Radiometric characterisation of AMSU-B

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ABSTRACT

The U.K. Meteorological Office is procuring the humidity sounding element of the Advanced Microwave Sounding Unit (i.e. AMSU-B). This consists of a five channel microwave radiometer with channels centred at 89, 150, 183±1, 183±3, & 183±7 GHz with a field of view of nominally 1.1° (i.e. 15km footprint at nadir). To characterise the radiometric behaviour of AMSU-B an extensive series of tests have been performed on the engineering model in a thermal-vacuum chamber where the instrument can view an *earth* target and *space* target. Results showing the sensitivity, absolute calibration accuracy and linearity of the five channels are presented and show the instrument is within specification.

1. INTRODUCTION

To enhance the atmospheric temperature and humidity sounding capability on the NOAA polar orbiting satellites the current generation TOVS (TIROS Operational Vertical Sounder) instruments will be upgraded for the ATOVS (Advanced TOVS) system due for launch on NOAA's K, L & M in the mid 90s. The existing operational TOVS consists of a 20 channel infrared sounder (HIRS) for temperature (surface to 20hPa) and humidity (surface to 400 hPa), a 3 channel infrared stratospheric sounding unit (SSU) for temperatures from 1 – 20 hPa and a 4 channel microwave sounding unit (MSU) for temperature retrievals through cloud up to 70 hPa. The new generation of instruments which will make up the ATOVS are an infrared sounder HIRS-3 and a new 20 channel Advanced Microwave Sounding Unit (AMSU). AMSU is comprised of three separate instruments AMSU-A1 & AMSU-A2 which have the 15 lower frequency channels (23.8–89.0 GHz) primarily for temperature sounding (surface to 2 hPa) and AMSU-B which has 5 higher frequency channels (89–183 GHz) primarily for humidity sounding (surface to 200 hPa). AMSU-A has a field of view of 3.3° (45km on the surface at nadir) and AMSU-B a field of view of 1.1° (15km at nadir).

The U.K. Meteorological Office (UKMO) are providing 3 AMSU-B flight instruments for the NOAA's K, L & M polar orbiting satellites through a co-operative agreement with NOAA. The AMSU-B engineering model (EM) was delivered to the UKMO in May 1992 by British Aerospace Space Systems Ltd (BAe) and the three flight models are now being assembled by BAe to be delivered to the UKMO in 1993. Before launch the instruments are being comprehensively tested to determine their actual fields of view, thermal and radiometric characteristics. This paper describes the radiometric tests which are being carried out by the UKMO on AMSU-B and presents the results for the engineering model which will be of interest to any future users of AMSU-B data.

2. FUNCTIONAL DESCRIPTION OF AMSU-B

AMSU-B is a 5 channel total power microwave radiometer with channels nominally centered at 89, 150 GHz and 3 centred on the 183.31 GHz water vapour line at 183.31±1, ±3 and ±7 GHz. More details of the spectral characteristics of AMSU-B are given in Table 1. The exact values of the central frequencies for each channel and their variation with instrument temperature in vacuum have been measured[1]. Once every 2.66667 secs AMSU-B scans through 90 Earth views, 4 space views and 4 internal black body target views. Note that there are also 4 possible viewing direction options for the space view which can be selected by ground command which either view closer to the limb of the Earth or closer to the spacecraft. During the commissioning phase of the spacecraft, investigations will be carried out to determine which of the 4 possible space view options give the lowest stable radiances and hence the most reliable calibration. The Earth nadir viewing angles range from −48.95° to +48.95° and AMSU-B has a 3dB beamwidth of nominally 1.10° which gives 90 Earth view samples. The samples are numbered sequentially such that sample 1 is at the edge of the swath where the scan line starts and samples 45 & 46 are 0.55° either side of nadir. Measurements of the antenna pattern of the AMSU-B EM on the compact antenna test range at Queen Mary &

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Westfield College London have verified[2] that the beamwidths are $1.1° \pm 0.11°$. The scanning and sampling is designed such that 9 AMSU-B footprints are equivalent to one AMSU-A footprint although the two instruments will not be aligned on the spacecraft to give coincident footprints. The four space views and internal target views during each scan are separated by 1° steps. To save time the antenna scan is not uniform, it accelerates and decelerates between Earth views, space views and internal target views.

Channel number designation	Centre Frequency of channel (GHz)	No. of Pass Bands	Channel Passband Limits Lower GHz	Upper GHz
16	89.0	2	87.6–88.6	89.4–90.4
17	150.0	2	148.6–149.6	150.4–151.4
18	183.31±1.00	2	182.06–182.56	184.06–184.56
19	183.31±3.00	2	179.81–180.81	185.81–186.81
20	183.31±7.00	2	175.31–177.31	189.31–191.31

Table 1. Nominal centre frequencies and passbands for AMSU-B

The radiances for the Earth views are derived from the measured Earth view counts received in the spacecraft telemetry (counts are proportional to the receiver output voltage averaged over the scene integration time of 18ms) and the calibration coefficients inferred from the internal target and space view data.

The internal target is comprised of a magnesium alloy substrate with pyramidal tines (aspect ratio 4:1) covered by a 1.3mm layer of Eccosorb. There are 7 two wire Platinum Resistance Thermometers (PRTs) in the internal target to monitor its temperature. The emissivity of a similar target has been measured radiometrically to be > 0.99999. The temperature of the internal target is not actively controlled but floats at the ambient temperature of that part of the instrument. It is anticipated to be around 20°C in orbit.

3. THE U.K. MET. OFFICE CALIBRATION FACILITY

The calibration facility is located on the Defence Research Agency (DRA) Farnborough site and allows the calibration performance testing of AMSU-B under the full range of operating conditions using an existing 3 metre thermal vacuum chamber. This allows a vacuum to be maintained to better than 10^{-5}torr. The temperature of AMSU-B is controlled by space radiation panels held at 80K on all sides of the instrument except in the Earth direction where a shroud is maintained at any desired temperature between 223K and 343K. Heaters between the space radiation panels and the instrument also allow additional control of the instrument temperature. AMSU-B, the external calibration targets and radiators are all mounted on a self supporting rig that can be removed from the chamber for ease of maintenance. A schematic diagram of the facility is shown in Figure 1 which shows the position of the instrument, the Earth view and Space view targets.

The 90 possible Earth views for AMSU-B are simulated by a movable black body target, hereafter referred to as the 'Earth target', which for most of the tests is placed in a nadir view (i.e. sample 46), but can be moved to be in any desired Earth viewing direction and in addition it can be placed in front of the space target. It is carefully temperature controlled over the range 80–310K so that ideally temperature gradients across the surface are less than 50 mK. In fact for the EM tests this could not be achieved and gradients of up to 0.5K had to be tolerated in order to get sufficient data. It is hoped to improve on this for the flight model tests. The Earth target must also remain at a stable temperature ($<$ 50mK variation) for longer than 5 minutes (110 scans) and in practice it remains stable for much longer than this. The Earth target temperature is measured to an absolute accuracy of better than 0.1K. A shroud surrounds the target which is maintained at a temperature as close to the target as possible and a snout (with reflective interior) closely couples the target to the instrument. Note the snout is not fitted during tests when the Earth target is moved. A similar black body target is used for the space view hereafter referred to as the 'space target'. This target is maintained at around 85K for all the tests. This obviously gives a much higher space view radiance than experienced in orbit (i.e. 2.73K) and so the instrument performance in space has to be extrapolated from these measurements.

Both targets are fabricated from aluminium substrates with pyramidal tines (aspect ratio 4:1) and coated with Eccosorb. The Earth view target is closer (~65cm) to the instrument than the space target (~135cm), to allow it

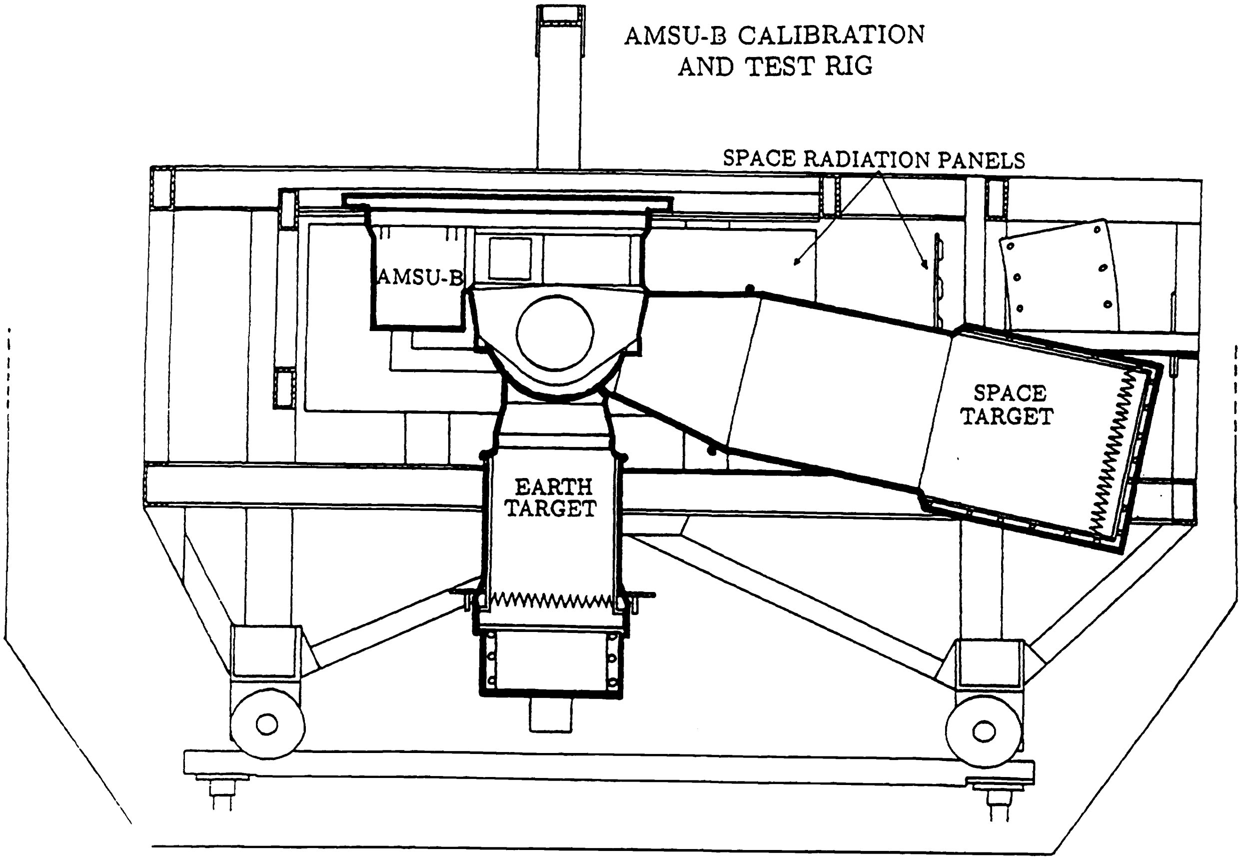

Figure 1. The UK Met Office facility for thermal and radiometric testing of AMSU-B.

to be placed in front of the space target, and so is smaller (29.5cm diameter) than the space target (40cm diameter). Considerable efforts were made to ensure an accurate calibration for the external target PRTs[3]. To determine a representative target temperature the PRTs are averaged together in a manner to best represent the proportion of the target that the antenna 'sees'.

4. AMSU-B CALIBRATION

AMSU-B has been designed to allow a two point calibration, for each scan line, from the internal target and space views. The instrument response is assumed to be linear between these two calibration points. This allows the radiance from the antenna to be given by,

$$R_{Earth}(i) = a(i) \times (C_{Earth}(i) - C_o(i)) \qquad \mu W/(cm^{-1}.ster.m^2) \tag{1}$$

where $C_{Earth}(i)$ is the measured count for channel i whilst viewing the Earth scene. Calibration parameters (slope & offset) are determined for every scan line from the internal target and space view counts. The slope $a(i)$ (the reciprocal of the instrument gain) for channel i is given by:

$$a(i) = \frac{B(\nu, T_{BB}) - B(\nu, T_{SP})}{(\overline{C}_{BB}(i) - \overline{C}_{SP}(i))} \qquad \mu W/(cm^{-1}.ster.m^2)/count \tag{2}$$

where $B(\nu, T)$ is the Planck function for a frequency ν and temperature T. The Planck function uses the updated Planck constant and Boltzmann constant values[4]. For the radiometric tests in the chamber the space view has to be simulated by a cold target placed in the space view. T_{SP} is then the mean temperature of the space target and T_{BB} is the mean temperature of the internal target as measured by their respective PRTs. T_{BB} was computed from 5 out of the 7 PRTs in the internal target (PRTs 5 & 6 in the EM were consistently biased low and so were not included in the average). $\overline{C_{BB}(i)}$ and $\overline{C_{SP}(i)}$ are mean internal target and space view counts respectively. The average is computed from the four consecutive samples which view the internal target and space view for each scan line. In addition values from scan lines before and after the current scan line can also be included in the average (see equation 5 below).

The zero radiance offset, $C_o(i)$, for channel i is given by,

$$C_o(i) = \overline{C}_{BB}(i) - \frac{B(\nu, T_{BB})}{a(i)} \qquad counts \tag{3}$$

$C_o(i)$ is related to the receiver noise and the dc offset applied to the video amplifier.

The radiance computed from equation 1, $R_{Earth}(i)$, can be converted into brightness temperature using the inverse Planck function $B^{-1}(\nu, R_{Earth})$,

$$T_{Earth}(i) = B^{-1}(\nu, R_{Earth}(i)) \qquad K \tag{4}$$

Note that $T_{Earth}(i)$ is strictly the antenna temperature which hereafter is referred to as brightness temperature. It is envisaged that users will require the option of obtaining either radiance or brightness temperature for their retrieval algorithms. For ease of interpretation the results of the radiometric tests described below are all presented in terms of brightness temperature as for scenes above 10K brightness temperature is linearly related to radiance at these frequencies. All the calculations however were in terms of radiance.

5. RADIOMETRIC TESTS

A series of tests were carried out in the UKMO calibration facility to fully characterise the radiometric response of the instrument. They are listed below in order of priority:

(i) Determine sensitivity of receiver output to antenna temperatures
(ii) Determine linearity of receiver output to antenna temperatures over range 80–310K
(iii) Check receiver dynamic range for antenna temperatures from 80–310K
(iv) Determine absolute calibration accuracy
(v) Determine $\frac{1}{f}$ noise
(vi) Determine variation of gain/offset with instrument temperature
(vii) Determine variation of gain with nadir viewing angle
(viii) Determine long term variation of gain/offset with time
(ix) Perform absolute calibration and linearity measurements on AMSU-A cross-calibration target

Some of these tests were carried out at several instrument operating temperatures. For the purposes of these tests the instrument temperature was defined as follows. Below 30°C it is the temperature measured by the thermocouple on the channel 17 receiver baseplate and above 30°C the thermocouple temperature on the channel 18/19/20 receiver baseplate. For future tests it is intended to use the channel 18/19/20 mixer temperature available in the spacecraft telemetry which will be used to represent the instrument temperature both in the chamber and in-orbit. For these tests a full set of measurements were made at instrument temperatures of 16°C, 26°C and 36°C which represent the minimum, nominal and maximum instrument temperatures expected in orbit. In addition a few radiometric checks were made at extreme instrument temperatures of 6°C and 46°C to extend the measurement range of any temperature dependent parameters.

Items (vii), (viii) and (ix) are discussed in detail in a more complete report on the test results[5] and are briefly referred to in the conclusions. The results of the remaining tests are described below.

5.1 Temperature Sensitivity

The temperature sensitivity or noise equivalent temperature (NeΔT) of the instrument is a measure of the minimum change in antenna temperature detectable by AMSU-B and is primarily a function of the input system noise. Other factors such as noise generated by the electronics and variations in gain also influence the sensitivity.

The sensitivity measurement is performed with the instrument at a stable temperature and the antenna scanning. The Earth target is at a temperature close to 300K. 100 scans (~4.4 minutes) of nadir Earth target counts (i.e. sample 46) are extracted, converted into brightness temperature (as described above) and then the standard deviation of the 100 brightness temperatures is computed to give the sensitivity value for each channel.

The results for the EM at several instrument temperatures are listed in Table 2 which also gives the specification for AMSU-B. Note the specification only applies for instrument temperatures between 16°C and 36°C. and is for space and internal target views averaged over 4 consecutive scan lines. The only channel which is marginal is channel 18 where at least for warmer instrument temperatures the required NeΔT values are close to that specified. Measurements were also made for other target temperatures in the range 80–300K and all gave similar values to those listed in Table 2.

Channel	Spec	Instrument Temperature					Measurement
		6°C	16°C	26°C	36°C	46°C	Uncertainty†
16	1.0K	0.37K	0.39K	0.40K	0.41K	0.42K	0.01K
17	1.0K	0.79K	0.79K	0.76K	0.78K	0.78K	0.02K
18	1.1K	0.96K	1.07K	1.12K	1.17K	1.21K	0.03K
19	1.0K	0.64K	0.71K	0.73K	0.75K	0.80K	0.02K
20	1.2K	0.88K	0.93K	0.94K	0.97K	1.04K	0.02K

† The 6°C and 46°C measurements have double these values.

Table 2 Radiometric sensitivity values for the AMSU-B EM (standard deviations taken over 100 samples).

The sensitivity figures given in Table 2 are computed using only the 4 internal target and 4 space view counts from the same scan line to compute the calibration parameters. To reduce the noise in these parameters a triangular weighting function can be convolved with the mean space view counts, $\overline{C}_{SP}(t)$, and internal target counts, $\overline{C}_{BB}(t)$, for each scan line which average up to n scan lines ahead and behind of the current scan line. With this triangular weighting function less weight is given to the lines further from the current scan line. This convolution can be written as,

$$\overline{C}_{BB} = \frac{1}{n+1} \sum_{i=-n}^{+n} (1 - \frac{|i|}{n+1}) \overline{C}_{BB}(t_i) \qquad \textit{counts} \tag{5}$$

where t_i is the time of the scan line before or after the current scan line that is $t_i = t + i \times 8/3$ secs. Figure 2 shows how the NeΔT values are reduced by about 0.1K when the number of scan lines included in the averaged calibration parameters are increased by up to 5. Beyond this the low frequency (> 20secs) receiver noise characteristics starts to influence the means and the NeΔT starts to rise again. An optimum value for n appears to be 2 (i.e. 5 scan lines) for the EM.

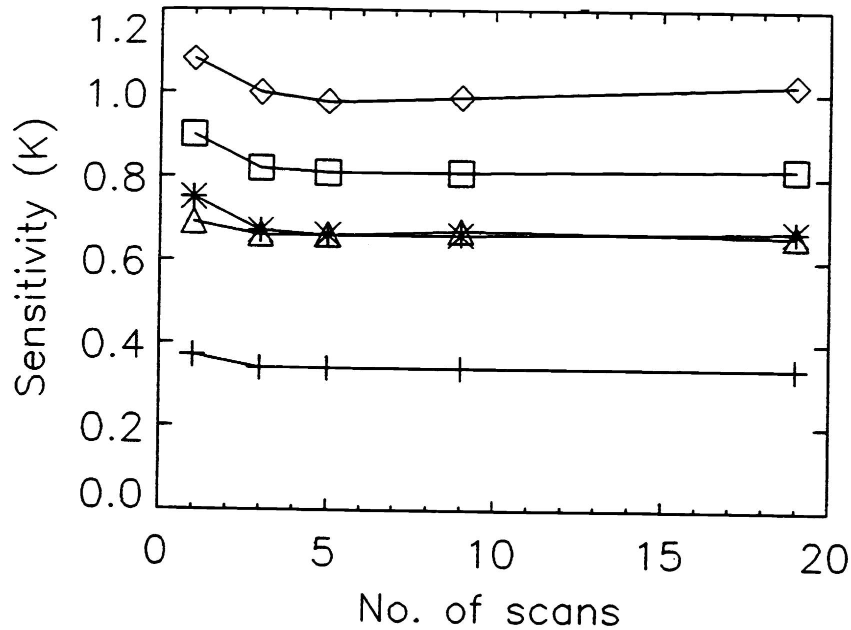

Figure 2. The variation of sensitivity with number of scan lines included in the average for the space view and internal target counts. The symbols for each channel are the same as defined in figure 4.

5.2 Power Spectrum

To measure AMSU-B's low frequency (> 20 secs) receiver noise characteristics a power spectrum of the radiometer's output, whilst viewing a thermally stable target, is required. Note that 'power' in this context refers to the radiometer output power, i.e. the square of the output voltage, not to radiant power, which is proportional to output voltage. High frequencies are dominated by white noise, with a uniform power spectral density. In this regime, the noise on the calibration parameters (a and C_0, defined in section 4) will decrease in proportion to the square root of the number of calibration data samples averaged (i.e. to the square root of the number of scans averaged). Lower frequencies are dominated by 1/f noise, with a power spectral density increasing rapidly as the frequency decreases, and hence the calibration noise will start to increase as the number of scans averaged exceeds a certain limit. The frequency at which the 1/f noise starts to dominate the white noise is known as the '1/f knee frequency', f_K.

During AMSU-B radiometric testing, the internal and Earth targets are held in a thermally stable environment for extended periods (>1 hr). For this test the antenna was parked viewing either the internal target or the Earth target, which were both maintained at about 300K. Power spectra were calculated using Fast Fourier Transform (FFT) routines on the radiometric data. It is important to choose a period of continuous, uncorrupted data as any discontinuities will dominate the Fourier transform. It is also advisable to choose a long period for analysis, because a higher number of samples will result in a better spectral resolution.

Consecutive Earth views are separated by 19 ms, so the 90 Earth views are sampled at a rate of 1/19 ms = 53 Hz. However, sampling at this rate is not continuous; there are breaks between Earth, space and internal target views. To achieve the regular sampling required for Fourier analysis it is necessary to take one FFT sample point per scan period (8/3 s). In the results to be presented in this section, two different methods are used to obtain these FFT sample points. In the first method, a separate FFT is done for each Earth view, resulting in 90 FFTs. The 90 power spectra are then averaged to reduce random variations. In the second method, the 90 Earth view data points are first averaged for each scan, then the averaged values are used as input for the FFT.

Each Earth view sample point is the integration of the receiver output signal over a period τ = 18 ms. Such an integrator will attenuate high frequencies but pass low frequencies; quantitatively, the frequency response in power units will be the square of the Fourier Transform of a uniform window in the time domain, i.e. $G(f)^2$ where $G(f) = sin(\pi\tau f)/(\pi\tau f)$. The first null in the frequency response occurs at $f = 1/\tau$ = 55.6 Hz; however the 'ripples' in the $sin(x)/x$ function extend to considerably higher frequencies. For a given time between samples, T, the Nyquist frequency (i.e. the highest frequency that can be represented by the sampled data) is given by $f_N = 1/(2T)$. Any higher frequencies will be aliased to lower frequencies, with attenuation given by $G(f)^2$.

For a white noise signal, the ratio of the 'true' integrated power, P, between $f = 0$ and $f = f_N$ to the measured integrated power, P_M, (i.e. including alias) is given by

$$\frac{P}{P_M} = \frac{\int_0^{f_N} G(f)^2 df}{\int_0^{\infty} G(f)^2 df} \qquad (6)$$

If we take a single sample every 8/3 s, then $f_N = 0.1875$ Hz. Integration of $G(f)^2$ (with $\tau = 18$ ms) gives $P/P_M = 0.0067$. Nevertheless, this situation corresponds fairly closely to the way the space view and internal target view data are actually used, except that in these cases 4 consecutive views are averaged, decreasing the width of the $sin(x)/x$ function and hence reducing the alias contribution by a factor of approximately 4. In the case where the Earth views are averaged prior to the FFT, each FFT sample point consists of a sequence of 90 18ms windows, with 1ms gaps between the windows. The frequency response of this function closely approximates to that of a uniform time-domain window with duration $\tau = 90 \times 19$ ms (except for frequencies close to 1/19ms = 53 Hz). The first null in $G(f)$ occurs at 0.58 Hz and the resulting value of P/P_M is 0.58. Thus there is still appreciable alias but it no longer dominates the signal. This method of data analysis is more relevant to the 'true' spectral response of the instrument.

f_K is defined as the point where the power spectral density of the 1/f noise is equal to that of the white noise, based on the first method of calculating power spectra. In practical terms, this is calculated by taking each frequency component of the power spectrum, in order of decreasing frequency starting at 0.125Hz and checking whether it is greater than twice the average of all higher frequency components. The first frequency where this condition is met gives f_K. Some attempts were made to carry out a similar calculation based on the spectra processed using method 2; however, results were erratic, which is perhaps not surprising in view of the fact that white noise levels are lower, with relatively more scatter than using method 1.

The average f_K values were calculated by averaging the various measurements of the internal target and the Earth target at 82K and 294K when the antenna was parked and scanning. The values are expressed in Table 3 as the reciprocal of f_K which is the maximum time calibration parameters can be averaged over before 1/f noise starts to increase the error in the average. Based on these data and allowing for the uncertainties, the maximum time (i.e. for channel 17) is about 18s (i.e. 7 scan lines) which is consistent with the small increase in NeΔT values, after averaging 9 scan lines, shown in Figure 2.

Channel	f_K^{-1} *secs*
16	685
17	18
18	24
19	55
20	124

Table 3. Maximum periods over which to average the calibration parameters before 1/f noise influences the mean.

5.3 Receiver Linearity

As implied by equation 2, a two point calibration is employed for AMSU-B (i.e. space and internal target). For all scenes with radiances in between these two calibration points it is assumed that the instrument response is linear. To verify this assumption the Earth target is placed in the nadir view and radiance measurements are made for Earth target temperatures ranging from 85K to 310K. This encompasses the full range of Earth scene temperatures but leaves the range from 2.7K to 85K unmeasured so that assumptions will have to be made about linearity over this range when interpreting the in-orbit space view data. The linearity measurements were made with the antenna in normal scan mode at three instrument temperatures 16°C, 26°C and 36°C. In addition at 6°C and 46°C measurements were made at 3 Earth target temperatures (85K, 200K & 300K) as a quick check that the linearity was still acceptable at extreme instrument temperatures. The space target temperature was kept constant at around 85K throughout. At each Earth target temperature ten 110 scan line 'runs' were made when the temperatures of both external targets were required to vary by less than 0.05K and the gradients across the Earth and Space targets to be less than 0.5K. In some cases data corruptions or target temperature changes >0.05K resulted in less than 10 runs being available reducing the number of runs in the average but all points plotted had at least 6 runs included in their mean.

Figure 3 shows for the EM the relationship between channel 16 nadir view counts and Earth target temperature for an instrument temperature of 26°C. This plot demonstrates several aspects of the instrument performance. Firstly the instrument can be seen to have a reasonably stable gain over the full range of linearity measurements for channel 16. Secondly the linear response for targets between 85 and 310K is a verification of the receiver's dynamic range and linearity. Thirdly when extrapolated to zero radiance (i.e. C_0) the instrument counts are positive. Similar plots were obtained for the other 4 channels.

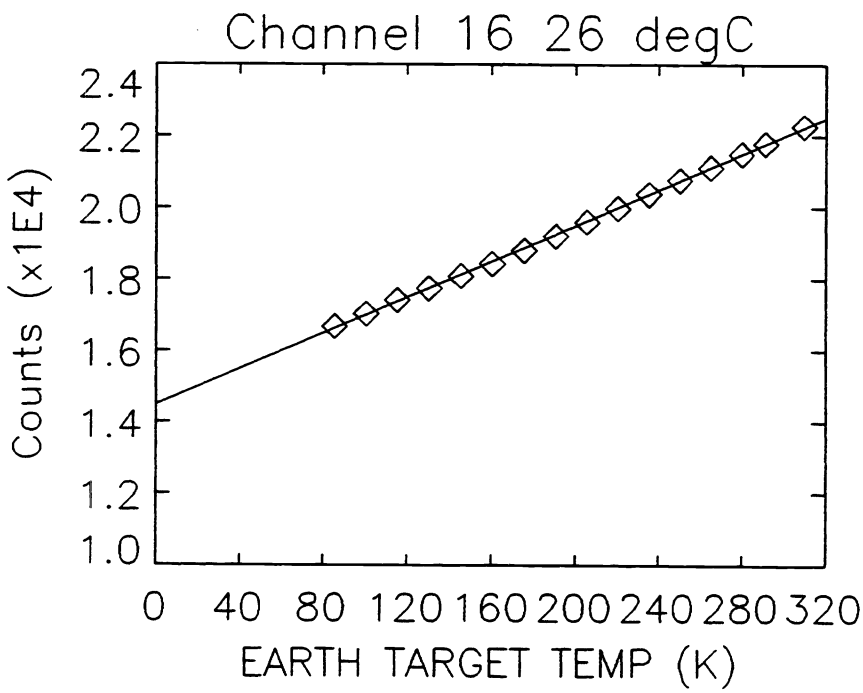

Figure 3. Plot of counts for channel 16 as a function of Earth target temperature measured by the PRTs.

If the counts are now converted into brightness temperature using the calibration procedure described above and the difference between the AMSU-B brightness temperatures and the actual target temperatures are plotted as a function of target temperature, Figure 4 is produced. This plot demonstrates the absolute calibration accuracy (see below) as well as the linearity of the receiver. The points for channel 20 in Figure 4 are from a reduced set of runs with fewer Earth target temperatures due to the data being taken at a different time.

The linearity specification for AMSU-B is that the peak departure from a best fit line through the data for each channel should not exceed 0.3× NeΔT (i.e. 0.3K for channels 16, 17 & 19, 0.33K for channel 18 and 0.36K for

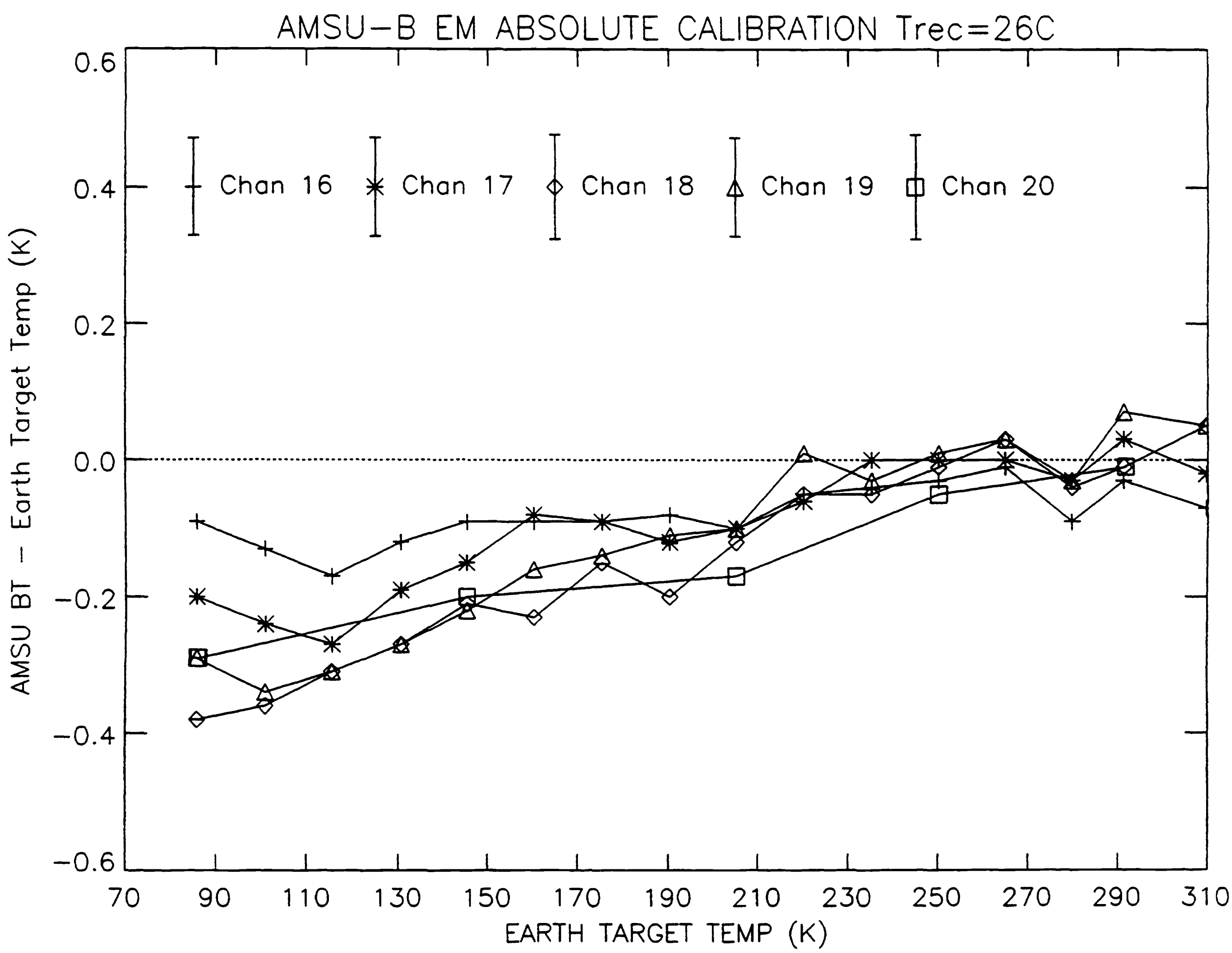

Figure 4. Difference between AMSU measured brightness temperature of the Earth target and the measured target temperatures over the full range of target temperatures for an instrument temperature of 26° C.

channel 20). The results for the EM, which can be inferred from Figure 4, show peak deviations no greater than ±0.1K. No evidence is seen of any significant changes with instrument operating temperature.

5.4 Absolute calibration accuracy

The absolute calibration accuracy is defined as the difference between the 'measured' brightness temperature and the actual brightness temperature of a target determined from PRTs on the target and a knowledge of the target emissivity. The bias can only be estimated with confidence for the internal target calibration point (i.e. warm bias) as the 2.73K space view (i.e. cold bias) cannot be reproduced in the chamber. The mean of all the uncorrupted 100 scan line averages of nadir view brightness temperatures, when the Earth target is at the same temperature as the internal target, subtracted from the Earth target temperature gives the measured warm bias. The standard deviation of the 100 scan line averages, which is the randomly varying component of the bias, is also computed.

Table 4 gives typical bias values measured for the EM. An error analysis for the warm bias measurements has been carried out which suggests the uncertainty in the Earth target temperature is ± 0.07 K and the standard error in the mean AMSU-B brightness temperatures ranges from ± 0.006K for channel 16 to ± 0.028K for channels 18 & 20. The total measurement uncertainties are plotted on Figure 4 and are up to ± 0.075 K. Given these uncertainties there is no significant warm bias measured. However the internal target PRTs are believed to be giving target temperatures 0.25 K too cold by comparing the internal target PRT temperatures with independent PRTs mounted on the target. If this bias in internal target PRT values is correct then the mean bias becomes +0.2K which is significant. Tests have shown that for the flight models the internal target PRTs do not have any significant biases. For all the results presented in Table 4 and Figure 4 the possible bias in the EM internal target temperatures has not been taken into account as we are trying to characterise the instrument. As the specification for AMSU-B is for the uncertainty in the bias to be less than ± 0.98K the instrument is well within this criterion. The randomly varying part of the bias for the various channels listed in Table 4 ranged from 0.02K to 0.09K. This is also well within the specification of 0.2K for AMSU-B.

AMSU-B Channel	16	17	18	19	20
Mean Bias measured at 293 K	−0.03	+0.03	−0.01	+0.07	−0.01
Mean Bias measured at 85 K	−0.09	−0.20	−0.38	−0.29	−0.29
Random bias required	<0.20	<0.20	<0.20	<0.20	<0.20
Random Bias measured	0.02	0.05	0.09	0.05	0.09

Table 4. Mean and random biases determined by viewing the Earth target at 293 K (same temperature as the internal target) and 85 K. The values are computed from ten 100 scan line averages of the nadir sample over a period of 2 hours

For the space view the best estimate of the bias in the absolute calibration which can be inferred in the laboratory is obtained from the measurements taken with the instrument viewing the Earth target at the same temperature as the Space target (i.e. ~85 K). In this case the error analysis must include the uncertainties in the measurement of the Space target temperature as this determines the channel gains and will not be present in the in-orbit configuration. Total uncertainties of ± 0.10K are estimated. At 85 K the mean biases measured range from −0.09 K for channel 16 to −0.38 K for channel 18. The values for all the channels are listed in Table 4. The random variations of the biases were the same as for the warm bias. The mean bias is plotted as a function of Earth target temperature in Figure 4 over the full range of Earth target temperatures. The mean bias gradually decreases from typically −0.2 K at 85 K to zero at 293 K. The reason for the cold bias at the space view calibration point (i.e. 85K) is still under investigation All the values measured are still well within the specification for the instrument. It should be borne in mind that for the in-orbit space view, problems of the antenna 'seeing' the limb of the Earth and/or parts of the spacecraft will also need to be considered in the bias. The biases given in Table 4 and shown in Figure 4 remained the same over the full range of instrument operating temperatures (i.e. 6–46°C).

5.5 Variation of Calibration with instrument temperature

It is important to be aware of any changes in the gain with instrument temperature. Table 5 lists the gains (i.e. $1/a(i)$) and offsets (i.e. $C_0(i)$) of each channel for the five instrument temperatures during the June/July 92 tests. The specification is for the change in gain with temperature to be less than 0.05dB/°C and the two righthand columns give this in terms of a change in gain (dG/dT) in units of $Counts/\mu W/(m^2.ster.cm^{-1})$/°C. The measured values defined as the difference between the 36°C and 16°C gains divided by the temperature difference are all significantly less than the specified upper limit. Note that Channel 20 has the largest relative variation in gain over the complete temperature range.

	Instrument Temperature					Measured	Required
Channel	6°C	16°C	26°	36°C	46°C	$\frac{dG}{dT}$	$\frac{dG}{dT}$
16	323.3 (11643)	329.4 (13137)	338.6 (14628)	346.5 (16208)	350.0 (17147)	0.85	<3.9
17	101.9 (21272)	101.1 (21428)	103.1 (22446)	101.5 (23141)	97.0 (22405)	0.02	<1.2
18	71.33 (25102)	69.15 (26697)	68.18 (29067)	66.89 (30793)	65.58 (32186)	−0.11	<0.8
19	53.42 (17555)	53.19 (19760)	54.08 (23231)	54.74 (26028)	53.19 (26961)	0.08	<0.6
20	27.17 (9534)	26.40 (10052)	26.65 (11510)	25.50 (11800)	23.40 (10438)	−0.05	<0.3

Table 5. AMSU-B EM gains in units of $Counts/\mu W/(m^2.ster.cm^{-1})$ and offsets in parentheses in counts as a function of instrument temperature

The offsets for each channel (defined as $C_o(i)$ in equation 1) do vary more significantly with instrument temperature. The offset would be expected to vary with receiver temperature since it is directly related to the system noise temperature.

6. CONCLUSIONS

An extensive series of radiometric tests on the AMSU-B EM have been successfully carried out in the UKMO test facility at Farnborough. The results show the EM is within specification in all aspects of its radiometric performance. The figures for the sensitivity of the 5 channels show that channels 16, 17 & 19 are all below 1.0K but channels 18 & 20 have sensitivities of typically 1.15K and 1.0K respectively. If the calibration parameters are averaged over 5 scan lines these sensitivities can be reduced by about 0.1K. 1/f noise measurements suggest that no more than 7 scan lines should be averaged. The receiver has a linear response for scene temperatures between 85 and 310K obviating the need for a non-linear correction factor. The changes in gain and offset with instrument temperature are all well within specification and there are no measurable variations of the gain with scan angle[5] when the Earth target was moved from one edge of the swath to the other. The absolute calibration of the instrument shows no significant bias for the internal target calibration point. The standard deviation of the bias over 100 scan lines is typically in the range 0.02 – 0.09 K. A cold bias of 0.2 K for the laboratory space view calibration point using the UKMO Earth target is still under investigation. In contrast the measurements with the AMSU-A cross calibration target gave no significant departures from linearity or absolute calibration biases at both Earth and space target temperatures.

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