TECHNICAL MEMORANDUM

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Evaluation and assimilation of ATMS data in the ECMWF system

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Abstract

This memorandum reports on the first experiences with ATMS data at ECMWF, both in terms of the contribution to the calibration/validation exercise, and in terms of initial assimilation trials. Comparisons in brightness temperature space against short-term forecasts are used to establish the fidelity of the data.

Monitoring of ATMS data against short-term forecasts show that the data are generally of good quality, with a noise performance that is well within specification and, after appropriate averaging, comparable to or better than that of AMSU-A. Biases vary smoothly with scan-positions, even before an appropriate antenna pattern correction has been established, and ATMS looks better than AMSU-A in this regard. Outer scan positions can be assimilated without restrictions due to biases, and together with the wider swath this leads to a much improved coverage from ATMS compared to one AMSU-A. There are indications of larger inter-channel and spatial error correlations in ATMS data than for AMSU-A, possibly linked to a weak cross-track striping effect.

The analysis and forecast impact in initial assimilation trials over two seasons are significantly positive in the short-range over the Southern Hemisphere and in the long range over the Northern Hemisphere, with an otherwise overall neutral impact.

1 Introduction

This memorandum reports on an evaluation of data from the Advanced Technology Microwave Sounder (ATMS) in the ECMWF system. ATMS was launched onboard the Suomi National Polar-orbiting Partnership (Suomi-NPP) satellite on 28 October 2011. Suomi-NPP is the preparatory satellite for the next generation of operational meteorological polar orbiting satellites of the USA. Alongside ATMS, it also carries the Cross-track Infrared Sounder (CrIS) and the Ozone Mapper and Profiler Suite (OMPS), both being of high relevance to Numerical Weather Prediction (NWP). Data from ATMS and CrIS started to arrive routinely at ECMWF on 26 June 2012.

The ATMS instrument continues the heritage of the AMSU-A and MHS radiometers, microwave instruments that are providing temperature and humidity sounding capabilities, respectively. AMSU-A in particular has been established as one of the leading satellite instruments contributing to today's forecast skill (e.g., Radnoti et al. 2010, Eyre et al. 2012, Jung and Riishøjgaard 2012). Microwave data is less affected by the presence of clouds than infrared data, therefore providing important information in areas not sensed by other nadir sounding instruments. A successful exploitation of ATMS data for NWP is of paramount importance to maintain or improve forecast quality for the future.

The aim of this memorandum is twofold. Firstly, we provide an evaluation of the ATMS data in terms of comparisons against short-term forecasts. This has been proven to be a powerful tool for the evaluation of new satellite data (e.g., Bell et al. 2008, Lu et al. 2011), and it is an integral contribution to the calibration/validation activity. Secondly, we report on initial assimilation trials with ATMS, in preparation for the operational assimilation of this new data source. The results presented here have been obtained during the calibration/validation phase for ATMS, and data characteristics are therefore subject to change as the data processing is further improved.

The structure of the memorandum is as follows. We first provide an overview of the ATMS instrument characteristics, followed by a description of the experiments used to evaluate the data. Section 4 summarises our findings from a comparison of ATMS data against short-term forecasts, whereas section 5 discusses the forecast impact from assimilating ATMS data. Finally, our conclusions are provided in the last section.

2 ATMS

ATMS is a 22 channel microwave radiometer that combines AMSU-A and MHS heritage channels with one additional temperature channel and two humidity sounding channels (Table 1, see also Muth et al. 2004 and NASA 2011). The temperature and humidity Jacobians for the main sounding channels are displayed in Fig. 1; ATMS channels 6-15 are similar to AMSU-A channels 5-14, and ATMS channels 18, 19 and 22 are similar to MHS channels 5, 4 and 3, respectively. All channels are sampled every 1.11°at 96 scan positions, with a cross-track swath width of 2,300 km, significantly wider than the 2,074 km for AMSU-A or MHS. As a result, ATMS data coverage shows no gaps between swaths in the tropics.

Table 1: ATMS channels. The FOV size differs by channel: channels 1 and 2 have a FOV of 75 km at nadir, 3-16 32 km, and 17-22 16 km. The polarisation changes with cross-track scan position, and only the polarisation at nadir is given. [1] indicates a polarisation difference to the equivalent AMSU-A or MHS channel, [2] indicates a new channel not previously available on AMSU-A or MHS, and [3] indicates a channel for which the central frequency has changed significantly compared to MHS.

Channel number	Frequency [GHz] and polarisation at nadir	Channel number	Frequency [GHz] and polarisation at nadir
1	23.8 V	12	57.29 ± 0.3222 ± 0.048 H
2	31.4 V	13	57.29 ± 0.3222 ± 0.022 H
3	50.3 H[1]	14	57.29 ± 0.3222 ± 0.010 H
4	51.76 H[2]	15	57.29 ± 0.3222 ± 0.0045 H
5	52.8 H[1]	16	88.2 V
6	53.596 ± 0.115 H	17	165.5 H[1,3]
7	54.4 H	18	183.31 ± 7.0 H[1]
8	54.94 H[1]	19	183.31 ± 4.5 H[2]
9	55.5 H	20	183.31 ± 3.0 H
10	57.29 H	21	183.31 ± 1.8 H[2]
11	57.29 ± 0.3222 ± 0.217 H	22	183.31 ± 1.0 H

The spatial sampling, field of view (FOV), and noise of the temperature-sounding channels of ATMS differ markedly from those of AMSU-A. The data are sampled more densely (1.11°compared to 3.33°), with a smaller footprint (32 km at nadir compared to 48 km), but larger noise (e.g., specification of 0.5 K compared to 0.25 K for tropospheric sounding channels). This is of relevance to NWP: to achieve a performance comparable to AMSU-A, and to reduce the noise to levels desirable for NWP, averaging of ATMS footprints is considered necessary. Several approaches have been developed, such as averaging of the neighbouring 3 scan-positions and scan-lines (referred to as 3x3 averaging), Backus-Gilbert weighted averaging, or Fourier-based methods. Here we consider only the simple 3x3 averaging. This will be applied to channels 3-22, and unless indicated otherwise only statistics for averaged data are shown here.

Another aspect of ATMS is that channels 1 and 2 have a significantly larger FOV size than the sounding channels (75 km compared to 32 or 16 km), even after the 3x3 averaging of the sounding channels. The spatial detail represented in these channels therefore does not match that of the temperature sounding channels. Channels 1 and 2 are frequently used in quality control decisions for NWP, and this mis-match in scales has to be kept in mind when adopting quality control procedures from AMSU-A. For channels 1 and 2 we use the central field of view in each 3x3 group unaveraged.

Due to problems with initial versions of the antenna pattern correction for ATMS, all our results are based on so-called antenna temperatures, ie, values before antenna pattern correction. For AMSU-A or MHS, brightness temperatures after antenna pattern correction are usually used at ECMWF instead.

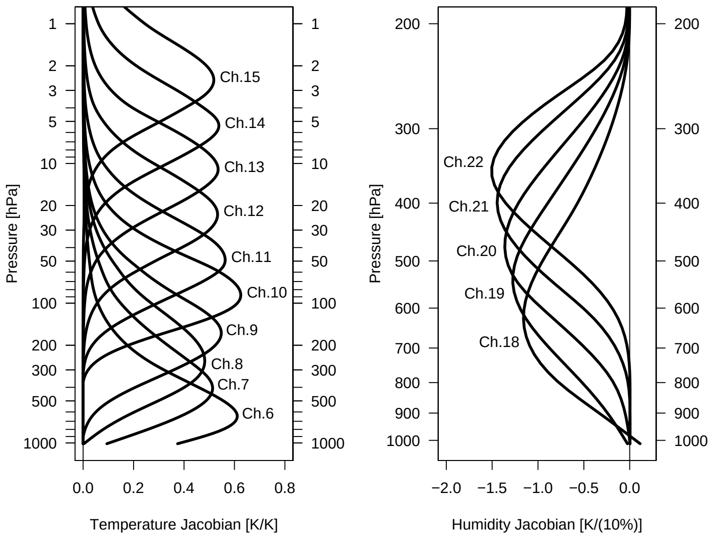

Figure 1: Temperature Jacobians for the main temperature sounding channels (left) and humidity Jacobians for the humidity sounding channels (right) of ATMS for a standard mid-latitude reference profile. Both are with respect to perturbations in layers of log(pressure), and the humidity Jacobians have been calculated with respect to a 10 % increase in humidity.

3 Experiments and quality control

ATMS brightness temperatures have been assessed in the ECMWF assimilation system. To do so, two experiments are presented here: a control experiment in which ATMS data are passively monitored, and another experiment in which ATMS data are actively assimilated. Both experiments use ECMWFs 12 h 4DVAR system, with a spatial model resolution of T511 ($\approx$ 40 km), an incremental analysis resolution of T255 ($\approx$ 80 km) and 91 levels in the vertical. Experiments were conducted over two seasons, the first period covering 15 December 2011 - 6 February 2012, and the second period covering 28 June - 31 August 2012. Ten-day forecasts were calculated from each 0 Z analysis.

The control and ATMS experiments otherwise use the full observing system assimilated operationally at ECMWF at the time. This includes conventional data as well as radiances from 5 AMSU-A instruments, 3 MHS instruments, 2 HIRS instruments, as well as from AIRS and IASI. In particular, NOAA-18 (AMSU-A and MHS), NOAA-19 (AMSU-A and MHS), and Aqua (AMSU-A) already provide similar microwave sounding data in this system in orbits similar to the NPP orbit with its 13:30 equator crossing time, as summarised further in Table 2.

Table 2: Other microwave sounding instruments used in the ECMWF operational system at the time of writing. Note that not all channels are used for all instruments.

Satellite	Equator crossing time	AMSU-A	AMSU-B/MHS
NOAA-15	16:43	Assimilated	Not available
NOAA-16	8:36	Monitored	Monitored
NOAA-18	14:57	Assimilated	Assimilated
NOAA-19	13:33	Assimilated	Assimilated
Aqua	13:37	Assimilated	Not available
METOP-A	9:30	Assimilated	Assimilated

In the ATMS experiments, the temperature sounding channels 6-15 and the humidity sounding channels 18-22 are used. Channels 6-8 and 18-22 with some surface sensitivity are used over open sea only (with a tighter test for sea-ice for channels 6, 18 and 19), whereas the other channels are used everywhere. The assimilation system uses RTTOV version 10 for all radiance simulations (e.g., Hocking et al. 2012), including those for ATMS.

For the temperature sounding channels, the quality control for cloud or rain contaminated observations is inspired by that currently used for AMSU-A, but with a number of modifications: Channels 6-8 are excluded if the absolute value of the FG-departure for channel 3 is larger than 5 K. In addition, channels 6-8 are also rejected if an observation-based estimate of the liquid water path (LWP) exceeds a certain threshold, with the thresholds being 0.12 kg/m^2 for channels 6, 7, and 0.15 kg/m^2 for channel 8. The liquid water path estimate is based on channels 1 and 2, and follows Grody et al. (2001). Note that channels 1 and 2 are used for this without the 3x3 averaging, yet due to the instrument design the footprint size of these channels is still larger than that of the sounding channels after averaging. This means cloud or precipitation features will appear spatially smoother in these channels. While this aspect is suboptimal, we have not found it a pressing problem, and the choice of LWP threshold introduces the larger uncertainty in terms of used data numbers. The above settings for the quality control have been derived based on simulations of cloud effects and comparisons of screened observations with other data, combined with FG-departure based analyses such a shown in Fig. 2. Figure 2 illustrates how FG-departures increase with LWP and the channel 3 FG-departure, and this information can be used as guidance to set thresholds to limit the forward model error arising from neglecting cloud effects. Note that estimates of situation-dependent background errors also indicate larger errors in the FG with increasing LWP, but the signal from neglecting clouds in the radiative transfer dominates the FG-departure signal (not shown).

For the humidity sounding channels, the quality control is as follows: Again, channels 18-22 are excluded when the absolute value of the FG-departure for channel 3 is larger than 5 K, and channel 18 is rejected if LWP $>$ 0.12 kg/m^2. In addition, a threshold check on a scatter index is used, excluding data for which Tb16 - Tb17 (46.94 + 0.248 θ) $>$ 10 K (following Bennartz et al. 2002, with θ the zenith angle in degrees). The scatter index aims to detect scenes for which significant scattering is present (due to clouds), and the value subtracted from the brightness temperature difference between channels 16 and 17 (Tb16 - Tb17) should ideally take the local conditions into account. Attempts to do so, based on FG-

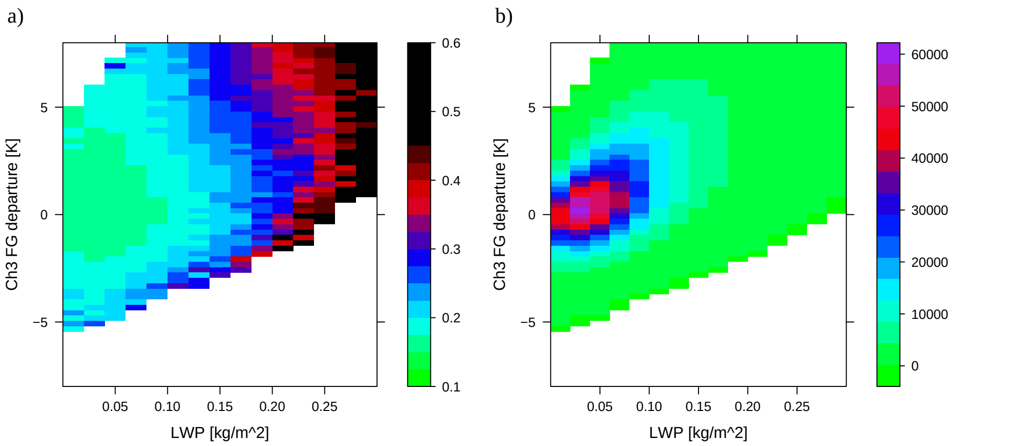

Figure 2: a) Root mean square of the FG-departure for ATMS channel 6 as a function of LWP and the channel 3 FG-departure. Statistics are based on data over sea, for the period 1-31 July 2012. Only bins with a minimum of 100 observations are shown. b) As in a), but for the number of observations per LWP/channel 3 departure bin.

Table 3: Percentage of observations passing rain and cloud-related quality control over open sea for ATMS.

Channel number	6,7	8	9-15	18	19-22
Number of observations passing quality control [%]	78	83	100	62	68

simulations, resulted in more data being used but a poorer forecast performance, so the simpler global formulation is being used here. This aspect may have to be revisited in the future.

The percentage of observations passing the rain and cloud-related quality control over open sea by ATMS channel is given in Table 3. For the temperature-sounding channels, the quality control is slightly less restrictive than that for AMSU-A, whereas for the humidity sounding channels the quality control for ATMS is more stringent, especially around the Intertropical Convergence Zone.

Bias correction for ATMS is performed in the variational framework (e.g., Dee 2004), and the bias predictors are the same as for equivalent AMSU-A or MHS channels, including airmass as well as scan-bias predictors (see Bormann and Bauer 2010). In the assimilation experiment, the data are thinned to a resolution of 140 km, giving preference to the scene that has the largest number of channels passing quality control. Observation errors are set to 0.35 K for the tropospheric temperature sounding channels 7-12 (0.4 K for channel 6), rising to 1.4 K for channel 15, with assumed observation errors of 2 K for the humidity sounding channels (see also Fig. 9).

4 Analysis of departure statistics

In the following, we present an evaluation of ATMS data in terms of departure statistics against clear-sky brightness temperatures simulated from short-term forecasts as used in ECMWFs 4DVAR assimilation system. This provides a comparison against a reference with stable and well-characterised error characteristics for every observation, making it a powerful tool for calibration/validation exercises. Statistics will be compared against those from AMSU-A and MHS instruments already assimilated in the ECMWF system. We concentrate on the sounding channels that are considered for assimilation in this report.

4.1 General evaluation

Standard deviations of FG-departures suggest a noise performance of ATMS that is well within specifications, and overall consistent with pre-launch measurements (cf, Bell et al. 2011 for pre-launch noise measurements). Figure 3 shows comparisons between standard deviations of FG-departures before and after 3x3 averaging, together with instrument noise estimates provided in the data. Note that differences between the instrument noise and the FG-departure values are expected due to errors in the FG, the radiative transfer or representativeness errors contributing to the FG-departures. For the temperature channels, the 3x3 averaging leads to the expected reduction of the standard deviation of FG-departures. For the humidity channels, the effect of the 3x3 averaging on the standard deviations is smaller compared to the temperature sounding channels. This is because the contribution of the random instrument noise to the standard deviations of FG-departures is smaller compared to spatially correlated errors in the FG, the representativeness, radiative transfer and quality control.

After the 3x3 averaging, the performance of ATMS is typically comparable to or better than that of AMSU-A instruments currently used in the ECMWF system (Fig. 4). For the tropospheric channels

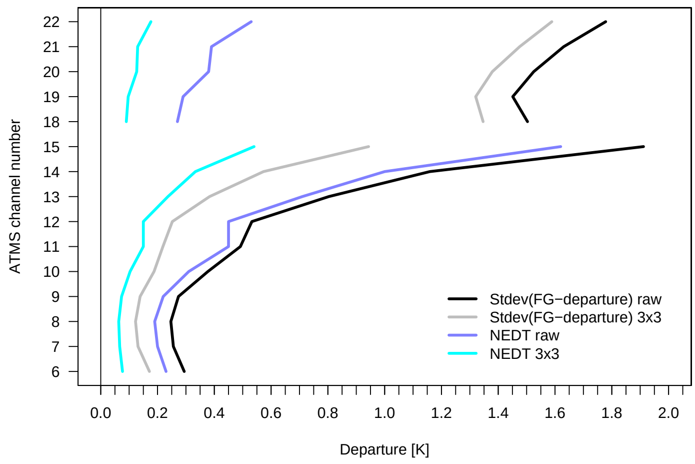

Figure 3: Standard deviation of FG-departures after quality control and bias correction for ATMS channels 6-15 and 18-22. Black indicates values before footprint averaging, grey after averaging 3x3 footprints. Blue and cyan are estimates of random instrument noise as provided in the data, before and after averaging, respectively. Statistics are based on all data over sea, between $\pm$ 60°latitude, for the period 1-31 July 2012.

(ATMS 6-9), ATMS performs clearly better than all the AMSU-A instruments currently assimilated in terms of standard deviations of FG-departures. Note that some of these channels have already failed for the AMSU-A instruments currently in orbit, and ATMS therefore restores lost observing capabilities here. In terms of mean biases, ATMS lies within the range of biases observed for AMSU-A instruments (as can be seen from the mean bias corrections shown in Fig. 4). Note, however, that for NOAA-15, NOAA-18 and Aqua an empirical scaling factor for the optical depth calculations is used, designed to

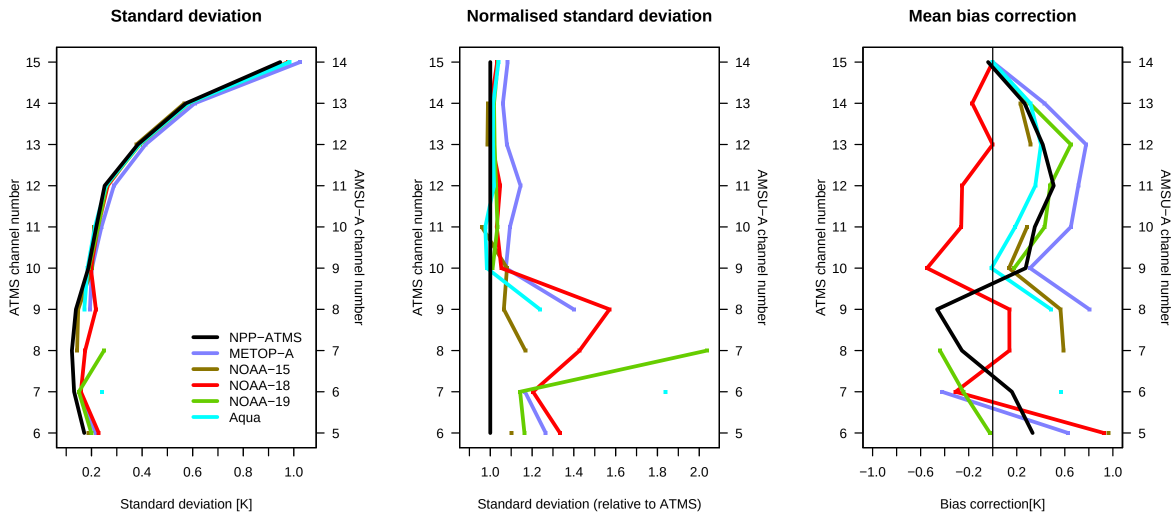

Figure 4: FG-departure statistics for ATMS temperature sounding channels after 3x3 averaging, in comparison to equivalent AMSU-A channels for all other AMSU-A instruments currently assimilated at ECMWF. The three panels show the standard deviation (left), normalised standard deviation (normalised to one for ATMS, middle), and the mean bias correction (right). Statistics are based on data after bias correction and quality control for 1-31 July 2012.

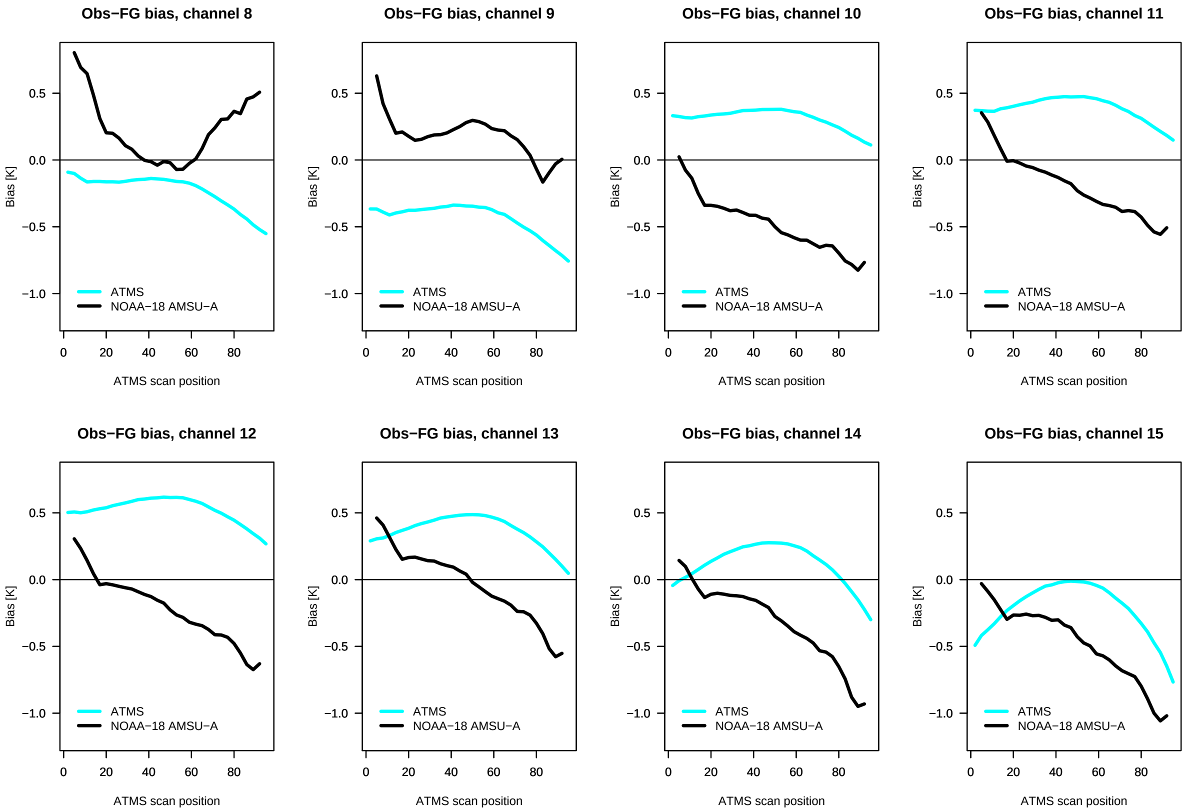

Figure 5: Observation minus FG bias (before bias correction) as a function of ATMS scan position for ATMS channels 8-15 (blue), in comparison to equivalent AMSU-A channels/scan-positions from NOAA-18 (black). Statistics are based on all data over sea, between ± 60°latitude, for the period 1-31 July 2012. Note that the AMSU-A values are based on antenna-corrected data, and include an empirical scaling factor for the optical depths in the radiative transfer calculations.

reduce airmass-dependent biases in the data (e.g., Watts and McNally 2004, Di Tomaso and Bormann 2011), the effect of which is not included in the mean bias corrections shown here.

For the humidity sounding channels, the ATMS performance of the 3 MHS-like channels are similar to that of existing MHS instruments, but larger FG-errors, errors of representativeness and quality control differences make a comparison less stringent (not shown).

A comparison of scan-position dependent biases for ATMS and AMSU-A is given in Fig. 5. The scan biases are considerably smoother for ATMS, especially for the outermost scan positions, for which the AMSU-A data tends to show marked differences in the bias characteristics. Due to these different bias characteristics, the outermost 3 AMSU-A scan-positions on either side are currently not assimilated at ECMWF. It appears that such a cautious data selection is not necessary for ATMS; the variational bias correction successfully removes biases for all scan-positions on the basis of a 3rd order polynomial in the scan-position. Hence, data from all scan-positions can be used for ATMS. Combined with the wider swath width, this leads to a significantly better spatial coverage of usable data from ATMS compared to AMSU-A (33 % more footprints after averaging, compare also Figures 6 and 7).

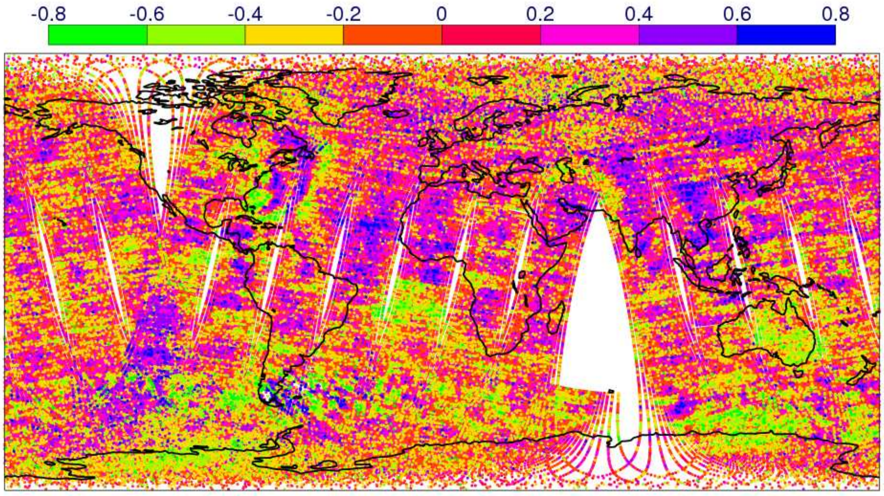

Figure 6: First Guess departure (observation minus First Guess, after 3x3 averaging and bias correction) for ATMS channel 12 between 1 July 2012, 21 Z and 2 July 2012 9 Z.

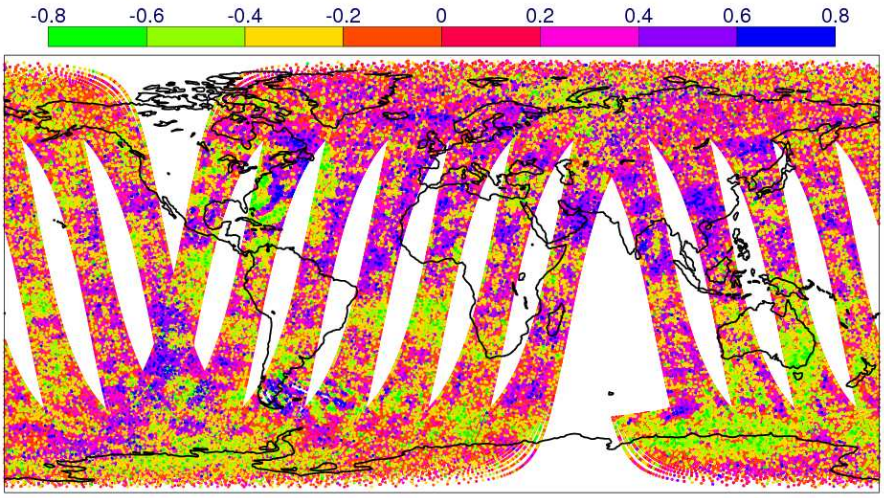

Figure 7: First Guess departure (observation minus First Guess, after 3x3 averaging and bias correction) for NOAA-19 AMSU-A channel 11 between 1 July 2012, 21 Z and 2 July 2012 9 Z. Only the scan positions considered for assimilation are shown here, ie, the outermost 3 scan positions on each side are not shown.

4.2 Striping and observation error characterisation

While the characteristics in terms of FG-departure statistics suggest a performance of ATMS comparable to or better than AMSU-A in terms of noise, closer inspection nevertheless suggests some noteworthy issues with the ATMS data. Figure 6 shows a weak cross-track striping pattern in the differences between observations and FG-equivalents, not present in the equivalent AMSU-A channel (cf Fig. 7). Similar pattern are apparent for many other channels. This suggests a scanline-dependent correlated error in the ATMS data. The effect has been noted by other authors in other assimilation systems (e.g., Collard et al. 2012, Doherty et al. 2012). The effect has been traced back to 1/f gain fluctuations in the low noise amplifier of ATMS (Kent Anderson 2012, pers. communication). These fluctuations mean that the true

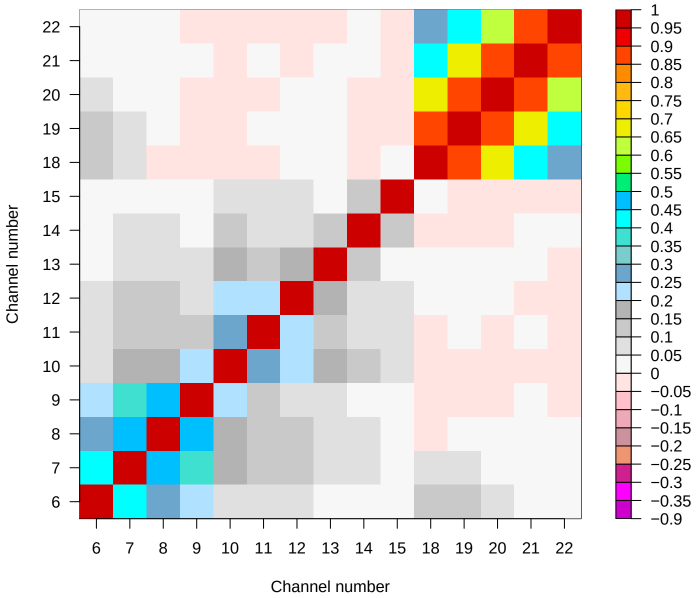

Figure 8: Estimates of inter-channel error correlations based on the Desroziers diagnostics for ATMS. Statistics are based on used data over sea for 1-31 July 2012 (only scenes for which all considered channels are assimilated).

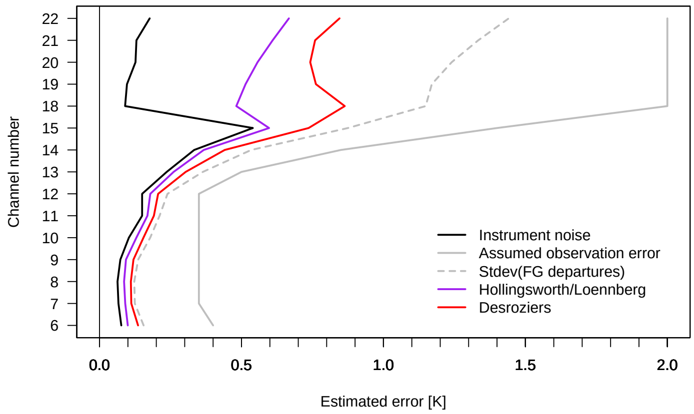

Figure 9: Estimates of observation errors for ATMS, based on the Hollingsworth/Lönnberg (purple) and the Desroziers method (red). Also shown are estimates of the instrument noise as provided in the data (black), the observation error assumed in the assimilation (grey), and the standard deviations of FG-departures (dashed grey). Statistics are based on used data over sea for 1-31 July 2012 (only scenes for which all considered channels are assimilated).

gain of the instrument exhibits relatively long period ($\approx$ 1 s) fluctuations. When the cold/warm target views are used to characterize this gain the resulting estimated gain is not accurate after timescales of around 1 s. Unlike thermal (white) noise 1/f noise cannot be dealt with easily by averaging, so efforts to address this by optimising the calibration averaging have been unsuccessful.

Similarly, observation error diagnostics suggest that there is a notable difference in the size of the contributions of random and correlated error for ATMS compared to AMSU-A. These diagnostics have been calculated from departures obtained from the assimilation of ATMS data, following the approaches used in Bormann and Bauer (2010). Estimates of spatial and inter-channel error correlations for ATMS point to the presence of errors that are correlated spatially and between channels (e.g., Fig. 8). The size of the correlations is considerably larger for ATMS than for AMSU-A counterparts; for AMSU-A, estimates for inter-channel error correlations are largely negligible (cf Bormann and Bauer 2010). This suggests an instrument-related feature, likely to be linked to the striping effects mentioned above. There appear to be two blocks of channels with more significant inter-channel error correlations, channels 6-9 and channels 10-15. Estimates for the observation errors (σ_o) are considerably larger than the instrument noise values provided in the data (again in contrast to what has been found in the past for AMSU-A), also suggesting the presence of a further error source not present for AMSU-A. For the humidity sounding channels, the observation error covariance diagnostics are more consistent with those found for MHS, with significant error correlations between the humidity sounding channels. These are most likely the result of errors of representativeness or radiative transfer, rather than instrument-related effects.

The presence of notable error correlations is likely to have implications on how ATMS data is to be assimilated. Currently, it is standard practice that such error correlations are ignored in the assimilation. However, Bormann and Collard (2012) show that neglecting interchannel error correlations can lead to a detrimental assimilation of observations affected by such error correlations if the diagonal observation errors are not inflated. Successful assimilation of observations with error correlations is possible when assuming a diagonal observation error covariance matrix, but considerable error inflation factors have to be used. While inter-channel error correlations could be taken into account in the assimilation, we chose to assimilate ATMS assuming diagonal observation errors in the present study, and our observation errors are inflated as shown in Fig. 9. In this context it is worth mentioning that an experiment was also conducted with smaller observation errors, consistent with the AMSU-A use. This experiment performed slightly more poorly than when inflated errors are used. This is in contrast to a large positive forecast impact that recently resulted from reducing the observation errors for AMSU-A from 0.35 K to 0.2 K for the tropospheric and lower stratospheric sounding channels in the ECMWF system. The lack of improvement from the observation error reduction may be related to the error correlations discussed above.

Further aspects of ATMS data have been studied on the basis of departure statistics, such as the temporal stability and within-orbit biases. Overall, the performance for the temperature sounding channels was found at least comparable to that of current AMSU-A instruments. Employing departure-based methods described in Lu et al. (2011) also gives no indication of significant pass-band shifts for the temperature sounding channels (shifts well below 10 MHz for channels 7-15). This is in contrast to recent findings for AMSU-A, where indications of passband shifts of several 10s of MHz have been diagnosed for channels 6-8 (Lu and Bell 2012). The result is likely to be related to the use of a phase lock local oscillator in ATMS (NASA 2011).

5 Assimilation results

We will now discuss the results from our assimilation trials with ATMS data. These trials were motivated by the overall good quality of the ATMS data, as summarised in the above departure characteristics. While the striping pattern discussed above has to be kept in mind when setting assimilation choices, we consider it small enough to nevertheless experiment with assimilation of the data.

Analysis diagnostics show consistently a positive impact on tropospheric humidity from the assimilation of ATMS data, as evidenced through reduced standard deviations of FG-departures for humidity sounding channels (e.g., Fig. 10). The reductions are very consistent for the two seasons and for water vapour channels from different instruments such as MHS, AIRS, IASI, and HIRS. They are most pronounced

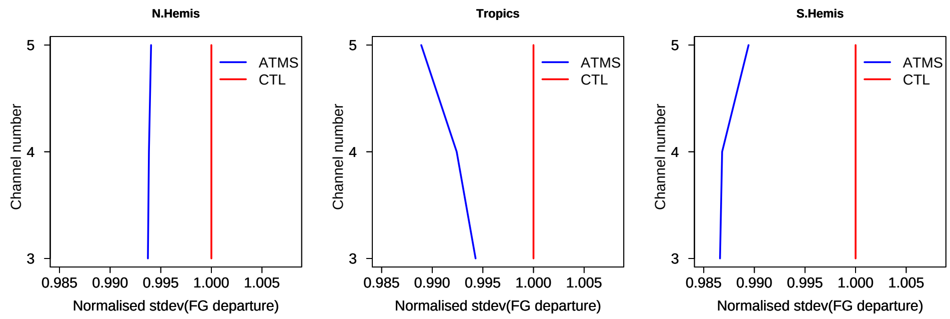

Figure 10: Standard deviations of FG departures for all used MHS data combined, normalised to one for the CTL experiment. Red shows statistics for the CTL, black for the ATMS experiment, over the Northern Hemisphere extra-tropics (left), Tropics (middle) and the Southern Hemisphere extra-tropics (right). Statistics are for the December-February period.

over the Southern Hemisphere for which they are typically between 1-2 %. The smaller FG departures suggest smaller errors in the FG and hence a positive impact on short-term humidity forecasts.

For other observations, changes in the departure statistics are generally small (typically less than 0.5 % for the standard deviations of FG-departures), with a slight tendency for reduced standard deviations.

The forecast impact from the assimilation of ATMS data is overall neutral to positive (e.g., Fig. 11). Averaged over the two seasons, the impact on the 500 hPa geopotential is significantly positive for the

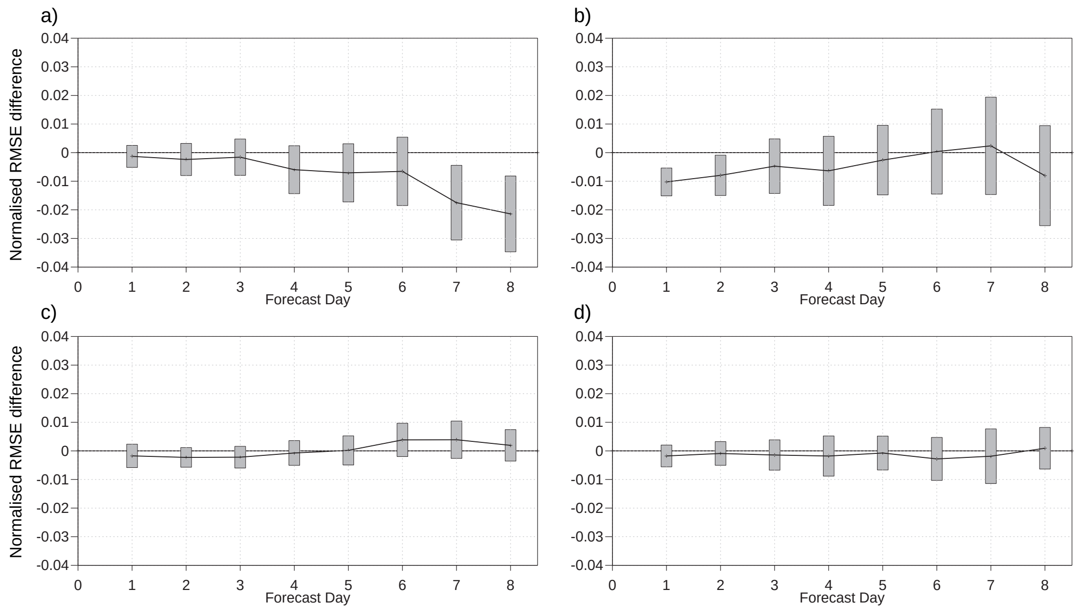

Figure 11: a) Normalised difference in the root mean squared forecast error for the 500 hPa geopotential over the Northern Hemisphere extra-tropics as a function of forecast range (days) for the ATMS and the control experiment. Negative values show a reduction of forecast errors resulting from the assimilation of ATMS data. The vertical bars indicate 95 % confidence intervals. Each experiment has been verified against its own analysis, and the scores for the two seasons have been combined, leading to a total of 102 cases. b) As a), but for the Southern Hemisphere. c) As a), but for the 850 hPa wind forecast over the tropics. d) As c), but for the 200 hPa wind forecast.

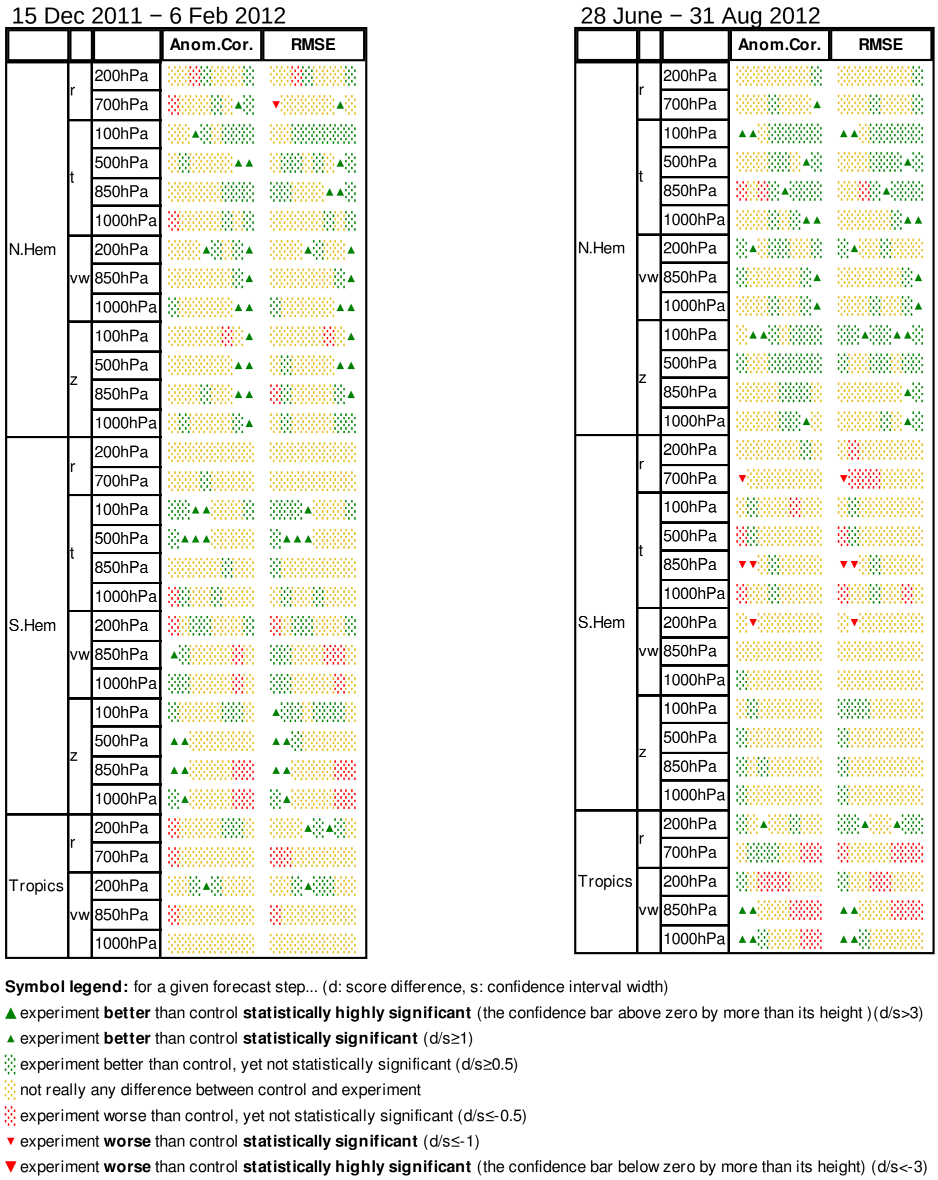

Figure 12: Scorecards for the December-February period (left, 45 cases) and the July/August period (right, 57 cases). Verification is against each experiment's own analysis. See symbol legend for further explanations.

Southern Hemisphere in the short range and for the Northern Hemisphere in the day 7-8 range, reaching 1-2 % over a range of tropospheric levels. The forecast impact for a range of parameters over the Southern Hemisphere is more positive for the December-February period, whereas the impact in the longer range for the Northern Hemisphere is present in both seasons (Fig. 12). There is a slight degradation for the 850 hPa temperature forecasts for day 1 and 2 over the Southern Hemisphere in the July/August experiment, not present for the other period. For humidity, the forecast verification is more difficult, as the results are highly sensitive to the choice of the verifying analysis. The observation-based evaluation of short-term forecasts presented above is considered more reliable in this regard. Nevertheless, the July/August period shows some reduction in the forecast error for upper tropospheric humidity in the tropics when verified against the own analysis.

Overall, the forecast impact of ATMS is very encouraging, given that the NPP orbit is currently fairly well observed in terms of microwave sounding observations, with NOAA-18, NOAA-19, and Aqua all providing AMSU-A temperature sounding capabilities, and NOAA-18 and NOAA-19 also featuring MHS instruments. It appears that the additional observations and their resulting influence of reducing analysis uncertainty are still providing benefit in the assimilation system.

6 Conclusions

This memorandum reports on the first experiences at ECMWF with ATMS data, both in terms of the contribution to the calibration/validation exercise, and extended assimilation trials. The main findings are:

- The instrument appears to be performing well, with noise values well within specifications and, after averaging, comparable to or better than current AMSU-A and MHS instruments.
- Scan-biases are much smoother than commonly found for AMSU-A, even before antenna pattern correction, allowing the outer scan positions to be included in the assimilation. Together with the wider swath this leads to a significantly improved coverage of usable observations with ATMS compared to AMSU-A.
- Small scanline-dependent biases have been identified, visible as striping effects in maps of FG-departures for higher channels. Also, there are some indications of larger inter-channel and spatial error correlations for ATMS than for AMSU-A, and this aspect is likely to be linked to the striping artifacts.
- The analysis and forecast impact is neutral to positive, with significantly positive impact at the short-range over the Southern Hemisphere, and at the longer range over the Northern Hemisphere. The striping effect does not preclude successful assimilation of the data.

The forecast impact results from these initial experiments are encouraging, especially given the number of observations already assimilated from similar orbits. The results highlight again that additional microwave sounding data still gives further benefits in terms of forecast skill, even when data from three or more orbits are already present, consistent with earlier results reported in Bormann (2010) and Di Tomaso and Bormann (2011). The positive forecast impact led to an operational assimilation of ATMS data at ECMWF from 26 September 2012 onwards.

The use of ATMS data at ECMWF is likely to be extended and refined as we gain further experience with the data. Surface-sensitive channels are currently assimilated over sea only, and this should be extended to an assimilation over land following approaches described in Krzeminski et al. (2008) and Di Tomaso and Bormann (2012). Quality-control procedures may need to be refined, for instance, bearing in mind the scale-mismatch between the quality control channels 1 and 2 and the other assimilated sounding channels. Also, ATMS data are still subject to refinements, with potential for improvements regarding the striping effect described here, and some alterations to the bias pattern once antenna pattern corrections are developed.

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