LONDON, METEOROLOGICAL OFFICE.

Met.O.19 Branch Memorandum No.53.

A calibration for the water vapour channel of Meteosat based on aircraft measurements of temperature and humidity. By EYRE,J.R

London,Met.Off.,Met.O.19 Branch Mem.No.53, 30cm.Pp.14,pl.8 Refs.

MET O 19 BRANCH MEMORANDUM No. 53

A CALIBRATION FOR THE WATER VAPOUR CHANNEL OF METEOSAT BASED ON AIRCRAFT MEASUREMENTS OF TEMPERATURE AND HUMIDITY.

by

EYRE J.R.

Met O 19
(High Atmosphere Branch)
Meteorological Office
London Road
Bracknell
Berks., RG12 2SZ

October 1979

A calibration for the water vapour channel of Meteosat based on aircraft measurements of temperature and humidity

1. Introduction

The Meteosat radiometer has three spectral channels. Two are conventional imaging channels, in the visible region and in the region of the infra-red window around 11 μm, but the third - the "water vapour" channel - is sensitive to radiation between about 5.7 and 7.4 μm. At these wavelengths almost all the radiation reaching the satellite (in cloud-free conditions) is emitted by atmospheric water vapour and originates in the layers between 600 and 200 mb. Of the present geostationary meteorological satellites, only Meteosat contains such a channel. Qualitatively, the channel provides information on humidity in the upper troposphere - a high brightness temperature indicating low humidity and vice-versa - and thus it yields images conveying useful indications as to the air motions in these layers. However it is intended that the data for this channel also be analysed quantitatively, in conjunction with data from the other channels, to provide a measurement of mean humidity in the upper troposphere.

At present the analysis of the water vapour (WV) channel data is hampered by a large uncertainty in the absolute calibration and it is towards this problem that the exercise described here was directed. In November-December 1978, Met. Research Flight made 4 flights out of Gibraltar over the Eastern Atlantic all related to the calibration of Meteosat channels. Two flights involved a measurement series at low levels to provide data for the calibration of the 11 μm channel (the IR channel); the results are reported elsewhere [1]. The other two flights yielded measurements of temperature and humidity in the upper troposphere (between 600 and 200 mb) which have been used together with Meteosat WV channel data to produce a calibration for this channel of the radiometer.

The first high level flight took place on 29th November 1978. It provided measurements of the atmospheric temperature and humidity profiles which have been used in conjunction with theoretical radiative transfer schemes and a knowledge of the Meteosat WV channel spectral response to calculate the radiation emitted along a slant path reaching the top of the atmosphere. The theoretical radiances have been compared with the Meteosat signals to provide a calibration for the radiometer. The second high level flight, on 7th December 1978, provided data which were found to be less useful.

2. The aircraft data, 29th November 1978

The aircraft instruments provided measurements of temperature and humidity on a series of constant presure level runs between 600 mb and the aircraft's ceiling altitude, together with additional but limited measurements of the profile shape between these levels. The details of the aircraft measurement plan are specified in [2]. The instrumental details and method of data analysis were very similar to those for the low level flights which are described in [1]. The only major change for the high level flights, except for that of altitude, was that the flight pattern consisted of straight, constant pressure level runs of about 100 km length across the wind.

The aircraft measurements were made under conditions which allowed the Meteosat WV radiances to be identified unambiguously as being uncontaminated by cloud. Medium and high level cloud were avoided but low cloud was tolerated, since the atmospheric layers below 800 mb contribute insiginficantly to the WV channel radiance. On this day a broken field of low cloud - cumulus and stratocumulus - was reported below the aircraft during measurements, and examination of nearby radiosonde ascents suggested a probable cloud top around 850 mb. The effect of such a cloud field is discussed in section 3.

The measurements in the selected location were made between 1100 Z and 1600 Z, and the average co-ordinates of the measurements were 31.7°N, 11.0°W. All the aircraft measurements of temperature and humidity were analysed and plotted on a TØ-gram, together with data from nearby radiosonde ascents - 1200 Z ascents from 08521, Madeira (32.7°N, 16.8°W) and 60155, Casablanca (33.6°N, 7.7°W). The "best" estimate of the representative profile with associated errors was then obtained from the available data as follows:

Temperature:	below 600 mb - average of the two radiosonde ascents with suitably large error bars allowed.
	600-350 mb - aircraft data.
	350-100 mb - average of radiosonde profiles.
	above 100 mb - U.S. standard atmosphere (1976).
Humidity:	below 600 mb - average of radiosonde profiles with very large error bars allowed.
	600-237 mb - aircraft data (Dobson-Brewer hygrometer).
	237-100 mb - interpolation between highest aircraft level and assumed stratospheric value with very large error bars allowed.
	above 100 mb - assumed stratospheric humidity mass mixing ratio of $3 \pm 2 \times 10^{-6}$.

The "best" profile with its estimated errors is given in table 1. Although in some parts of the profile the uncertainties are large, the layers involved contribute little to the radiation reaching space in the 6 μm region of the spectrum, and so these uncertainties have comparatively little effect on the calculated radiances.

Comparison of measurements differing in time by about 3 hours at 400 mb indicates that there is negligible contribution to the uncertainty in the profiles from variations with time. This is confirmed by the histogram analyses (see section 4). The uncertainties given in table 1 include the scatter in the available measurements and the effects of some small spatial gradients apparent in the data.

3. Calculation of WV channel brightness temperature

The brightness temperature "seen" by the WV channel was calculated using the atmospheric profile given in table 1 and a zenith angle appropriate to Meteosat and the mean co-ordinates of the aircraft measurement area (i.e. zenith angle = 38.8°). Values of transmittance from each level of the profile to space were calculated using three different atmospheric transmission models:

i) The widely used model LOWTRAN 3B [3], calculating mean transmittances over 20 cm^{-1} intervals. This model allows for several atmospheric absorbing gases, although only water vapour is significant in this region of the spectrum.

ii) A Goody band model.

iii) A Malkmus band model.

Models (ii) and (iii) are described in Appendix A. Both calculate mean transmittances over 50 cm^{-1} intervals for water vapour only.

Using the calculated values of transmittance, the radiative transfer equation can be integrated along a slant path to find a radiance at the top of the atmosphere for each spectral interval (20 cm^{-1} or 50 cm^{-1}, depending on the model) across the range of the radiometer response. These radiances are then convolved with the spectral response of the instrument (obtained from [4]) and the result expressed as a brightness temperature. Thus for each atmospheric profile considered, a brightness temperature can be calculated for each of the three different spectral models.

Calculations were performed for 5 different atmospheric profiles:

1) "Best" profile - as given in table 1.
2) "Wet" profile - as (1) but with humidity increased by errors in table 1.
3) "Dry" profile - as (1) but with humidity decreased by errors in table 1.
4) "Hot" profile - as (1) but with temperature increased by errors in table 1.
5) "High SST" - as (1) but with surface temperature increased by errors in table 1.

The calculated brightness temperatures are given in table 2(a).

The agreement between the three spectral models is very good. Of the two band models, the Malkmus model is expected to be more accurate (for given spectral line data) since the distribution of line strengths which it assumes is a closer representation of the real distribution for the 6 μm water vapour band.

The results from profiles (1)-(5) can be used to estimate the error in brightness temperature caused by the uncertainties in the atmospheric profile. By comparing the results from profiles (1), (2) and (3), the error caused by humidity uncertainties is calculated to be ± 2.7 deg.; from (1) and (4) that caused by temperature uncertainties is ± 1.5 deg. Therefore the combined error is ± 3.1 deg. The sea-surface temperature used is an assumed value. However comparison of (1) with (5) shows that, as expected, large uncertainties in surface temperature do not affect the results. It should be noted that this method of error analysis is not entirely satisfactory; all the errors are applied in the same direction on each profile and so will overestimate the random measurement error from each source. On the other hand, the calculations assume the profiles to vary linearly between the levels at which the profiles are specified - a simplification which will tend to underestimate the error.

Table 1 is considered adequate to represent the profile itself, but it is not obvious whether it contains enough levels for an accurate integration of the radiative transfer equation. This problem was investigated by including more levels in the layers from which most of the radiation "seen" by the WV channel originates. Extra levels were added at 650, 575, 525, 475, 425, 375, 325 and 300 mb, obtaining temperature and humidity values by linear interpolation. The brightness temperature was then recalculated using this "fine resolution" profile. The results are shown in table 2(b), from which it is concluded that the error introduced by the limited resolution of the original profile is insignificant compared with that from other sources.

The effect of stratospheric water vapour is shown in table 2(c). Here LOWTRAN calculations have been repeated truncating the atmosphere at different levels to calculate the brightness temperatures which would be seen if there were no atmosphere above each level. It can be seen that neglecting layers above the tropopause (160 mb) causes a change of only 0.2 deg. in brightness temperature.

The effect of low level cloud was investigated using LOWTRAN by changing the profile in table 1 to represent a "worst case" for the low cloud problem - complete cloud cover with a cloud top at 810 mb and 3°C. At and above 800 mb the profile was kept unchanged. The resulting brightness temperatures were:

With cloud : - 21.67°C,
Without cloud : - 21.52°C.

Therefore the difference is only 0.15 deg. for the "worst case", and for the flight the cloud cover was broken with a probable cloud top at 850 mb.

It is evident that the choice of spectral model and the use of coarse or fine resolution profiles do not have critical effects on the calculated brightness temperature compared to the error caused by uncertainty in the atmospheric profiles. Taking as the best estimate of the brightness temperature that obtained with the Malkmus model using the fine resolution profile, we obtain a value,

brightness temperature = <u>- 21.55°C.</u>

The major error in this value is that caused by the uncertainties in the atmospheric profile (leading to an error of ± 3.1 deg., although this may be an overestimate).

4. <u>Analysis of satellite data</u>

Three sets of IR and WV images were analysed for 29th November 1978. They were slots 22, 26 and 30 (S22, S26 and S30) corresponding to times of 1055Z, 1255Z and 1455Z respectively for the end of the full-earth image. Because image referencing is difficult using the WV image alone, the analysis proceded as follows:

i) Image co-ordinates (in terms of line and pixel numbers) were calculated for:

a) the mean latitude and longitude of the measurement area (32.7°N, 11.0°W),
b) Agadir, on the coast of Morocco (30.47°N, 9.58°W).

Although the absolute values of the co-ordinates were dependent upon the different assumptions which could be made when converting latitude and longitude to Meteosat image co-ordinates, the difference between the two sets was found to be constant at 23 lines, 25 pixels.

ii) For each IR image, Agadir was identified and located from the shape of the coast-line.

iii) For each pair of IR and WV images, the registration of one with the other was checked using high cloud elements identifiable on both. It was found to be good to within 1 pixel in each case.

iv) The co-ordinates of the flight area were then calculated (= co-ordinates of Agadir + 23 lines, 25 pixels).

In this way the mean co-ordinates of the flight area were identified for each WV image to an estimated accuracy of within 2 pixels.

The histograms for each WV image were then calculated for the following arrays of pixels:

a) a 32 x 32 array centred on the flight area mean co-ordinates,
b) an 8 x 8 array centred on the flight area mean co-ordinates,
c) the eight 32 x 32 arrays immediately surrounding the central 32 x 32 array.

The mean, standard deviation and median were calculated for each histogram. The results are given in table 3. For S26, the histograms themselves are shown in figure 1.

Also analysed were 100 x 100 arrays of pixels in the space view near each corner of each of the 3 WV images. The results are given in table 4.

5. Interpretation of satellite data

a) Space view.

Because of the asymmetry of the space view histograms (caused by the proximity to zero counts of the mean space view signal), the median, rather than the mean, gives a more appropriate estimate of the "average space view signal". For 29th November 1978, the mean value of the medians for the three images analysed is 2.0. Assuming space to have a brightness temperature of about 4K, the equivalent radiance (as a fraction of typical earth view radiances) differs negligibly from zero.
Therefore,

<u>2.0 counts</u> corresponds to <u>zero radiance</u>

b) Earth view (aircraft measurement area)

Here, there is little to choose between mean and median. In theory the median may be more appropriate since the non-linearity of the Planck function converts normally-distributed random variations in temperature and humidity into non-normally-distributed variations in radiance. However the histogram statistics show no systematic difference between mean and median.

Although the mean co-ordinates of the flight area can be located very accurately, the length of each flight leg is $\simeq$ 100 km (equivalent to $\sim$ 20 pixels). Therefore the 32 x 32 arrays are probably more representative of the flight area than the 8 x 8 arrays. However, table 3 shows that the average difference between the two sets of medians is only about 1 count, which at $\sim$ 135 counts is equivalent to a brightness temperature change of only 0.2 deg. [4].

The choice of the appropriate "best" estimate of the radiance counts equivalent to the aircraft measurement brightness temperature is therefore not critical, since the various possible choices are not very different. Taking as the best estimate the average of the 32 x 32 array medians for the 3 slots, we obtain:

<u>136.6 counts</u> corresponds to <u>-21.55°C (= 251.6K)</u>

It is difficult to estimate the error in the WV channel counts but it is evident from the space view standard deviations that a large part of the earth view standard deviation is caused by random instrumental noise and not atmospheric variability. Also the standard deviation of the radiance counts represents a smaller error in brightness temperature than that for the aircraft measurements, since 5 counts (at $\sim$ 135 counts) is equivalent to about 1 deg.

6. The aircraft data, 7th December 1978

On this flight no manually recorded humidity values were obtained above 350 mb (and the automatic hygrometer is unreliable at the temperatures found at these heights). Since the humidity above 350 mb contributes significantly to the WV channel radiance (see table 2(c)), it is unlikely that a calibration derived from these data would be accurate. Accordingly the data have not been analysed further.

7. Summary of results

This exercise has provided a two-point calibration for the WV channel of Meteosat for 29th November 1978:

2.0 counts corresponds to zero radiance and
136.6 counts corresponds to a brightness temperature of 251.6 K.

This calibration allows interpretation of the WV images for this day in terms of brightness temperatures and, if the temperature fields are known from some other source, in terms of mean upper troposheric humidity. It is noted that this calibration differs from the latest calibration suggested by ESA [5] by about 7 deg. at 136.6 counts. The applicability of the result to other days depends on a knowledge of the variation of calibration with time which, it is hoped, will soon be available from ESA.

Appendix A

Random band models used in calculating mean transmittances for the 6 µm water vapour band.

The Goody and Malkmus random band models assume different simplified distributions of spectral line strengths. The number of lines, $N(S)dS$, of strength between S and S + dS is given by:

$$\text{Goody} \quad : \quad N(S)\,dS = \frac{N_0}{k} \exp\left(-\frac{S}{k}\right) dS \ ,$$

$$\text{Malkmus} : \quad N(S)\,dS = \frac{N_0}{S} \exp\left(-\frac{S}{k}\right) dS \ .$$

In both cases N_o and k are constants which can be adjusted to fit the spectral line data for a given spectral interval, $\Delta\nu$, using the method given by Rodgers [6], where the fitting is performed so as to achieve exact agreement in the strong and weak absorption limits. The resulting mean transmittances, $\bar{\tau}$, over the interval, $\Delta\nu$, are given by:

$$\text{Goody} \quad : \quad \bar{\tau} = \exp\left\{-\left(\frac{1}{w^2} + \frac{1}{s^2}\right)^{-1/2}\right\} \ ,$$

$$\text{Malkmus} : \quad \bar{\tau} = \exp\left\{-\frac{s^2}{2w}\left[\left(1 + \frac{4w^2}{s^2}\right)^{-1/2} - 1\right]\right\} \ ,$$

where $w = \frac{1}{\Delta\nu}\, m \sum_i S_i$ and $s = \frac{2}{\Delta\nu} \sqrt{m} \sum_i \sqrt{S_i\alpha_i}$.

Here m is the absorber amount (with units determined by those of S), S_i and α_i are the strength and Lorentz half-width for the ith line, and the summations are over all lines in the interval, $\Delta\nu$.

The values of $\sum_i S_i$ and $\sum_i \sqrt{S_i\alpha_i}$ can be computed from tabulated spectral line data. In the case of the 6 µm water vapour band, the values used are those for 50 cm^{-1} intervals given by Houghton [7] which have been computed from the spectral line data given by McClatchey et al. [8].

References

[1] Eyre J.R., Met O 19 Branch Memorandum No. 51, October 1979, Aircraft measurements related to the determination of sea surface temperature from Meteosat.

[2] MRF Trials Instructions No. 32 - Meteosat calibrations.

[3] Selby J.E.A., Shettle E.P., McClatchey R.A., AFGL-TR-76-0258, Env.Res.Pap. 587 (1976), Atmospheric transmittance from 0.25 to 28.5 μm: Supplement LOWTRAN 3B.

[4] Meteosat 1, Calibration Report, Issue 3, Jan-Dec. 1978.

[5] Meteosat 1, Calibration Report, Issue 5, April-June 1979.

[6] Rodgers C.D., NCAR Technical Note, NCAR/TN - 116 + 1A, March 1976, Approximate methods of calculating transmission by bands of spectral lines.

[7] Houghton J.T., The Physics of Atmospheres, C.U.P., 1977.

[8] McClatchey R.A. et al., AFCL-TR-73-0096, Env.Res.Pap. 434 (1973), AFCRL atmospheric absorption line parameters compilation.

[4] and [5] are ESA documents obtainable from: ESOC/MDMD, Robert Bosch Strasse 5, 6100 Darmstadt, W. Germany.

Acknowledgments

I am indebted to Mr. R.W. Lunnon for his work concerning the planning and preliminary data analysis for this project, and to Mr. D. Offiler for the initial processing of the aircraft data. I should also like to thank the staff and aircrew of MRF for providing the aircraft measurements and the staff of ESOC at Darmstadt for supplying the necessary satellite data.

Table 1

Atmospheric profile - 29th November 1978

Pressure mb	Temperature °C		Dew point °C		Humidity mass mixing ratio Kg/Kg
1014 (surface)	18	± 3	13	± 3	
1000	15	± 3	11	± 3	
900	9	± 3	5	± 3	
800	5	± 3	-10	± 10	
700	1	± 2	-17	± 10	
600	-7	± 1	-27	± 2	
550	-9	± 2	-35	± 5	
500	-14	± 1	-44	± 2	
450	-19	± 1	-55	± 2	
400	-26	± 1	-58.5	± 2	
350	-34.5	± 1	-51	± 2	
314	-39.5	± 2	-54	± 2	
284	-45	± 2	-58	± 2	
261	-50	± 2	-61	± 2	
237	-54	± 2	-68	± 2	
190	-64	± 2	-72	± 8	
160	-67	± 3	-76	± 10	
100	-64	± 2			$3 \pm 2 \times 10^{-6}$
50	-57	± 3			$3 \pm 2 \times 10^{-6}$
20	-50	± 3			$3 \pm 2 \times 10^{-6}$
10	-45	± 3			$3 \pm 2 \times 10^{-6}$
5	-39	± 3			$3 \pm 2 \times 10^{-6}$
2	-15	± 3			$3 \pm 2 \times 10^{-6}$
1	-3	± 3			$3 \pm 2 \times 10^{-6}$

Surface brightness temperature = 20 ± 2 °C

Mean co-ordinates of flight area:

Latitude = 31.7°N, Longitude = 11.0°W

Table 2

2(a) Calculated brightness temperatures - different models and atmospheric profiles

Profile No.	LOWTRAN °C	Goody model °C	Malkmus model °C
1	-21.52	-21.96	-21.50
2	-24.52	-24.73	-24.31
3	-18.77	-19.52	-19.02
4	-20.02	-20.51	-20.05
5	-21.52	-21.96	-21.50

2(b) Calculated brightness temperatures - effect of limited number of levels

	Fine resolution profile °C	Coarse resolution profile °C	Difference deg.
Goody Model	-22.01	-21.96	0.05
Malkmus Model	-21.55	-21.50	0.05

2(c) Calculated brightness temperatures - effects of the higher layers

Pressure level of truncation mb	Brightness temperature °C
0	-21.52
1	-21.53
2	-21.53
5	-21.53
10	-21.53
20	-21.54
50	-21.55
100	-21.53
160	-21.32
190	-21.00
237 *	-20.30
261	-19.70
284	-18.77
314	-17.27

*Maximum height of humidity measurements

Table 3

Analysis of WV channel histograms

Segment	Mean			Standard deviation			Median		
	S 22	S 26	S 30	S 22	S 26	S 30	S 22	S 26	S 30
Central 32 x 32	137.2	136.6	137.0	10.7	6.1	8.0	137.1	136.5	136.1
Central 8 x 8	136.6	135.1	134.9	8.6	5.1	6.1	137.0	134.2	135.0
NW 32 x 32	129.5	125.1	121.3	6.3	9.5	8.4	129.3	125.0	122.1
N 32 x 32	133.5	131.0	126.2	5.6	9.3	8.5	133.8	131.3	126.4
NE 32 x 32	137.9	135.5	133.2	5.5	9.1	8.5	138.2	136.1	133.1
W 32 x 32	136.6	138.1	138.1	11.5	7.0	8.3	136.2	137.5	138.2
E 32 x 32	143.4	139.5	136.6	11.2	5.6	5.8	143.2	139.2	136.3
SW 32 x 32	141.6	137.9	132.5	11.6	9.5	8.5	141.4	137.8	132.0
S 32 x 32	147.9	151.8	152.1	11.3	6.9	7.4	148.2	151.6	152.2
SE 32 x 32	146.4	148.1	149.2	10.2	5.4	6.8	146.8	148.3	148.9

Key

Meteosat co-ordinates of centre:

S 22	Line 1962, pixel	1468
S 26	Line 1966, pixel	1470
S 30	Line 1969, pixel	1472

32 x 32 NW	32 x 32 N	32 x 32 NE
32 x 32 W	32 x 32 8x8	32 x 32 E
32 x 32 SW	32 x 32 S	32 x 32 SE

Table 4

Analysis of WV channel histograms - space view

Lines and pixels of 100 x 100 array	Mean			Std.Dev.			Median		
	S 22	S 26	S 30	S 22	S 26	S 30	S 22	S 26	S 30
L 101-200, P 101-200	4.8	3.0	3.2	5.9	3.4	3.6	2.4	1.7	1.9
L 101-200, P 2301-2400	4.8	3.0	2.7	5.8	3.3	3.3	2.3	1.7	1.4
L 2301-2400, P 101-200	4.8	4.9	3.5	6.1	6.1	4.2	2.3	2.4	1.9
L 2301-2400, P 2301-2400	4.6	4.4	3.2	5.9	5.7	4.0	2.1	2.0	1.5

Figure 1 Histograms of 32x32 pixel arrays. WV image. Day 333 (1978) Slot 26