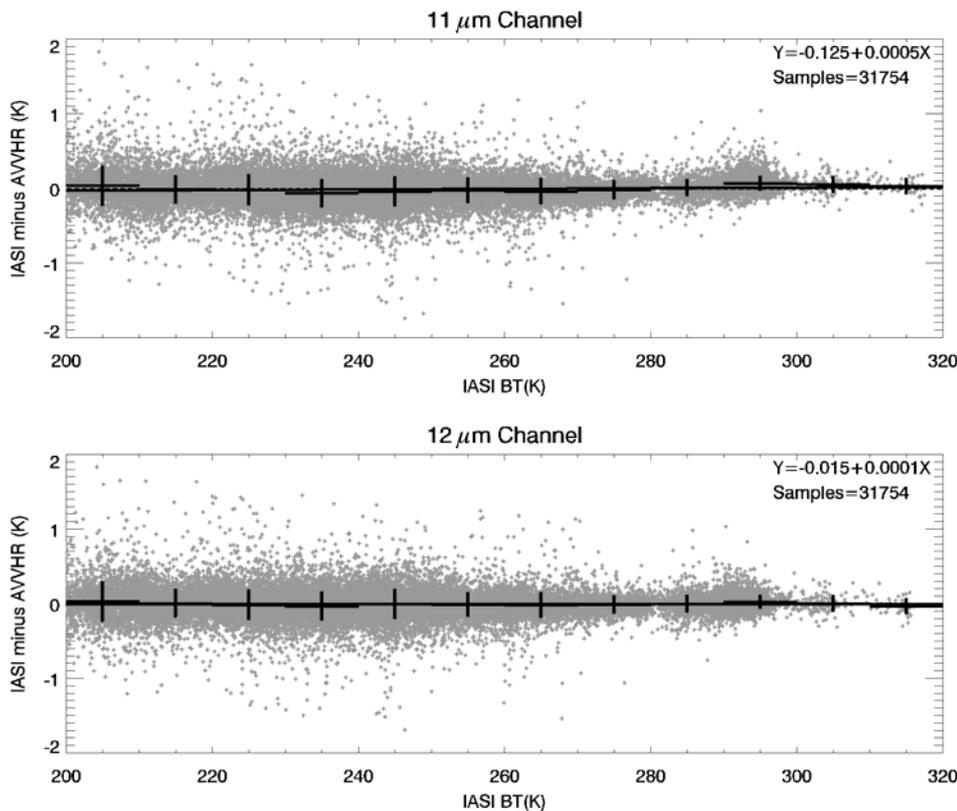

Figure 2. **Values of the mean bias (IASI-AVHRR) between 220-230 K (squares) and at 290-300 K (triangles) for the Walton et al. calibration for the AVHRR for the 11 and 12 µm channel for the 1st and 15th days of the first 6 months of 2008**

REFITTING THE AVHRR CALIBRATION FOR THE IN-ORBIT CASE

While the previous section has shown the biases that currently exist within the current operational calibration, a new physically based calibration also exists. This calibration was developed to explain the biases seen within the AVHRR pre-launch calibration data and enabled us to parameterise the calibration in terms of physically meaningful quantities. The calibration equation is shown in Eq. 1 where R_E and R_{ICT} are the Earth scene and ICT radiances respectively, ε_{ICT} is the estimated value of the ICT emissivity (assumed to be 0.985140) and C_E, C_{ICT} and C_S are the respective observed counts. Also present are a number of calibration parameters. α and α' are biases related to the Earth scene/ICT scene observations respectively, ρ is related to the emissivity of the ICT as well as the existence of temperature gradients across the blackbody, and γ is the non-linear term. For a full discussion of these parameters see Mittaz, Harris & Sullivan (2009). From the pre-launch study it was realised that the first three of these parameters (α,α' and ρ) will have been contaminated by the

$$R_E = \alpha + \left[\frac{(\varepsilon_{ICT} + \rho)R_{ICT} - \alpha' - \gamma(C_S - C_{ICT})^2}{(C_S - C_{ICT})} \right](C_S - C_E) + \gamma(C_S - C_E)^2 \qquad (1)$$

scattered light from the test chamber environment which, of course, does not exist in-orbit. The non-linear (γ) term is solely a function of detector physics so we don't expect its value to change between the pre-launch and in-orbit cases as the detector was kept at the same temperature (105K). We are then left with the problem of determining the in-orbit values for the three contaminated parameters. We have therefore taken the IASI/AVHRR matchup data and re-fitted the contaminated parameters to the in-orbit data. Figure 3 shows the result of such a fit to all the data taken on the 15th of each month. To retain some level of independence the data actually plotted in Fig. 3 is the data taken on the 1st of the month for the six month period and so was not used in the fitting process. The improvement over Fig. 1 is quite dramatic with the new calibration matching the IASI radiances to better than 0.1K over the complete range of scene temperatures for both the 11 and 12 µm channels.

11 μm Channel

Y=-0.125+0.0005X
Samples=31754

12 μm Channel

Y=-0.015+0.0001X
Samples=31754

Figure 3. **A comparison between the Mittaz et al. calibrated AVHRR brightness temperatures and those derived from IASI spectra for the matchups obtained on the 1st day of the month for the months January-June 2008 in the nadir only case. The Mittaz et al calibration has been fitted to a different set of days (the 15th of the month) with a zero SRF shift. Unlike the Walton et al. calibration shown in Fig. 2 this time trends as a function of scene temperature are small, particularly for the 12 µm channel**

The variation between the pre-launch and in-orbit parameters is in line with what is expected. Table 1 shows the two sets of parameters and in particular shows a dramatic decrease in the α' parameter. This is because in the pre-launch case the α' parameter is completely dominated by the effect of radiation from the test chamber environment being scattered into the calibration system via the ICT. In the in-orbit case such radiation does not exist, so the value of α' drops to close to zero.

	11 μm		12 μm	
	Pre-launch	In-orbit	Pre-launch	In-orbit
α	0.86	1.27	0.64	1.09
α'	2.21	0.02	1.99	0.12
ρ	0.027	-0.006	0.025	0.0004

Table 1. **Shows the change between the pre-launch Mittaz et al. calibration parameters and the in-orbit values fitted to the IASI/AVHRR data. The change in the parameters is an indication of the effect of contamination by the pre-launch test environment.**

Further investigating the new calibration, Fig. 4 shows the mean bias between the AVHRR and IASI in more detail and shows a distinct curve in the bias for the 11 μm channel. While small (generally < 0.1K) this curve in the bias was also noted in the pre-launch data for NOAA-17 (see Figure 1 of Mittaz & Harris 2008) and is therefore likely to be due to an real effect in the calibration which has not been taken into account in the Mittaz et al. calibration. The most likely culprit is in the current simplicity of the detector model. Presently the detector response is modelled as a simple quadratic, but the biases seen for NOAA-17 and shown in Fig. 4 imply that the true detector response is more complex than this. It must be stressed, however, that the biases shown here are still much smaller than the biases seen in the operational (Walton et al.) calibration and for many purposes can probably be ignored.
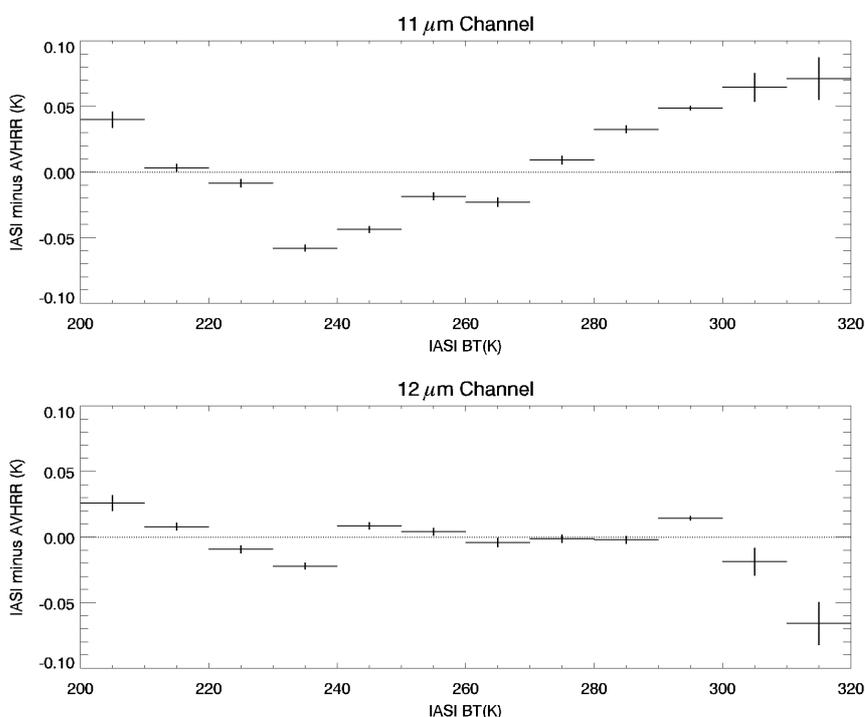
Figure 4. **The mean biases for the 11 and 12 μm channels. While the 12 μm biases are generally small (<0.03K), the 11 μm bias shows a systematic curve which may be related to a deficiency in the simplistic detector model used by the new calibration.**

THE SCAN ANGLE BIAS

Finally Fig. 5 shows the bias in the calibration as a function of scan angle and shows that while at scene temperatures used for surface temperature determination (BT > 260K) the effect is very small, for cold scenes the bias can be large. The existence of such a bias has been noted in previous work using the Walton et al. calibration (Blumstein et al. 2007 and Wang & Cao 2008). While it is not yet possible to determine the origin of this bias, Fig. 5 shows that the new calibration has not corrected for it and that care should be taken if applying re-calibrated AVHRR data for cold scene temperatures.
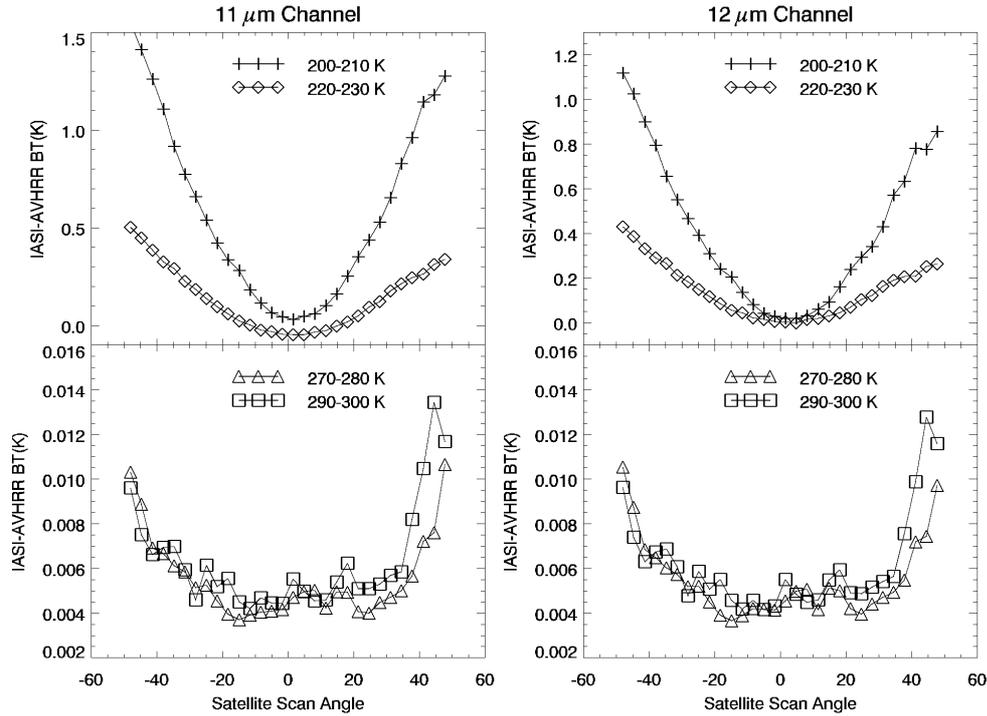
Figure 5. The bias as a function of satellite scan angle. While the bias is small for scene temperatures used to determine surface temperatures, for cold scenes the biases can be very large.

THE 3.7μm CHANNEL

Finally there is the calibration of the 3.7 μm channel. Unfortunately IASI does not fully cover the 3.7 μm channel and so cannot be used as a TOA calibration source. However, unlike the strongly non-linear 11 and 12 μm channels, the 3.7 μm channel is, to a good approximation, linear thereby simplifying the calibration (the issue of the non-linearity of the 3.7 μm channel has been discussed in Mittaz, Harris & Sullivan 2009). Studying the in-orbit data has, however, highlighted another problem, that of Earthshine contaminating the calibration. Figure 6 shows the impact of the Earthshine, which is particularly noticeable as the gain loop seen in the top left panel. The top right panel shows that for the night time data there is a strong correlation between the gain and the underlying scene radiance from the Earth which shows that the calibration is being contaminated by Earth emission reflected into the calibration system via the ICT. This can be corrected for since the Mittaz et al. calibration is physically based so an extra term r_{Earth} can be added representing the Earthshine to give

$$R_E = \alpha + \left[\frac{r_{Earth} + (\varepsilon_{ICT} + \rho)R_{ICT} - \alpha' - \gamma(C_S - C_{ICT})^2}{(C_S - C_{ICT})} \right](C_S - C_E) + \gamma(C_S - C_E)^2 \qquad (2)$$

where r_{Earth} is a function of the underlying scene radiance determined from the correlation shown in Fig. 6. Further, as shown in Mittaz, Harris & Sullivan (2009) the calibration can also be written as a function of the instrument self emission R_{Self} which can then be modelled as a function of ICT temperature. By using both r_{Earth} and R_{Self} a model of the gain variation round the orbit can then be constructed. This is shown by the red line in the lower left hand panel in Fig. 6 and shows what the true instrument gain is doing without the effect of Earthshine. As shown by the last panel of Fig. 6, the Earthshine is adding a bias of up to 0.25K to the radiances which with the new calibration can be removed.

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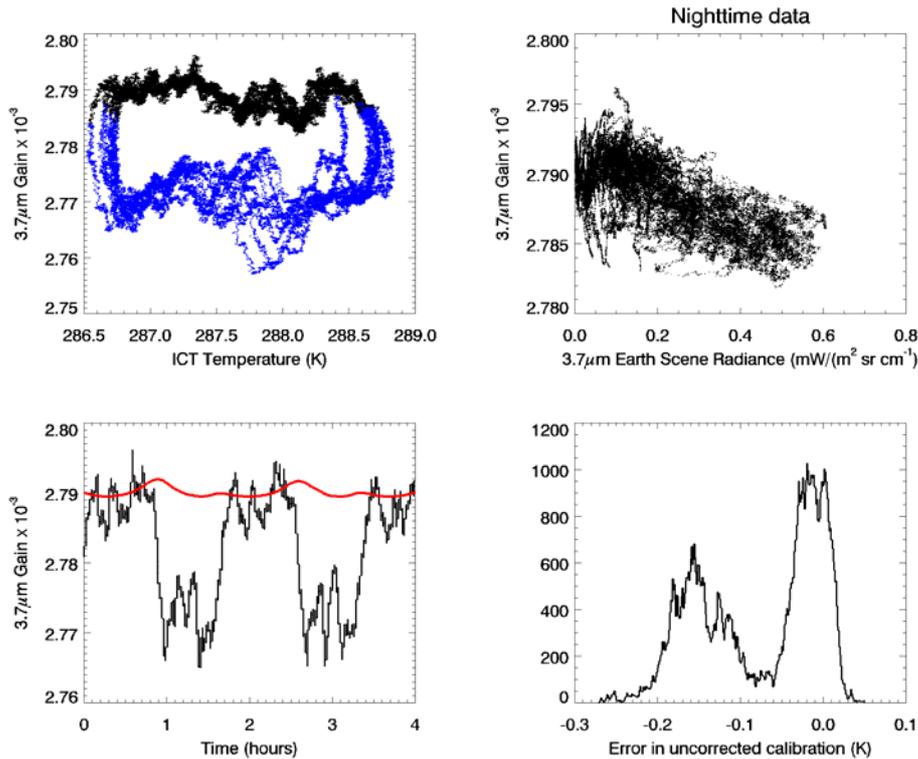
Figure 6. **The top left hand panel shows the raw (Mittaz et al.) gain as a function of the ICT temperature and the presence of a loop indicates the presence of Earthshine contaminating the calibration. The top right hand panel shows the strong correlation between the gain and the underlying scene radiances for the night time data which can be used to model out the Earthshine. The lower two panels show the result of modelling out the Earthshine with the red curve in the bottom left panel showing the variation of the corrected gain while the bottom right panel shows the scale of the bias introduced by the difference between the contaminated gain and the corrected one.**

DISCUSSION AND CONCLUSION

We have shown that the current AVHRR calibration is severely compromised and that a number of different effects have to be considered if the calibration is to be accurate. The major problem with the current 11 and 12 µm operational calibration is related to the contamination of the pre-launch data by the test chamber environment which causes large biases in the operational calibration. To solve this we have derived a physically meaningful calibration which can be refitted to an in-orbit calibration reference to provide a final AVHRR calibration. By using IASI as a reference we have then showed that this new calibration can match IASI to within 0.1K at nadir, significantly better than the scene dependent bias of up to 0.5K seen in the Walton et al. calibration. We have also showed that at least for the six month studied here that the calibration is stable over such a timescale. Remaining issues with the calibration of the non-linear 11 and 12 µm channels include a significant discrepancy between the IASI and AVHRR radiances for cold brightness temperatures at high scan angles but for scene temperatures used for surface temperature determinations even this is not a problem. Finally, using our new physical calibration we have also provided a correction to the effect of Earthshine contamination which affects the 3.7 µm channel.

Given the success of the new calibration and methodology shown above, in the future we intend to recalibrate the complete historic AVHRR data record. Since instruments such as IASI are relatively recent we will use satellites such as the (A)ATSR to refit the AVHRR to accurate TOA calibration sources which can take us back to 1991. Before that we intend to use a combination of using AVHRR overlap periods to propagate the calibration to beyond 1991, as well as investigate using simulated radiances using historic atmospheric models such as the ERA-40 analyses together with radiative transfer models such as the CRTM (Community Radiative Transfer Model) to provide top-of-atmosphere radiances with which to re-calibrate the AVHRR. A combination of these techniques validated over periods where accurate satellite data exists (such as the (A)ATSR) should then provide

a much better AVHRR data record extending back almost 30 years for the use of the climate community.

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