SATTELITE INTERCALIBRATION OF IR WINDOW RADIANCE OBSERVATIONS

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ABSTRACT

The paper provides an outline of a satellite intercalibration technique applied to IR window measurements by Meteosat-6 and NOAA-14 AVHRR (channels 4 and 5) and channel 4 of the GOES-8 imager. The goal is to arrive at an intercalibration of the IR window channels within about 1 K which is the typical error claimed for current operational satellite calibration. This can only be achieved if differences in observed target areas, viewing geometry, spectral response, and collocation in time and space are properly considered and corrected for. The intercalibration of the different IR window observations provides an agreement of the order 1-2 %, corresponding to about 1-2 K for typical surface temperatures.

INTRODUCTION

Quantitative application of satellite observations requires the absolute calibration of the observed raw radiance data. Calibration techniques of the thermal IR window channels (about 10.5 – 12.5 μm) of the meteorological satellites rely on onboard calibration employing a blackbody (e.g. Menzel et al., 1981, Weinreb et al., 1997) or on vicarious techniques, where calculated radiances are associated with raw measurement units (e.g. Schmetz, 1989, van de Berg et al., 1995, Gube et al., 1996).

A satellite intercalibration is beneficial for two reasons:

i. intercalibration will identify problems and increase the confidence in the operational calibration of individual satellites, i.e. intercalibration will serve as a monitoring tool.

ii. intercalibration provides the basis for a normalised calibration which is a prerequisite for the derivation of global products from different satellites. Normalisation is to be done with respect to a particular satellite, where a polar orbiter due to its eventually global coverage is best suited. This is being done in support of the International Satellite Cloud Climatology Project (ISCCP) where geostationary IR radiance observations are normalised to polar orbiting AVHRR measurements in the IR window (Desormeaux et al., 1993).

This paper presents a calibration of the Meteosat IR channel from polar orbiter and GOES radiance data, which is then used for comparison with the operational IR calibration of Meteosat. The usefulness of satellite intercalibration in the IR window region has earlier been demonstrated by Beriot et al. (1982).

THE PROBLEM

Any satellite intercalibration compares the radiances over a well-defined area called the calibration target. Ideally, these two measured radiance values are identical, which would imply that both satellites have identical radiometers, viewing angle, and calibration. In practice, any two measurements differ because of the following reasons:
The two satellites do not have the same spectral response. As the measured radiance is the integral over the actually emerging radiance folded with the filter response function, different radiances are measured by each satellite

\[ R(\text{measured}) = \frac{\int R(\Theta) \Phi_v \, dv}{\int \Phi_v \, dv} \]  \hspace{1cm} (1)

with 
- \( R \): radiance at the top of the atmosphere in the direction \( \Theta \) of the satellite
- \( \Phi_v \): filter response function
- \( v \): wavenumber

The satellites do not view the target at exactly the same time. Even small time differences between the views of a given target might mean that surface temperatures and/or atmospheric conditions (e.g., clouds) have changed. In such a case, the radiances are not comparable.

The satellites do not view the target with the same spatial resolution. For instance, the Meteosat IR window has a spatial resolution of about 5 km x 5 km at the subsatellite point, NOAA AVHRR has a 1 km x 1 km resolution, and the GOES-8 imager has a nadir ground resolution of 4 km x 2.3 km. A sensible comparison of the measurements of these instruments must therefore be based on a larger number of pixels since this minimises uncertainties due to collocation errors and time differences. The area should display a rather uniform radiation field to allow averaging over pixels of different ground resolutions.

The satellites do not view the same scene under the same viewing angle. For channels sensing the troposphere, the observed radiance typically decreases with satellite zenith angle, an effect which is usually known as "limb darkening." For the Meteosat IR window channel the difference between nadir view and a 70° degree viewing angle can amount to up to 7 K (Menzel et al., 1993).

A PRACTICAL METHOD

Clear Radiance Observations

In order to overcome some of the sampling problems discussed above, only cloudfree ocean areas are selected as intercalibration target areas. This ensures a spatially rather homogeneous surface, which gives similar results when averaged over various pixels sizes (see (ii) in the above list). Small time differences (see (ii) in the above list) between the two satellite measurements are also not too serious for open ocean areas, as the sea surface temperature (which is the main contribution to the IR window signal) is practically constant on this time scale. Also, the correction for different spectral response (see (i) in above list) can be best modeled for a given scene, so that different, scene-dependent corrections do not need to be considered and properly accounted for.

Clear radiances are obtained from the satellite images by a scene classification which in our case is performed on a pixel basis (Lutz, personal communication). The method resembles the threshold technique derived by Saunders and Kriebel (1988). Only pixels classified as completely clear are retained for the comparison. Theoretically, a scene classification of the satellite data with the better resolution should be sufficient; due to (even small) time differences of the two satellite views, however, there might occur cases of clouds moving into an area which is classified as cloudfree for one satellite, but which is then of course cloudy for the other satellite. Thus, the pixel classification is done for both of the two satellites: A valid target area is defined by a given area which is a cloudfree ocean area in both satellite images.

Spectral Response

In general, satellite intercalibration should be restricted to a comparison of radiances from similar channels; even small differences in the spectral response lead to different measurements which must be corrected in order to achieve the required accuracy. Figure 1 and Figure 2 show the spectral response of the Meteosat-6 IR channel, the two infrared window channels onboard AVHRR, and of the infrared window channel 4 onboard the GOES-8 imager.
Fig. 1. Spectral response functions for Meteosat-6 IR and for channels 4 and 5 of the AVHRR instrument onboard NOAA-14.

Such corrections can be inferred from radiative transfer calculations that consider the spectral response function of the different instruments. Ideally, the radiative transfer model should be fed with the actual profiles of temperature and relevant absorbers over the calibration targets, as could e.g. be provided by short-term forecast data from a numerical weather prediction model. The spectral response correction, however, can be simplified since radiative transfer simulations with a detailed model for a large number of atmospheric profiles show that, at least for IR window channels, the relationship between radiances of similar satellite channels can be described by simple linear functions (Tjemkes and Schmetz, 1997). The model results also show that the actual correction function remains practically constant for viewing angles between 0° and 50°, so that a correction which is independent on viewing angle can be achieved. It is, however, important that both instruments have the same viewing angle since the limb darkening is not negligible. Figure 3 shows an example of the functions derived for Meteosat-6 and NOAA-14 AVHRR channel 4 for one viewing angle for a given set of standard atmospheric profiles.

Nadir simulations for TIGR dataset

Fig. 3. Filter function correction for NOAA-14 AVHRR channel 4, viewing angle is 0°. Dots show the radiation model results for a set of standard profiles. TIGR stands for "Thermodynamic Initial Guess Retrieval".
The correction functions are defined as linear relations between Meteosat-6 IR and the three other instruments used in this study:

\[
\text{Meteosat-6 Radiance} = \text{intercept} + \text{slope} \times \text{measured radiance (AVHRR/GOES)}
\]  
(2)

Table 1 provides the coefficients.

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>NOAA-14 AVHRR channel 4</th>
<th>NOAA-14 AVHRR channel 5</th>
<th>GOES-8 imager channel 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>intercept</td>
<td>4.5549</td>
<td>-4.7486</td>
<td>5.3129</td>
</tr>
<tr>
<td>slope</td>
<td>1.0393</td>
<td>0.9830</td>
<td>1.0380</td>
</tr>
<tr>
<td>intercept error</td>
<td>3.52 \times 10^{-2}</td>
<td>3.92 \times 10^{-2}</td>
<td>4.06 \times 10^{-2}</td>
</tr>
<tr>
<td>slope error</td>
<td>4.98 \times 10^{-4}</td>
<td>4.69 \times 10^{-4}</td>
<td>5.80 \times 10^{-4}</td>
</tr>
</tbody>
</table>

Viewing Geometry

Different satellite viewing angles impact the radiances at the top of the atmosphere. In the infrared window channels that are subject of this paper, one generally observes a limb darkening, i.e. a decrease of radiance with increasing viewing angle. In order to ensure similar viewing geometries only such targets are retained for the comparison where the two viewing angles do not differ by more than 5 degrees.

It may be argued that even the same value of viewing angle for the different satellites is an insufficient precondition since the atmospheric paths are different, and the atmosphere may vary in horizontal direction to cause different atmospheric effects. A detailed analysis of one intercalibration case, however, has shown that the horizontal variability in the atmosphere does not significantly affect the results. This point will be further discussed in the next section.

INTERCALIBRATION RESULTS

This method has been applied to satellite data obtained on 20 June 1997. The 1530 UTC Meteosat image was compared to NOAA-14 data obtained during the afternoon orbit across the Atlantic ocean and to the 1445 UTC GOES-8 image. Clear sea surface pixels were extracted from the image data, and selected target areas of 3 x 3 NOAA or GOES pixels, respectively, were chosen as comparison points with the condition that all these pixels have been classified as cloud-free.

For each of these comparison points the measured NOAA and GOES radiance, respectively, is corrected for the differences in filter response according to the coefficients of Table 1. This gives an inferred Meteosat-6 radiance which is related to the observed count, thus resulting in a local calibration coefficient \( \alpha \):

\[
\alpha = \frac{\text{inferred Meteosat-6 Radiance}}{\text{Meteosat Count} - \text{Meteosat Space Count}}
\]  
(3)

A Meteosat "count" is the engineering unit of the radiometer; each measurement lies in the range of 0-255 counts. The "Space Count" is the radiometric offset of the Meteosat IR channel, and it amounts to 5 counts for Meteosat-6. The final calibration coefficient is then simply the mean over all local coefficients.

In order to quantify the quality of the final calibration coefficient, this coefficient was compared to the operational Meteosat-6 calibration coefficient as derived by the EUMETSAT MPEF (Meteorological Products Extraction Facility). The MPEF uses a vicarious technique for calibration, which is described in Gube et al. (1996). For a
comparison to the operational MPEF calibration coefficient, the inferred radiances have to be expressed as "W/m²/sr", which for a given satellite channel is only a constant conversion factor.

Meteosat-6 IR versus AVHRR Channels 4 and 5

The NOAA-14 data were available in the GAC (global area coverage) format which – compared with the original AVHRR data – is of a reduced ground resolution of 4 km at nadir. The NOAA orbit was across the Atlantic Ocean, and the measurements of the two satellites were taken within 10 minutes over each target. The condition of similar (within 5 degrees) viewing geometry limits the target areas to strips on both sides of the path of the polar orbiter (Figure 4). A total of more than 44,000 target areas were found for this case, and Figure 5 shows the radiance to count relations for AVHRR channel 4 for all targets.

The results are summarized in Table 2 and show the generally good agreement between the calibration coefficients obtained by the different methods. It is worth noting that our analysis gives a systematic difference between the AVHRR channels 4 and 5 of 0.8 K which could suggest a calibration uncertainty between these two channels. Other explanations would be errors in the radiative transfer model, which is unlikely, or errors in the Meteosat-6 filter function.

Table 2. Summary of Intercalibration Results for Meteosat-6 and NOAA 14

<table>
<thead>
<tr>
<th></th>
<th>AVHRR channel 4</th>
<th>AVHRR channel 5</th>
<th>Meteosat operational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration coefficient for Meteosat (W/m²/sr/count)</td>
<td>0.07646</td>
<td>0.07544</td>
<td>0.07489</td>
</tr>
<tr>
<td>Standard deviation of coefficient</td>
<td>0.866 * 10⁻³</td>
<td>0.953 * 10⁻³</td>
<td>-</td>
</tr>
<tr>
<td>Deviation from MPEF Coefficient (%)</td>
<td>2.1</td>
<td>0.8</td>
<td>-</td>
</tr>
<tr>
<td>Equivalent temperature difference (K, at 290 K)</td>
<td>1.3</td>
<td>0.5</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 4. Calibration targets with similar viewing geometry for Meteosat and NOAA for test case 20 June 1997, 1530 UTC. The figure shows the NOAA-14 orbital track (with time marks) across the Atlantic Ocean. White spots to the east and west of the track show the location of extracted calibration targets.
Figure 6 shows the local calibration coefficients as a function of the local satellite zenith angles, and the local coefficients remain practically constant over the observed range. This result supports the use of an angle-independent correction for filter function.

Figure 4 clearly depicts the two different strips of target areas found east and west of the polar orbiter subsatellite track. For the “western” points, the two satellites have very similar viewing directions westwards through the atmosphere, while for the “eastern” points the polar orbiter looks eastward while Meteosat still looks westwards upon these areas where one could argue that the atmospheric contribution – and thus the filter function correction – might be different for these different views. A separate analysis of the two strips, however, showed no great difference: The “eastern” points resulted in a mean calibration coefficient of 0.07629 W/m²/str/count, the “western” points gave a mean value of 0.07654 W/m²/str/count, which is just a 0.3% difference.

Fig. 5. Local count-to-radiance relation for all identified calibration targets for the NOAA/Meteosat comparison. Radiance units are mW/m²/sr/cm⁴.

It should be noted, however, that the good agreement between the operational and the cross-satellite calibration using NOAA may also be due to the fact that these data are not completely independent. The operational Meteosat-6 calibration uses sea surface temperatures as target areas for the vicarious calibration, and these sea surface temperature fields in turn largely result from an analysis of the polar orbiter data.

Meteosat-6 IR versus GOES-8 Channel 4

The identical scheme was also applied to the GOES-8 image obtained at the same time during June 20 1997. This geostationary satellite is located over 75ºW which is much further west than Meteosat so that the viewing geometries are drastically different. Again with the constraint that the local satellite zenith angles should not differ by more than 5º, more than 36000 target areas were found, where again each target area was a mean value over 3 x 3 GOES pixels and the corresponding Meteosat measurements. The condition of similar viewing geometry produced target areas along the 40ºW meridian over the North Atlantic (not shown). Despite of a larger scatter (not shown), the mean result also shows good agreement to the operational calibration coefficient (Table 3) with a difference of 1.3% corresponding to 0.8 K at a brightness temperature of 290 K.
Table 3: Summary of Intercalibration Results for Meteosat-6 and GOES-8

<table>
<thead>
<tr>
<th>Calibration coefficient (W/m²/sr/count)</th>
<th>GOES-8 channel 4</th>
<th>Meteosat operational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard deviation of</td>
<td>0.07395</td>
<td>0.07489</td>
</tr>
<tr>
<td>coefficient</td>
<td>1.320 * 10⁻³</td>
<td>-</td>
</tr>
</tbody>
</table>

It is of interest to note that the calibration targets are generally seen with much higher viewing angle (44° - 60°) than for the NOAA/Meteosat comparison.

CONCLUSIONS

A strategy for the intercalibration of IR window measurements from meteorological satellites has been presented, and the reasoning behind the various steps has been discussed. Given two images of two satellites, the intercalibration scheme involves the following steps:

- identify cloud-free sea surface pixels in each image
- include those pixels in the analysis which are collocated in space and time (i.e. within 30 minutes) and which are observed under similar viewing angles
- convert the radiance values of one satellite to "pseudo-radiances" for the other satellite, i.e. correct for the difference in filter function (correction is provided by radiation model)
- correlate these pseudo-radiances with the co-registered counts, which gives the calibration coefficient.

Application of the method to Meteosat-6 and to three other sensors onboard polar orbiter satellites or another geostationary satellite shows that the quality of the results is comparable to other vicarious calibration techniques, i.e. the agreement is within 1-2% for the calibration coefficient which translates to uncertainties of about 1-2 K for typical sea surface temperatures.

The method presented here will also be used in the operational processing of future meteorological satellites supported by EUMETSAT, as it will be added to the existing vicarious calibration methods based on radiative transfer models (e.g. Schmetz 1989, Gube et al., 1996). This will further increase the capability of calibration monitoring and contribute to the international efforts to arrive at a compatible calibration of similar satellite sensors onboard different spacecraft.

REFERENCES


