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SATELLITE INTERCALIBRATION OF THE METEOSAT WATER VAPOUR CHANNEL

This paper describes the intercalibration of water vapour (WV) channel (5.7–7.1 µm) observations of the geostationary Meteosat satellite with collocated and calibrated satellite radiances from i) 6.3 µm band radiances from the HIRS instrument on polar orbiting satellites and ii) from 183.3±1 GHz radiances of the microwave instrument SSM/T-2 on the polar orbiting DMSP satellites.

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ABSTRACT

This paper describes the intercalibration of water vapour (WV) channel (5.7–7.1 μm) observations of the geostationary Meteosat satellite with collocated and calibrated satellite radiances from i) 6.3 μm band radiances from the HIRS instrument on polar orbiting satellites and ii) from 183.3±1 GHz radiances of the microwave instrument SSM/T-2 on the polar orbiting DMSP satellites. Radiative transfer calculations show that all three observations are sensitive to radiation from the upper tropospheric humidity with very similar contribution functions. Radiative transfer simulations for climatological profiles are used to derive a transfer function from one satellite observation to another which corrects for different satellite response functions. Meteosat raw radiance observations (counts) are collocated in time and space with calibrated polar orbiter observations to perform the intercalibration. The intercalibration is used to assess systematic errors of the Meteosat WV channel which has no onboard calibration but rather relies on a vicarious calibration technique. Results for the period July 1998 until May 1999 suggest that the operational calibration coefficients for both Meteosat-5 and Meteosat-7 WV channel have a high bias against HIRS of about 8 - 15%, causing a warm bias of about 1.5 - 3°K in brightness temperature. A case study with SSM/T2 for a period in July 1998 also indicates a high bias of Meteosat of 12 – 13 %. Reasons for the high bias and ways to alleviate the problem are briefly discussed.

1. INTRODUCTION

There is a growing interest to quantitatively observe the upper tropospheric humidity from space, primarily for two reasons: i) water vapour radiances are used in the operational data assimilation at NWP centers (e.g. Eyre et al., 1993; Munro et at., 1998), and ii) water vapour is the most important greenhouse gas, and the role of the upper tropospheric humidity (UTH) fields for the outgoing longwave radiation and the greenhouse effect is important (e.g. Shine and Sinha, 1991, Schmetz et al., 1995). The value of geostationary WV observations for NWP is due to their frequency in time which, in a 4-d var data assimilation system, can provide information on upper tropospheric winds. For climatological studies geostationary satellites are of particular interest since they resolve diurnal cycles

and give the capability to simultaneously observe motion and moisture fields.
The European Meteosat satellites are part of a ring of geostationary satellites which regularly observe the tropical and mid-latitude regions of the earth with a water vapour (WV) channel sensitive to the UTH field between about 600 and 200 hPa. The current generation of Meteosat satellites does not have an adequate on-board calibration system providing absolute calibration, although the recent Meteosat-7 has an on-board black-body which can be utilised at least for a relative monitoring. So far, the operational Meteosat calibration relies on vicarious techniques for both the WV (Schmetz, 1989) and IR channel (Gube et al., 1996). While the IR method has always been robust and adequately accurate, the WV calibration needed continuous improvement (van de Berg et al., 1995) because it is prone to both random and bias errors. This is primarily due to incorrect radiosonde humidity measurements (Gaffen et al., 1991), which are used as input for a radiative transfer model to compute theoretical radiances for the vicarious calibration.

A way to cross-check the accuracy of the operational vicarious calibration is to match up Meteosat observations with radiance observations from other satellites that are i) sensitive to radiation exiting the same levels in the atmosphere as for the Meteosat WV channel, and ii) that are absolutely calibrated. Intercalibration will help to improve the confidence level in the operational calibration of Meteosat WV observations or will identify problems. It also provides a basis for the consistent derivation of long-term satellite-observed brightness temperature and upper-tropospheric humidity data retrieved from different satellite sensors.

2. OPERATIONAL CALIBRATION

The operational WV channel calibration of Meteosat is described in detail in van de Berg et al. (1995). It is based on the collocation of clear sky WV raw radiance (count) observations with radiances computed from radiative transfer (RT) model with radiosonde profiles of temperature and humidity. The profiles are taken at standard pressure levels. The RT model has a vertical discretization of 50 hPa layers. Input humidity profiles are obtained from the radiosonde measurements. The profiles above 300 hPa are linearly extrapolated to 0% at 100 hPa, an approximation which has been qualified as reasonably accurate by Takayama (1992).
Using the spectral response function of the Meteosat WV channel the radiance at the top of the atmosphere is computed and is related to clear-sky raw radiance measurements (counts) from Meteosat around the radiosonde station. A careful declouding analysis involving the IR and WV channels is utilized to select only clear-sky cases. The collocations are then put into a linear regression analysis which determines the slope and hence the WV calibration coefficient. It is important to note that the regression is constrained by imposing the offset which is known from satellite measurements into deep space (space count), thus the regression only determines the slope (i.e. the calibration coefficient). Various quality checks are applied as described by van de Berg et al. (1995). The calibration is run operationally twice per day using 00UT and 12UT radiosonde observation data. In order to avoid too frequent updates the calibration is renewed only if the current calibration suggests a change by more than 1%. The precision of the method was estimated to be about 4% while bias errors are difficult to estimate.

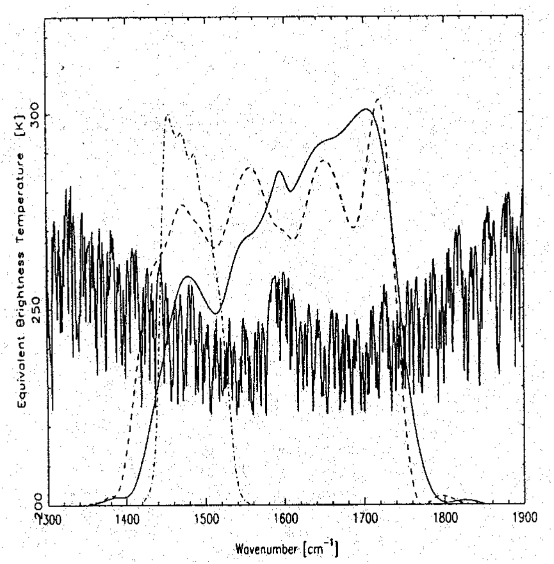


Figure 1: Spectral response functions of the HIRS channel 12 on NOAA 14 (dash-dotted), Meteosat-7 WV1 (dashed), and Meteosat 5 WV2 (solid) channels. Also shown is the top of the atmosphere spectrum for a standard tropical atmosphere.

3. INTERCALIBRATION WITH HIRS

For the derivation of an inter-satellite calibration coefficient for the Meteosat-5 and -7 WV channels we use radiances from channel 12 of the HIRS on NOAA–14. The estimated noise for this channel is 0.22 K at 270 K. We assume that the HIRS observations have no bias error, although an analysis of HIRS observations by Bates (1996) indicates that the HIRS instruments have a high relative accuracy but that the absolute accuracy is compromised due to uncertainties in the on-ground characterisation of the instrument. During the period considered here, Meteosat-7 observations are from the nominal satellite position at 0° longitude while Meteosat-5 observations were made at 63° E (so-called Indoex-position). The intercalibration of two satellite instruments is not straightforward due to the differences listed below. The list also describes the manner in which we solved or alleviated the problems:

- The two satellites do not have the same spectral response (see Figure 1). Since measured radiances are integrals over the emerging radiances folded with the spectral response function, different radiances R are measured by each satellite:

$$\mathrm{R(measured)} = \frac{\int \mathrm{R}(\Theta)\Phi_\nu \, d\nu}{\int \Phi_\nu \, d\nu} \tag{1}$$

  where R is the radiance at the top of the atmosphere in the direction □ of the satellite, Φ the filter response function and ν the wavenumber. The comparison of radiances from two satellites requires transfer functions which are inferred from radiative transfer simulations as described by Tjemkes et al. (1999) using radiosonde observations from the TIGR dataset (Scott et al., 1991) as input.
- The satellites do not view the target at exactly the same time. Time differences between the views of a given target might imply that atmospheric conditions (e.g. clouds) have changed. Tests have shown that time differences should not exceed 5 minutes (Tjemkes et al., 1999).
- 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 whereas the HIRS intrument on NOAA-14 has a resolution of about 20 km x 20 km. The more uniform the area the

more robust is the collocation in time and space to errors. Here we take averages over all Meteosat pixels within one HIRS pixel.

- The satellites do not view the intercomparison area under the same viewing angle. This could introduce important errors because for channels sensing the troposphere the observed radiance typically decreases with satellite zenith angle, an effect which is usually known as "limb darkening". In order to eliminate the effect we confine the comparison to differences in viewing angle of less than 5°. No limb darkening correction is applied to correct the observations for remaining differences in viewing angle which is possible since the maximum viewing angle is limited to 50°. Since the method only considers observations with nearly the same observational viewing angle, the method is also referred to as the iso-secant method (Beriot et al.,1982). It is also interesting to note that tests show no need to view the intercomparison area along the same line of sight.

The upper panel of Figure 2 shows results for the operational calibration Meteosat-5 (crosses). It also includes an intercalibration against Meteosat-7 (squares). We observe a consistent bias of the two Meteosat calibrations versus HIRS of the order 10%, corresponding to about 2.5 K at 240K. In the beginning of the comparison period Meteosat-5 showed a bias versus HIRS of nearly 20%, which, however, diminished later. The reasons for such changes in the bias are not yet understood. The lower panel of Figure 2 shows the time series for Meteosat-7 against HIRS. It also includes the intercalibration result with SSM/T2 (the square in July 1998) as described in the following section.

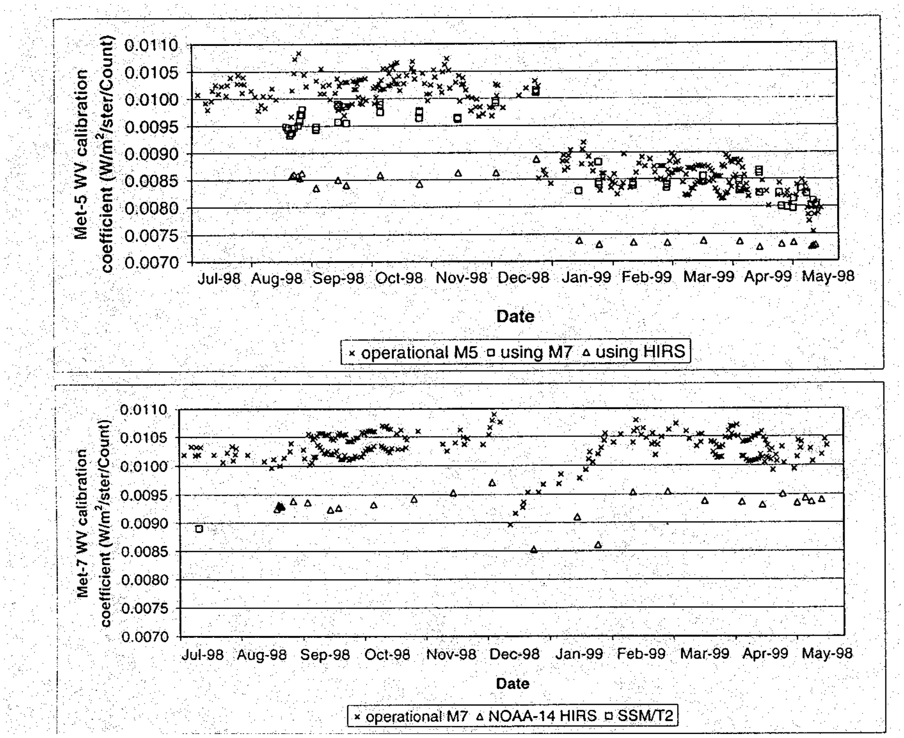


Figure 2: Comparison of the operational calibration of the WV channels (crosses) of Meteosat-5 (upper panel) and Meteosat–7 (lower panel) with intercalibrations results based on HIRS channel 12 on NOAA-14 (triangles). For Meteosat-5 an intercalibration with Meteosat-7 as reference is also included (squares). The square in the lower panel for Meteosat-7 in July 1998 refers to the intercalibration with SSM/T2. The jump in December 1998 is due to a gain change of the satellite radiometer due to a decontamination.

4. INTER-CALIBRATION WITH SSM/T2

The SSM/T-2 instrument flying on the Defense Meteorological Satellite Program (DMSP) satellites has three water vapour channels at 183.3±1 GHz, ±3 GHz, and ±7 GHz. The footprint corresponds to a spatial resolution of approximately 48 km at nadir view. During each scan period, four discrete calibration measurements of a hot target (~300°K) and cosmic background (~3°K) are monitored and they are used for the calibration of brightness temperature through linear interpolation. The absolute accuracy of SSM/T-2 brightness temperature is estimated to be about 1-2°K (Falcone et al., 1992). For the cross-calibration of Meteosat WV channel we use 183.3±1 GHz channel brightness temperature (TB_{T2}) whose weighting function is very similar the the WV channel of Meteosat (see Figure 3). The details of this inter-calibration are described in a paper by Sohn et al. (1999). The intercalibration can be summarised as follows:

- All Meteosat pixels with nearly equal viewing angles within an SSM/T-2 footprint (48 km resolution) are selected in an area of 30°N-30°S and 30°E-30°W, around the sub-satellite point of the geostationary Meteosat. Data are from 10 and 11 July 1998 and include eight SSM/T-2 overpasses.
- Each Meteosat pixel is examined for cloud contaminated by applying a scenes analysis based on pixel-based threshold techniques (Lutz, 1999).
- clear-sky brightness temperatures (TB_{WV}) and corresponding counts (C_{WV}) of the Meteosat-7 WV channel are compiled by averaging over all Meteosat-7 pixels within a collocated SSM/T-2 scene.
- In total 947 pairs of TB_{WV} and TB_{T2} have been obtained for this pilot study.
- The transfer function between a simulated brightness temperatures for Meteosat-7 WV channel and SSM/T-2 183.3±1 GHz channel is obtained using radiosonde temperature and moisture profiles in the TOVS Initial Guess Retrieval (TIGR) database (Scott et al., 1991) as inputs for both infrared and microwave transfer models. Profiles at latitudes higher than 60° are not included leaving a total number 1615 simulations. This yields the following transfer function:

$$TB_{WV} = 50.07 + 0.77\, TB_{T2} \qquad (2)$$

where TB_{WV} are the Meteosat-7 WV and TB_{T2} the SSM/T2 equivalent brightness temperatures, respectively.

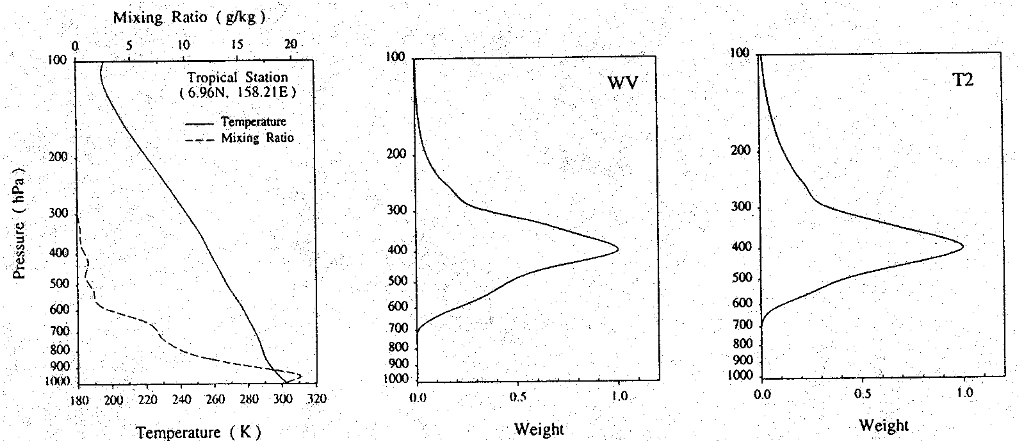
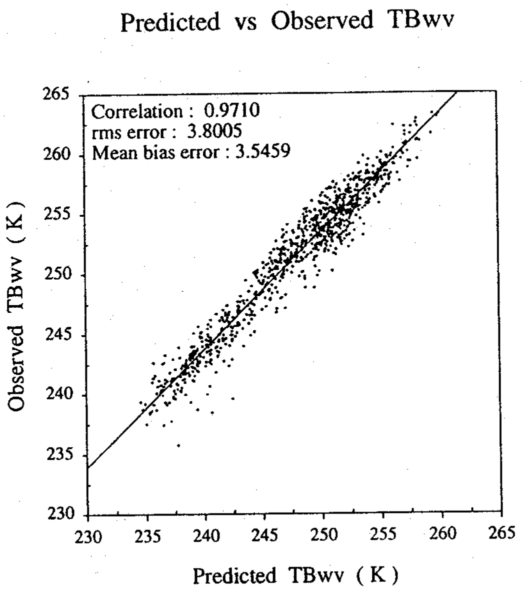


Figure 3: Humidity and temperature profiles, and normalized weighting functions for a tropical station station of TIGR dataset. WV and T2 in diagrams represent Meteosat water vapour channel and



SSM/T-2 183.3±1 GHz channel, respectively.

Figure 4: Scatter plot of brightness temperature estimated from Meteosat water vapour channel and Meteosat brightness temperature calculated from SSM/T-2 183.3±1 GHz measurements.

Figure 4 displays the scatter plot of the brightness temperature for Meteosat-7 estimated with Equation (2) versus the observed Meteosat WV brightness temperatures using the operational calibration. Clearly there is bias, with brightness temperatures from the Meteosat-7 WV channel are overestimated by about 3°K, suggesting that the current operational calibration coefficient is biased high. We obtain a new calibration coefficient with the value of 0.00899 Wm^{-2} sr^{-1} for the analysis period from June 10 to June 11, 1998 whereas the operational calibration coefficient was 0.01019 Wm^{-2} sr^{-1} until 0730 UT 11 July and was changed into 0.01032 Wm^{-2} sr^{-1} after 0930 UT 11 July. The relative difference between the operational value and the new coefficient estimated in this study suggests that the current Meteosat-7 operational calibration coefficient is biased high by about 12-13%.

It is interesting to note that the intercept of the regression (zero radiance count) corresponds to the offset count of Meteosat-7 radiometer measured during space scans; this puts additional confidence on this inter-calibration with SSM/T2.

6. SUMMARY AND CONCLUSIONS

This paper presents results from two intercalibration studies for the Meteosat water vapour channel:

- A comparison with channel 12 of the HIRS instrument on NOAA-14 for the period July 1998 through May 1999 shows a warm bias in the operational Meteosat WV calibration of the order of 10% which corresponds to a warm bias of about 2.5 K at a reference brightness temperature of 240K. This bias is not constant throughout the period. In fact for Meteosat-5 over the Indian Ocean at 63° the bias is in the beginning of the intercalibration period more of the order of 15 - 20%. Such large biases are never observed for Meteosat-7 for which the bias reduces well below 10 % for the period April/May 1999.

  Reasons for the variability are not completely clear, however the operational vicarious calibration is the most likely cause for mainly two reasons: i) it depends on radiosonde humidity measurements in the upper troposphere where radiosonde measurements of humidity are less reliable (Gaffen et al., 1991; Soden and Lanzante, 1996); ii) since water vapour soundings above 300 hPa are rarely completed to sufficiently high levels the operational calibration requires a linear extrapolation of humidity above 300 hPa to 0% at 100 hPa.

- A pilot study for a satellite intercalibration using SSM/T-2 183.3±1 GHz brightness temperatures to calibrate the Meteosat water vapour channel confirms that the Meteosat-7 operational calibration coefficient is 12-13% higher, at least for two selected days (10 and 11 July 1998) (Sohn et al., 1999).

The finding of a high bias in the operational Meteosat WV calibration is also consistent with independent results by Geer and Harries et al. (1998) who report a bias of about 2.4 K for Meteosat WV observations for January 1997 in comparison to radiances computed with the MODTRAN radiation model and ECMWF analyses data. However, at the current stage of investigations we do not rule out that part of the bias be explained by uncertainties in the characterisation of the HIRS instruments, the observations of which are used in the ECMWF analyses.
Recent work utilising the available on-board blackbody of Meteosat-7 may help to better understand the apparent bias problem with the Meteosat water vapour channel.

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