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Report on oxygen sounding channel frequencies and polarisations

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Contents

Part I
Executive summary

The Advanced Microwave Sounding Unit (AMSU) has proved to be a very successful instrument and can now be considered a mature part of the Global Observing System. It has become an established and important data source both for numerical weather prediction (NWP) and climate monitoring. Future refinement of AMSU should focus primarily on delivering the same scientific capability as cost-effectively as possible. However scientific changes can be considered under two scenarios. Firstly some relaxation of the specification may be possible if this can be shown to not adversely affect the value of the data to NWP or climate monitoring, nor introduce greater complexity in the data processing or assimilation, and provides flexibility which could yield a more cost-effective instrument. Secondly changes can be considered which provide significant benefits to one or both of NWP or climate (without degrading the value to the other) in a cost-effective manner without increasing the complexity of the data processing.

In this report two issues are studied. Firstly the question of the choice of polarisation for the sounding channels and secondly the precise channel bandwidth specification for the tropospheric sounding channels.

The polarisation question asked whether the polarisation choice for sounding channels matters, and if it does, how close is AMSU to an optimal choice. It is shown that the sensitivity to choice of polarisation is very small, but that AMSU is closer to the worst case performance than the best case performance. This is because AMSU changes polarisation for two adjacent near surface sounding channels. This is demonstrated to be sub-optimal. However the degradation is small. The climate requirement is for continuity so changes of marginal benefit to NWP are not justified. On the basis of this the conclusion is to promote a continuation of the AMSU polarisation choices. However if any new tropospheric sounding channels are proposed, as is considered in the second part of this study, these should be quasi-horizontal polarisation.

The second part of the study dealt with the usage of the spectrum between 53 and 55 GHz. Surprisingly the AMSU only measures about half the band (52.60-5.25 GHz) which has primary (passive-only) protection under the Radio Regulations of the World Radio Conference. In particular there are two bands, one between AMSU channels 4 and 5 and the other between AMSU channels 5 and 6 which are not exploited. As a result there are large gaps between the altitudes of peak weighting function sensitivity, particularly between AMSU channel 5 (750 hPa) and AMSU channel 6 (400 hPa). As AMSU channels 5 and 6 deliver the largest part of the impact of AMSU on weather forecast accuracy a channel peaking between these two would probably be beneficial to NWP. The study showed significant benefits from measuring in these bands, as has also been demonstrated in a separate study by *Lipton* [2003]. The impact is around 30% of the impact of removing AMSU channel 5. This is an important and significant improvement and it is recommended that the cost of adding these channels is evaluated to establish if the addition of these two new channels is cost-effective. The channels are proposed as new channels so that the climate data record is not degraded. *Lipton* [2003] and this study showed that comparable benefit can be achieved by a single very wide bandwidth channel centred on the AMSU channel 5 central frequency but sounding the entire frequency range covered by AMSU channel 5 and the new channels. However such a wide band channel may have greater sensitivity to the surface than could be achieved by separate channels.

Part II
Introduction

The Advanced Microwave Sounding Unit (AMSU) and its predecessor, the Microwave Sounding Unit, have been the backbone of spaceborne atmospheric sounding for nearly 30 years, proving to become an indispensable part of the global observing system for operational weather forecasting, and a significant factor in the rapid advances in forecast accuracy achieved in the last ten years. However the design of these instruments, including the channel bandwidth and polarisations, originate from the early 1970s and the justification for the bands has not been revisited except for one study by *Lipton* [2003]. The current AMSU channels are shown in Annex 1. In section 1 the options for polarisation are discussed and what this implies for the measurements, leading onto results showing the sensitivity of the measurements to changing polarisation. In section 2 the frequency bandwidth is presented and the position of the channels is discussed in the context of information content, frequency protection and trace gases. The two parts of the study result in a recommendation for options to be costed which could give significant improvements to the microwave sounder on post-EPS without jeopardising the climate record.

Part III
Background, constraints and justification for the study on post-EPS microwave sounder polarisation

1 The sensitivity of MSU and AMSU to the polarisation of surface reflectance and emission and the justification for this study

The choice of polarisations for AMSU and MSU channels between 50 and 55.5 GHz is interesting. For both instruments the window channel (50.3 GHz) is "quasi-vertical" (QV). QV means that the instrument measures vertical polarisation at nadir. As the instrument scans, the single plane of polarisation measured rotates such that the measurement is a mixture of vertical and horizontal polarisation. Channels which are measuring horizontal polarisation at nadir are referred to as "quasi-horizontal" (QH). These names are however slightly misleading since a QH channel will tend towards measuring vertical polarisation once the nadir scan angle exceeds 45°. In the nadir view isotropic emission will be identical in vertical and horizontal planes, so QH=QV. At 45° there is an exactly equal mix of vertical and horizontal polarisation, so QV=QH. It is therefore readily apparent that there will be two regions where the difference between QV and QH is the largest. One will be at the very edge of the scan, where the nadir angle equals 48°. Here QV will slightly favour horizontal polarisation and QH will slightly favour vertical polarisation. Since the difference between vertical and horizontal polarisation will be very large for a highly polarising surface at the edge of the scan (48°) this slight tendency towards vertical or horizontal polarisation is important. The second region will be at angles intermediate between nadir and 45°. It is obvious that there will be an angle at which the product of the V-H difference and the tendency towards vertical polarisation in QV will be a maximum. This is illustrated in Figure 1 for a calm flat surface.

For an AMSU-like instrument there is a maximum emissivity difference close to 30° of around 0.07, sufficient to give 20 K brightness temperature differences in the absence of atmospheric absorption. The second maximum where QV−QH becomes negative is predicted for the edge of the scan.

Surface roughness and scattering will tend to reduce polarisation differences, and many surfaces will have lower permittivity than water giving rise to less polarised reflectance.

The AMSU and MSU channel polarisations are always QV for the window channels and generally QH for the tropospheric sounding channels. AMSU channel 4 is treated like a window channel, as its polarisation is QV. Two exceptions are AMSU channel 7 and MSU channel 3 which are both QV, despite being tropospheric sounding channels.

Errors in modelling emissivity are much larger in horizontal polarisation, primarily because the sensitivity to geophysical variables which are poorly known is higher. Therefore if the primary purpose of window channels is to analyse skin temperature the choice of vertical polarisation is logical. It provides the least sensitivity to errors in the calculation of emissivity and the greatest sensitivity to skin temperature across most of the scan, in particular for nadir views from 15 to 45°. However if the main purpose of such channels is cloud detection then it is illogical as the sensitivity to clouds is highest in horizontal polarisation.

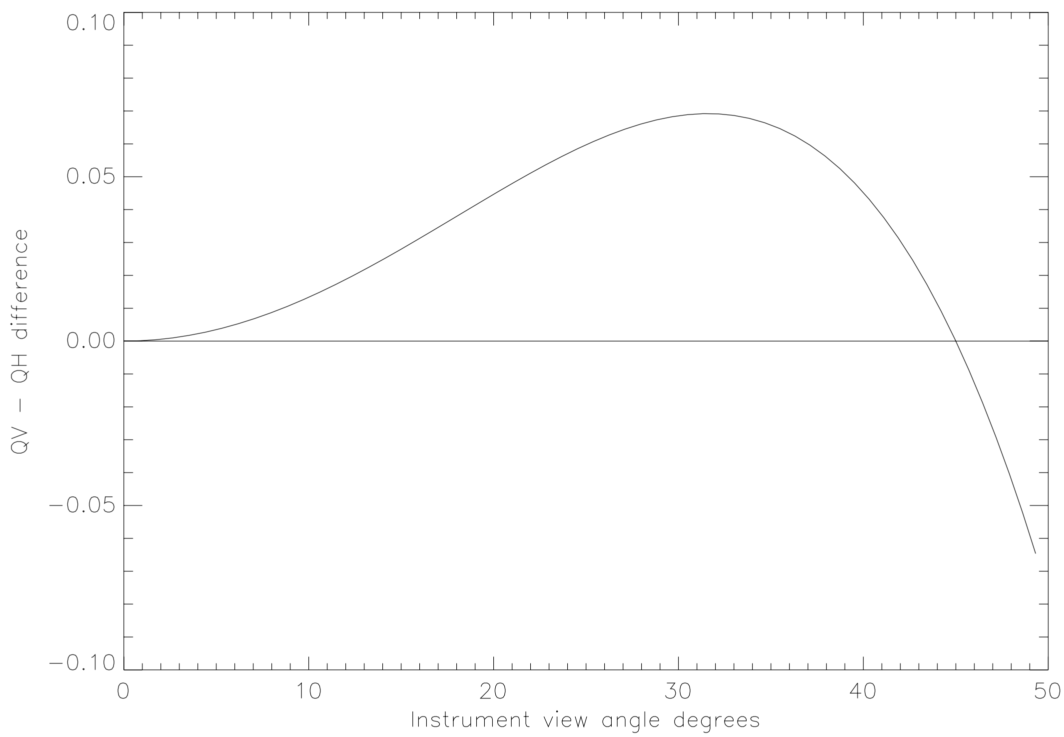

Figure 1: Emissivity difference in QV and QH for a highly polarised flat smooth surface (permittivity 10-8i).

For the sounding channels the choice of QH is logical as the lower emissivity will reduce sensitivity to errors in skin temperature [*English*, 2007]. However changing from QH to QV means that there is a change in the surface contribution to the error in the measurement. So there would appear to be a risk in switching arbitrarily from QH to QV for channels with some residual sensitivity to the surface. *Karbou et al.* [2007] has shown that AMSU channels 6 and 7 see the change from land to sea when averaged over long periods so only AMSU channel 8 and above can be considered insensitive to the earth's surface, and even then only for a surface at sea level.

In section 2 numerical experiments are described to investigate whether these choices in polarisation make any practical difference to the effectiveness of an AMSU-like sounder.

channels	1	2	3	4	5	6	7	8	9	10
R (O+F)	2.0	2.0	2.0	0.7	0.2	0.15	0.2	0.25	0.4	0.6
channels	11	12	13	14	15	16	17	18	19	20
R(O+F)	0.6	0.6	0.6	1.0	3.0	8.0	5.0	4.0	4.0	4.0

Table 1: R-Matrix (O+F) for AMSU channels

2 Experiment design and methodology

The Met Office 1D-Var (*NWPSAF* [2007]) was used to study the choice of polarisation of AMSU channels. A slight modification of the 1D-Var code was necessary to be able to analyse u and v wind components in addition to temperature and humidity variables.

The ECMWF profile dataset (*Chevallier* [2001]) was chosen to represent the true atmospheric state. The same dataset was used to provide background atmospheric profiles and surface variables by adding random Gaussian noise to the truth. The noise was generated from the eigen values and eigen vectors of a typical short range forecast error covariance matrix, B [*English*, 1999]. For u and v wind, a background error of 2 ms^{-1}, uncorrelated with other atmospheric and surface variables, was assumed.

ATOVS brightness temperatures were generated using the radiative transfer model RTTOV-8 with the truth profile data as input. Random measurement errors were added to these brightness temperatures based on the measurement error covariance matrix to generate simulated observation data. The diagonal R-matrix which is the combined observation error and forward model error assumed is shown in Table 1. The forward model error and observational error are assumed identical for V and H polarisation channels, but note that background wind speed error are larger for H-polarisation than V-polarisation in radiance space.

A set of 16 experiments was designed, each having a different polarisation choice for AMSU channels. Observation data corresponding to each experiment were generated at viewing angles of 10, 30 and 50°. The experiments are listed in Table 2. Retrievals were performed for each experiment using the 1D-Var and the results are presented in the next section.

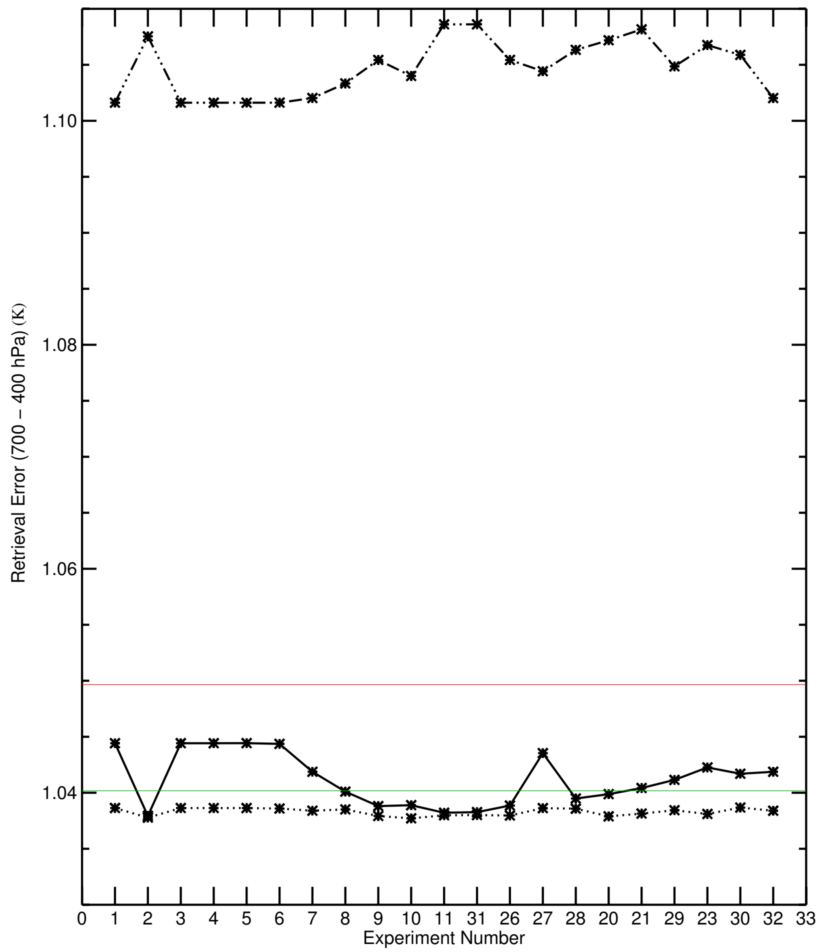

Figure 2: Layer averaged (700 to 400 hPa) temperature retrieval error (in K) for experiments listed in Tables 2 and 3. The dotted line is for viewing angle 10°, solid line for 30° and dash-dotted line for 50°. The horizontal green line shows the retrieval error at 30° when channel 3 is removed from the analysis and red line when channel 4 is removed. When channel 5 is removed, the retrieval error is about 1.17.

Experiment number	QV channels	QH channels
1	1-20	-
2	-	1-20
3	1-8, 15-20	9-14
4	1-7, 15-20	8-14
5	1-6, 15-20	7-14
6	1-5, 15-20	6-14
7	1-4, 15-20	5-14
8	1-3, 15-20	4-14
9	1-2, 15-20	3-14
10	1,15-20	2-14
11	15-20	1-14
12	1-17, 19-20	18
13	1-17, 20	18-19
14	1-17	18-20
15	1-16	17-20
16	1-15	16-20

Table 2: List of experiments.

3 Results

3.1 Temperature

Figure 2 shows layer averaged (700-400 hPa) temperature retrieval errors on the y-axis and experiment numbers as in Table 2 on the x-axis. The three line styles are for 3 angles, dotted line for viewing angle 10°, solid for 30° and dash-dotted for 50°. At 10° viewing angle, it can be seen that switching polarisations have no effect and at 30° and 50°, the effects are opposite to each other. Although the effect at 30° and 50° is opposite, there is only one field of view where $\theta_n > 45°$. So 30° is more representative of most of the scan.

At 30° viewing angle, experiment 2 which has all channels in QH polarisation shows the best performance and experiment 1 which has all channels in QV polarisation shows the worst performance. Experiment 11 which has all AMSU-A channels in QH polarisations gives retrieval errors similar to experiment 2. Switching the polarisations of window channels 1 and 2 to QV (experiments 10 and 9) also does not change the results compared to experiment 2. Switching the polarisations of channels 3, 4 and 5 from QH to QV (experiments 8, 7 and 6) leads to an increase in the retrieval errors,

Experiment number	QV channels	QH channels
31	6,7,8,15-20	1-5, 9-14
26	1-2, 6-8, 15-20	3-5, 9-14
27	3-5, 15-20	1-2, 6-14
28	3, 15-20	1-2, 4-14
20	4, 15-20	1-3, 5-14
21	5, 15-20	1-4, 6-14
29	3-4, 15-20	1-2, 5-14
23	4-5, 15-20	1-3, 6-14
30	3,5, 15-20	1-2, 4, 6-14
32 (AMSU-A)	1-4, 7,15-20	5,6, 8-4

Table 3: List of additional experiments.

whereas for channels 6 and above changing the polarisation does not affect the performance. Figure 3 shows that temperature retrieval error averaged between 1000 and 700 hPa also gives similar results.

These results lead us to conclude that at 30° viewing angle, polarisation of channels 1-2 and 6-14 can be QV or QH, but channels 3, 4 and 5 should be QH. Some additional experiments were also performed to confirm these conclusions. The new experiments are listed in Table 3 and the results are shown in Figures 2 and 3.

Experiment 31, where only 6, 7 and 8 are in QV polarisation performs as well as experiment 2 confirming that these channels can be QV or QH. The same is true for experiment 26 where channels 1, 2, 6, 7 and 8 are QV polarised and the rest are QH polarised. Experiment 27, where channels 3, 4, and 5 are QV polarised and the rest QH polarised gives the largest retrieval errors. Setting only one channel among 3, 4 and 5 to QV (experiments 28, 20 and 21) and setting combinations of them to QV (experiments 29, 23 and 30) suggests that the maximum impact of switching to QV is for channel 5, followed by channel 4. A run with the current AMSU-A polarisation specification (experiment 32) gives larger retrieval errors than an all-QH experiment. Experiments which have channels 3 and 4 in QH polarisation also performs better than AMSU which has these channels in QV polarisation. These results confirm that for temperature retrieval the channels which seem to be most affected by changing the polarisations are AMSU-A channels 3, 4 and 5.

To further determine whether the impact of reversing polarisation is significant, the result of reversing the polarisation of a particular channel is

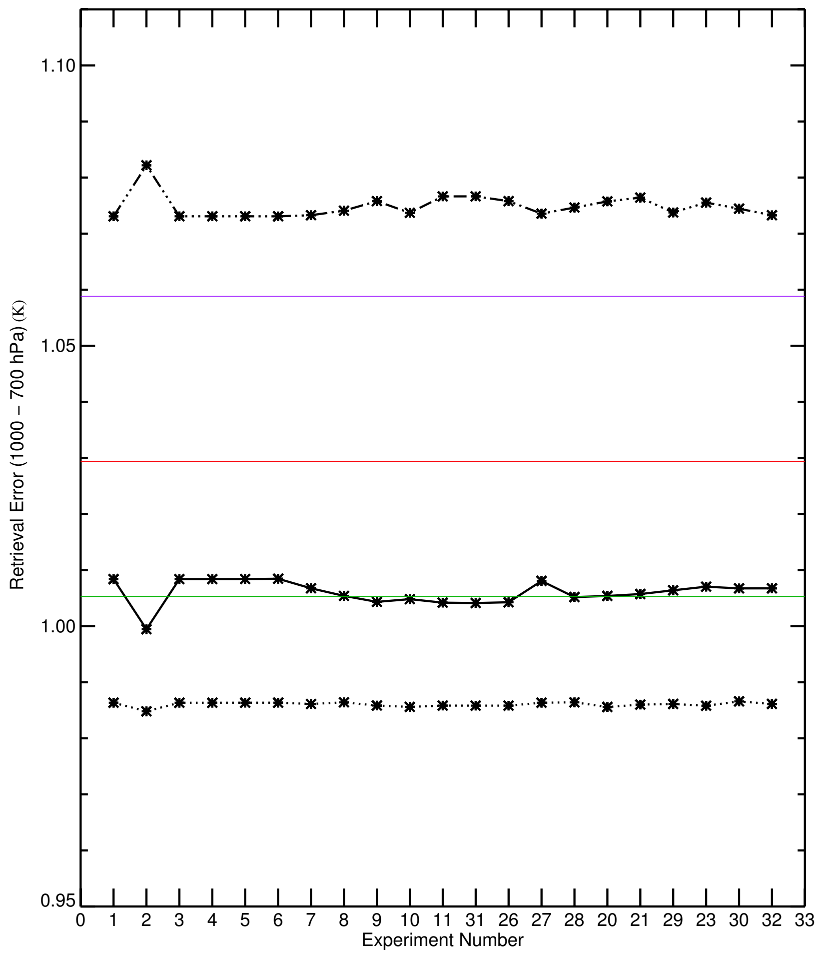

Figure 3: Layer averaged (1000 to 700 hPa) temperature retrieval error for experiments listed in Tables 2 and 3. The dotted line is for viewing angle 10°, solid line for 30° and dash-dotted line for 50°. The horizontal green line shows the retrieval error if channel 3 is removed from the analysis, red line if channel 4 is removed and purple when channel 5 is removed. The polarisations of other channels remain the same as in experiments 6 or 7.

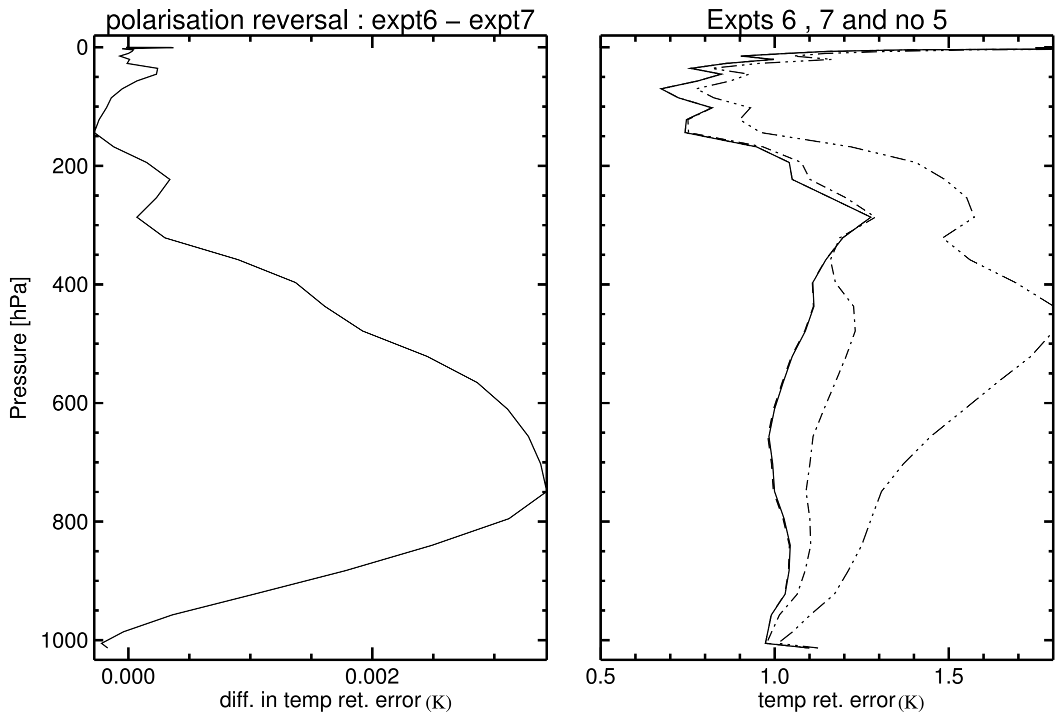

Figure 4: The right panel shows temperature retrieval error for experiments 6 where channel 5 is in QV polarisation (solid), experiment 7 where channel 5 is in QH polarisation (dashed) and when channel 5 is removed (dash-dotted) at a viewing angle of 30°. The dash-dot-dot-dotted line shows the background error. The left panel shows the difference between experiments 6 and 7.

compared with losing that channel. For example, experiments 6 and 7 differ only in that the polarisation of channel 5 is different. The results of these experiments are compared to that of an experiment where channel 5 is removed, keeping the polarisations of other channels as in experiment 6 or 7. Similar experiments are performed to study the significance of each AMSU channel. For channels 3, 4 and 5 the layer averaged retrieval errors when these particular channels are removed are shown by the horizontal lines in Figures 2 and 3. The layer averaged retrieval errors between 700 and 400 hPa when channel 5 is removed is quite large (about 1.17, not visible in Figure 2) compared to when the channel 5 polarisation is reversed. This can be more clearly understood from Figure 4, the right panel of which shows the larger retrieval error when channel 5 is removed (dash-dotted line) compared to when its polarisations are opposite (solid and dashed lines). This shows that although the retrieval performance is slightly degraded when channels

3, 4 and 5 are QV polarised, this is not significant compared to the impact of removing the channel.

This study has shown that channels 3, 4 and 5 when in QH polarisation performs slightly better but the study has not shown any clear preference for the polarisation of other channels. Although channel 6 is shown not to have been affected by reversal of polarisations over sea, this may not be true over elevated surfaces, like over the Antarctica, where channel 6 weighting function peak at similar altitudes above the ground as channel 5. Therefore it is best if channels 5 and 6 remain in QH polarisation as in the current AMSU specification. In the case of window channels the analysis here does not show any sensitivity to polarisation choice. However, aspects that are not considered here such as cloud detection for cloud screening may be sensitive to choice of polarisation of window channels.

3.2 Humidity

In the case of humidity, the result presented in Figure 5 shows that all channels in QH polarisation gives the smallest retrieval errors at 30°. Even at 10° viewing angle (dotted line), all channels in QH polarisation perform better. At 50°, the opposite is true, ie., all channels in QV gives the best performance and all in QH gives the worse performance.

Reversing the polarisations of the temperature channels does not have any impact on humidity retrieval errors (experiments 3 through 11) at any viewing angle. The temperature retrieval experiments in the previous section showed that channels 1-14 in QH (experiment 11) gives the best performance. But humidity retrieval error for experiment 11 (Figure 5) shows that this alone does not give a better humidity performance. To get a better humidity retrieval performance, some of the humidity channels are also required to be in QH polarisation. Switching the polarisations of channels 18 and 19 does not make any change to humidity retrieval results whereas switching channels 20 and 17 to QH gives a slightly better performance. But it is only appropriate that if channel 20 is switched to be in QH polarisation, channels 18 and 19 are also in QH polarisation.

3.3 Correlated errors

The issue of correlated errors was examined by increasing the vertical polarisation by 5% and decreasing the horizontal polarisation by 5% while generating simulated observations. These observations were generated for experiments 6, 7 and 8. Experiments 6 and 7 differ only in the polarisation of channel 5 and experiments 7 and 8 in the polarisation of channel 4

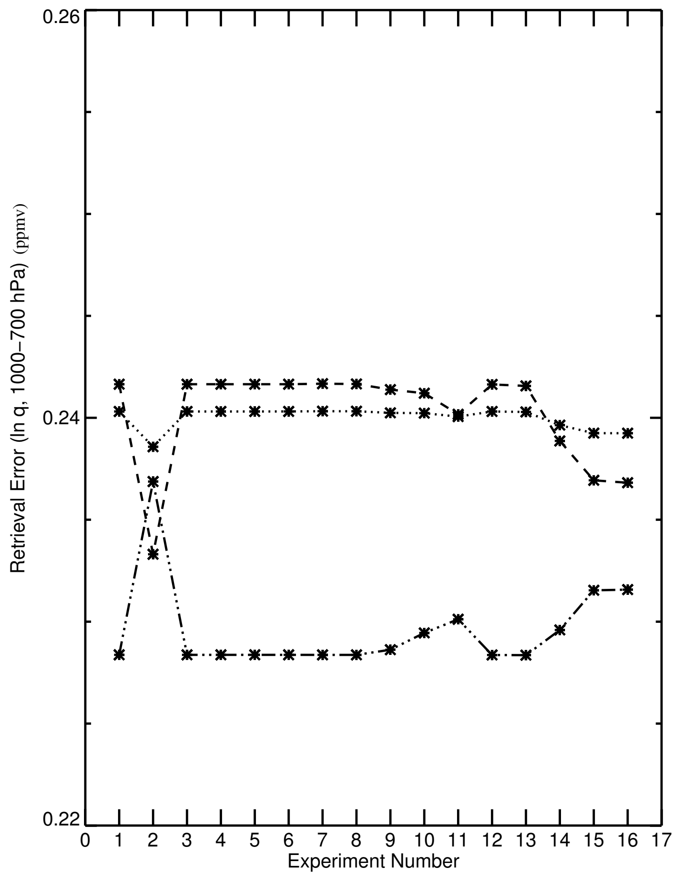

Figure 5: Layer averaged (1000 to 700 hPa) humidity retrieval error for experiments listed in Tables 2 and 3. The dotted line is for viewing angle 10°, dashed line for 30° and dash-dotted line for 50°.

(Refer to Table 2). Correlated errors were introduced only while simulating observations while for the 1D-Var analysis, errors were assumed to be uncorrelated. The analysis showed a slight, but not significant impact on channel 5 when correlated errors were assumed. Channel 4 had a smaller impact than channel 5.

4 Conclusions

This study shows that there are only very small differences when switching polarisations of AMSU A and B channels. Considering that these differences are not significant and that climate requirements need continuity of measurements we do not recommend any change to the current AMSU specifications. From an engineering point of view, if switching polarisations of channels can favour cost reductions, the study does not show any preference for the polarisation of channels 7-14. For the remaining channels there is a slight advantage for channels 1-6 and 15-20 to be in QH polarisation, but this is not sufficient to justify a change from AMSU specification. However, a change to QV for these channels is definitely undesirable.

Part IV
Determination of frequency options for a microwave sounder

5 Background, constraints and justification for the study on channel frequency choices for a post-EPS microwave sounder

5.1 Comparison of channel spectral response for MSU and AMSU

Measurements at 53-55.5 GHz primarily sense radiation emitted at levels from 800 to 200 hPa. As such they provide very important information about the troposphere, regardless of most cloud cover (precipitating clouds, or clouds with high liquid water content at altitudes greater than 2 km can still pose problems). In this spectral region the Microwave Sounding Unit (MSU) has one band between the strong oxygen absorption line close to 55 GHz and a second band on the high frequency side of the oxygen line near 53.6 GHz. The Advanced Microwave Sounding Unit increased the measurements in this frequency range, with a new channel measuring between the oxygen lines near 54.1 and 54.6 GHz (AMSU channel 6) and a wider bandwidth for the channel otherwise most similar to MSU channel 2 which was changed to straddle the oxygen line at 53.6 GHz (AMSU channel 5). However this meant the channel was measuring much more radiation emitted from lower altitude than MSU channel 2 and the weighting function peak of the channel dropped from about 650 hPa to 750 hPa. The change in the channel posed problems for those attempting to construct climate data records as the implications of measuring radiation emitted from a wider and lower range of altitudes is extremely difficult to determine.

The change from MSU channel 2 to AMSU channel 5 was not the only surprising change. Why was the frequency space between 53.8 and 54.1 GHz avoided? Why did the high frequency edge of the MSU channel 2 band move to a lower frequency in the new AMSU channel 5? Why were frequencies between 53.1 and 53.4 GHz not measured? Could the change have been done in a manner more sympathetic to the climate requirement?

These are obvious questions to ask when examining the frequency specification of the AMSU-A channels. The purpose of this study is to consider whether these details matter both for NWP and climate and to attempt to quantify the impact and propose alternatives. In taking this forward four issues will be borne in mind. Firstly the presence of spectroscopic features which might make some frequency space more difficult to analyse and interpret correctly than others. The most obvious aspect of this is to avoid any strong trace gas absorption lines. The second aspect is frequency protection. International agreements on protecting the most important passive microwave frequencies are closely tied to existing use of the data. In fact the region 53-55.5 is one of the few where protection exists in bands which have never been proposed for use! Extending a channel and picking up RFI on the edge of the band is clearly not desirable. Thirdly the climate requirement for continuity for long time series must be a strong constraint especially noting the widespread use of the MSU-AMSU data record. Once these constraints were fully considered the study assessed the impact of additional measurements using a 1D-var approach with simulated observations, making realistic assumptions about errors but assuming that any proposed channel is both feasible and affordable. The scope of the study is therefore limited to the scientific benefits of additional or modified channels.

The question of trace gases is considered in section 5.2, radio-frequency protection in section 5.3, the design of experiments to test value for NWP in Section 5.4 and the climate requirement in section 5.5. A set of channels for further testing and evaluation is proposed in section 6 and the results are presented in section 7.

5.2 Spectroscopy of minor gases 53.0-55.5 GHz.

The main trace gases in the region 53-55.5 GHz are listed in annex 2. The impact of the strongest spectroscopic features is now discussed.

5.2.1 Sulphur dioxide (SO_2)

There is a strong sulphur dioxide line in the lower frequency sideband of AMSU channel 5. Whilst SO_2 usually has an atmospheric concentration of 1 DU it can rise to 3 DU or more during episodes such as volcanic eruptions. This study needs to establish whether this SO_2 line is strong enough to cause difficulty in processing AMSU channel 5 during such events. Interestingly the SO_2 line was not covered by the original MSU channel 2 band.

There are two weaker SO_2 lines at 54.1 and 54.6 GHz. GENLN2 was run for the bands of interest with and without SO_2 lines for a profile from a volcanic event and the impact was small compared to instrument noise. So SO_2 is not considered a concern for any of these bands.

5.2.2 Nitric acid (HNO_3)

There are HNO_3 absorption features close to the oxygen line near 54.7 GHz but the impact of these will be insignificant compared to oxygen absorption.

5.2.3 Ozone (O_3)

Ozone concentrations can exceed 500 DU, almost entirely in the stratosphere, and therefore strong ozone lines are of interest. There is a strong ozone line at 53.68 GHz and two weaker lines at 54.78 and 54.98 GHz. The line at 53.68 GHz is most interesting as it falls inside the existing upper sideband of AMSU channels 5 and was also in the MSU channel 2 band. GENLN2 runs also confirmed that we can safely neglect these O_3 lines.

5.2.4 Hydrogen peroxide (H_2O_2)

There are several H_2O_2 absorption features but owing to its highly reactive nature hydrogen peroxide concentrations in the atmosphere are extremely low, despite its increasing anthropogenic production, and H_2O_2 can be ignored.

5.2.5 Nitrogen dioxide (NO_2)

Like hydrogen peroxide NO_2 is a highly reactive oxidiser. It is a pollutant for which even low atmospheric concentrations can be dangerous and total NOx (NO+NO_2) emissions have been on the increase in recent years. This may give a misleading impression of its occurrence, as concentrations are always very low. In any case all the NO_2 lines fall between 53.0 and 53.13 GHz and are, therefore, easily avoided.

5.2.6 Nitrogen oxychloride (NOCl)

The weak single NOCl line at 53.1 GHz is not a concern.

5.3 Radio-frequency protection requirements

Table 4 shows the existing protection for the frequency bands being considered here. The whole spectrum from 60 MHz above the centre of the oxygen line at 52.54 GHz to 120 MHz above the centre of the oxygen line at 54.13

Band GHz	Where used	Protection status
50.2-50.4	MSU channel 1 AMSU channel 3	Primary: passive emissions only
50.4-52.6	-	Unprotected
52.6-54.25	MSU channel 2 AMSU channels 4-5	Primary: passive emissions only.
54.25-59.3	MSU channels 3-4 AMSU channels 6-14	Primary but shared with fixed active services

Table 4: Protection of relevant frequencies under ITU-R SA.1028 1 and 1029.

GHz has primary protection for passive emissions only. Therefore all channel configurations within this frequency space are currently afforded protection. However it is unrealistic to expect bands which are not being used (and for which we have no plans) to remain protected indefinitely. Therefore the frequency space from 52.6 to 53.4 GHz must be regarded "at risk" as must 53.85 to 54.25 GHz. To require protection for 1650 MHz whilst only exploiting 450 MHz is not a tenable position. Therefore this study will also help answer the question as to whether there is an NWP case to continue to protect these frequencies for future use, even if their exploitation is not immediate. Note that the presence of existing bands with fixed links (54.25-59.3) and no protection (50.4-52.6 GHz) makes it likely that active users will soon express an interest in the band 52.6-54.25 GHz.

5.4 Operational use of AMSU and MSU observations in NWP

AMSU channels 5, 6 and 7 are three of the most important sources of information for global NWP. In the Met Office 4D-var system the short range forecast (six hour) used as background fits the observations very closely, as shown in Table 5, and although the analysis fit is closer in any one cycle the system does not need to pull very strongly to the radiances (i.e. much of the information in the observations is already captured by the background).

The standard deviation of the fit to background of AMSU channels 6 and 7 is 0.12 K with an analysis fit of 0.09 K. However on occasion there are significant errors in the background. For example in Figure 6 an area is highlighted in the South Pacific where differences vary from -0.3 K to +0.5 K. Another area can be seen just north of the Antarctica peninsula which has values below -0.5 K. Larger differences are not restricted to the

	AMSU Ch. 4	AMSU Ch.5	AMSU Ch.6	AMSU Ch.7
Background St.Dev. K	0.30	0.19	0.12	0.12
Analysis fit	0.26	0.14	0.09	0.09

Table 5: Fit of AMSU-A channels 5 to 7 to NWP background and analysis

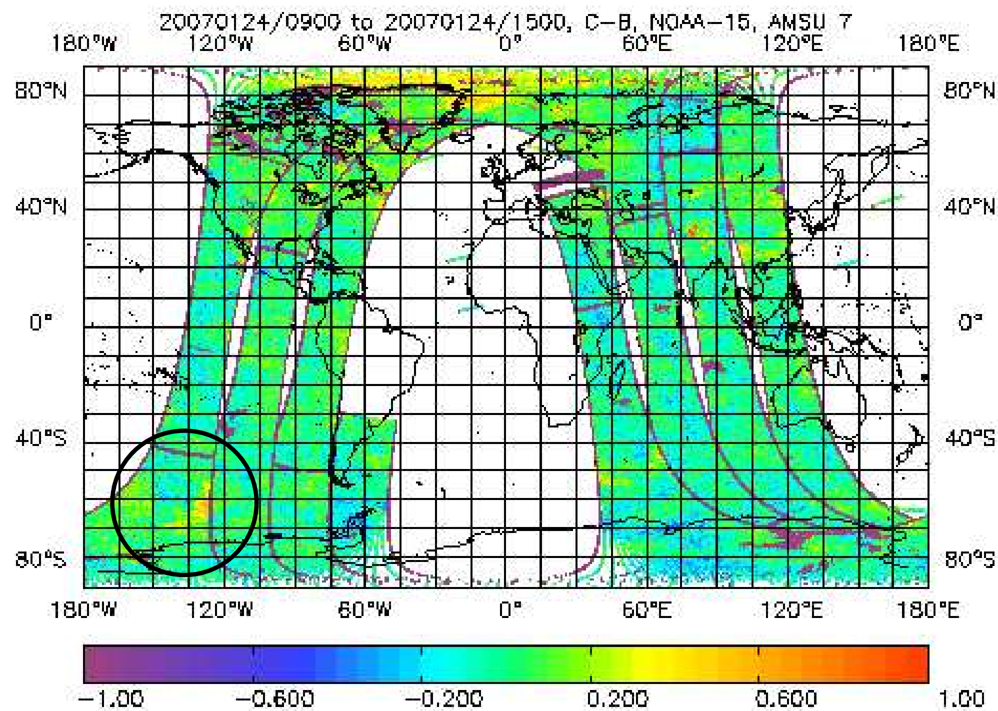

Figure 6: Typical fit of AMSU channel 7 (NOAA-15) to background for one 4D-var assimilation (09:00-15:00, 24/01/07). The circle highlights the area discussed in the text, where large differences are found.

southern hemisphere. Some differences larger than +0.5 K can be seen east of Greenland. However, in most places and for most of the time, the fit is within ±0.1 K. The positive impact of AMSU-A data on NWP arises from the reduction or elimination of these areas of higher error, which represent problems in the large scale analysis.

The AMSU-A instrument is a mature observation source which is doing its job successfully. Large changes to this instrument are neither necessary nor desirable. However this does not mean that some adjustments that are cost neutral (or cost reducing) should not be considered.

It is interesting to note the increase in mis-fit for AMSU channel 5 compared to AMSU channel 6. The sensitivity of AMSU channel 5 to the surface is much higher than for MSU channel 2. This is because the addition of the low frequency sideband of AMSU-5 has made interpretation much harder. That is to say that by mixing what are, in effect, two channels one peaking close to 800 hPa and another peaking around 650 hPa it has become much more difficult to interpret the atmospheric temperature information at 650 hPa because the surface effects on the 800 hPa measurement are so large.

Figure 7 illustrates the problem by showing how the mis-fit of AMSU observations to the background increases as surface to space transmittance increases. This increase is much more rapid for land points than for sea points. This is very unlikely to be due to increasing background temperature errors and can almost certainly be attributed to errors in the representation of the surface [*English*, 2007]. There is a substantial difference in the surface to space transmittance in the two sidebands for AMSU channel 5 (8% and 14%). As a consequence the contribution of errors in the treatment of the surface have a much bigger impact on the lower frequency sideband.

This is further illustrated by examining the O-B differences for AMSU channel 5 as a map in Figure 8. A lot of structure can be seen in the O-Bs which arises from variations in the surface e.g. snow over Canada and Greenland, mountain ranges such as Tibet, variations in Africa and Australia. Whilst some of this is due to an elevated surface there is no question that the use of AMSU channel 5 has proven difficult.

One question the study will therefore attempt to answer is whether the change from MSU channel 2 to AMSU channel 5 significantly reduced the potential of AMSU-A to improve the lower tropospheric analysis.

5.5 Use of AMSU and MSU observations in long term climate data records

Spencer and Christy [1992] and subsequently many authors have used MSU

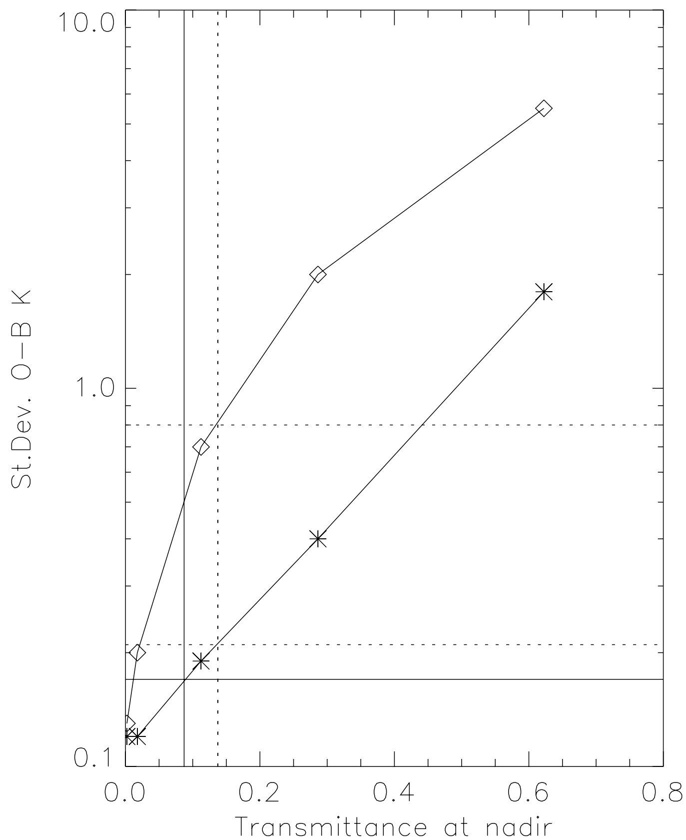

Figure 7: Relationship of mis-fit of AMSU observations to surface to space transmittance for sea points (asterisk) and land points (diamonds). The vertical continuous and dotted line show the surface to space transmittance for the lower frequency side band of AMSU channel 5 and the higher frequency sideband respectively (almost equivalent to MSU channel 2). The horizontal continuous and dotted lines show the corresponding expected values of the standard deviation of O-B.

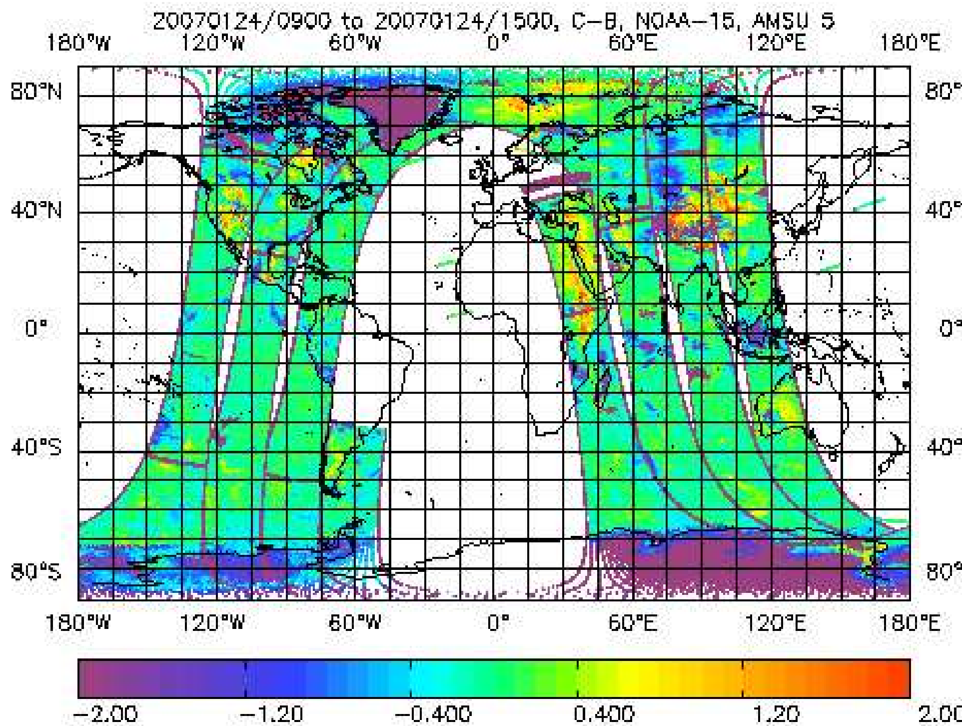

Figure 8: As in Figure 6 but for AMSU channel 5.

channel 2 and AMSU channel 5 to construct an important long term climate data record for mid-tropospheric temperatures. However the value of this data record has been partly undermined by debate about the removal of biases due to, for example, orbit drift. One of the most notable, and arguably avoidable, problems in the time series is the transition from MSU channel 2 to AMSU channel 5.

The climate requirements for an AMSU-like sensor can be summarised as

1. Overlap with AMSU, preferably on same platform for at least one full annual cycle, if not in an A-train type configuration.

2. Legacy channels or ability to regain these from a higher spectral resolution instrument (proven and understood due to the overlap). Preferably including both MSU and AMSU instrument channel frequencies directly.

3. Similarity in viewing geometry.

4. Same sampling in the diurnal cycle as legacy observations.

5. Dedicated ground-truth calibration system at several locations globally (e.g. Global Climate Observing System (GCOS) Reference Upper Air network documents at
`http://hadobs.metoffice.com/aopc_wg_aro/` and
`www.wmo.ch/pages/prog/gcos` *WMO-GCOS-112* [2007])

If these aspects are in place then modifications to channels will not degrade the climate data record.

6 Proposed bands for testing

In section 5 it was argued that some of the changes from MSU to AMSU-A may not have benefited lower tropospheric sounding, in particular between 700 and 400 hPa. Furthermore the changes have had a negative impact on the long term climate data record because of the additional uncertainty arising from the transition from MSU to AMSU. Before determining that the AMSU-A channels are mature and should be used as they are on post-EPS missions it is necessary to evaluate what the impact would be in removing these deficiencies.

It was established that there are no constraints either from trace gas spectral lines nor from spectrum management (frequency protection). As engineering issues are out of scope of this study, which considers only the scientific merit of measuring different parts of the oxygen absorption band, the only consideration is to measure as much bandwidth as possible in such a way that scientific processing and data assimilation are as effective as possible.

Firstly there is a minor issue with the higher frequency edge of the AMSU channel 5 band. When the AMSU channel 5 band was specified not only did it move the local oscillator frequency to sit close to the oxygen line with a side band above and below the line frequency, it also reduced the spectral coverage of the band by a small but significant amount. The question arises whether restoring this measurement would be useful either as an extension of the bandwidth of the existing channel or as a new rather narrow but separate channel (N4 in Figure 9). This is called "New1" and is illustrated in Figure 9.

Secondly there is the question of the remaining frequency space between the high frequency edge of the AMSU channel 5 band and the next oxygen line. Measurements in this region would supply information on temperatures between 800 and 400 hPa with almost no sensitivity to the surface, thus

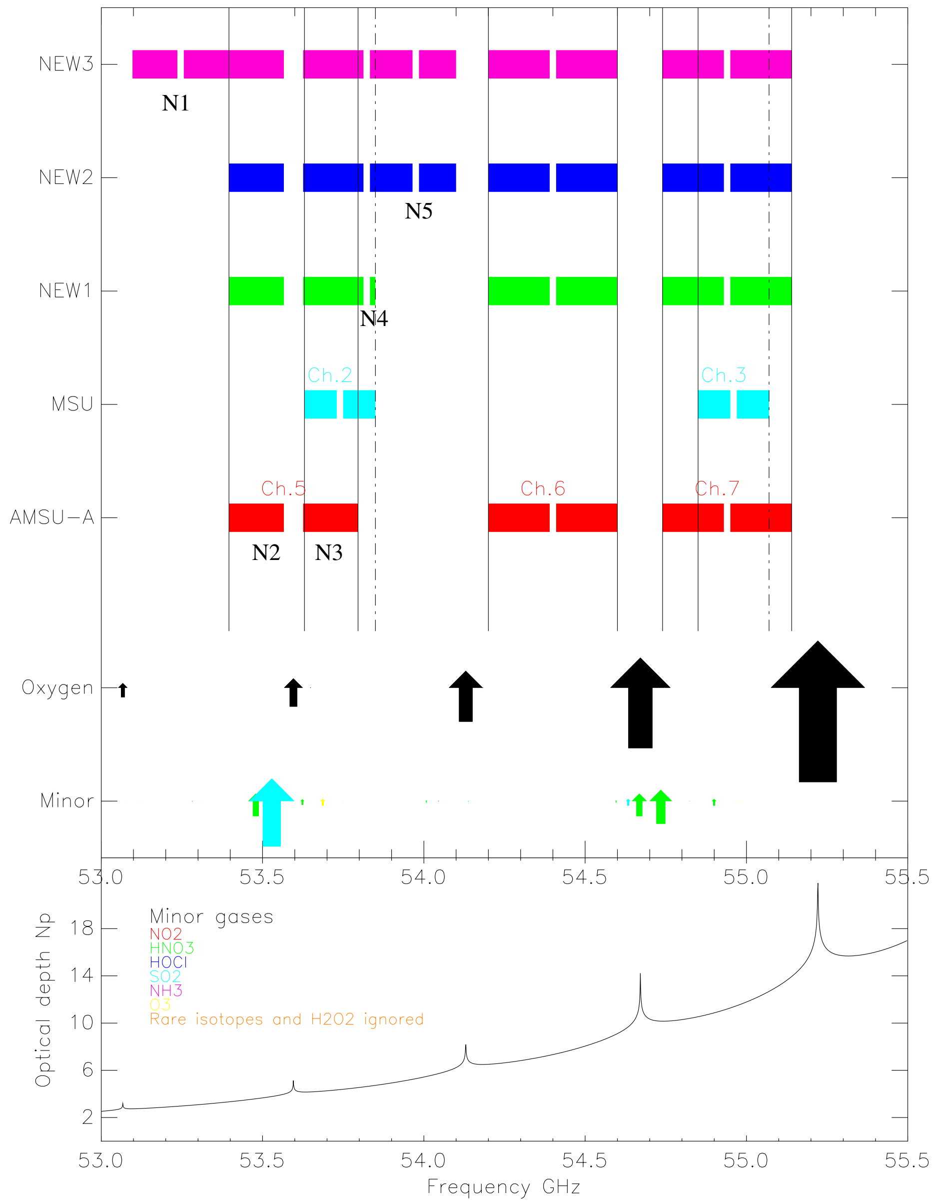

Figure 9: Comparison of MSU, AMSU and proposed channel configurations with oxygen and minor gas spectroscopic features.

channels	N1	N2	N3	N4	N5
R(O+F)	0.2	0.23	0.23	0.39	0.2

Table 6: R-Matrix (O+F) for AMSU channels

allowing greater exploitation of microwave sounding data over surfaces such as ice and snow which are very difficult to accurately characterise. Adding this measurement as a new channel (N5 in Figure 9) in addition to N4, is called "New2" and is also shown in Figure 9.

Finally there is the frequency space between 53 GHz and the lower frequency edge of AMSU channel 5. This is sounding at low altitude, sensitive primarily to temperatures between the surface and 700 hPa. To use such a channel would require extremely accurate characterisation of the surface. However the inclusion of this channel (N1 in Figure 9) would represent the most complete use of the spectrum between 53 and 53.5 GHz. Including N1 in addition to N5 and N4 constitutes "New3" and is the final concept illustrated in Figure 9.

The precise specification of the bands are as follows:

53.097-53.236 and 53.256-53.396	Oxygen line to AMSU-5 (N1)
53.796-53.850	Add "missing" part of MSU-2 (N4)
53.850-53.965 and 53.985-54.100	MSU-2 to Oxygen line (N5)

The combined observation and forward model error for the new channels are as shown in table 6.

RTTOV coefficients

RTTOV-8 coefficients have been generated to allow computation of New1, New2, New3 in addition to MSU and AMSU.

7 Results

This section presents the temperature retrieval performance of the proposed instrument configurations (Refer to figure 9).

Simulated background and observations were generated using the same procedure as in section 2 in Part III for instruments AMSU-A, MSU, NEW1, NEW2, and NEW3. The retrieval performance is shown in figure 10.

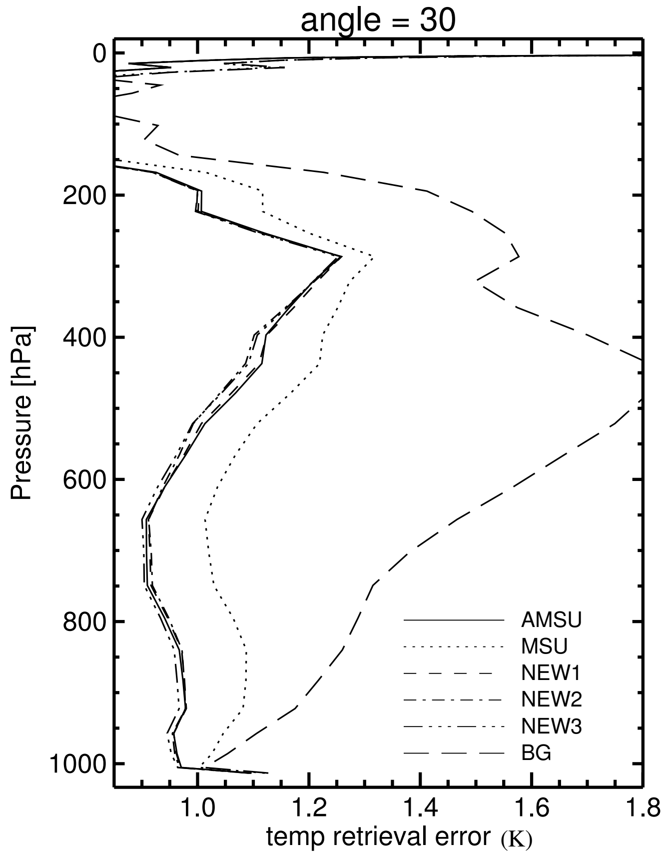

Figure 10: Temperature retrieval errors for the new instruments.

The first question to answer is whether the removal of the narrow band when going from MSU to AMSU will have any bad impact on retrieval performance. To find this out, a narrow channel (N4) is added to AMSU-A (NEW1 configuration). Figure 10 shows that including this leads to a slight improvement between 600 and 400 hPa, though it cannot be termed significant.

The second question was whether including a channel between the high frequency edge of AMSU-5 and the next oxygen line (channel N5, NEW2 configuration) would give a positive impact. The dash-dotted line in figure 10 shows clearly that NEW2 does improve the retrieval performance compared to AMSU-A all the way from 600 hPa to upper troposphere.

The third instrument proposed, namely NEW3, was to find out if adding a channel between 53 GHz and low frequency edge of AMSU-5 (channel N1) can add to low level temperature information. Figure 10 shows that

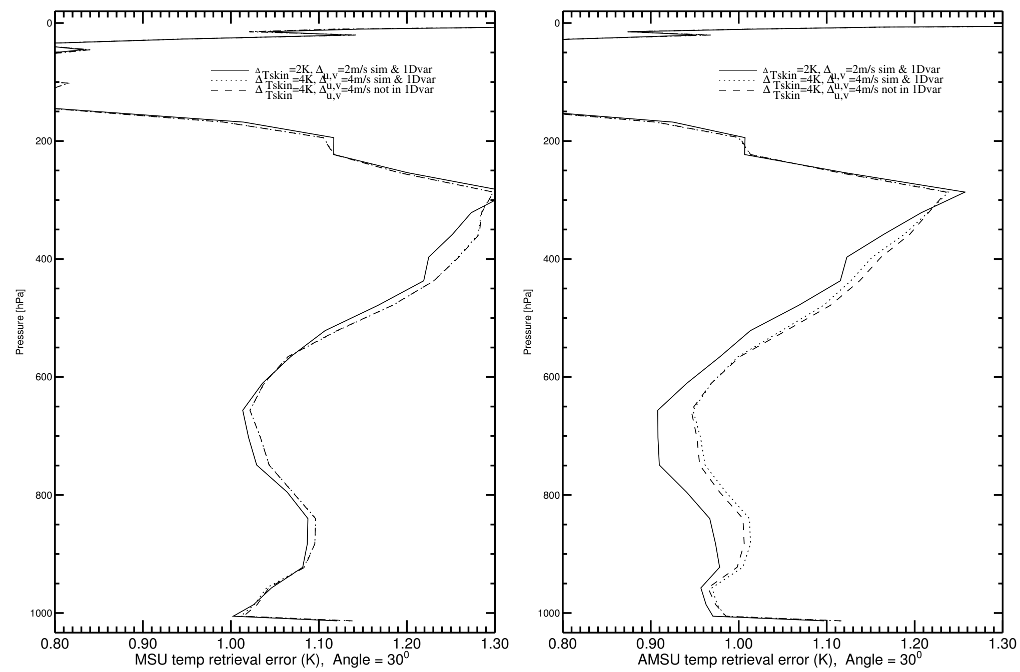

Figure 11: Left panel top: MSU temperature retrieval errors for three cases of background Tskin and emissivity errors. Solid line: case 1 - Tskin error = 2K and u,v error = 2m/s). Dashed line: case 2 - Tskin error = 4K and u,v error = 4m/s when generating the background but not in the 1Dvar. Dotted line: case 3 - Tskin error = 4K and u,v error = 4m/s when generating the background and in the 1Dvar. Left panel bottom: Difference in retrieval error between case 1 and case 2 (dashed line) and case 3 and case 1 (dotted line). The right panel shows the same for AMSU-A.

this configuration gives the best performance with significant improvement compared to other configurations, from the surface up to about 500 hPa. Because the new channel added is more sensitive to the surface, accurate surface characterisation will be required.

Surface

The next study was to see the sensitivity of each instrument to errors in the representation of surface. To determine this, background data was generated with an increased Tskin error of 4 K and an increased u and v wind speed error of 4 m/s. The Tskin error was 2 K and u and v wind speed error was 2 m/s for the original experiments.

Two sets of retrievals were performed. For the first 1D-Var run, background Tskin and emissivity errors were not increased despite the simulated data having increased error. In the second experiment, the 1D-Var assumed the same background error that was used for generating the simulated data, which means that the retrieval system was aware of the larger errors in the background. The results for MSU and AMSU are shown in figure 11. For NEW1, NEW2 and NEW3 the results are not very different from that of AMSU, hence only MSU and AMSU results are shown.

Figure 11 shows that increasing the Tskin and emissivity errors affect all instruments throughout the troposphere. Surprisingly, there is not much difference if the 1D-Var is or is not aware of the large surface background errors. For all configurations in the middle troposphere the performance is only slightly worse if the 1Dvar is not aware of the large errors in the background. Also, examining the Tskin retrieval errors shows that they are larger if the 1D-Var is not aware of the larger background errors. Comparing the performance of the instruments in the middle troposphere (from 600-400 hPa), shows that MSU is less sensitive to surface errors than AMSU-A.

The significance of the newly proposed channels was then tested by running the 1D-Var dropping each channel from the configuration. The retrieval results are compared for the affected instruments to their original results with the particular channel included. The channels were dropped in the order of their decreasing sensitivity to surface.

Among the newly added channels, the most surface sensitive is channel N1 which is to the right of the low frequency edge of AMSU channel 5 as shown in Figure 9. The only affected instrument if this channel is dropped is NEW3. The difference in temperature retrieval errors with and without N1 is plotted on the top left panel of Figure 12. The configuration performance is degraded when this channel is dropped, especially between the surface and about 700 hPa where the channel is sensitive.

The next channel that was dropped was channel N2 which is the lower frequency band of AMSU-5. The instruments affected are AMSU, NEW1, NEW2, and NEW3. The 1DVar was rerun for all these instruments without including channel N2. The difference between the retrieval errors from the new runs and the original retrieval errors is plotted on the top-right panel of figure 12. As expected, AMSU is the worst hit followed by NEW1. NEW2 and NEW3 are comparatively less affected as channels N1 and N5 on these instruments provide robustness to loss of N2.

In the next scenario, channel N4 that was missed out on going from MSU to AMSU was dropped and the 1D-Var was rerun for the affected instruments MSU, NEW1, NEW2, and NEW3. The results on the bottom-right panel of figure 12 shows that MSU is significantly affected when this channel is

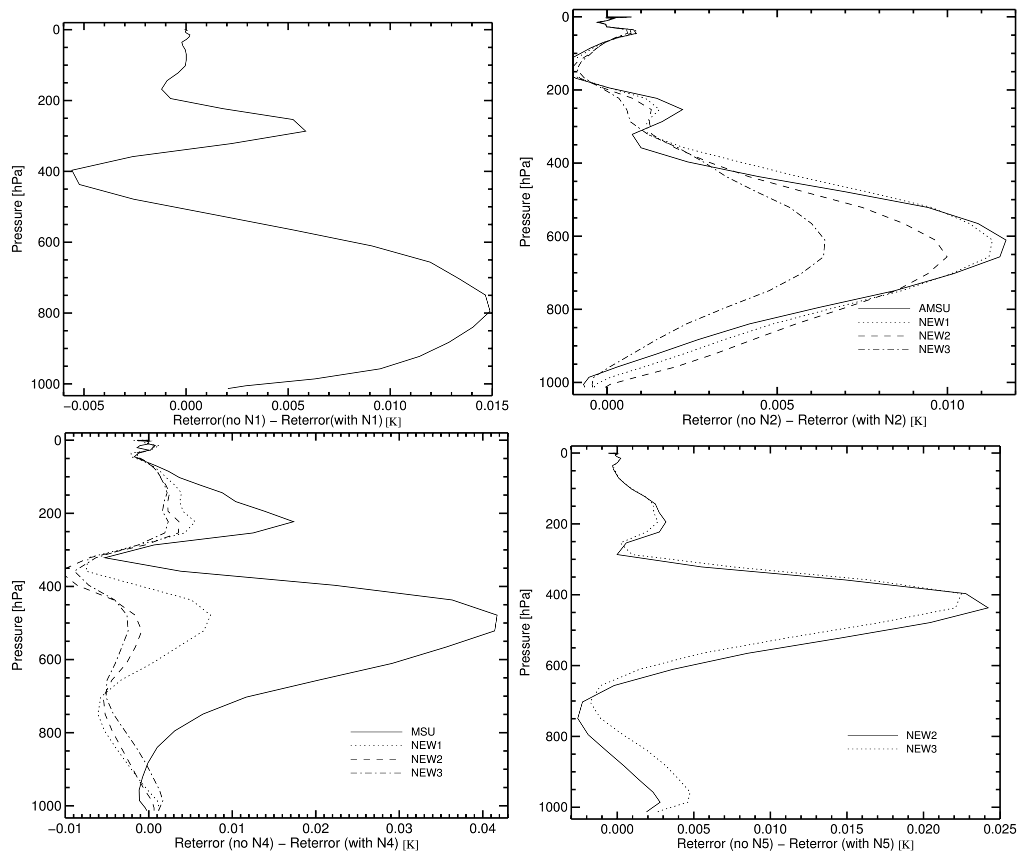

Figure 12: Top left: Impact of channel N1, Top right: Impact of channel N2, Bottom Left: Impact of channel N4, Bottom right: Impact of channel N5. All plots are for viewing angle 30°.

removed. The removal of N4 has a neutral impact on other instruments.

In the last scenario, channel N5, which covers the region between the high frequency edge of AMSU-A and the next O_2 line, is dropped from the 1D var run for instruments NEW2 and NEW3. The comparison to the results when this channel is included is plotted on the bottom-right panel of figure 12. The results indicate that removing this channel has significantly affected the performance of NEW2 and NEW3 and is more than the impact of channels N1 and N2. Also, this channel is not as much affected as channel N1 over uncertain surface conditions.

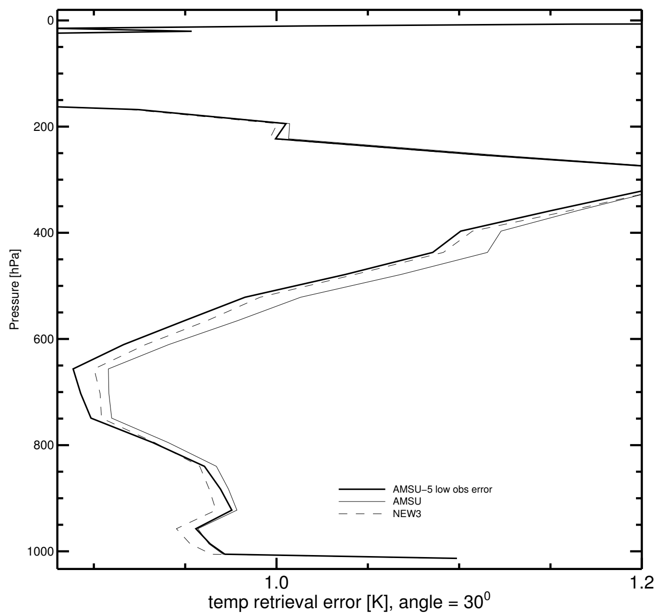

Figure 13: Temperature retrieval errors for AMSU-A (solid) and NEW3 (dashed). The thick and lines respectively represent cases with low and high observation error for channel 5.

Low observation error - AMSU Channel 5

We also examined if the extra information in NEW3 is simply due to increased bandwidth or bandwidth and additional vertical structure. This was tested by artificially reducing the assumed noise on AMSU channel 5 to the value which would be obtained if it had total bandwidth equivalent to NEW3 and the same system noise temperature. The original observation error of AMSU-5 was 0.18. This was reduced to 0.10 both when simulating the obs and in the 1DVar. Figure 13 shows that retrieval errors for AMSU-A (solid) and NEW3 (dashed) with the original observation error (thin lines) and AMSU-A with low observation error(thick solid line).

Figure 13 shows that AMSU with low observation error for channel 5 performs better than the new configuration from about 800 hPa up to about 500 hPa. This suggests that in this altitude range the improvement in NEW3 compared to original AMSU results from the larger bandwidth and not due to the extra vertical structure information from using N5. Closer to the surface, it is an interesting result that NEW3 performs significantly better than the new AMSU. The low retrieval errors for NEW3 compared to both AMSU simulations suggests that N1 can add extra information close to the surface.

8 Conclusion

The study shows that adding channel N4, thus replicating MSU-2 has no significant advantage for NWP. Using the new channel configuration as in NEW3 gives useful extra information for NWP. In order to maintain climate data records the additional band must be added as new channels, thus leaving existing channels unchanged.

Addition of new low altitude sensing channels between AMSU-4 and AMSU-5 does not seem to increase the sensitivity of retrieval error to mis-specification of the surface. This is also true for the channel between AMSU-5 and AMSU-6. The advantage of using these channels leads to the conclusion that addition of two new QH polarised channels as specified in NEW3 should be taken into consideration.

The specifications for the recommended channels are:

1. 53.097-53.236 and 53.256-53.396 (N1)

2. 53.796-53.938 and 53.958-54.100 (Combined N4 and N5)

Annex 1: AMSU channel specification

Channel	Central frequency GHz	Approximate altitude of peak sensitivity
1	23.8± 0.0725	Surface and total column water vapour
2	31.0± 0.050	Surface and cloud liquid water
3	50.3± 0.050	Surface and cloud liquid water
4	52.8± 0.105	Surface and cloud liquid water and temperature profile
5	53.596± 0.115	Temperature profile peak 750 hPa
6	54.400± 0.105	Temperature profile peak 400 hPa
7	54.940± 0.105	Temperature profile peak 250 hPa
8	55.500± 0.0875	Temperature profile peak 150 hPa
9	57.20934± 0.0875	Temperature profile peak 85 hPa
10	57.20934± 0.0217	Temperature profile peak 50 hPa
11	57.20934± 0.3222± 0.048	Temperature profile peak 25 hPa
12	57.20934± 0.3222± 0.022	Temperature profile peak 12 hPa
13	57.20934± 0.3222± 0.010	Temperature profile peak 7 hPa
14	57.20934± 0.3222± 0.0045	Temperature profile peak 2 hPa
15	89 ± 1.000	Surface and total column water vapour and cloud
16	89 ± 0.900	Surface and total column water vapour and cloud
17	150 ± 0.900	Water vapour, peak surface
18	183.31 ± 1.000	Water vapour peak 700 hPa
19	183.31 ± 3.000	Water vapour peak 500 hPa
20	183.31 ± 7.000	Water vapour peak 300 hPa

Annex 2: Full list of spectroscopic lines: 53-55 GHz

Species	Line frequency GHz	Line strength [cm^{-1}/molec. cm^{-2}]
NO_2	53.039611	8E-27
HNO_3	53.041620	3E-26
NO_2	53.044588	8E-27
NO_2	53.048605	8E-27
O_2	53.066952	2E-27
HOCl	53.082302	1E-26
NO_2	53.117857	8E-27
O_2	53.119086	1E-30
NO_2	53.122624	8E-27
NO_2	53.128230	9E-27
HNO_3	53.281604	1E-25
HNO_3	53.479197	2E-24
SO_2	53.528783	6E-24
O_2	53.595786	5E-27
HNO_3	53.623577	5E-25
O_2	53.647860	3E-30
O_3	53.686833	6E-25
HNO_3	53.751858	3E-26
HNO_3	54.007851	2E-25
NH_3	54.044276	3E-27
HNO_3	54.070418	3E-26
O_2	54.130016	9E-27
SO_2	54.138800	1E-25
O_2	54.181940	5E-30
HNO_3	54.595654	2E-25
SO_2	54.633398	6E-25
HNO_3	54.667964	2E-24
O_2	54.671172	1E-26
O_2	54.722796	9E-30
HNO_3	54.723276	2E-25
HNO_3	54.734578	3E-24
O_3	54.787071	1E-27
HNO_3	54.824785	5E-26
HNO_3	54.899494	6E-25
O_3	54.981937	2E-27
HNO_3	55.023818	1E-26

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