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Radiometric calibration for microwave sounders

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Abstract

This note examines the radiometric calibration scheme being proposed for the Microwave Sounder (MWS) on Metop-SG. We show how the proposed radiometric transfer function can be derived, and attempt to explain its meaning in physical terms. We also compare with the current approach used for AMSU and MHS.

1. Introduction

The MWS is an instrument that is similar, in principle, to instruments like AMSU-A, AMSU-B, MHS and ATMS. However, in the MWS processing the intention is to design the system so that it takes account of as many instrumental parameters as possible, rather than adding corrections later. For example: mirror reflectivity; nonlinearity; antenna pattern; etc. To this end, the instrument provider is proposing a particular form of the radiometric calibration equation, which at first sight seems unfamiliar.

In this note we examine the proposed approach in more detail. It is, in principle, applicable to any microwave sounder, not just MWS. Section 2 presents the fundamental equations; section 3 compares with previous approaches; section 4 looks at pre-launch characterisation; section 5 presents conclusions.

2. Instrument calibration equation

In this section we derive a relationship that can be used to compute earth-view radiance from raw instrument counts.

We start with the following fundamental assumptions:

- The incoming radiation is reflected off an imperfect scan mirror, of reflectivity R_θ, where θ is the scan angle.
- There are cold and warm calibration views: cold space and the on-board calibration target.
- The energy entering the receiver is related to the counts from the analogue to digital converter (ADC) via a quadratic transfer function. Thus, for the earth view:

$$a_0 + a_1 C_E + a_2 C_E^{\ 2} = (1 - R_\theta) B_{REF} + R_\theta\, B_E \qquad \text{(1a)}$$

where B_{REF} is the black body radiance[1] at the temperature of the reflector and B_E is the radiance of the earth scene. We assume that the a_0, a_1 and a_2 coefficients do not depend on scan angle. Therefore the same equation applies to the space and black body views also:

$$a_0 + a_1 C_{SP} + a_2 C_{SP}^{\ 2} = (1 - R_{SP}) B_{REF} + R_{SP}\, B_{SP} \qquad \text{(1b)}$$

$$a_0 + a_1 C_{bb} + a_2 C_{bb}^{\ 2} = (1 - R_{bb}) B_{REF} + R_{bb}\, B_{bb} \qquad \text{(1c)}$$

[1] The radiance is related to temperature via the Planck function. In practice, there are several formulations that could be used. In atmospheric science the "wavenumber" formulation is usually used for spectral radiance, but engineers sometimes use a "power spectral density" which has the normal variation with temperature but has no variation with frequency. The justification for the latter is unclear to the author.

It is assumed that for a given channel the coefficient a_2 is constant over the lifetime of the instrument – regardless of any ageing of the receiver front-end components. In other words, assume that *nonlinearity originates in the power detector, the output of which is directly related to ADC counts*[2]. It will be shown later that current operational algorithms for AMSU and MHS do not follow this assumption.

It is convenient to introduce the quantity x, defined as

$$x = \frac{C_E - C_{SP}}{C_{bb} - C_{SP}} \tag{2}$$

Thus x = 0 when the earth counts are equal to the space counts, and x = 1 when the earth counts are equal to the black body counts. We then write the radiance calibration equation in terms of a linear function of x, plus a nonlinear correction, *Q*, which is zero at x = 0 and x = 1.

$$\begin{aligned} B_E &= \alpha + \beta x + Q \\ &= \alpha + \beta x + \gamma x(1-x) \end{aligned}$$

To solve the calibration equation, first consider the case of x = 0 (earth counts = space counts). Setting $C_E = C_{SP}$ in (1a), and comparing with (1b), we get

$$(1-R_\theta)B_{REF} + R_\theta\, B_E = (1-R_{SP})B_{REF} + R_{SP}\, B_{SP}$$

from which

$$B_{E,x=0} = \frac{R_{SP}}{R_\theta} B_{SP} + \left(1 - \frac{R_{SP}}{R_\theta}\right) B_{REF} \tag{3}$$

We can see that if R_θ is greater than R_{SP} (which is the case for channels with QV polarisation), then $B_{E,x=0}$ will be greater than B_{SP}. In other words, the cold reference point needs to be *greater* than the space temperature *in order to compensate for the cold bias that would result if there was no reflectivity correction* (Saunders et al., 1996).

Similarly, when x = 1 (earth counts = black body counts),

$$B_{E,x=1} = \frac{R_{bb}}{R_\theta} B_{bb} + \left(1 - \frac{R_{bb}}{R_\theta}\right) B_{REF} \tag{4}$$

So, interpolating for intermediate temperatures, we can now write the calibration equation as:

$$B_E = (1-x)B_{E,x=0} + x\,B_{E,x=1} + \gamma x(1-x) \tag{5}$$

To find γ, we compute the second differential of (1a) and compare with the second differential of (5) to get

[2] Some instruments have a configurable amplifier between the power detector and the A/D convertor, in which case the treatment needs to be modified slightly: if the gain of this amplifier is g, then $a_2 = \mu / g^2$, where μ is fixed over the instrument lifetime.

$$\frac{d^2 B_E}{dC_E^{\ 2}} = 2\frac{a_2}{R_\theta} = -2\gamma\left(\frac{d^2 x}{dC_E^{\ 2}} + \left(\frac{dx}{dC_E}\right)^2\right)$$

From (2), d^2x / dC_E^2 is zero and $dx/dC_E = (C_{bb} - C_{SP})^{-1}$. So the calibration equation becomes

$$B_E = (1-x)B_{E,x=0} + x\,B_{E,x=1} - \frac{a_2}{R_\theta}x(1-x)(C_{bb} - C_{SP})^2 \tag{6}$$

Substituting (2) and (3) into (6), and rearranging a little, gives

$$\boxed{B_E = \left(1-(1-x)\frac{R_{SP}}{R_\theta} - x\frac{R_{bb}}{R_\theta}\right)B_{REF} + x\frac{R_{bb}}{R_\theta}B_{bb} + (1-x)\frac{R_{SP}}{R_\theta}B_{SP} - \frac{a_2}{R_\theta}x(1-x)(C_{bb} - C_{SP})^2} \tag{7}$$

It can be seen that there are four distinct terms in Eq (7):

- A term involving emission by the main reflector, which vanishes if the reflectivity has no angular dependence
- Two terms forming the conventional linear transfer function, but modified slightly by the reflectivity ratio
- A nonlinearity correction

Eq (7) suggests that for the in-orbit calibration process (i.e. the generation of antenna temperatures), the inputs are (broadly speaking) as follows:

1. Warm and cold calibration view counts, appropriately averaged and smoothed. These are used to compute x, and also appear as a scaling in the nonlinear term.
2. Warm target radiance, including any corrections due to temperature sensor measurement error, determined pre-launch.
3. Cold space radiance, including corrections due to antenna sidelobes viewing earth or satellite.
4. Nonlinearity coefficient a_2. Depends on channel and instrument temperature.
5. Reflectivity of the main mirror, pre-computed as a function of scan angle, using pre-launch measurements. Considered further in Section 4.
6. Temperature of the main mirror (estimated from instrument temperatures since it can't be directly measured).

Note that this scheme does not envisage explicit computation of the three coefficients a_0, a_1 and a_2, unlike in the AMSU/MHS scheme. Rather, the earth-view antenna temperatures are computed as the main output. (See Appendix for a treatment that does include computation of a_0, a_1 and a_2).

3. Comparison with the AMSU/MHS approach

The operational AMSU/MHS calibration algorithms do not take account of antenna reflectivity (though it can be considered later as a correction). So, as already noted, we tend to get a cold bias for QV channels and a warm bias for QH channels. The bias is greatest at cold scene temperatures, and close to zero when the scene temperature is equal to the black body temperature.

The calibration equation of Saunders (1994) and Robel (2009) can be written

$$B_E = B_{bb} - \frac{C_{bb} - C_E}{G} + \mu_2 \frac{(C_E - C_{SP})(C_E - C_{bb})}{G^2}; \quad G = \frac{C_{bb} - C_{SP}}{B_{bb} - B_{SP}}$$

Using the terminology of Section 2, this is equivalent to:

$$B_E = x B_{bb} + (1-x) B_{SP} - \mu_2 x (1-x)(B_{bb} - B_{SP})^2 \tag{8}$$

We note that the nonlinearity parameter μ_2 has the units of *inverse radiance*, whereas the units of a_2 in (1) are *radiance*. The assumption of Saunders is that the nonlinearity of the receiver is a fixed function of *receiver input power*, whereas the assumption of Section 2 is that the nonlinearity is a function of *detector power*, and hence ADC count. It seems likely that the latter is more consistent with the physical design of the receiver. For post-launch performance, where the instrument characteristics are similar to pre-launch characteristics, the two approaches are equivalent, but as the instrument ages (receiver gains tend to decrease) they diverge. This could be important for climate applications (e.g. John et al., 2013).

In practice, most AMSU and MHS channels have only very small nonlinearity corrections, so the difference between the two nonlinearity approaches does not have great significance.

Another area where the approaches differ is that the AMSU/MHS processing is split into two distinct stages. The first is the calibration stage, involving only the space and black body readings. These are used to compute the "counts to radiance" coefficients a_0, a_1 and a_2. The NOAA 1B files include these coefficients, together with raw earth-view counts. In the second stage, the coefficients are applied to the counts to create antenna temperatures. It is at this second stage that correction for the antenna reflectivity may optionally be applied. Labrot et al. (2011) suggest the following simplified correction, assuming that the reflector is at the same temperature as the black body

$$\Delta T = \alpha (T_{bb} - T_E)(\cos 2\theta_E - \cos 2\theta_{SP}) / 2 \qquad \text{where } \alpha = 1 - \frac{R_{90^\circ}}{R_{0^\circ}}.$$

As a final stage, antenna pattern correction is applied (to account for side-lobes viewing cold space, etc.) to create brightness temperatures. This is the same in the MWS approach, though the latter uses a more sophisticated model.

Does it matter which approach is used? Whereas the approach of Section 2 appears more theoretically correct, in practice the antenna reflectivity effect is sufficiently small that it could be implemented as a secondary correction. The only major difference, as previously noted, is the treatment of the nonlinearity correction with respect to instrument ageing.

4. Pre-launch measurements

Pre-launch, the MWS instrument will be tested with two external precision calibration targets: an earth target (variable temperature, variable position) and a space target (fixed temperature of around 80K; fixed position). We assume that the external targets have higher precision than the internal target, which is reasonable because the latter has potted PRTs which cannot be re-calibrated after installation. This is the same approach as was used for AMSU-B.

Initially, many of the constants in equ (7) are unknown, so we define a "linear" first-guess radiance:

$$B_{Lin} = x\left(B_{bb} + \delta B\right) + \left(1 - x\right) B_{SP}$$

where $B_{bb}+\delta B$ is the black body radiance computed from instrument telemetry, and δB is the PRT measurement error. For a precision earth target, the true B_E can be computed from its known temperature, so we obtain measurements of $B_{Lin} - B_E$ as a function of x. We can then fit a polynomial:

$$B_{Lin} - B_E = k_0 + k_1 x + k_2 x^2 \tag{9}$$

In general, k_0, k_1 and k_2 will vary with scan angle. By comparison with (7) it is possible to obtain expressions for k_0, k_1 and k_2 in terms of the inputs.

For instruments like AMSU, MHS and MWS, the on-board calibration target is at a scan angle of 180° from nadir. Therefore, with the earth target at nadir $R_\theta = R_{bb}$. The nadir measurements allow us to compute two important parameters:

- When x = 1, the antenna emission term vanishes from Eq (4), and B_E = B_{bb} . Thus *this relationship allows cross-calibration of the on-board PRTs with the external target*.
- When x = 0, the antenna emission term introduces an offset between B_E and B_{SP} (Eq 3), allowing determination of R_{SP}/R_{bb}. It is assumed that the mirror temperature (and hence B_{REF}) can be estimated from other instrument temperatures.

In practice, we do not normally have the luxury of a calibration run at precisely x = 0 or x = 1, so we use the fitted polynomial of (9):

- Warm: $\delta B = k_0 + k_1 + k_2$; hence the PRT corrections
- Cold: $(1 - R_{SP}/R_{bb})(B_{SP} - B_{REF}) = k_0$; hence R_{SP}/R_{bb}

A third parameter is the nonlinearity constant, related to k_2:

- Nonlinearity: $k_2 = (a_2 / R_{bb})\,(C_{bb} - C_{SP})^2$

To summarise, the nadir runs allow us to compute the following parameters: δT_{bb}, R_{SP}/R_{bb}, a_2 / R_{bb}. These are all potentially functions of instrument temperature.

What about off-nadir? The theoretical form for reflectivity angular dependence is:

$$R_\theta = R_0 \cos^2\theta + R_{90^0} \sin^2\theta$$

We have already established R_{SP}/R_{bb}, and the space and black body viewing angles are known. But we don't yet have the information to compute R_{bb}/R_θ. However, there also exists a theoretical relationship between the horizontal and vertical reflection coefficients (e.g. Yang et al., 2015)

$$R_h^{\,2} = R_v$$

where h refers to polarisation parallel to the reflector plane and v is orthogonal. So for a QV channel, $R_{90} = R_0^2$ and for a QH channel $R_0 = R_{90}^2$. This now allows us to calculate R for any angle θ and suggests that there is no need for any measurements at earth target angles other than nadir. In practice, such measurements are desirable in case there are other effects not considered in this treatment. If necessary, a look-up table could be provided for the reflectivity angular dependence. So, referring to Eq (7) we can see that the final calibration parameter needed is R_{bb}/R_θ, which is a function of angle and possibly of instrument temperature. It is easy to re-write (7) in terms of the calibration parameters identified in this section (not shown here).

To illustrate these concepts, Figure 1 shows the output from a simple model of Eq (7): it shows the departure from the simple linear transfer function (Eq 8, with no nonlinear term) for several different scan angles, making some assumptions about mirror reflectivity and temperature. Brightness temperature units are used (rather than radiance). We see:

- The characteristic cold bias at nadir for QV channels, much smaller at edge of scan
- The curves all coincide when the scene temperature is the same as the reflector temperature
- The inclusion of nonlinearity modifies the curves in the central portion, but there is no change at $x = 0$ or $x = 1$ (as expected). The nonlinearity shown here (for illustration) is rather large and takes the form of reduced instrument gain at higher scene temperatures, as might be expected if the detector saturates; in fact AMSU-B channel 16 showed the opposite behaviour.

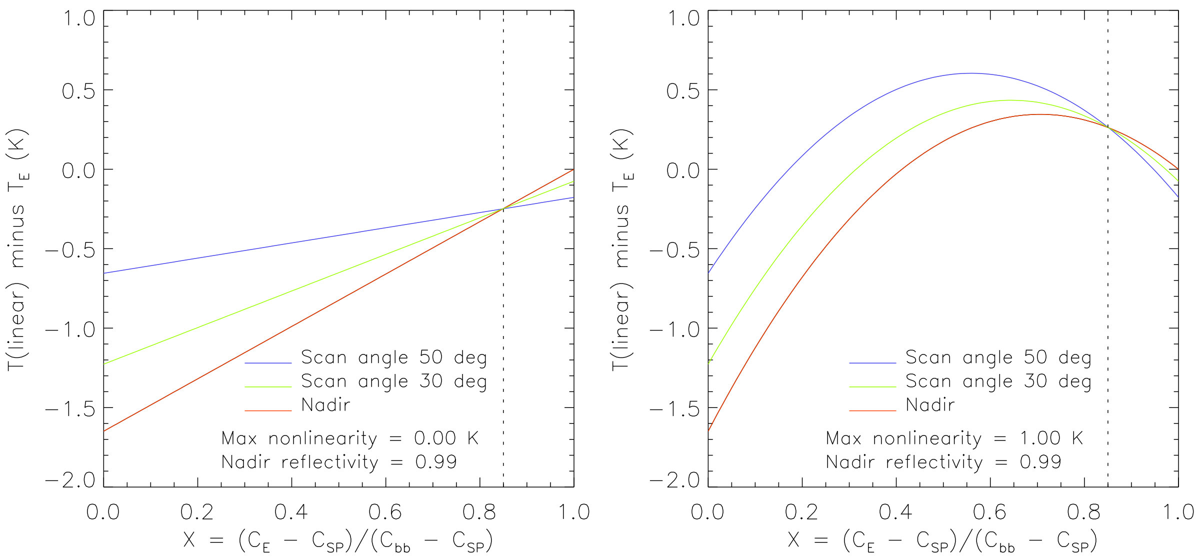

Figure 1: Illustration of the calibration relationships. Linear brightness temperature (computed as xT_{bb} + (1–x)T_{SP}) minus T_E from Eq (7). Nadir reflectivity assumed to be 0.99 (QV channel). Left: no nonlinearity; right: with nonlinearity included. The vertical dotted line is the x value that corresponds to the reflector temperature (250K). Space target assumed to be at 80K; on-board target at 280K.

For comparison, in Figure 2 we reproduce a figure from Saunders et al. (1995) which shows experimentally determined departures for AMSU-B. The cold bias at nadir in Fig 2 is about 0.25 times that shown in Fig 1, therefore the AMSU-B mirror emissivity at nadir is about 0.25 times that assumed in Fig 1, i.e. 0.25*(1–0.99) = 0.0025. This suggests that the AMSU-B mirror reflectivity ranges from ~0.9975 at nadir to ~0.995 at a scan angle of 90°.

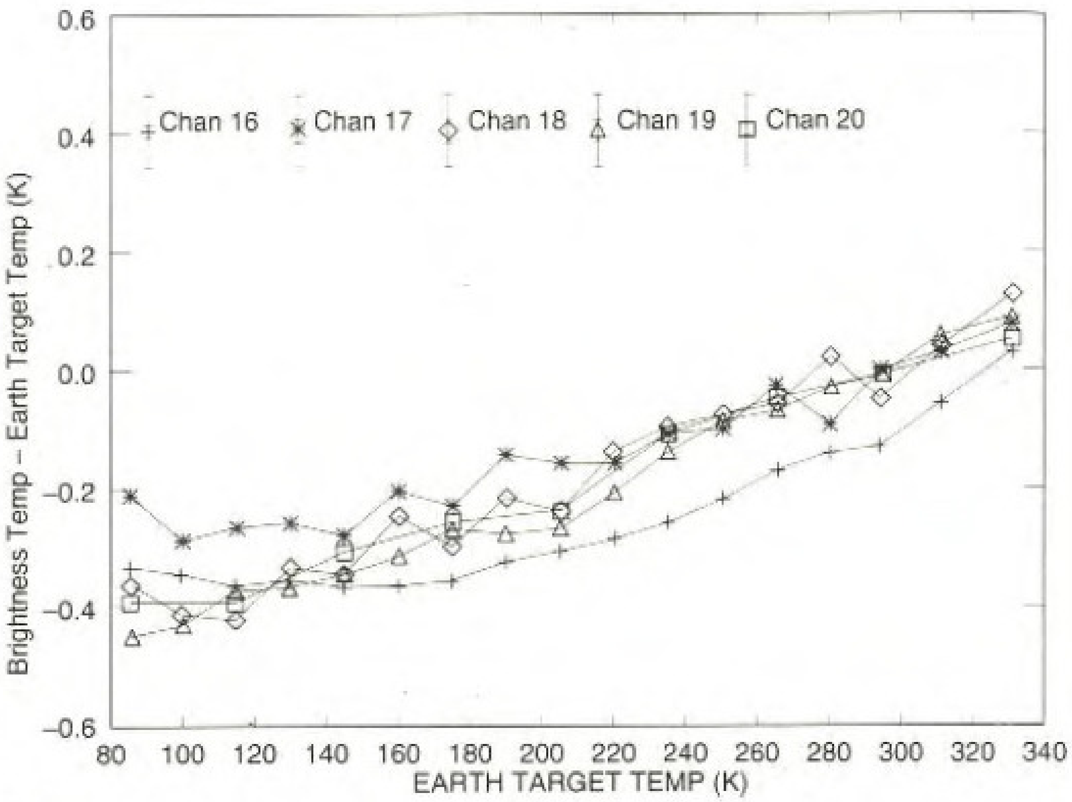

Figure 2: Results of AMSU-B radiometric testing: Difference between measured brightness temperatures when viewing the Earth target and the measured target temperatures, for nadir view of the PFM instrument. A linear calibration was used. Reproduced from Saunders et al., 1995.

5. Conclusions

The calibration equation of Eq (7) (or similar variants) is feasible for operational use in MWS data processing. It is physically justified in terms of its ability to include mirror reflectivity and nonlinearity. Pre-launch calibration can be used to provide the necessary calibration parameters, namely: δT_{bb}, R_{SP}/R_{bb}, a_2/R_{bb} and R_{bb}/R_θ. In principle, only the nadir run is necessary, since the angular dependence of R_θ can be obtained from theory; in practice, measurements at other angles are desirable, in case there are other instrumental effects that need to be included.

Because the nonlinearity and reflectivity corrections are expected to be rather small, an alternative, equally valid, scheme would be to apply a simple linear calibration as a first step, and apply the corrections subsequently.

Finally, we note that the operational AMSU/MHS scheme does not appear to model correctly the nonlinearity parameter as the receiver ages. In practice this is unlikely to matter since AMSU nonlinearity corrections are small, but it would be as well to treat MWS correctly as it is anticipated that the data will be of long-term importance for climate applications. If there is a configurable amplifier between the detector and the ADC, this will need to be accounted for in the calibration process.

6. References

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Appendix: a polynomial formulation of the calibration equation

Section 2 derives an expression for earth radiance in terms of the raw counts and the calibration measurements. However, it is also possible to use a method that is closer to that used operationally in the AMSU level 1b datasets: a polynomial in earth counts, with the polynomial coefficients computed by the level 1 processor. So we use equation (1a) as the fundamental equation for earth-view BT, i.e.

$$B_E = \frac{a_0 + a_1 C_E + a_2 C_E{}^2 - (1 - R_\theta) B_{REF}}{R_\theta} \tag{10}$$

and derive a_0 and a_1 from (1b) and (1c). Eliminating a_0, we get a_1

$$a_1 = \frac{B_{bb} R_{bb} - B_{SP} R_{SP}}{C_{bb} - C_{SP}} \; - \; a_2 (C_{bb} + C_{SP}) \; - \; B_{REF} \frac{R_{bb} - R_{SP}}{C_{bb} - C_{SP}}$$

Then substituting in (1c) we get a_0:

$$a_0 = B_{bb} R_{bb} - \frac{C_{bb}(B_{bb} R_{bb} - B_{SP} R_{SP})}{C_{bb} - C_{SP}} + a_2 C_{SP} C_{bb} + B_{REF} \frac{C_{bb}(1 - R_{SP}) - C_{SP}(1 - R_{bb})}{C_{bb} - C_{SP}}$$

These equations can be made more compact by defining a gain $G' = \dfrac{C_{bb} - C_{SP}}{B_{bb} R_{bb} - B_{SP} R_{SP}}$ to give

$$a_1 = \frac{1}{G'} \; - \; a_2 (C_{bb} + C_{SP}) \; - B_{REF} \frac{R_{bb} - R_{SP}}{C_{bb} - C_{SP}} \tag{11}$$

$$a_0 = B_{bb} R_{bb} - \frac{C_{bb}}{G'} + a_2 C_{SP} C_{bb} + B_{REF} \frac{C_{bb}(1 - R_{SP}) - C_{SP}(1 - R_{bb})}{C_{bb} - C_{SP}} \qquad (12)$$

Note that in the classical limit ($R_{SP} = R_{bb} = 1$), these equations reduce to the Saunders (1994) formulation:

$$a_1 = \frac{1}{G} - a_2 (C_{bb} + C_{SP})$$

$$a_0 = B_{bb} - \frac{C_{bb}}{G} + a_2 C_{SP} C_{bb}$$

The advantages of using equations (10), (11) and (12) are:

- It is easy to understand the physical principles behind equation (10)
- Compact storage using polynomial coefficients (following AMSU practice)
- Computation of the polynomial coefficients can be delegated to a calibration task

Mathematically, the result is the same as using (7).