Ice Contamination of Meteosat/SEVIRI Implied by Inter-Calibration Against Metop/IASI

Tim J. Hewison, *Member, IEEE*, Johannes Müller

***Abstract*— The inter-calibration of the infrared channels of the geostationary Meteosat/SEVIRI satellite instruments 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 is shown to be consistent with the contamination of SEVIRI by a layer of ice ~1 µm thick building up on the optics, which is believed to have condensed from water outgassed from the spacecraft. This ice 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 confirm 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.**

***Index Terms*— Calibration, Decontamination, Earth Observing System, Infrared image sensors, Radiometers, Satellites**

I. Introduction

The radiometric calibration of broad band channels of satellite instruments can appear to 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 grow larger with time and change abruptly after decontamination procedures [1]. 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. These 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 [1]. 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 grows larger until a spacecraft decontamination event takes place in early December 2008, when the bias was reduced by about 0.7 K. It continues to degrade thereafter. The fact that the bias does not return to zero immediately after the decontamination suggests either some contaminants remain after the decontamination or an inaccurate representation of the nominal SRF.

Variable biases of 1-2 K have also been observed in the 13.3 μm channel of GOES-12 [1]. An analysis of the possible causes came to the conclusion that it was due to the failure of Imager anti-ice heater as well as erroneous characterization of the SRF during pre-launch testing [2].

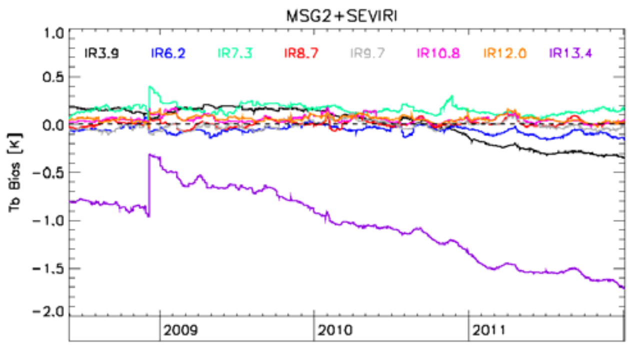

Fig. 1. Example time series plot showing relative bias of IR channels of Meteosat-9/SEVIRI (MSG2) wrt Metop-A/IASI, expressed as brightness temperature difference for standard radiance scenes (corresponding to a 1976 US Standard Atmosphere with clear sky). A spacecraft decontamination in Dec 2008 reduced the bias of the 13.4 µm channel, which subsequently continued to deteriorate.

A. Decontamination Procedures

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-8 and -9 since they were launched on 2002-08-28 and 2005-12-21, as listed in Tables 1 and 2, respectively. These tables also list 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. After 2008, the impact of contaminations on the instrument or cooler performance was so far not considered large enough to justify a mission outage for a further decontamination campaign. However, this does not exclude potential decontaminations in the future.

The long wave channels are most affected by contamination, which peaks around the 12 μm ice librational band. The gain increases observed following decontaminations are accompanied by a corresponding reduction in the radiometric noise, as shown in Table 3. However, as the radiometric noise level is only recorded to two decimal places, there is greater uncertainty in their relative changes.

Similar decontamination procedures are conducted for the IASI [3], although the build-up of ice only increases its radiometric noise, without introducing an apparent calibration bias, because of its channels' high spectral resolution.

TABLE 1
GAIN CHANGES MEASURED FOLLOWING METEOSAT-8 DECONTAMINATIONS.

Date / *Channel*	*2003-03*	*2003-08*	*2004-01*	*2005-01*	*2006-01*	*2008-01*
3.9 µm	+10%	n/a	+6%	+9%	+7%	+9%
6.2 µm	+24%	n/a	+7%	+12%	+9%	+13%
7.3 µm	+13%	n/a	+3%	+5%	+4%	+6%
8.7 µm	+10%	n/a	+4%	+6%	+5%	+6%
9.7 µm	+11%	n/a	+1%	+2%	+1%	+2%
10.8 µm	+52%	n/a	+12%	+19%	+14%	+18%
12.0 µm	+140%	+144%	+27%	+41%	+30%	+38%
13.4 µm	+101%	n/a	+20%	+30%	+22%	+33%

TABLE 2
GAIN CHANGES MEASURED FOLLOWING METEOSAT-9 DECONTAMINATIONS.

Date / *Channel*	*2006-02-*	*2006-06-*	*2006-12*	*2007-12*	*2008-12*
3.9 µm	+6%	+6%	+6%	+6%	+6%
6.2 µm	+21%	+8%	+6%	+10%	+7%
7.3 µm	+13%	+4%	+3%	+6%	+4%
8.7 µm	+8%	+6%	+4%	+6%	+3%
9.7 µm	+6%	+1%	+1%	+2%	+0%
10.8 µm	+44%	+22%	+14%	+23%	+16%
12.0 µm	+115%	+49%	+34%	+50%	+35%
13.4 µm	+66%	+27%	+23%	+30%	+23%

TABLE 3
RADIOMETRIC NOISE LEVELS MEASURED BEFORE AND AFTER 2008 DECONTAMINATIONS OF METEOSAT-8 AND -9.

Date / *Channel*	Meteosat-8 2008-12		*Meteosat-9 2008-12*	
	Before	After	Before	After
3.9 µm	0.11 K	0.11 K	0.10 K	0.10 K
6.2 µm	0.04 K	0.04 K	0.04 K	0.04 K
7.3 µm	0.06 K	0.06 K	0.05 K	0.05 K
8.7 µm	0.07 K	0.07 K	0.07 K	0.07 K
9.7 µm	0.11 K	0.11 K	0.11 K	0.11 K
10.8 µm	0.06 K	0.06 K	0.06 K	0.06 K
12.0 µm	0.13 K	0.11 K	0.12 K	0.10 K
13.4 µm	0.22 K	0.17 K	0.25 K	0.21 K

II. Theory

The basic hypothesis to be tested here is that the change in bias of the SEVIRI channels is due to a build-up of ice, which condenses on the surfaces of the cold optics after outgassing from other material on the satellite. This process has been known about since at least the time of Meteosat First Generation [4]. This material is most likely to be water ice [5]. 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 [6]. 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.

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 Fig. 2, 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 normalizes the SRF, so it appears to be approximately shifted by $2\ \mathrm{cm}^{-1}$ 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.

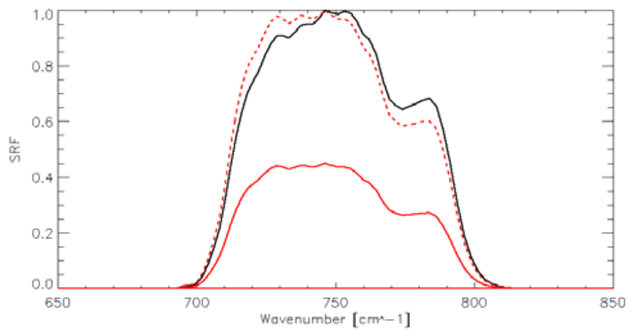

Fig. 2. Spectral Response Functions of Meteosat-9 13.4 µm channel:

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 of ice layer 2 µm thick,

Red dashed line shows the normalised SRF after 2 µm ice layer

The radiance, L_i, measured in channel i of an uncontaminated instrument, with SRF, $r_{i,\nu}$, viewing a scene with radiance spectrum, L_ν, is:

$$L_i = \frac{\int L_\nu r_{i,\nu} d\nu}{\int r_{i,\nu} d\nu} \tag{1}$$

Viewing the hot black body, with radiance $B_\nu(T_H)$, the uncontaminated instrument sees a radiance, $L_{i,H}$:

$$L_{i,H} = \frac{\int B_\nu(T_H) r_{i,\nu} d\nu}{\int r_{i,\nu} d\nu} \tag{2}$$

Viewing this scene when the SRF is convolved with an ice transmittance, τ_ν, the radiance, $L_{i,H}'$, is:

$$L'_{i,H} = \frac{\int B_\nu(T_H) r_{i,\nu} \tau_\nu d\nu}{\int r_{i,\nu} \tau_\nu d\nu} \tag{3}$$

Assuming the space view radiances remain zero, the apparent gain of the instrument, $G_i = L'_{i,H}/L_{i,H}$, is applied to calculate the apparent radiance of a scene, L_i':

$$L_i' = \frac{\int L_\nu r_{i,\nu} \tau_\nu d\nu}{\int r_{i,\nu} \tau_\nu d\nu} \frac{L'_{i,H}}{L_{i,H}} \tag{4}$$

A. Ice Transmittance Model

In this study we use the composite model of ice optical constants compiled from various observations by Warren and Brandt [7]. 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.

Fig.3 shows calculated transmittance spectra of layers of various ice of thickness from 0.1 to 1.0 µm, superimposed on the SRFs of the 8 IR channels of Meteosat/SEVIRI.

Additionally, thin films of ice can introduce interference effects, which can modify its transmittance – especially where its thickness approaches the wavelength of radiation. The effect of thin ice layers was analyzed for channels of Landsat/TM in the reflected solar band [8]. However, these have not been accounted for in this analysis, as the optical characteristics of the underlying surface are not known.

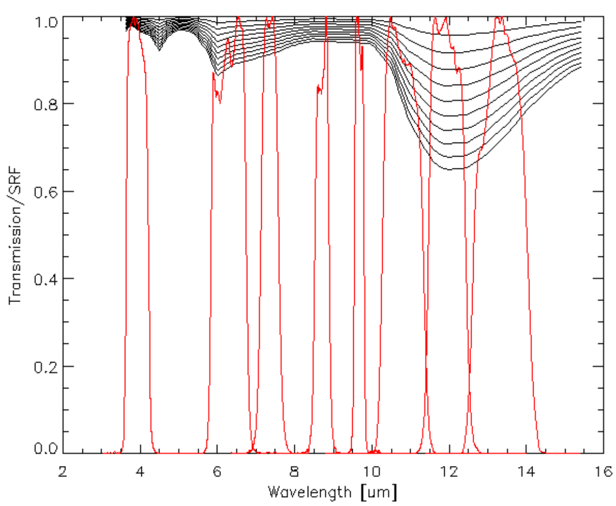

Fig. 3. Transmittance spectra of ice layers of different thicknesses (black): 0.1 to 1.0 µm layers (thickest layers have lowest transmittance) and Spectral Response Functions (SRFs) of Meteosat-8 infrared channels (red).

III. Predicted and Observed Gain and Bias Changes in Meteosat/SEVIRI

Modifications to an instrument's SRF will introduce an apparent bias, which will be scene-dependent – not just varying with radiance, but also with the scene spectra. Usually the bias will be worse for clear sky scenes with stronger spectral contrasts and smaller for overcast scenes, which are closer to black body spectra.

To evaluate the difference between L_i' and L_i, a range of different radiance spectra, L_ν, have been considered, and the calculation repeated over the range of ice transmittance spectra, $\tau_{i,\nu}$, given in Fig. 3. This was first performed for modeled radiance spectra corresponding to a US Standard Atmosphere in clear sky conditions, for which the GSICS s*tandard bias* [1] shown in Fig. 1 is evaluated. The calculation was also repeated with the addition of an optically thick layer of cloud with tops at 194 hPa, which produces brightness temperatures of ~216-222 K. The radiative transfer simulation was performed using v11.1 LBLRTM with the HITRAN 2004 database with v2.0 AER updates using the standard atmospheric profiles supplied with LBLRTM [9]. The resulting biases, L_i'-L_i, are expressed in terms of brightness temperatures in Fig. 4.

In clear skies only the 13.4 µm channel, which spans one side of an ice librational band, is predicted to have a significant sensitivity to ice contamination. This is because the ice modifies the SRF, and hence weighting function, of this channel, which lies on the edge of an atmospheric CO_2 absorption band. The resulting ~0.7 K change in the *standard bias* of the 13.4 µm channel bias for an ice thickness of 1 µm is consistent with the changes observed in the inter-calibration of Meteosat-9/SEVIRI during the 2008 decontamination. Since the decontamination, the bias in the 13.4 µm channel has continued to increase at a rate of -0.4 K/yr.

The only other channel with a statistically significant trend in Fig. 1 is 3.9 µm (-0.1 K/yr), which was not expected from the model results shown in Fig. 4. This may be due to thin film effects, which can influence the transmittance of ice layers in this channel and cause non-monotonic bias changes due to the build-up of ice layers with thickness of the order of wavelength. The longer wavelength of the 13.4 µm channel means thin film effects will not become important until the thickness of the contamination layer approaches a fraction of its wavelength.

Inter-calibration results after each decontamination procedure confirm the bias in both these channels briefly return to values comparable to those found after the previous decontaminations, but then continue to degrade. Meteosat-9 was launched later than Meteosat-8, so it is expected to have a higher rate of outgassing and contamination, as witnessed by the higher rate of change of gains during decontaminations early in each spacecraft's life, shown in Tables 1 and 2. However, the 13.4 μm channel of both instruments showed jumps of ~ +0.7 K during their most recent decontamination procedures of December and January 2008, respectively, despite both taking place approximately 1 year after the previous decontaminations.

Scenes with high cloud produce radiance spectra closer to those of a black body at the cloud top temperature (216 K). In these cases, a small positive brightness temperature bias at 13.4 μm is predicted, and a small negative bias is introduced in the 10.8 μm channel. However, because of the non-linear nature of the Planck function, these biases are very small when converted into radiances. In practice, it would not be possible to detect such changes at low scene radiances because they are close to the standard uncertainty of the inter-calibration at these scene radiances – and 0.25 K and 0.08 K for the 10.8 μm and 13.4 μm channels, respectively [10].

The calculations gave very similar results when repeated using Meteosat-8 SRFs and when using radiances modeled from tropical and mid-latitude summer profiles. When cloud was added to the atmospheric profiles at low- and mid-levels, the predicted biases varied within the ranges shown in Fig. 4 for scenes with clear sky and high cloud.

Table 2 shows a 35% change in gain in the 12.0 μm channel was measured following the 2008 decontamination of Meteosat-9, which implies from Fig. 3 that the ice layer was ~1 μm thick, similar to that required to produce a change in bias of ~0.7 K for typical scene radiances, as shown in Fig. 4. Other channels are less sensitive to ice contamination, so there is more uncertainty in implying ice thickness from their gain changes. Nevertheless, the observed patterns of gain changes of the most recent decontaminations shown in Table 1 and 2 are broadly consistent with ice thicknesses of ~1 μm and the relative changes between channels on other decontaminations follow the same pattern as the ice transmission spectra shown in Fig. 3.

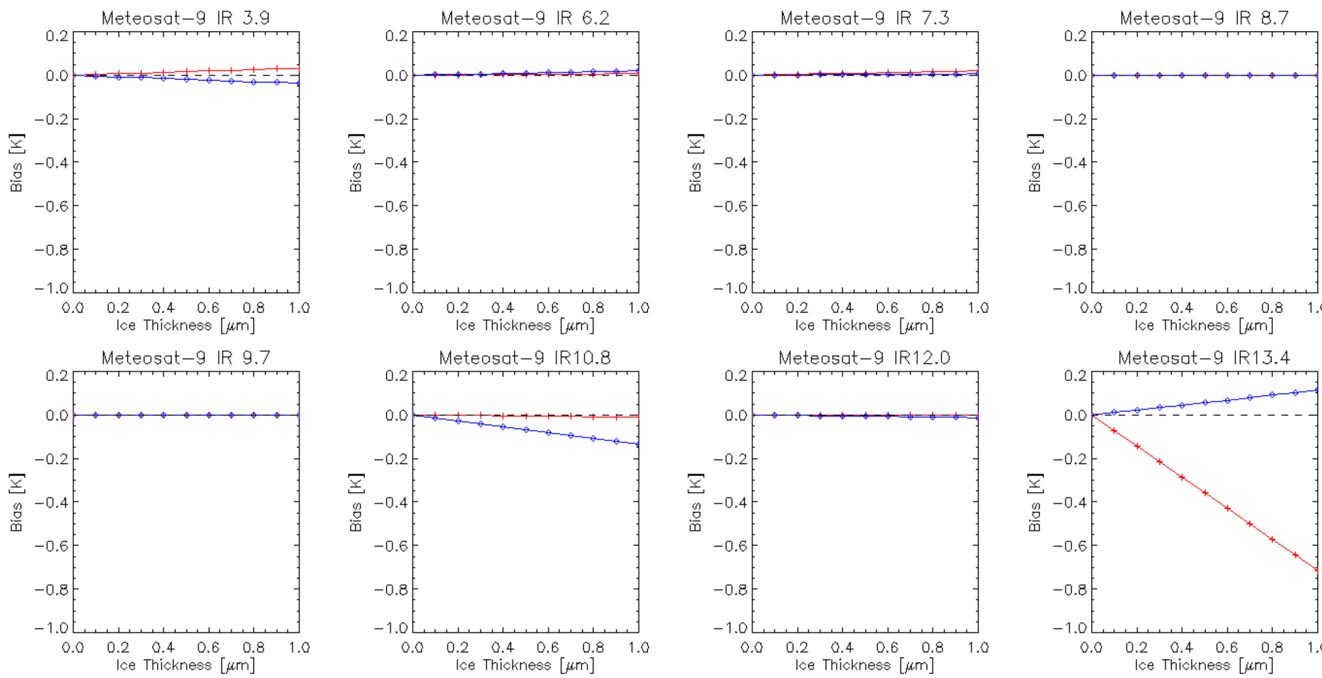

Fig. 4. Bias in brightness temperatures modeled by modifying Meteosat-9's SRF by the transmittance of different thicknesses of ice. Solid lines show the predicted differences in brightness temperature compared with the uncontaminated instrument, accounting for calibration gain changes, based on calculation in US Standard Atmosphere with clear skies (red line with crosses) and thick cloud with tops at 194 hPa (blue line with diamonds).

Warren and Brandt estimated the uncertainty on the imaginary part of the refractive index of ice in their compilation as ranging from 2-20% over these wavelengths [7]. For weak to moderately absorbing ice layers, the uncertainty on the gain change and apparent calibration bias will be approximately linear with the uncertainty in the absorption coefficient. We therefore assume the standard uncertainty due to the refractive index model is ~25%, accounting for the extrapolation of the model to low temperatures.

IV. Conclusions

The radiometric calibration of broad band channels of satellite instruments can appear to 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 radiometric biases, which can be addressed empirically by applying corrections derived from inter-calibration, such as the GSICS Corrections [1].

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. 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) are shown to be consistent with contamination of its optics by the build-up of an ice layer ~1 μm thick during the period in 2008 between decontaminations. The bias of this channel measured by the end of 2011 suggests the ice may be twice this thick. However, the noise levels of the instrument remain within the required levels, so no further decontaminations have been conducted so far.

It may be possible to extend the simple model presented here to account for observed changes in the 3.9 μm channel by including thin film effects. Furthermore, 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.

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Tim J. Hewison (M'96) received the Ph.D. doctorate in meteorology from the University of Reading, Reading, UK in 2006, based on his thesis on the use of ground-based microwave radiometers for atmospheric temperature and humidity profiling.

He is currently a Meteorological Scientist at EUMETSAT, Darmstadt, Germany, concentrating on the calibration of current, past and future satellite instruments. He also currently chairs the Research Working Group of the Global Space-based Inter-Calibration System (GSICS).

Johannes Müller received his Doctor of Natural Science from the University of Cologne, Cologne, Germany in 1991 for his thesis on the ground calibration of a satellite radiometer. He worked for several research organizations as well as industry before joining EUMETSAT in 2005 as an Instrument Data Processing Engineer.