ON THIN ICE?
CONTAMINATION EFFECTS ON METEOSAT/SEVIRI CALIBRATION

Tim J. Hewison, Johannes Müller, Rebeca Gutiérrez-López
EUMETSAT, Eumetsat-Allee 1, D-64295 Darmstadt, Germany

Abstract

The inter-calibration of the infrared channels of the geostationary Meteosat-9/SEVIRI satellite instrument shows most channels are radiometrically consistent with Metop-A/IASI, which is used as a reference instrument. However, the 13.4 μm channel shows a cold bias of ~1 K in warm scenes, which changes with time. This has previously been shown to be consistent with the contamination of SEVIRI by a layer of ice ~1 μm thick building up on the optics, which modifies the spectral response functions and hence the weighting functions of channels in stronger atmospheric absorption bands, thus introducing an apparent calibration error. Analysis of the radiometer's gain using views of the on board black body source and cold space confirmed a loss consistent with transmission through a layer of comparable thickness, which also increases the radiometric noise – especially for channels near the 12 μm libration band of water ice. Inter-calibration, such as the Global Space-based Inter-Calibration System (GSICS) Correction, offers an empirical method to correct this bias.

During 2012-2013, the observed biases for the IR channels of SEVIRI on Meteosat-10 were found to change much more rapidly than for Meteosat-8 or -9. This was expected because Meteosat-10 was only launched on 5 July 2012 and the rate of outgassing and contamination is greater during the early period of a satellite's life. The availability of Metop-A/IASI during this period allows us to study the influence of this rapidly changing contamination in detail for the first time. The results show that not only is the 13.4 μm channel strongly influenced, but also that the shorter wavelength channels experience rapid changes in calibration bias. Although this effect is small (max ±0.5 K for the 3.9 μm channel), it changes in a sinusoidally-varying way, similar to the interference effects from thin films of ice with thickness of the order of the channels' wavelength. A simplified model is presented to characterise this bias and compared with observations from the first year of Meteosat-10 and 5 years of Meteosat-9 operations.

INTRODUCTION

The radiometric calibration of broad band channels of satellite instruments can be influenced by factors that modify the spectral response functions (SRFs). Most current infrared radiometers include calibration systems, typically using an onboard black body source and a view of cold space, which would appear to account for any such changes. However, a change in the instruments' SRF can modify the weighting function, which defines the vertical distribution of atmospheric emissions to which that channel is sensitive. This can introduce an apparent radiometric calibration error.

The inter-calibration of the SEVIRI imagers on Meteosat-8 and -9 with Metop-A/IASI revealed biases in the 13.4 μm channels, which grew larger with time and changed abruptly after decontamination procedures [Hewison *et al.,* 2013]. This supports the theory that the bias can be (at least partly) explained by a build-up of ice in the cold optics due to condensation of outgassing material from the spacecraft. This paper considers this theory of contamination and attempts to model its impact on the calibration bias of SEVIRI's infrared (IR) channels. The model predictions are compared with observations – both in the form of inter-calibration of SEVIRI with IASI, and by examination of SEVIRI's relative gain changes before and after decontamination procedures.

An example time series of the relative bias of the infrared channels of Meteosat-9/SEVIRI with respect to Metop-A/IASI is shown in Fig. 1. These GSICS *Standard Biases* correspond to radiance differences found with respect to the inter-calibration reference in typical clear sky conditions [Hewison *et al.,* 2013]. Most channels show small (<0.4 K) and stable biases during this period. However, the 13.4 μm channel shows a negative bias, which slowly grew larger until a spacecraft decontamination event took place in early December 2008, when the bias was reduced by about 0.7 K. It continued to degrade thereafter.

Like Meteosat-9, most channels of Meteosat-10 show small (<0.4K) biases (see Figure 2), except the 13.4 µm channel, which has a bias that grew from -0.4 to -2.7 K between decontamination events, when it was reset. However, variations in the bias of the shorter wavelength channels are also apparent – particularly the 3.9 µm channel, which appears to undergo periodic oscillations. Similar oscillations are also evident for Meteosat-9, albeit over a period of several years instead of weeks.

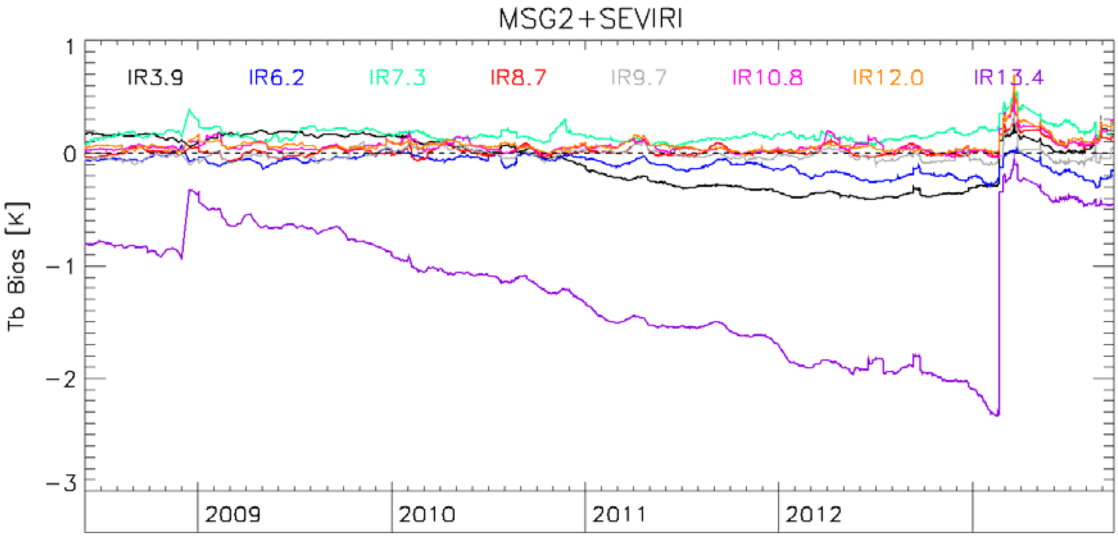

Figure 1: **Time series plot showing relative bias of IR channels of Meteosat-9/SEVIRI (MSG2) wrt Metop-A/IASI, expressed as brightness temperature difference for standard radiance scenes (corresponding to a 1976 US Standard Atmosphere with clear sky). Spacecraft decontaminations in Dec 2008 and Feb 2013 introduced step bias changes.**

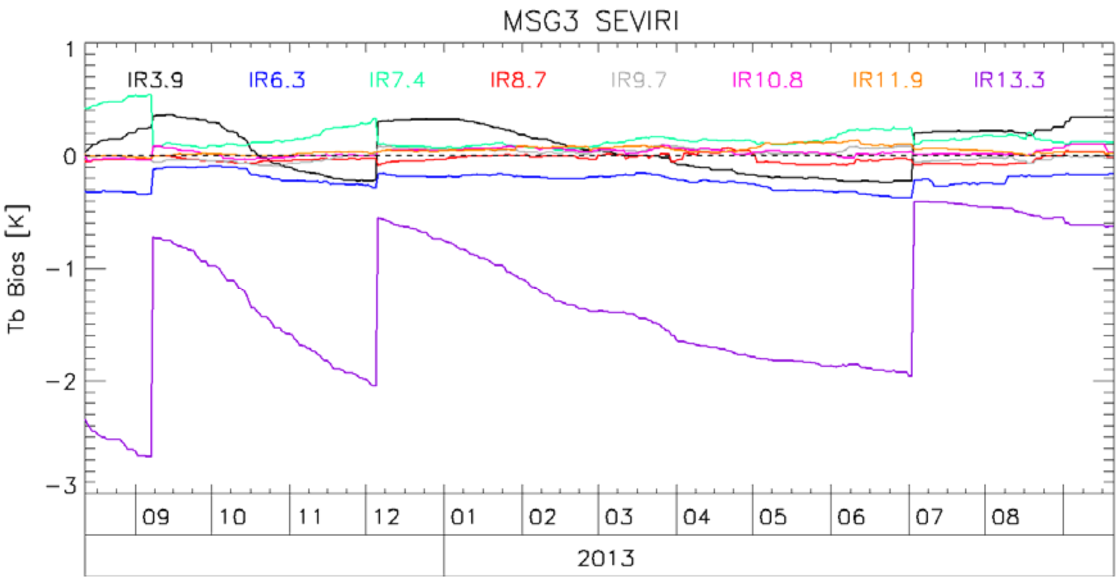

Figure 2: **As Figure 1, but for Meteosat-10/SEVIRI (MSG3).**
Decontaminations in September and December 2012 and July 2013 introduced step bias changes.

Decontaminations

Condensation of particle or chemical contamination on the cold optics of the SEVIRI affects the instrument's radiometric performance. Also, the passive cooling system is impacted by contamination, so that it loses its effectiveness and, in an extreme case, may not be able to maintain the instrument's operating temperature. Decontamination operations must be performed to ensure that the instrument remains within the acceptable mission limits. The process is relatively simple; however, it does take several days where nominal operations are not possible. Heaters are employed to warm the detector optics and the coolers, causing the contaminants to evaporate, after which the instrument is allowed to cool down back to 95 K. Several decontaminations have been performed on Meteosat-9 and -10, as listed in Table 1. This table also lists the mean changes in gain observed for the three detectors in each channel following each decontamination. The accumulation of contaminants on the cold surfaces slows down with time, as the abundance of such molecules decreases with mission time. The long wave channels are most affected by absorption, which peaks around the 12 µm ice librational band.

	Meteosat-9						*Meteosat-10*		
Date / *Channel*	*2006-02*	*2006-06*	*2006-12*	*2007-12*	*2008-12*	*2013-01*	*2012-09*	*2012-12*	*2013-07*
3.9 µm	+6%	+6%	+6%	+6%	+6%	+4%	+7%	+2%	+4%
6.2 µm	+21%	+8%	+6%	+10%	+7%	+19%	+20%	+14%	+15%
7.3 µm	+13%	+4%	+3%	+6%	+4%	+12%	+11%	+9%	+9%
8.7 µm	+8%	+6%	+4%	+6%	+3%	+8%	+8%	+8%	+8%
9.7 µm	+6%	+1%	+1%	+2%	+0%	+4%	+3%	+2%	+2%
10.8 µm	+44%	+22%	+14%	+23%	+16%	+45%	+45%	+35%	+36%
12.0 µm	+115%	+49%	+34%	+50%	+35%	+97%	+112%	+80%	+79%
13.4 µm	+66%	+27%	+23%	+30%	+23%	+57%	+75%	+40%	+46%

Table 1: **Gain Changes Measured Following Meteosat-9 and -10 Decontaminations.**

THEORY: ICE ABSORPTION EFFECT

The original hypothesis tested by Hewison and Müller [2013] is that the change in bias of the SEVIRI channels is due to a build-up of water ice, which condenses on the surfaces of the cold optics after outgassing from other material on the satellite. However, since the rates of outgassing and condensation are unknown, it is not possible to estimate the ice thickness on purely theoretic grounds. Furthermore, it is not known exactly where in the instrument optics the ice is likely to condense, although in SEVIRI, the first surfaces to trap contaminants are the optical bandpass filters inside the cold IR optical bench. The effect of contamination is difficult to assess because it depends on the optical surfaces that receive contaminants and their coatings' characteristics are not known. The contamination will affect both the gain of the associated channels, as well as their Spectral Response Functions (SRFs), which will influence the radiometric noise and bias of the instrument's final calibrated radiances.

Hewison and Müller [2013] concentrated on analysing how differential absorption by this ice layer modifies the instrument's SRF. Although much of this is compensated for in the calibration processes, whereby the instrument's view of cold space and a hot black body are used to derive its gain and offset, any unidentified changes in the SRF could bias the observed scene radiances. This process is illustrated in Figure 3, which compares the nominal SRF of Meteosat-9's 13.4 µm channel with that after convolving it with the transmission spectrum of a 2 µm thick layer of ice. The calibration process effectively normalises the SRF, so it appears to be approximately shifted by 2 cm^{-1} with respect to the original SRF. This illustrates why applying empirical shifts to the SRF can provide a good approximation to the channel's response to ice contamination.

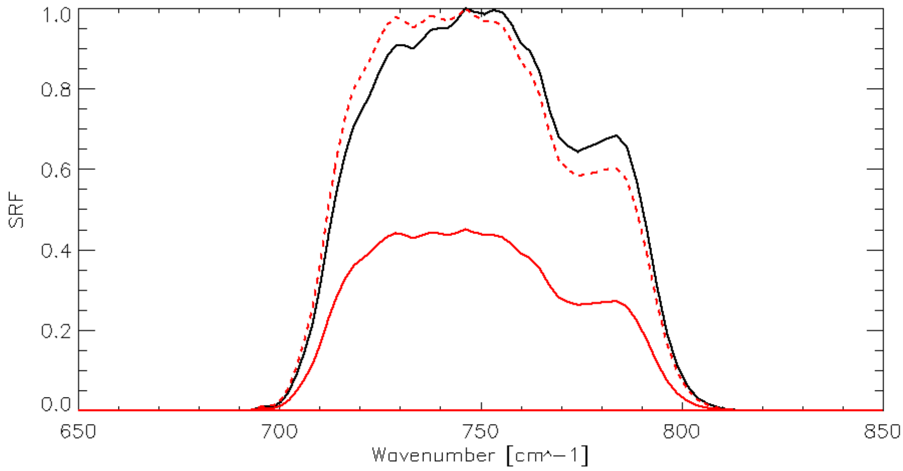

***Figure 3:* Spectral Response Functions of Meteosat-9 13.4 µm channel:**
Black solid line shows the nominal SRF, based on pre-launch tests at 95 K,
Red solid line shows the SRF convolved with transmission spectrum due to absorption by ice layer 2 µm thick,
Red dashed line shows the normalised SRF after 2 µm ice layer.

In this study we use the composite model of ice optical constants compiled from various observations by Warren and Brandt [2008]. Although these are strictly only valid at 266 K and are temperature dependent, no quantitative data was found for ice at temperatures close to those of SEVIRI's cold optics. Hewison and Müller [2013] analysed this absorption model to estimate the transmittance spectra of layers of various ice of thickness from 0.1 to 1.0 µm. These are shown in Figure 4, superimposed on the SRFs of the 8 IR channels of Meteosat/SEVIRI.

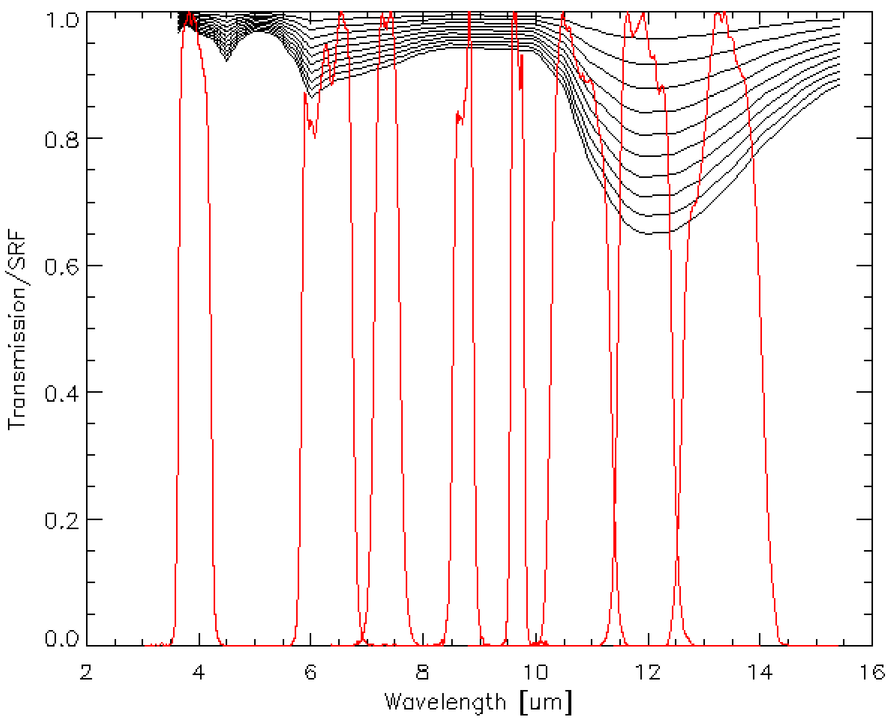

***Figure 4:* Transmittance spectra due to absorption by ice layers of different thicknesses (black): 0.1 to 1.0 µm layers (thickest layers have lowest transmittance) and Spectral Response Functions of Meteosat-8 infrared channels (red).**

Hewison and Müller [2013] analysed the impact of the absorption by ice layers on SEVIRI's calibration, showing the standard bias of the 13.4 µm channel was expected to grow linearly from 0 to -0.7 K as the ice thickness increased from 0 to 1 µm. It was also shown that absorption by the ice layer was not expected to have a significant impact on the calibration of the other channels.

THEORY: THIN FILM INTERFERENCE EFFECT

However, thin films of ice can also introduce interference effects, which can modify its transmittance – especially where its thickness approaches the wavelength of radiation. These were not accounted for in the analysis of Hewison and Müller [2013].

The expected pattern of these interference effects is illustrated in Figure 5 by considering the transmittance through a lossless dielectric layer of ice of different thicknesses on a planar slab, whose refractive index was assumed to be 1.8. These values were calculated following Born and Wolf [1999] using the refractive index of ice from Warren and Brandt [2008]. The values of transmittance predicted by this simple model would not be expected to be observed in practice, as the material and dielectric properties of the substrate are not known and the ice layer would not have a perfectly smooth surface, or be of uniform thickness.

Because the SEVIRI channels are relatively broad, interference effects can modify their SRFs as they have different impact at the extreme wavelengths across their response band. And changing the SRF of channels that are sensitive to atmospheric absorption, like the 13.4 μm channel, will change their *weighting function*, which will appear as an apparent calibration bias.

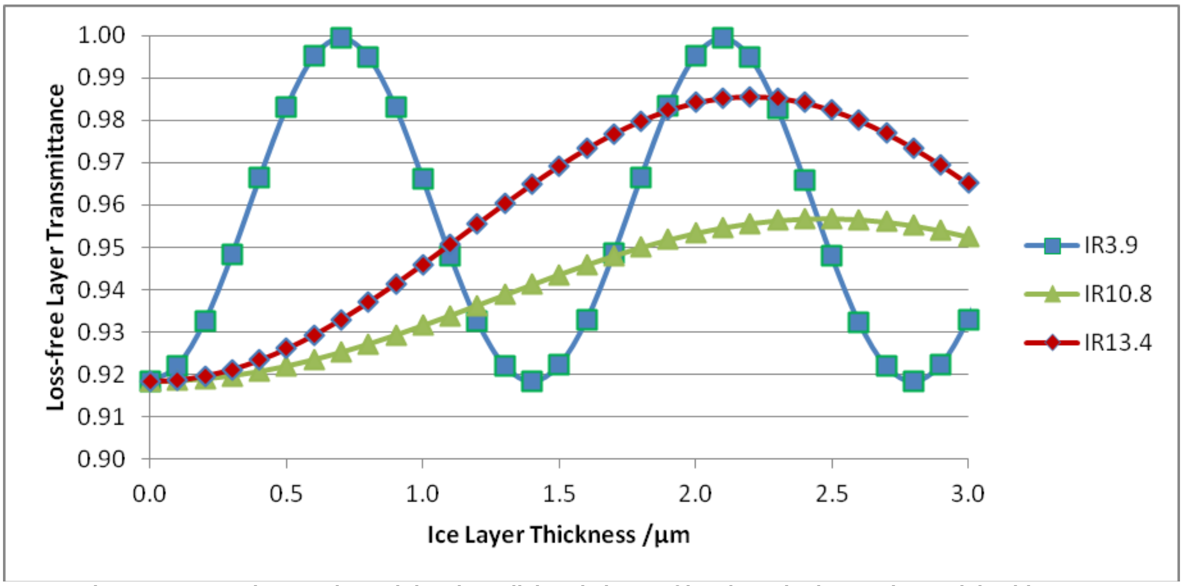

Figure 5: Transmittance through lossless dielectric layer of ice deposited on a planar slab with n=1.8.

The characteristic sinusoidal variation shown in Figure 5 follows the same pattern as the observed bias changes in SEVIRI's 3.9 μm channel (and, to a lesser extent, 6.3 and 7.4 μm channels) shown in Figures 1 and 2, which appear to undergo periodic oscillations and abrupt changes during decontamination events. The period of these oscillations is a function of the age of the satellite as well as the wavelength of the channel in question. In the case of IR3.9, the bias reverts back to +0.3 K after each decontamination, then continues to oscillate about a nominal value of +0.15 K with a magnitude of ± 0.3 K.

This pattern of bias oscillations was most obvious for Meteosat-10, where, for the first time, it was possible to monitor the bias by inter-calibration against IASI during the first months of operation, when the rate of outgassing and contamination is at its highest.

It can be seen in Figure 2 that the bias of the Meteosat-10 13.4 μm channel changed by -1.4 K in the last three months of 2012 prior to the decontamination in December. Comparisons with the analysis of Hewison and Müller [2013] and the gain changes shown in Table 1 suggest there was an ice thickness of ~2 μm at this time. As illustrated in Figure 5, the transmission of the ice layer is expected to reach a maximum around this ice thickness. The rapid removal of this layer would result in the abrupt change in the bias of IR3.9 observed in Figure 2.

Similarly, the observed change during the September 2012 decontamination implies ~3 µm ice had accumulated. However, this time, Figure 5 suggests ice transmission would revert back to values expected with minimal contamination, as this thickness corresponds to the channel's wavelength in the ice layer, resulting in constructive interference. Indeed Figure 2 shows a very small change in the bias of IR3.9 at that time. However, the thin-film interference theory, as illustrated in Figure 5, suggests the bias of IR3.9 would be expected to undergo two full oscillations over the period from launch to this first decontamination. These are not evident in Figure 2.

Looking into the results of the onboard blackbody measurement, similar patterns can be found. In Figure 6, the 3.9 µm channel shows a behaviour that is different from the others (10.8 µm channel and 13.4 µm channel are also shown). Just after SEVIRI's activation the gain rises briefly and then falls rapidly until the decontamination in September 2012. In comparison with Figure 5, this would indicate that at the point the ice thickness is around a turning point for the transmission. Considering the fact that the gain of the 12.0 µm channel nearly doubles after the September 2012 decontamination, there is a strong case for an ice thickness beyond 2 µm. This is supported by the analysis of Hewison and Müller [2013] and the discussion above. In contrast, the longer wavelength channels' gains show only monotonous behaviour in Figure 6. After the September 2012 decontamination, the 3.9 µm channel gain starts decreasing with the accumulation of contaminants until October, when it turns and starts increasing. However, the 10.8 µm and 13.4 µm channels' gains continue falling as the absorption by the contaminant is much more important for these channels than at 3.9 µm (Figure 4).

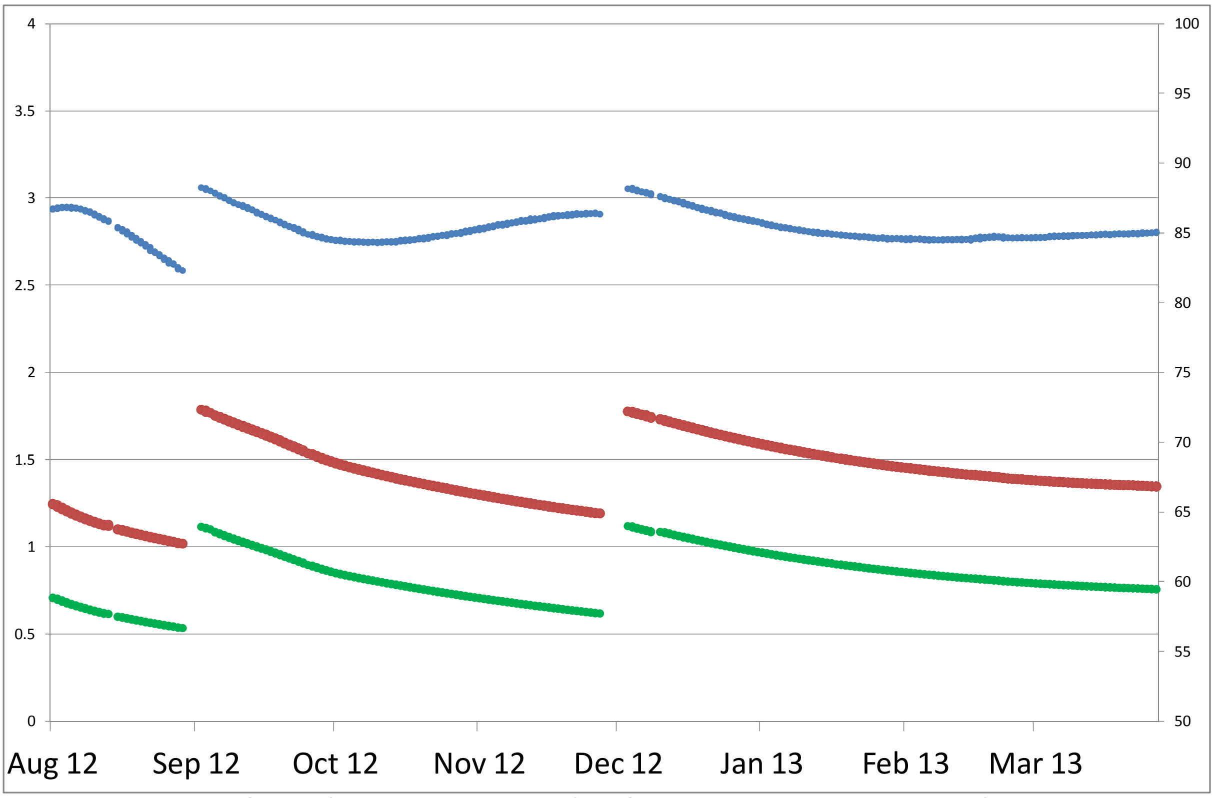

Figure 6: **Time Series of *Reduced Gain* derived from SEVIRI blackbody measurements of Meteosat-10.**
(The reduced gain is blackbody derived gain divided by the adjustable electronic amplification onboard.)
This allows comparing blackbody measurements taken at different electronic settings [DC/mWm^{-2}sr^{-1}(cm^{-1})$^{-1}$]:
3.9 µm channel, blue (left axis), 10.8 µm, green (right axis), 13.4 µm green, (right axis).
Note that the scale for IR 3.9 is different from the other channels.

CONCLUSIONS

The radiometric calibration of broad band channels of satellite instruments can be influenced by factors that modify the spectral response functions (SRFs). Although most current infrared radiometers include calibration systems, typically using an onboard black body source and a view of cold space, a change in the instruments' SRF can modify the weighting function, which defines the vertical distribution of atmospheric emissions to which that channel is sensitive. If, as is usually the case, these changes are not accounted for by the users, they can appear as scene-dependent radiometric biases, which can be addressed empirically by applying corrections derived from inter-calibration, such as the GSICS Corrections [Hewison *et al.*, 2013].

Changes in the gain of Meteosat/SEVIRI's IR channels and the bias of its 13.4 µm channel (by inter-calibration with Metop/IASI) were shown to be consistent with absorption by a ~1-2 µm thick ice layer building up on the optics during the period between decontaminations [Hewison and Müller, 2013]. This paper has extended the previous analysis to account for observed changes in the 3.9 µm channel by including the interference effect of thin films of ice. These can also modify the SRFs of this relatively broad channel and introduce apparent calibration biases, which oscillate with increasing ice thickness. However, it is difficult to quantify the bias thus introduced as the characteristics of the ice layer and underlying surface and not known.

This analysis provides an example of how inter-calibration can be a powerful tool in the diagnosis of the root causes of apparent radiometric errors in satellite instruments. A similar analysis could also be undertaken for other satellite instruments with broad spectral response functions, such as HIRS – especially those where inter-calibration with respect to hyperspectral reference instruments is possible. This study also highlights the importance of the commissioning period to allow these studies to be conducted.

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