The Absolute Calibration Of Total Power Millimeter-Wave Airborne Radiometers

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ABSTRACT

The launch of the Advanced Microwave Sounding Unit (AMSU) on the polar platforms, NOAA-K, L, M and N will provide vertical temperature and humidity soundings for inclusion in numerical weather prediction. It is important therefore, that calibration and validation of the data generated takes place. The microwave radiometers, MARSS and Deimos, onboard the Met. Offices C-130 are to be used to this end, so it is vital that their calibration be well understood. This presentation will investigate the factors that can effect the calibration of airborne radiometers.

INTRODUCTION

The U.K. Meteorological Office operates two total power microwave radiometers, MARSS and Deimos, aboard the Met. Research Flights C-130 aircraft (for a more full description of these instruments see [1] and [2]). Both are along track scanning and use two blackbody targets, an ambient and a hot (held at a 334K), for their calibration. Table I lists their various performances. In both instruments the scanning and calibration systems lie outside of the aircraft pressure plate and so are exposed to a wide range of temperatures and humidities. The mechanisms by which the calibration of an airborne radiometer can be effected will be examined in this presentation.

EXTERNAL CALIBRATIONS

It is important that we define what definition of brightness temperature is to be used. Throughout the rest of this paper, the brightness temperature of a blackbody is defined as being the same as its physical temperature. Choice of definition becomes important below 10K, where the radiance and the Rayleigh-Jeans brightness temperature tend to zero but our definition does not. An effective brightness temperature must therefore be used when viewing cold scenes, such as cold space views, and can be calculated by expanding the Planck function to include second order terms .

A scheme of linear interpolation between the measured brightness temperatures of the two internal blackbody targets is used to calibrate the radiometers. However, in reality we find that in order that the radiometer equation be linearized the inclusion of corrective terms to the blackbody targets are required. Through a process of using external targets and well understood radiative scenes to check the calibration the

TABLE I
SUMMARY OF RADIOMETER SYSTEMS

Instrument	Deimos		MARSS	
Frequency/GHz	23.8	50.1	89.0	157.0
View Angles	+35° To -5° Downwards		+40° To -40° Up And Down	
Beamwidth (3d)	11°		10°	
Polarization	V&H	V&H	Mixed	V or H
Sensitivity, ΔT	0.6K	0.6K	0.3K	0.5K
Accuracy	1.5K	1.5K	0.9K	0.8K

nature and size of these corrective terms can be measured. From analysis of data taken with our radiometers, it was found that for both MARSS and Deimos a constant correction, K_{amb}, to the cold target temperature was required. The hot target correction, K_{hot} required for MARSS varies directly with ambient temperature and for Deimos, one that varies inversely with it. By using an external target that is of a similar temperature to the internal ambient target, we can directly measure K_{amb} in terms of the differences between the physical and brightness temperatures of the two targets. K_{hot} can be calculated using a value of K_{amb} and a cold scene of a well-defined brightness temperature. A target containing boiling liquid nitrogen is often used since it is of known temperature, and we ourselves use one. Our target consists of pyramidal radio absorbent foam onto which the nitrogen is added. When using such a target consideration must be made of the reflection of radiation off the roughed surface of the nitrogen (see [3]) and to the formation of water 'clouds' above the target. The reflections will depend on the ambient temperature, the wavelength of the radiation being measured and the atmospheric pressure, but an increase of about 2K is quite common for ambient temperatures around 300K. The effect of any water 'clouds' formed is hard to quantify due to the difficulty in calculating the liquid water burden above the target and is strongly dependent on frequency, though it is not thought to be a major factor.

High altitude flights can also be used to make calculate K_{hot} using cold space views, though it should be remembered that any value of K_{amb} used has not been directly measured at the low temperatures seen at these altitudes.

THERMAL GRADIENTS WITHIN THE CALIBRATION TARGETS

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Thermal gradients across the internal calibration targets are one mechanism by which the calibration is effected. They result in a difference between the actual and measured temperatures of a target. In targets that are heated, this effect is more pronounced and produces a negative target temperature correction that increases in magnitude with decreasing ambient temperature, as is observed in MARSS. The ambient target may also be effected by this but to what extent will depend upon how the ambient temperature is changing. The targets we use are made of a substrate that is covered on one side with tessellated square based pyramids. The substrate is made of aluminium, the spines are coated in a Radio Absorbent Material (RAM) to a thickness of 1mm, and we use PRTs embedded within it to monitor its temperature. The thermal conductivity of this RAM is quite poor, 1W/m/K, compared to the aluminium and it is across this layer that the largest thermal gradients occur.

An analysis of the heat flow across this layer, for the hot target in Deimos, was conducted in order to gauge the worst case errors that this effect can cause. The heat supplied by the target heater, the conduction across the RAM and the heat loss at its surface due to radiative exchange were all considered, for an equilibrium state of the target at 334K with an ambient temperature of 240K. The heat loss due to convection was ignored as airflow over the target has been minimized and this can be validated by analysis of the duty cycle of the target heater. This gave a maximum temperature correction of 4.2K, though the magnitude will depend upon frequency, because the higher frequencies have a smaller penetration depth in the RAM. Though the relationship between the ambient temperature and the corrections produced is non-linear, it will appear to be so across the range of ambient temperatures that are likely to be encountered. This follows on from the analysis that was performed.

For MARSS this mechanism provides a likely explanation of the hot target correction, it is of a similar magnitude to measured corrections, 1.83K and 0.91K for 89GHz and 157GHz respectively at 270K. In addition, it varies with ambient temperature in the same manner. For Deimos K_{hot} acts in the opposite manner and so this would appear not to be its source.

MIRROR REFLECTIVITY AND RESULTANT VIEW ANGLE DEPENDENCIES

It is an excepted fact that in I.R. radiometers the loss of signal due to the non-unity reflectivity of a scan mirror can cause view dependence problems. This also occurs in microwave radiometers, and was proposed by P.Evans as a means of explaining view dependencies in AMSU-B (see [4]). The nature of the effect can be calculated by considering the E-normal and E-parallel polarization reflectivity's for a metal mirror at some angle of incidence. Small differences in these will cause the reflectivity of the mirror to change with scan angle as the polarization of the measured radiation changes. Values for the reflectivities can be calculated from the impedance of the metal, equation [1], and Fresnells laws, equations [2] and [3]. Where Z_{metal} is the impedance of the metal, Z_{air} is the impedance of air, σ is the conductivity of the metal, δ is the skin depth at a particular frequency, θ_{inc} is the angle of incidence and θ_{refr} is the angle of refraction, which is zero for good conductors.

In the case of AMSU-B, the mirror was made of Beryllium and the incidence angle was 45°, this gave a value of 0.99805 for the squared modulus of the E-normal reflectivity and 0.9902 for the E-parallel. For a stainless steel mirror, such as are now used in MARSS and Deimos, the values are 0.988 and 0.997. The total reflection efficiency is expressed in terms of the polarization angle, measured at zero scan position, plus the scan angle, θ. Equation [4] gives the total reflection efficiency.

$$Z_{metal} = \frac{(1+i)}{\sigma * \delta} \quad [1]$$

$$A_{normal} = \frac{Z_{metal} Cos(\theta_{refr}) - Z_{air} Cos(\theta_{inc})}{Z_{metal} Cos(\theta_{refr}) + Z_{air} Cos(\theta_{inc})} \quad [2]$$

$$A_{parallel} = \frac{Z_{metal} Cos(\theta_{inc}) - Z_{air} Cos(\theta_{refr})}{Z_{metal} Cos(\theta_{inc}) + Z_{air} Cos(\theta_{refr})} \quad [3]$$

$$A_{total} = \sqrt{|A_{norm}|^2 Cos^2(\theta) + |A_{par}|^2 Cos^2(\theta)} \quad [4]$$

The resultant error produced by a mirror with these reflectivities will depend on the relative contribution it makes to the measured brightness temperature. This produces errors of up to 0.2K for AMSU-B viewing a scene of 80K with a mirror at a temperature of 300K, and for a stainless steel mirror under the same conditions, errors of up to 2.632K can occur.

Any surface covering on the mirror such as an oxide layer or an anodized finish, as with mirrors made of aluminium, will effect the reflectivity and increase any view dependence, although by how much it is difficult to calculate.

RECEIVER NON-LINEARITY

There are two main sets of items in a microwave heterodyne receiver that can cause non-linearity, the video frequency amplifiers and the detectors. The gain of the video amplifiers is a function of their temperature and so this is controlled by placing them on a heated plate. Doing so eliminates the majority of thermally generated gain problems.

In MARSS and Deimos, the detectors are square law diodes and as such their linearity is a function of the incident power. There are regions at the top and bottom of the incident power range where the response is non-linear, though a diode is usually chosen to avoid them.

Any non-linearity of the detector will most probably effect the calibration through the calculation of K_{hot}. Any external calibration using a low temperature scene will produce a positive hot target correction if the non-linearity is pronounced. This is of the wrong order to explain the hot target correction in MARSS but could explain that in Deimos. The linearity of the receiver response with scene brightness temperature can be tested with the addition of a polarizing grid to the above-described calibration. The measured brightness temperature will fall off as $\cos^2\theta$, where θ is the angle between the polarization measured by the radiometer and the orientation of the grid. This has been done for Deimos to within an accuracy of greater than 3K and no non-linearity was detected.

STANDING WAVE AND REFLECTION PROBLEMS

Leakage of the local oscillator (LO) signal, via the mixers in the receiver, is another mechanism by which the calibration can be affected. If the leaked LO signal undergoes reflection back into the receiver, it can interfere with the incident LO signal and thus effect the gain. In the most severe cases, this can result in the formation of standing waves.

By placing a metal plate in the optical path of a radiometer, the maximum impact that this has on the calibration can be directly measured. For MARSS, values of ±4K at 89GHz and ±1.5K at 157GHz were measured.

When the reflection into the receiver of the leaked LO signal is coupled with changes in the optical path of the radiometer, such as might be caused by slight imperfections in the scanning system, view dependencies arise. The calibration therefore is no longer valid across all the views in a scan.

In MARSS and Deimos, it is believed that the window in the scanning drum is the most likely item to reflect any leaked LO signals. In both instruments, the window is made of TPX, a plastic material, and an analysis of its reflectivity has been made. If the window is treated as a plane parallel-sided slab of dielectric, as described in [5], its reflectivity at each of the LO frequencies can be calculated. The reflectivity is given in equation [6] in terms of, d the thickness of the slab, m its refractive index, λ the wavelength of the radiation being considered. The terms r_1 and r_2 represent the field reflectivities at each surface of the slab in terms of the refractive indexes of air and the material.

$$\chi = \frac{2\pi d}{\lambda} m \qquad [5]$$

$$|\Gamma|^2 = \frac{(r_1 + r_2)^2 - 4 r_1 r_2 \sin^2 \chi}{(1 + r_1 r_2)^2 - 4 r_1 r_2 \sin^2 \chi} \qquad [6]$$

In Deimos, this analysis was included at an early stage in the design process in order to minimize the effect, but in MARSS, it was not and the effect is noticeable at 157GHz for certain views. This can be remedied by the replacement of the window with one of a thickness chosen to minimize the effect or the removal of it altogether.

CONTAMINATION OF VIEWS BY SIDE-LOBES

The contamination of calibration views due to the side-lobes of the antenna pattern is another mechanism that effects the calibration. It will be most pronounced for the hot target, resulting in a reduction of the measured brightness temperature. It acts upon the calibration in the same manner as do thermal gradients within the hot target, but it is of a smaller magnitude.

A magnitude can be put on the effect if we calculate the percentage of the beam that belongs in the main lobe. This was done for the 24GHz channel of Deimos using the measured antenna pattern and assuming a main lobe scene brightness temperature of 340K and a side-lobe brightness temperature of 250K. The resultant reduction in the target brightness temperature was of the order of less than 1K, though it will depend on frequency.

From this, it can be seen that the effect is in fact quite small and it is most pronounced at the lower frequencies. In this respect, it tends to reduce the expected difference between the hot target corrections for two frequencies due to the presence of thermal gradients in the hot target.

The antenna pattern of the instrument as a whole can be measured using Sun views, or, views of a coastal crossing. With MARSS, the response of the radiometer to the Sun for Sun angles of 2.5° to 20° was used and the response was seen to fit a Gaussian curve well (see [2]). With Deimos, coastal crossings were used where the sharp delineation seen between the brightness temperatures of the sea and the land much the same produced the same effect. Again, no large deviation from a single lobed Gaussian was seen.

SUMMARY

The major mechanisms by which the calibration of airborne microwave radiometers can be effected have been discussed. Their relevance with respect to the actual calibration of two such radiometers has been investigated, and values for the various effects have been calculated.

It was found that for the MARSS radiometer the most important effect were thermal gradients within the hot target. For Deimos a different set of mechanisms are required to explain the observed hot target correction, which have yet to be fully explained.

REFERENCES

1. T.J.Hewison, "The Design of Deimos: A Microwave Radiometer with Channels at 23.8GHz And 50.3GHz For the U.K. Met. Research Flight C-130 Aircraft", Proc. IGARSS 1995, pp.2261-3.
2. Dr.D.Jones, Ph.D. Thesis, Reading University, 1995.
3. E.A.Vinogradov, E.M.Dianov and N.A.Irasova, 1967, "Dielectric Characteristics of Liquid Nitrogen at λ=2.3mm", Soviet Physics-Technical Physics, vol. 11, pp.983.
4. P.Evans, "AMSU-B View Dependence", Met. Office (RSI) Branch Working Paper No. 112.
5. J.Lesurf, "Millimeter-wave Optics, Devices And Systems", 1990, pp. 117-118.