Document NWPSAF-MO-TR-033

Version 1.1

17th December 2015

NEΔT specification and monitoring for microwave sounders

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This documentation was developed within the context of the EUMETSAT Satellite Application Facility on Numerical Weather Prediction (NWP SAF), under the Cooperation Agreement dated 29 June 2011, between EUMETSAT and the Met Office, UK, by one or more partners within the NWP SAF. The partners in the NWP SAF are the Met Office, ECMWF, KNMI and Météo France.

Change record			
Version	Date	Author / changed by	Remarks
1.1	17/12/2015	N C Atkinson	From SA Tech memo 24

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Abstract

The concept of Noise Equivalent Delta Temperature (NEΔT) is introduced, in the context of scanning microwave sounders in general, and in particular for the sounder on EPS-SG. The impact of the calibration process on the NEΔT is considered. Methods of computing the NEΔT in orbit, using calibration-view readings, are considered, and a method is proposed that accommodates non-random as well as random noise. Both single-sample NEΔT and the NEΔT for spatially-averaged BT fields can be computed. Results are shown using observed data from MHS, AMSU-B and ATMS.

1. Introduction

The Noise Equivalent Delta Temperature (NEΔT) is an important parameter for any microwave or infrared radiometer. For the end user, it tells them what level of instrument noise to expect in the data, which is crucial to effective use of the data in NWP assimilation. For the manufacturer, it is an important part of the instrument specification, and meeting this specification is usually considered high priority. Long-term monitoring of NEΔT is essential for understanding how the characteristics of the instrument change with time.

Measuring the NEΔT before launch is usually possible to high accuracy, with the aid of temperature-controlled precision calibration targets. However, in-orbit monitoring is less straightforward, and different centres tend to have different ways of monitoring instruments. Furthermore, engineering definitions of NEΔT, which can be applied directly by the manufacturer, do not always correspond directly to the definitions that might be required by the user.

This paper discusses these issues, with particular reference to the upcoming Microwave Sounder (MWS) on EPS Second Generation (EPS-SG), and makes recommendations on the monitoring capabilities that are desirable in the EPS-SG ground segment.

2. Definitions of NEΔT

At a fundamental level, the NEΔT can be defined using the ideal noise equation for a total power radiometer (Ulaby et al., 1981, equ. 6.64):

$$\Delta T = Tsys\left[\frac{1}{B\tau}+\left(\frac{\Delta G}{G}\right)^2\right]^{\frac{1}{2}}$$

where *Tsys* is the system noise temperature (including atmosphere contribution), *B* is the bandwidth, τ is the integration time and *ΔG/G* represents instrument gain fluctuations. There may be additional terms, e.g. calibration noise. Although *Tsys* can sometimes be measured pre-launch, this definition is not very convenient for post-launch monitoring.

A more practical definition of NEΔT for space-borne microwave sounders is the standard deviation of the calibrated scene brightness temperature, when viewing a uniform scene of defined temperature, for samples of a defined integration time.

Commonly, the integration time is the single-sample integration time (e.g. 18 ms for AMSU-B). This is the definition used by NOAA for ATMS. Thus the ATMS noise levels for sounding channels were originally specified as 3 times the noise specification of AMSU-A – since 9

ATMS footprints fill 1 AMSU-A footprint. In practice the specification was subsequently tightened slightly.

For MWS, EUMETSAT and ESA have defined NEΔT in terms of the time for the antenna to sweep out an angle equal to the 3dB beam width. Thus for most channels the single-sample NEΔT will be larger than the value of this specification.

It is also a common requirement to consider the NEΔT after spatial filtering – e.g. 3x3 averaging to synthesise an AMSU-A-like footprint. If we assume that noise is proportional to the square root of the integration time (i.e. random noise), then the relevant scaling factors for MWS are given in Table 1.

Table 1: NEΔT multipliers for MWS, assuming random noise

Channels	Nominal footprint (km)	Single sample NEΔT relative to spec	3x3 sample NEΔT relative to spec
1-2	40	1.53	0.51
3-16	20	1.085	0.36
17-24	17	1.0	0.33

The NEΔT usually has a weak dependence on scene temperature, being proportional to the square root of (T_{scene} + T_{rec}) where T_{rec} is the receiver noise temperature (typically several hundred K).

3. Smoothing of calibration views

For all microwave sounders, calibration is performed using an internal black body and a cold space view. The antenna passes through each calibration view once per scan and there is more than one reading of the calibration view – e.g. two for AMSU-A, four for MHS. The purpose of the multiple readings is to reduce calibration noise. A further reduction in noise can be achieved by averaging over several successive scans. Typically 7 scans are used with a triangular weighting (e.g. Saunders et al., 1995). For ATMS, 10 scans are used.

For an earth scene that is close to the temperature of the warm target, the brightness temperature difference is proportional to the difference between the earth counts and the warm calibration counts. Therefore to obtain the noise in the calibrated brightness temperature we compute the square root of the sum of the squares of the two components, scene noise and calibration noise.

With a random noise model, the effect of calibration noise, as a function of number of lines in the triangular weighting, is shown in Table 2.

Table 2: Effect of calibration noise assuming a random noise model

Number of scans averaged with triangular weighting	Total noise / scene noise		
	2 samples per scan (e.g. AMSU-A)	4 samples per scan (e.g. MHS)	5 samples per scan (e.g. MWS)
1	1.224	1.118	1.096
3	1.090	1.046	1.037
5	1.057	1.029	1.023
7	1.042	1.021	1.017
9	1.034	1.017	1.014

So we see that a useful (~10%) reduction in noise is possible through the calibration averaging process. This is consistent with Fig. 2 of Saunders et al. (1995).

If too many scans are averaged then long-period fluctuations (e.g. 1/f noise or instrument temperature instabilities) can cause the calibrated NEΔT to increase. The calibration process can follow, and remove, long-period gain fluctuations (i.e. greater than the length of the averaging function), but fluctuations on a shorter time scale will cause an increase in the effective NEΔT. Note that 1/f (or "flicker") noise is a fundamental characteristic of semiconductors; although often masked by random noise. It has been found to be noticeable in some microwave sounders (e.g. ATMS: Doherty et al., 2014).

If not enough scans are averaged then the calibration noise itself causes a "striping" in the brightness temperature field (similar to the effect of 1/f noise). Being one-dimensional, the striping would become more apparent after spatial averaging. For example, with only 1 scan used for calibration, 4 samples per scan, and 3x3 averaging in the BT field, it is readily shown that the calibration noise increases the total noise by a factor 1.32 (c.f. 1.118 without 3x3 averaging) – certainly significant for NWP.

A 7 scan line filter seems a reasonable compromise, though it could be fine-tuned if necessary.

4. Ways of monitoring NEΔT

A difficulty with measuring NEΔT in orbit, using instrument telemetry alone (i.e. no NWP) is that the earth views cannot normally be used for this purpose due to scene inhomogeneity. It is possible to make some use of earth view brightness temperatures, by selecting regions where scene variations are small (e.g. uniform land/sea with no cloud), but that is not ideal for routine monitoring, and is not the focus of this report. Instead, we look at the estimation of NEΔT using the calibration views. The challenge is to correctly account for different types of noise and the calibration process.

4.1. NOAA/ATMS method (SDR processing)

The ATMS Sensor Data Record (SDR) includes estimates of warm-view and cold-view NEΔT. These estimates use the standard deviation of the four warm/cold samples, divided by a fixed gain. Each value uses just one scan line, but the RMS can be used to get more representative values.

This NEΔT is an underestimate of the true NEΔT because it takes no account of calibration noise or non-random (e.g. 1/f) noise. It only considers variation on a time scale of less than 4 samples.

4.2. Met Office method

This method used by the Met Office for many years for monitoring AMSU and MHS is described in Atkinson and McLellan (1998). In brief, the operational calibration coefficients are used to convert each of the warm calibration counts and cold calibration counts to radiance. The warm NEΔR is the standard deviation of the warm radiances minus the expected radiance (computed from the PRTs). The cold NEΔR is the standard deviation of the cold radiances. A correction factor 16/15 is applied to account for the fact that each warm/cold count reading has already been used in the calibration process, with a weight 1/16. The gradient of the Planck function at 290K is used to convert from NEΔR to NEΔT in K.

This method of computing the NEΔT correctly accounts for calibration noise. However, it is slightly optimistic if there is 1/f noise present, because the 1/f noise causes correlations between the four individual calibration view readings within a scan.

4.3. EUMETSAT method

EUMETSAT monitor NEΔT by computing, for each scan line (*j*), a weighted standard deviation of the warm counts for that scan line and neighbouring lines (Ackermann, 2014, pers. comm.)

$$NE\Delta T_j = \frac{1}{G}\sqrt{\sum_{k=j-n}^{k=j+n} w_{k,j}\overline{C_k^2} - \left\{\sum_{k=j-n}^{k=j+n} w_{k,j}\overline{C_k}\right\}^2}$$

Where the means ($\overline{C_k^2}$, $\overline{C_k}$) are computed over the 4 samples within a line (k), and w is the triangular weighting function. G is the channel gain (counts/K). The NEΔT is estimated for each line, then an overall value is computed as the RMS over many scan lines. This calculation could be done for both the warm and cold counts, but EUMETSAT report the warm NEΔT.

It can be seen that there are similarities with the NOAA/ATMS method, but because more than one scan line is used the result is more accurate. It makes some allowance for 1/f noise, but not in any rigorous sense.

The EUMETSAT NEΔTs tend to be close to, or a few percent smaller than, the Met Office NEΔTs (see Table 3).

A simulation using random numbers shows that the EUMETSAT NEΔT underestimates the true standard deviation of the input by 2.1%, for a 7-scan weighting. This is because it is not accounting for the difference between population standard deviation and sample standard deviation (with a uniform weighting, this would be a factor sqrt(28/27) = 1.018).

4.4. NOAA STAR method

NOAA STAR monitors NEΔTs for many instruments at http://www.star.nesdis.noaa.gov/icvs/

Prior to March 2015, NOAA computed NEΔT as follows (Jörg Ackermann, pers. comm.). For each scan line, the warm target counts are averaged, and the result is converted to brightness temperature (BT) using the operational calibration coefficients. The NEΔT is computed as the standard deviation of the resulting BTs, over a full orbit, multiplied by the square root of the number of samples per scan. This method has a major drawback that the result is strongly influenced by long-period drift in the calibration target temperature (Tian et al., 2015).

Results were found to be inconsistent compared with other methods. MHS NEΔTs were up to a factor of 2 smaller than expected, while AMSU-A values were in some cases larger than expected and in other cases smaller.

After March 2015, NOAA STAR switched the monitoring to a method based on Allan Deviation (see section 4.6).

4.5. A proposal for MWS

This is effectively a refinement of the Met Office method. But instead of using the operational calibration coefficients it is proposed to use a scan-line averaging function in which the weight of the centre line is set to zero, and the other lines have uniform weight. So if the normal triangular function is [1,2,3,4,3,2,1]/16, in the modified version we use [1,1,1,0,1,1,1]/6. Simulations show that this correctly preserves the magnitude of the calibration noise (to within 2% with a 7-line width), but it also allows for a good estimate of the contribution due to 1/f noise, i.e. fluctuations with a period ranging from a few samples to a small number of scan lines, which cannot be removed by the calibration process. Longer period fluctuations are removed by the calibration process and do not contribute to the NEΔT.

So the method is:

1. For each line, average the calibration counts for that line, as normal
2. Apply the averaging function to get smoothed counts $\overline{C_w}$, $\overline{C_C}$
3. Compute $STDEV\left(\left(C_W - \overline{C_W}\right)/G\right)$ where *G* is the gain. Similarly for the space counts.

The gain could be taken from the slope of the operational calibration curve, or it could be a fixed linear gain – the choice will make little difference to the result. The calculation could be performed either in radiance or BT space. The latter has been used for the calculations in this report.

A variant of the method shown in this section is to compute a rolling standard deviation in step 3, over a relatively small number of scan lines. We then get a value for each scan line, as in EUMETSAT's method. An overall standard deviation can be computed at the end, if required, as the RMS of the individual values.

The EUMETSAT ("EUM"), Met Office ("MetO") and modified ("Mod") NEΔTs are compared for Metop-B MHS in Table 3.

Table 3: NEΔT comparison for Metop-B MHS. File NSS_MHSX.M1_D14104_S1357_E1452_B0815354_SV

Channel	Warm NEΔT				Cold NEΔT			
	EUM (K)	MetO (K)	Mod (K)	Mod / MetO	EUM (K)	MetO (K)	Mod (K)	Mod / MetO
1	0.241	0.247	0.258	1.043	0.171	0.176	0.181	1.028
2	0.412	0.420	0.447	1.062	0.347	0.349	0.375	1.074
3	0.445	0.462	0.470	1.018	0.348	0.359	0.369	1.028
4	0.344	0.357	0.362	1.013	0.270	0.281	0.285	1.015
5	0.308	0.318	0.327	1.030	0.245	0.251	0.261	1.040

Channel 2 shows the largest difference between the Met Office and modified NEΔT. This is consistent with its larger "striping index" – a measure of the along-track to cross-track counts variability, see Atkinson (2014).

4.6. Allan Deviation

Tian et al. (2015) have proposed an alternative measure of NEΔT, based on the "two-sample Allan deviation". This uses the difference in warm (or cold) counts between two neighbouring lines. If there are *M* lines and *N* calibration views, then the NEΔT is defined as:

$$NE\Delta T_{Allan} = \frac{1}{2G(M-1)N}\sqrt{\sum_{j=1}^{M-1}\sum_{i=1}^{N}\left(C_{j+1,i} - C_{j,i}\right)^2}$$

Where $C_{j,i}$ are the counts for line j and view i, and G is the channel gain.

Note that other forms of overlapping Allan deviation are possible, that make use of more than two lines (see Tian et al., 2015, for details). But the two sample Allan deviation has the advantage that its value is the same as the standard deviation when the input data are random. The Allan deviation is insensitive to long-term drift in the input counts.

Values of $NE\Delta T_{Allan}$ for the MHS test case are shown in Table 4.

Table 4: NEΔT computed from two-sample Allan deviation. Same MHS data as Table 3.

Channel	Warm Allan deviation (K)	Cold Allan deviation (K)
1	0.247	0.168
2	0.417	0.353
3	0.452	0.349
4	0.349	0.276
5	0.309	0.247

We can see that the values are very close to the "EUM" and "MetO" values from Table 3, but 4–7% smaller than the "Mod" values.

The advantages of the Allan deviation method appear to be firstly simplicity and secondly it is generic, i.e. does not depend on the details of the instrument. On the other hand, the method does not take account of calibration noise, which depends on both the number of calibration samples per scan and the number of scans averaged for calibration views (section 3). Also, it may not fully account for 1/f noise, as fluctuations on a time scale longer than 2 scans are ignored.

When NOAA initially implemented the Allan deviation method on the STAR web site, it was noticed that the AMSU-A, MHS and ATMS values plotted were significantly lower than those expected based on Met Office and EUMETSAT methods – and also significantly lower than the above expression for $NE\Delta T_{Allan}$., by a factor close to 1/√2 for AMSU-A. For MHS and ATMS the discrepancy was greater, up to a factor 0.5. The reason was found to be that STAR computed the Allan deviation based on the *average* of the warm views in each line (Ninghai Sun, pers. comm.). This was changed in early December 2015; plots generated after that date are in good agreement with expectations.

5. Effective NEΔT after spatial filtering

The Met Office method of computing NEΔT cannot be used for spatially-filtered scenes because of the strong correlation between the averaged calibration counts and the operational calibration coefficients. However, we can adapt the method of section 4.5. To avoid unwanted correlations between the counts being tested and the counts used in the calibration, it is proposed to insert extra blank lines in the averaging function.

So to generate a 3x3 sample NEΔT, we proceed as follows:

1. Smooth the calibration counts using an averaging function [1,1,1,0,0,0,1,1,1]/6
2. For each line, average three consecutive warm counts from that line and subtract the smoothed warm counts for the line. Do the same for the space counts.
3. Compute the standard deviation of the counts differences from step 2, normalised by the gain.

Results for MHS are shown in Table 5.

Table 5: Comparison of single sample and 3x3 NEΔTs for MHS. Same case as Table 3.

Channel	Warm NEΔT			Cold NEΔT		
	Single sample (K)	3x3 (K)	Ratio	Single sample (K)	3x3 (K)	Ratio
1	0.258	0.110	0.43	0.181	0.076	0.42
2	0.447	0.203	0.45	0.375	0.184	0.49
3	0.470	0.187	0.40	0.369	0.152	0.41
4	0.362	0.136	0.38	0.285	0.113	0.40
5	0.327	0.137	0.42	0.261	0.116	0.44

We see that the ratio of 3x3 NEΔT to single-sample NEΔT is in the range 0.38 to 0.49, compared with 0.33 that would be expected if the noise were random. Channel 2 has the highest NEΔT ratio (i.e. spatial averaging is least effective at lowering the NEΔT), as would be expected from the striping index of Atkinson (2014).

Another example, this time for selected channels of ATMS, is shown in Table 6. It is known that channels 5, 7, 16 and 22 are significantly affected by 1/f noise, but for channel 14 random noise dominates. This is consistent with the ratios shown in Table 6: channel 14 is very close to the ideal ratio of 0.33.

Table 6: Comparison of single sample and 3x3 NEΔTs for ATMS. One orbit on 13th April 2014.

Channel	Warm NEΔT			Cold NEΔT		
	Single sample (K)	3x3 (K)	Ratio	Single sample (K)	3x3 (K)	Ratio
5	0.271	0.122	0.45	0.141	0.061	0.43
7	0.269	0.116	0.43	0.141	0.060	0.42
14	1.175	0.403	0.34	0.609	0.215	0.35
16	0.287	0.151	0.52	0.201	0.104	0.52
22	0.699	0.349	0.50	0.610	0.325	0.53

In the Met Office assimilation system, the fit to background of ATMS channel 7 is typically in the range 0.13 K to 0.16 K. For a typical BT of 230K, the expected instrument noise is 0.106 K (interpolate between the warm and cold 3x3 NEΔT of Table 6). This suggests that model noise is of the order 0.1K – comparable with the observation – and re-enforces the message that minimising the instrument noise is essential to effective use of the data in NWP.

One way of validating these calibration-view-only NEΔTs is by making use of periods when the instrument is parked in target view or space view, or during a pitchover manoeuvre when the instrument is viewing cold space. To compute the earth-view NEΔT, the operational averaging function is used to smooth the warm calibration views. An example for NOAA-17 AMSU-B is shown in Table 7.

Table 7: NOAA-17 AMSU-B parked in the warm calibration view. 2nd July 2002, file NSS.AMBX.NM.D02183.S1512.E1706.B0011213.GC

Channel	Warm view NEΔT			Earth view NEΔT		
	Single sample	3x3 (K)	Ratio	Single sample (K)	3x3 (K)	Ratio

	(K)					
1	0.399	0.141	0.35	0.404	0.157	0.39
2	0.499	0.246	0.49	0.490	0.215	0.44
3	0.984	0.433	0.44	0.959	0.407	0.42
4	0.741	0.288	0.39	0.730	0.288	0.39
5	0.832	0.312	0.37	0.844	0.329	0.39

Comparing the warm view and earth view NEΔTs (with AMSU-B parked for one orbit), the 3x3-averaged NEΔTs are not as consistent at the single-sample NEΔTs. However, they are the right order of magnitude and do not appear to be biased significantly high or low. Note that for this instrument channel 2 has the highest striping ratio (Atkinson, 2014).

6. Conclusions

The impact of calibration-view averaging across scan lines has been shown. Even if the nominal instrument specification can be achieved without this averaging, it is still expected to be beneficial to apply the averaging, especially if users wish to use spatial smoothing to reduce noise. For some channels, NWP background errors are comparable with, or lower than, the instrument noise, therefore it is important to optimise the calibration process so that noise is minimised.

A method has been proposed that is suitable for routine monitoring of the single-sample NEΔT, using calibration-view readings alone. The method takes account of random noise, calibration noise and fluctuations due to other causes, such as 1/f noise. The single-sample NEΔT can be readily translated to the convention of the EUMETSAT/ESA spec for MWS, by multiplying by the appropriate factor.

For some applications (e.g. global NWP) it is desirable to assimilate spatially-averaged observations. Hence there is a need to monitor the spatially-averaged NEΔT. For MWS, it is suggested to monitor 3x3-sample NEΔT, to allow direct comparison with instruments such as AMSU-A. A method has been proposed for estimating this quantity. Examples have been shown of its use with MHS, AMSU-B and ATMS.

The ratio of 3x3-sample NEΔT to single-sample NEΔT is a useful diagnostic. It is closely related to the striping index described in Atkinson (2014), but arguably of more relevance to the end user. It is recommended to monitor both the 3x3-sample NEΔT and the striping index.

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