

SENSITIVITY OF THE HEIGHT ALLOCATION OF THIN CLOUD TRACERS TO ERRORS IN SATELLITE CALIBRATION

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ABSTRACT

The paper discusses the sensitivity of the height assignment of optically thin cirrus clouds to satellite calibration errors. Thin cirrus are often used as tracers for the derivation of high-level wind vectors. The height assignment is based on bi-spectral techniques, which in the case of Meteosat use both the IR (10.5 - 12.5 μm) and WV (5.7 - 7.1 μm) channels. Height allocation errors for typical errors in calibration are of the order of 500 m. It is shown that a high bias in the calibration, implying a lower height assignment, leads to better wind quality. This can be explained by the fact that wind shear through optically thin cirrus can be substantial over the typical cloud geometric thickness of a few kilometers. Thus cloud tracking of optically thin cirrus rather represents the displacement of volume and thus does not correspond to winds at cloud top.

1. INTRODUCTION

Fields of thin cirrus clouds are good tracers of the atmospheric wind field since they are rather passive over the time scale of 15 – 60 minutes, which is usually taken as image sequence for cloud tracking from geostationary satellite images. This is in contrast to convective cloud types (e.g. low level cumuli) which rapidly change morphology or decay throughout the current observation intervals of operational geostationary satellites. However, the advantage of a fairly passive nature of cirrus clouds is compromised by difficulties in their height assignment because cirrus is most often semi-transparent at thermal infrared wavelengths. The simple single channel estimation of brightness temperature, applicable to opaque cloud, would then be too high resulting in too low heights. This problem can be alleviated by using multi-spectral height assignment techniques of which bi-spectral techniques using an IR window channel, typically at 10 - 12 μm , with either a water vapour channel at 6.3 μm or a CO₂ channel around 13 μm are widely used. The utility of those bi-spectral approaches has been discussed in detail in various papers addressing the height assignment of semi-transparent clouds from satellite radiance observations (e.g. Szejwach, 1982; Schmetz et al., 1993; Menzel et al., 1983).

It has also been demonstrated that improvements in the height assignment of clouds have a beneficial impact on the quality of atmospheric motion vectors based on the tracking of thin clouds. Working groups at the previous three International Winds Workshops also emphasised the potential

improvements to be expected from a better height assignment of vectors from tracking of tenuous clouds. An important ingredient to the success of the height assignment techniques is the correct calibration of the satellite radiances. The purpose of this paper is to analyse the sensitivity of the height assignment techniques to calibration errors. Results for the WV intercept method and for the CO₂ technique are presented. The motivation for this paper stems from the current work addressing potential bias problems in satellite radiances, notably with the Meteosat 6.3 μm channel. While this problem is under study it can be expected that it has an impact on the height assignment. Here we recall that a conceptual improvement to the vicarious calibration of the Meteosat water vapour channel (Schmetz, 1989) led to a significant improvement in the quality of cloud motion winds as reported by Schmetz et al., 1993. Interestingly, later work by van de Berg et al. (1995) showed that the vicarious calibration of the 6.3 μm channel had a high bias due to the radiosondes used in the radiative transfer model. The implication of these findings will also be discussed in this paper.

2. HEIGHT ASSIGNMENT METHODS

In case of a an opaque cloud the satellite measured brightness temperature in the IR window channels is close to the temperature at cloud top. Atmospheric attenuation of the upwelling radiance can cause an effect of about 2 – 3 K, but only for low level clouds in moist tropical regions. Likewise the emissivity of optically thick water clouds only slightly deviates from an emissivity equal to one. In the case of Meteosat the radiances are expressed in units of Wm⁻² sr⁻¹; the radiances L can then be approximated by (e.g. Schmetz et al., 1994):

$$L = \exp(a + b/T) \quad (1)$$

where a and b are regression coefficient. For the Meteosat-7 IR-1 channel these coefficients are $a = 6.9676$ and $b = -1255.6097$, for the WV-2 channel they are $a = 9.241$ and $b = -2236.7561$. The sensitivity of the observed brightness temperature to a relative error $\Delta\alpha/\alpha$ in the calibration is obtained from:

$$\Delta T = \frac{-T^2}{b} \frac{\Delta\alpha}{\alpha} \quad (2)$$

Assuming a relative error of 2% for the IR calibration, we obtain a $\Delta T = 1.4$ K at 290 K. A 5% error in the water vapour calibration of Meteosat gives an error $\Delta T = 1.5$ K at 260 K. Such ΔT values translate to height errors of only 200 m for a lapse rate of 0.7 K per 100m. Height errors, of course, become more significant when the lapse rate approaches zero.

2.1 Bi-spectral Height Assignment Techniques

The water vapour intercept method has become a standard height assignment technique for optically thin clouds observed from geostationary satellites. The method, originally devised by Szejwach

(1982) has been implemented by EUMETSAT (Schmetz et al., 1993), NOAA/NESDIS (Nieman et al., 1993), JMA (Tokuno, 1996) and CMA (Xu and Qisong, 1996) and shall not be repeated here. It suffices to say that the method combines radiative transfer calculations for opaque clouds with observed radiances for the semi-transparent cloud and the clear atmosphere. The method is more sensitive to errors in the water vapour calibration than to errors in the IR calibration. This is easily understood in a qualitative manner from the sketch of the water vapour intercept method (e.g. Fig. C1 in Schmetz et al., 1993).

The CO₂ ratio technique (Menzel et al., 1983) has been in use with the first generation of GOES satellites and will also be utilised with Meteosat Second Generation. It is based on simultaneous observations in the IR window and 13 μm CO₂ channel of both the cloudy radiance and the clear sky atmosphere. The basic retrieval equation for the cloud top pressure pc reads:

$$\frac{L_1^{clear} - L_1}{L_2^{clear} - L_2} = \frac{\int_{ps}^{pc} \tau_1(p) dB_1}{\int_{ps}^{pc} \tau_2(p) dB_2} \quad (3)$$

where L corresponds to the measured clear and cloudy radiances in the two channels, indicated by subscript 1 and 2, τ is the transmittance calculated between the surface pressure ps and the cloud pressure pc , and B the Planck function.

The cloud top pressure is obtained by minimising the difference between the measured left hand side of the equation and the calculated right hand side of the equation. The sensitivity to calibration errors becomes obvious from Equation (3) since the differences between measured clear sky and cloudy radiances changes as the calibration coefficients change.

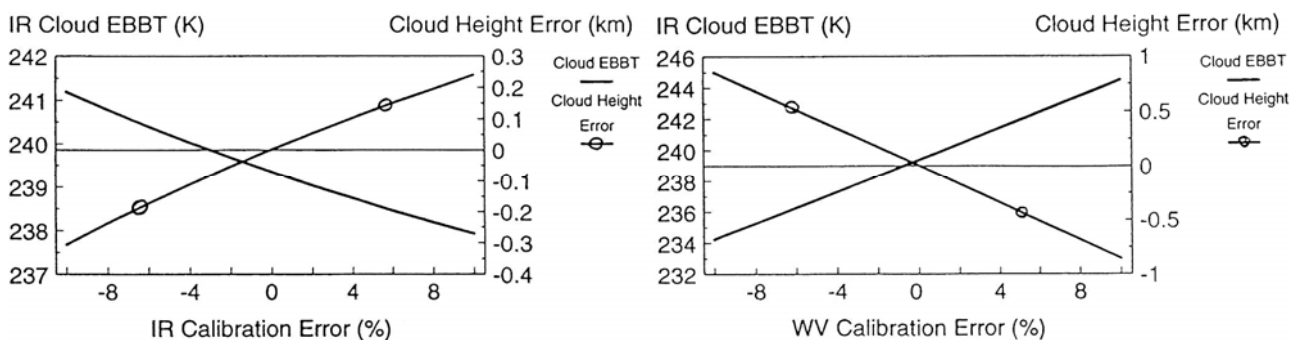


Figure 1: Sensitivity of the WV intercept method to bias errors in the IR and WV calibration. Note that an adjustment of the observed to the calculated radiances has been performed following Nieman et al. (1993).

2.2 Sensitivity Tests

WV Intercept Method: Figure 1 shows the sensitivity of the semi-transparency correction for thin clouds as applied in the current operational Meteosat system (Schmetz et al., 1993). The left panel shows the results for errors in the IR calibration and the right panel the results for errors in the WV calibration. The corresponding errors in the brightness temperature and the height are presented. It is to be seen that an error of 2% in the IR calibration yields an error of only about 100- 200 m in height. The sensitivity to WV calibration is larger; assuming a systematic error of 5% (which is quite realistic for the current system) results in height errors of more than 500m. It is noted that the assumed atmospheric temperature profile is a mid-latitude standard atmosphere; in an atmosphere with a temperature gradient closer to isothermal height errors would be larger. It is also important to note that the sensitivity test does assume that the observed radiances and calculated radiances are perfectly compatible, i.e. no bias exists. Since this is rarely fulfilled in real cases, height errors would be larger if no bias adjustment to measurements would be performed. An example of a practical bias adjustment of measured and observed clear sky radiances is presented by Nieman et al. (1993).

CO₂ ratio technique: Figure 2 shows a typical result for the CO₂ ratio technique as described by Arriaga (1994). Here real data from GOES-8 are used. The IR and CO₂ calibration has been modified by +5% and -5%, respectively. Figure 2 presents the results for 52 cases as a histogram where the deviation in cloud height is shown for classes of 250 m. The deviation has been calculated with respect to results for the unperturbed calibration. Deviations vary between classes of - 750 m and + 750 m with a mean bias of 200 m. Again it has been assumed that there is no bias between calculated and measured radiances.

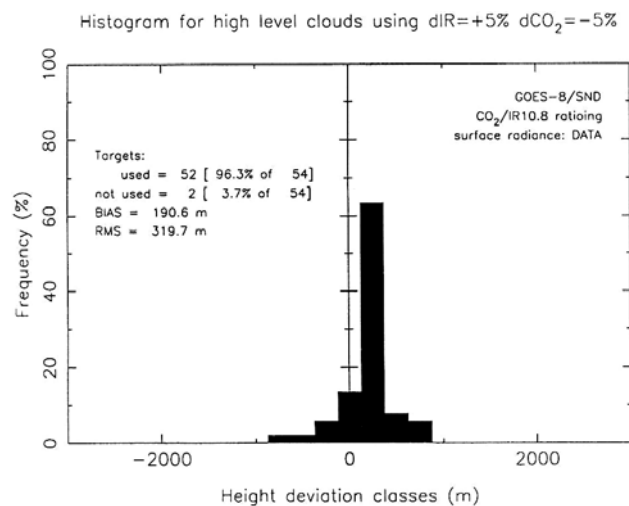


Figure 2: Histogram of height deviations due to a change in the calibration of the CO₂ and IR channels of the GOES-8 sounder for a case study on 20 June 1997.

2.3 The Impact on Wind Quality

The important test is, of course, to determine the sensitivity of the cloud motion wind product to calibration errors. This can be done by comparing the quality of wind vectors against NWP model

analysis. Results will vary in such a comparison since the heights of the wind vectors are different due to the changes in calibration. A concise test of this kind is performed by utilising the quality indicators as proposed by Holmlund (1998), who combines five different quality indicators into a global consistency check, which objectively assigns a number between one (good) and zero (bad) to a wind vector. Here we just use the quality indicator calculated in comparison to the analysis of the ECMWF forecasting model. A wind product from Meteosat-6 for 20 June 1997 is analysed consisting of a total of 2909 winds. Then the QI is computed for height assignments based on different variations of the calibration coefficient of both the IR and WV calibrations. Figure 3 shows the results of this analysis:

In order to highlight significant changes in the height assignment, we confine the presentation in Figure 3 to 79 cases, for which the difference between the baseline height allocation and the height assignment using a + 5% change in the water vapour calibration, differs by more than 10hPa. Plotted in Figure 3 are the vector difference, the vector RMS difference and the forecast wind speed (for reference). We observe that the lowest vector difference and RMS error occurs for a change of the WV calibration by + 5% and for a simultaneous change of both the IR and WV calibration by 5%. In both cases the normalised RMS, i.e. the RMS divided by the forecast wind speed, is lowest with 0.26, indicating the best quality.

The interesting aspect of this result is that an increase of the operational water vapour calibration leads to a better wind quality, although the operational WV calibration presumably has already a high bias of the order 5%, as suggested by the radiance monitoring at ECMWF (Saunders, Kelly and Munro, 1997, personal communication).

This result is consistent with previous experience with the Meteosat system: In 1987 the operational Meteosat WV calibration was conceptually improved to a physical vicarious calibration using a radiation model with radiosonde profile data to calibrate observed clear sky radiances (Schmetz, 1989). The result was an increase in the WV calibration by up to 10%. This led to a significant improvement in wind quality as reported by (Schmetz et al., 1993). A revisiting of the vicarious WV calibration by van de Berg et al. (1995), which included improved quality checks of radiosonde profile data, lowered the WV calibration by 8%. This indicates that the first version of the vicarious WV calibration gave to a high radiances which however had a beneficial impact on the wind quality.

The interpretation of this observation is that the height assignment of thin cirrus to cloud top, which is attempted by the bi-spectral techniques, is not generally the best-fit height of cloud wind displacement vectors to the local wind field. Tracking of thin cirrus rather represents a volume. Over a geometric thickness of about 2 km the wind speed can vary by more than 10 m/s as observed by aircraft (Quante, 1989). On the other hand measurements by Wylie et al. (1995) also show that a cirrus cloud of 2 km geometric thickness typically has a visible optical depth of about 0.5 corresponding to an IR optical depth of only 0.25, which in turn gives a transmittance of nearly 80%. Thus it is to be expected that the tracking of optically thin cirrus cloud represents an average over a rather deep geometric layer. A more elaborate study using existing field data would be worthwhile in order to quantify the effect more accurately.

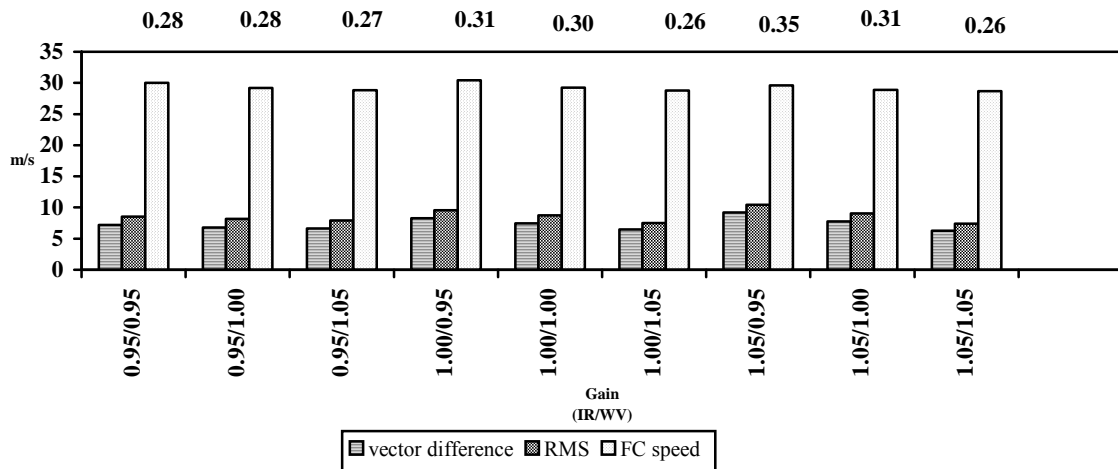


Figure 3: Quality of high level winds from Meteosat-6 for 20 June 1997 in terms of mean vector difference and vector rms between the ECMWF analysis and the satellite tracked vectors. The x-axis gives the variations of the IR and WV calibration. Numbers on top of each set of bars provides the normalised rms, i.e. the rms divided by the forecast wind speed. Best results are obtained if the WV calibration is increased by 5%.

3. CONCLUDING REMARKS

This study addresses the sensitivity of the height assignment of optically thin cirrus cloud to satellite calibration errors. The salient points can be summarised as follows:

- the impact of realistic calibration bias errors of 2% in the Meteosat IR calibration leads to a height assignment error of about 200m using the water vapour intercept method for thin cirrus
- the impact of realistic calibration bias errors of 5% in the Meteosat WV calibration leads to a height assignment error of about 500 m (maximum about 1000 m) using the water vapour intercept method for thin cirrus
- a sensitivity test for the CO₂ ratio method using data from GOES-8 shows errors of about 500 - 750 m for calibration errors of 5%.
- a sensitivity test of the quality of high level cloud winds using data from Meteosat-6 shows that a high bias of about 5% in the WV calibration, i.e. a height assignment to lower levels, improves the apparent quality of winds when compared to an NWP analysis
- the height assignment of the wind vectors to lower levels is consistent with the observation that wind speed may increase significantly with altitude through the cirrus and that the tracking rather represents a deep volume through the cirrus
- the assimilation of winds from the tracking of cirrus cloud in NWP may benefit from considering the wind as layer mean rather than a single level wind, similar to the considerations being made for clear sky water vapour winds.

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