Post-launch characterisation of satellite instruments

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ABSTRACT
Post-launch characterisation is a critical first step in the assessment of new satellite data prior to operational assimilation. A number of approaches, including simultaneous nadir overpass, aircraft and ground-based validation, are briefly reviewed. The main focus of the paper, however, is to explain the use of NWP models in the validation of new satellite sounding data. This is illustrated through recent work on SSMIS, FY3-A, MSU/AMSU-A and ATMS. The use of NWP systems, which offer excellent spatio-temporal coverage and accuracy, has elucidated a range of subtle instrument biases, manifested at the sub-Kelvin level.

1 Introduction

Many of the key components of the satellite observing system for NWP can be considered mature. Nevertheless, new additions to the constellation are often based on novel technologies, offering some combination of: improved performance; lower costs; and reduced power, size and mass budgets. New agencies are significantly enhancing the observing network, based on different engineering legacies. These new additions can exhibit performance characteristics that differ significantly from heritage instruments –new instruments often pose new challenges.

At the same time, the steady improvement in NWP forecast accuracy means that new instruments must effectively correct ever decreasing errors in background fields to drive further improvements in NWP skill. To take the example of satellite sounding data, it is estimated that background errors in observation space, expressed as brightness temperatures, for channels peaking in the mid troposphere are 100mK or less. Consequently, the performance requirements for new instruments are becoming ever more stringent. These requirements cover not only the amplitude of the random noise characteristics of the observations, but also the complex biases that inevitably exist in measurements. These biases can originate from a range of sources, including: inherent design flaws; calibration systems; inaccurate spectral characterisation and stability; or inadequate pre-launch characterisation. The performance requirements for many climate applications are, perhaps, even more demanding.

Characterising the on-orbit performance of a new instrument is a crucial first step towards exploiting the data in NWP data assimilation systems, and has been the main focus of calibration/validation campaigns. In this paper we briefly review the approaches used to date. The main focus of the paper will be to illustrate how NWP models have been used effectively to characterise the performance of several satellite instruments.

The conclusions from the process of characterising instrument on-orbit can have several consequences:

- They inform the decision on whether a new observation is assimilated in operational NWP systems. Most often instruments perform at the expected level, or remaining biases can be addressed through bias correction or changes in the ground processing, however in some instances the decision has been made not to use the data at some NWP centres.

- The findings inform the design of bias correction schemes. Many radiative transfer model biases can be corrected using well established correction schemes however it is sometimes the case that observed biases are not well modelled by existing schemes.
- The findings can highlight deficiencies in radiative transfer modelling, and lead to improved observation operators.
- In the longer term the results have led to improved specification, design and pre-launch characterisation of satellite instruments.

In this paper we illustrate these points with reference to satellite instruments recently evaluated using NWP model fields.

In Section 2 we briefly review alternative approaches to characterising satellite instruments. In Section 3 we illustrate, through several recent examples, how NWP has been used effectively for instrument characterisation. Finally in section 4 we summarise and conclude.

2 Methods for characterising satellite data on-orbit

2.1 Simultaneous nadir overpasses

The technique of simultaneous nadir overpasses (SNO) exploits the occasional spatio-temporal coincidence of sun synchronous polar orbiting satellites to quantify and correct inter-satellite biases. These coincidences generally occur in the polar regions, but for satellites in non sun-synchronous orbits these coincidences take place at lower latitudes (the extended SNO technique – or SNO-x).

As an example, Zou and Wang (2011) have used the technique to study inter-satellite biases in MSU and AMSU-A instruments. Using spatio-temporal colocation criteria of 65km and 50seconds they found SNOs typically occur every 7–10 days. The SNO technique comprises two aspects: in the first the inter-satellite bias is estimated from SNO pairs; in the second part these biases are modelled by a number of parameters, some corresponding to identified physical mechanisms, and the datasets corrected according to this model. Zou and Wang invoke a number of parameters to model the bias – including a global radiance offset, radiometer non-linearity and spectral shifts in the pass bands of channels. Estimated inter-satellite biases are significantly reduced using the technique.

Potential weaknesses of the technique are related to the limited geographical location of the SNO colocations, and the associated limited dynamic range of atmospheric and surface states sampled by SNO. In practice, however, this is not a serious issue for temperature sounding channels as the seasonal variation of atmospheric temperatures samples most of the global range of temperatures for sounding channels. For humidity sounding channels this is a more significant issue. The technique also makes an implicit assumption that the weighting functions for nominally identical channels are matched.

The technique has been effective in achieving improved inter-instrument homogeneity and has been used to identify long term drifts in some satellite instruments (e.g. NOAA-16 AMSU-A).

2.2 Aircraft underflights

Aircraft provide mobile observation platforms to obtain measurements co-located with satellite observations. For the characterisation of satellite radiance measurements aircraft provide two means of validation:

- Direct comparisons of radiometric measurements made by airborne radiometers and satellite instruments. For window channels that are only weakly affected by atmospheric conditions this offers a direct quantification of the differences between airborne and satellite observations. For example, during the JAivex campaign (Larar et al., 2010), it was shown that differences between IASI and an aircraft radiometer were around 0.1K in the 11 micron window region.
- Provision of co-located 'ground truth' observations in the form of dropsonde temperature and humidity profiles coupled with radiometric measurements of surface skin temperature. Above the aircraft flight altitude atmospheric state can be obtained from NWP models. A radiative transfer model is then used to map the measured atmospheric state to observation space and compared with the coincident satellite measurement.

In the former approach, this method can be developed further by using traceably calibrated aircraft radiometers to establish the absolute radiometric uncertainties in the aircraft radiometer and hence infer the absolute uncertainties in the satellite instrument. Tobin et al. (2013) have developed this concept and employed traceably calibrated airborne radiometers in the validation of observations from the Suomi-NPP CrIS radiometer. Absolute radiometric uncertainties are estimated to be 0.3K for the long wavelength channels of CrIS. This method is unique in enabling a determination of the absolute uncertainties in the satellite radiance measurements, at least at the location of the colocation.

A drawback of aircraft validation campaigns is that the geographical coverage of the colocations tends to be limited, and hence the scope to characterise complex state dependent biases, or orbital biases, is limited.

2.3 Ground based observations

Ground-based observations have formed part of satellite Cal/Val campaigns in recent years (Calbet et al., 2011). This aspect of Cal/Val is normally focussed on the validation of level 2 products. Few of these campaigns have directly addressed the issues of bias and uncertainties in the level 1 radiance data from satellite instruments. The ground-based reference upper air network (GRUAN, Immler et al., 2010) aims to make high quality measurements of atmospheric state at a number of sites globally. Establishing metrological traceability is a key aim of the network and this should ensure absolute uncertainties can be determined for the observations made at GRUAN sites and, in turn, satellite observations validated through comparisons with the GRUAN measurements. The EU funded GAIA-CLIM project (2015–18) aims to show how satellite observations can be traceably linked, thorough NWP models and reanalysis systems, to these ground-based reference measurements.

2.4 Other techniques

Several other techniques are used in the validation of satellite sounding measurements. Satellite manoeuvres on-orbit, in which the spacecraft is rotated so that radiometers can directly view cold space, are used to assess biases due to instrument self emission. For microwave imagers, views of radiometrically homogeneous and stable scenes, such as the radiometrically cold ocean surface, or rainforest scenes have been used to assess the long term stability of microwave instruments (Ruf, 2000).

3 Characterisation using NWP

3.1 General aspects

The value of using NWP models in characterising satellite observations stems from the high accuracy of current global NWP models. This high accuracy results from a number of factors, including: the diverse range of high quality observations used in the analysis; the efficiency of current data assimilation schemes is extracting information from the observations in a consistent way; and finally the high quality of current forecast models in propagating observation information between analysis cycles. For tropospheric temperature sounding channels background errors (in observation space) are estimated to be in the range 50-100mK. For humidity sounding channels the value is in the 1–2 K range.

As a consequence computed first guess brightness temperatures are a good proxy for 'truth' in characterising new instruments. At first sight this seems counter intuitive: *is the model being corrected by observations, or vice versa?* The validity of the approach is based on the relatively small amplitude and quasi-random nature of the day-to-day short range forecast errors. By contrast, instrument errors and gross radiative transfer modelling errors (the main targets of our study) can be as large as 1K and are relatively stable from cycle-to-cycle. The examples below illustrate how NWP models have been used successfully in the on-orbit characterisation of satellite instruments.

3.2 The Special Sensor Microwave Imager/Sounder

The Special Sensor Microwave Imager/Sounder (SSMI/S, or SSMIS, Kunkee et al., 2008) followed the Special Sensor Microwave Imager (SSMI) series of instruments which formed part of the US Defence Meteorological Satellite Program (DMSP) payload, successfully flown since 1987 (Colton and Poe, 1999).The first SSMIS instrument, on-board the DMSP F-16 satellite, was launched in October 2003.In addition to the SSMI-like imager channels, SSMIS included a series of sounding channels at 50-60 GHz and at 183 GHz which provided temperature information from the surface to the mesosphere as well as humidity information in the troposphere.

SSMIS is a conical scanning instrument, equipped with a large aperture (60cm diameter) off-axis paraboloidal main reflector. Unlike cross track scanning instruments, which generally employ smaller reflectors (30cm diameter or less) which can be carefully shrouded from the space environment on-orbit, the main reflector of conical scanner and associated fore-optics and calibration load, are relatively exposed. This aspect of conical scanner design contributed to two significant instrument biases suffered by SSMIS.

During the early phases of the Cal/Val campaign, SSMIS measured brightness temperatures were compared with simulations from NWP fields (both ECMWF and Met Office, see Bell (2008)). An analysis of first guess departure time-series revealed that two significant biases were evident in the SSMIS temperature sounding channels (see Figure 1): gain anomalies caused by solar radiation impinging on the surface of the warm calibration load causing depressions of ~1 K in the measured brightness temperatures, and; orbital biases caused by thermal emission from the main (emissive) reflector, which experienced temperature variations of 80K during an orbit, resulting in brightness temperature errors of ~1 K. In comparison to the magnitude of the geophysical errors being corrected (50–100 mK in observation space) these errors were unacceptably large. The inclusion of the temperature sounding channels on SSMIS, for which NWP models/RT modelling provide excellent validation data, enabled the rapid detection of these effects. The simulation of the instrument attitude on-orbit also proved to be a very valuable tool in understanding these effects. In a conventional microwave imager instrument these effects are much more difficult to detect. Nevertheless, it has been shown subsequently that imager missions have suffered similar biases due to emissive reflectors, for example Geer et al. (2010), showed that TMI suffered similar biases due to reflector emission.

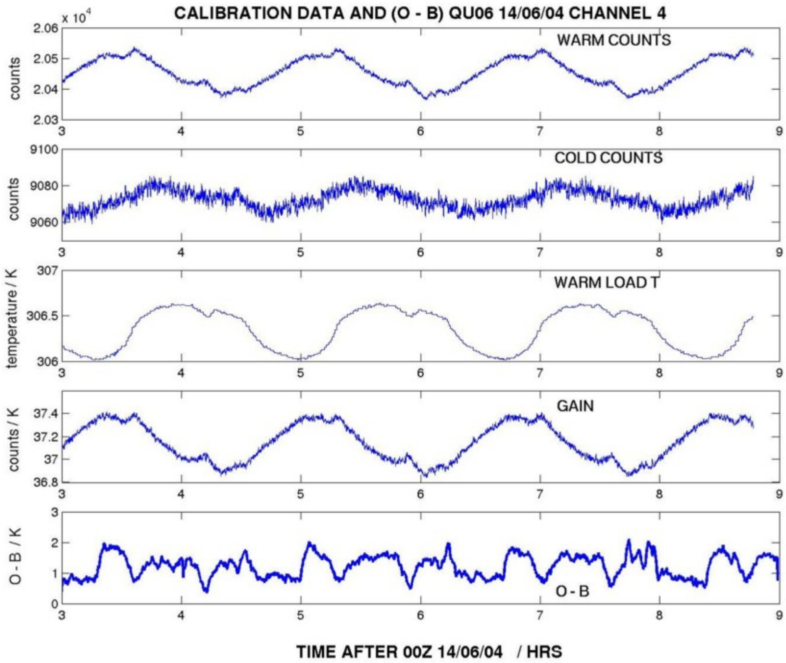

Figure 1: Calibration data (warm load counts, cold load counts and warm load temperature – top three rows) together with computed instrument gain (second row from bottom) and time series of first guess departures (OB, bottom row) for three orbits of F16 SSMIS data (Channel 4 at 54.4 GHz) from 14th June 2006, showing how transient heating of the warm calibration target results in gain anomalies which are correlated with negative anomalies in the first guess departures. The departures also show a periodic saw-tooth behaviour resulting from the emissive reflector.

As a short-term solution, to enable the use of the SSMIS data, algorithms were developed to correct the data. For the gain anomalies, a Fourier filtering technique was developed. This approach was based on the relatively transient nature of the anomalies, compared to the slow cyclical variation of the true gain throughout an orbit. For the reflector emission problem, a physical model was developed to simulate the variation of temperature of the reflector surface during an orbit.NWP simulations were used to tune the model and to derive effective emissivities for each of the channels. The estimated emissivity varied from 0.01–0.02 for the 50–60 GHz temperature sounding channels, to 0.04 for the humidity sounding channels at 183 GHz. For the lower frequency imager channels at 19–37 GHz the derived emissivity was close to 0. These corrections significantly reduced the orbital biases, to several tenths of a Kelvin.

Independent laboratory measurements (Shannon Brown, pers. comm.) subsequently confirmed that the process used to roughen the graphite epoxy reflector shell of SSMIS, prior to vapour depositing a conductive aluminium reflective layer, resulted in significant reductions in the effective conductivity of the aluminium reflector surface. For some of the spare reflectors examined, this degradation amounted to a two orders of magnitude reduction in the conductivity of the reflector surface, relative to the bulk conductivity of aluminium, resulting in an increase in the expected emissivity from 0.0015, to 0.015, in approximate accordance with the effective emissivities derived using NWP models for the 50 GHz channels.

In the longer term, the lessons learned from F-16 SSMIS were used to modify the design and pre-launch characterisation of subsequent SSMIS instruments. A fence was introduced to eliminate the direct solar intrusions causing the gain anomalies, and reflector emissivities were determined pre-launch to quality control the reflectors and ensure high reflectivities. The position of the temperature sensor was changed to ensure more representative measurements of the reflector surface temperature were obtained. The latest satellite in the series, F-19, was launched in April 2014 and early indications are that the instrument exhibits much lower biases than the other SSMIS instruments.

For the earlier instruments, complex orbital biases remain a challenge that continues to hamper the use of the data in NWP systems. Some success has been achieved through the use of an ascending/descending bias model. At the Met Office this has been extended to use a Fourier series expansion in the orbital angle (φ) within a variational bias correction framework (Booton, 2013).

3.3 FY3-A Microwave Temperature Sounder

The first of China's latest series of polar orbiting meteorological satellites, FY3-A, was launched in May 2008 (Dong et al., 2009).The satellite carried several instruments of potential interest to NWP users, including the Microwave Temperature Sounder (MWTS). MWTS is a cross track scanning four channel microwave sounder, with channels centred at 50.3, 53.596, 54.94 and 57.29 GHz. These are equivalent to AMSU-A channels 3, 5, 7 and 9.

An initial inspection of brightness temperatures showed the MWTS observations were biased relative to observations from AMSU-A (See Figure 2). These biases appeared to be state dependent: for MWTS channel 4 which peaks in the lower stratosphere for example, the measured brightness temperatures in the tropics were biased warm (by ~2 K) relative to AMSU-A, whereas the biases at high latitudes were much smaller. Related to this observation, contemporaneous work by Peubey and Bell (2014) had shown that shifts in channel centre frequencies would be manifested as airmass dependent biases as well as cross scan biases. The bias patterns observed in MWTS matched those expected to result from a shift in the pass band centre frequencies. Consequently an analysis of the channel shifts in MWTS was carried out. This involved line-by-line radiative transfer calculations for each of the four MWTS channels, assuming the nominal centre frequencies as well as centre frequencies shifted by 50 MHz either side of the nominal frequency, in steps of 1 MHz. For each assumed centre frequency, statistics (mean and standard deviation) of first guess departures, relative to ECMWF background fields, were computed for an ensemble of observations valid during a single 12-hour analysis cycle. This analysis showed that the variance of the first guess departures could be substantially reduced by assuming significant frequency shifts for the MWTS channel centre frequencies (see Figure 3). The shifts were in the range 30–55 MHz depending on channel.

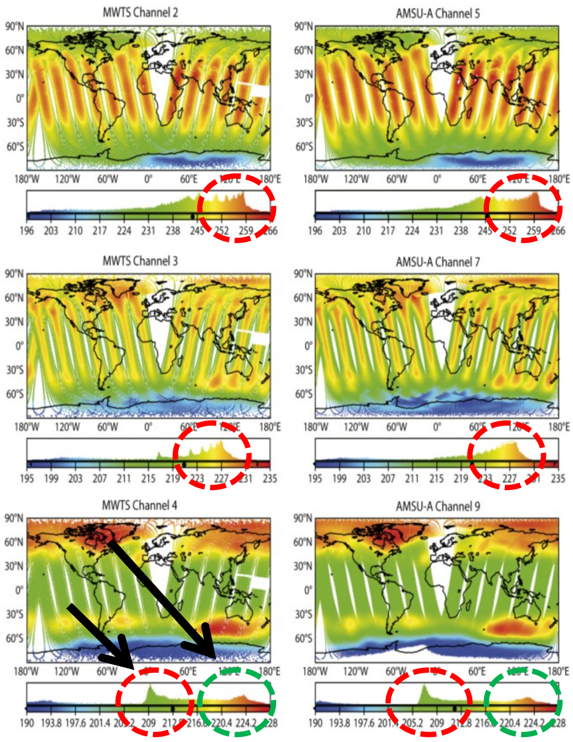

Figure 2:Brightness temperatures measured by the FY3-A MWTS, channels 2–4, compared with similar coincident measurements from equivalent channels of AMSU-A(5,7 and 9 respectively).Reproduced from Lu et al.(2011a).

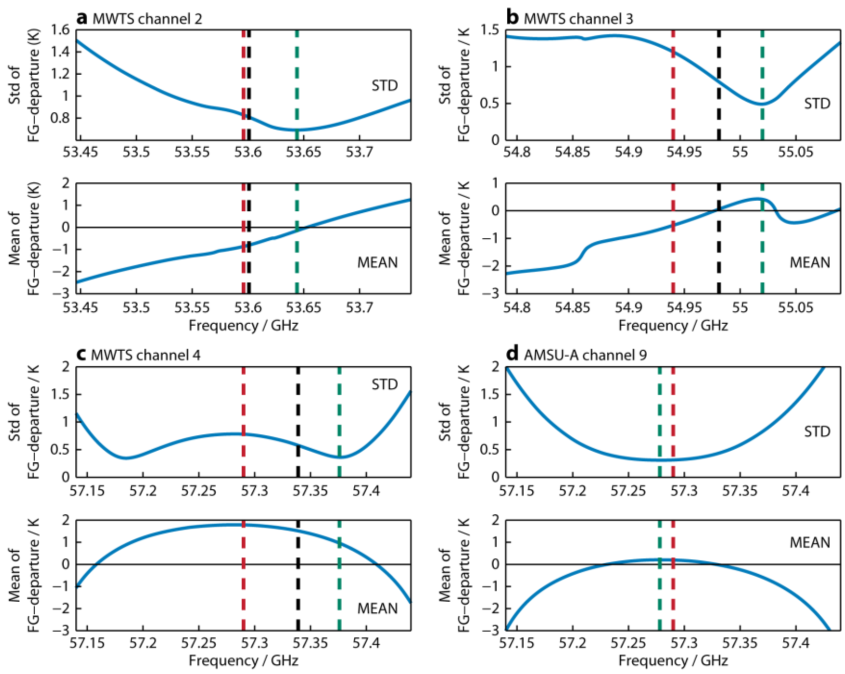

Figure 3:Standard deviations (top row in each subplot) and mean (bottom row of each subplot) of first guess departures versus assumed channel centre frequency for FY3-A channels 2, 3 and 4 together with MetOp-A AMSU-A channel 9. Red dotted line shows pre-launch specified channel centre frequency, black dotted line shows pre-launch measured channel centre frequency; and green dotted line shows optimised estimate of channel centre frequency. Reproduced from Lu et al.(2011a).

Radiometer non-linearities were also found to play a role in the biases evident for MWTS. Such biases are manifested as a bias which increases with decreasing brightness temperatures, at least for brightness temperatures above 150 K, as is the case for all of the MWTS channels. Although a much smaller effect it could be seen in the departures and corrected using a quadratic correction model.

Having corrected for these two effects the MWTS data quality was significantly improved (Lu et al., 2011a) and provided improvements to analysis and forecast accuracy in pre-operational tests in the full ECMWF forecasting system (Lu et al., 2011b).

3.4 MSU/AMSU A

Data from the Microwave Sounding Unit (MSU), which was first carried on the TIROS-N satellite launched in 1978, has been used widely in NWP systems and in atmospheric reanalysis. It was carried on the series of NOAA polar meteorological satellites until NOAA-14, launched in 1994. It was succeeded by the Advanced Microwave Sounding Unit which was carried on NOAA-15 through -19 as well as NASA's Aqua satellite (launched 2003) and the first of EUMETSATs series of polar satellites (Metop).

It is well established that many of the tropospheric sounding channels of MSU and AMSU exhibit biases relative to NWP models. It has also long been recognised that these biases could originate from inaccuracies in the underlying spectroscopic parameters, or in the assumed characteristics of the instruments themselves. For example, errors in the experimental determination of line strength, line mixing, or line broadening parameters could result in biases in the forward calculated brightness temperatures. Typically these biases have been modelled by empirical models that account for the observed airmass dependence of the biases. Bias models in which the computed optical depth for each atmospheric layer (so called 'gamma' corrections, Smith, 1983) is scaled have also been employed. These correction schemes have been very successful in significantly reducing the biases evident for a range of radiance measurements and are incorporated in static bias correction schemes (for example as employed at the Met Office) as well as within variational bias correction systems.

The methods developed to diagnose effective pass band shifts for the FY3-A MWTS, described above, using NWP model fields and RT modelling, were applied to the AMSU-A instruments used in the ECMWF data assimilation system. It was found that many of the tropospheric temperature sounding channels of AMSU-A appeared to have large shifts, of 10's MHz, relative to the nominal frequency. The analysis was repeated using NWP fields from several NWP centres (ECMWF, Met Office, NCEP and CMA). The large shifts were relatively insensitive to the choice of NWP model. The calculations were also repeated using a new set of improved spectroscopic parameters (Tretyakov, 2005). The large shifts diagnosed for the lower peaking AMSU-A channels (6–8) were often associated with large reductions in the variance of the first guess departures. Conversely, small or near-zero shifts diagnosed for channels 9 and above were associated with relatively small changes in the variance of the departures. A likely explanation for this is that channels 9 and above are served by a single phase locked local oscillator. The active frequency locking of these channels appears to be successful in stabilising these channels. For the lower peaking channels the lack of this active locking appears to result in shifts and drifts in some of the channels.

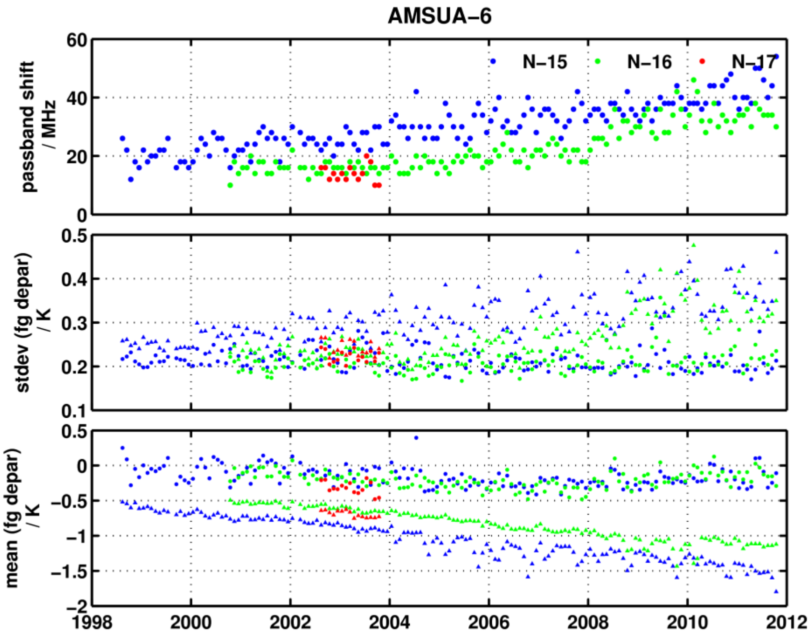

Figure 4:Estimated shifts in channel centre frequencies for AMSU-A channel 6 (54.4 GHz) for NOAA-15, -16 and -17 during the period 1998–2012 (top panel), together with standard deviations (middle panel) and means (bottom panel) of first guess departures. Circles/triangles show departure statistics using new/old estimates of channel centre frequencies. Reproduced from Lu and Bell (2014).

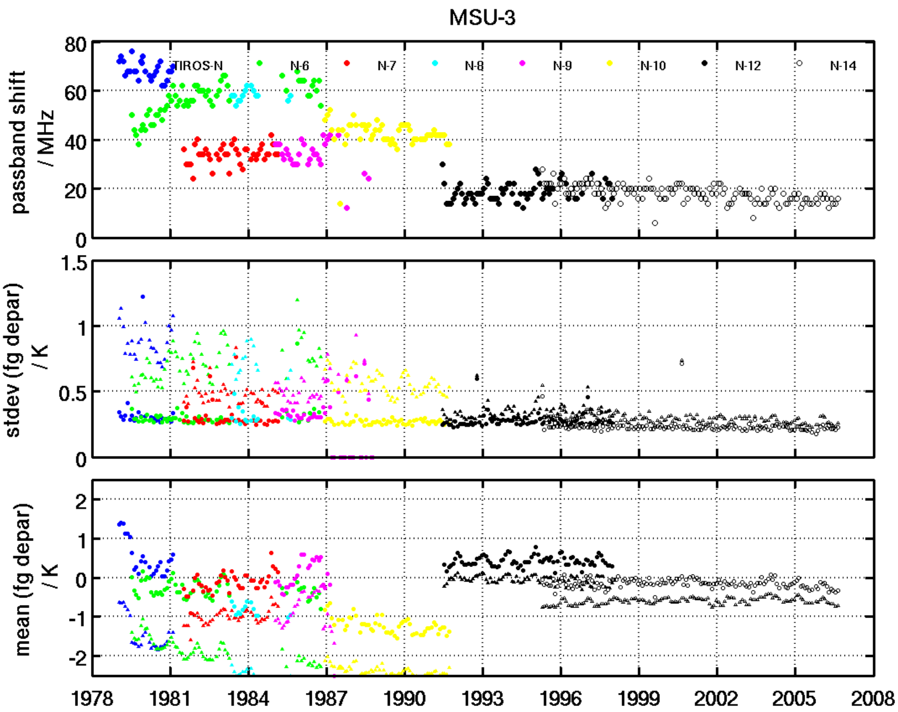

Figure 5:Estimated shifts in channel centre frequencies for MSU channel 3 (53.6 GHz) for NOAA satellites during the period 1978–2007 (top panel), together with standard deviations (middle panel) and means (bottom panel) of first guess departures. Circles/triangles show departure statistics using new/old estimates of channel centre frequencies. Reproduced from Lu and Bell (2014).

Using ERA-Interim reanalysis fields this analysis could be extended back to the earliest NOAA satellites, to examine the time dependence of the drifts. For the AMSU-A instruments large time dependent drift are evident for channel 6 on NOAA-15 (see Figure 4) and for channels 6, 7 and 8 on NOAA-16. For the other AMSU-A instruments the shifts for channels 6,7 and 8 seems to be stable over the lifetime of the instrument. Accounting for the analysed frequency drift reduced the variance and seasonal dependence of the departures. In most cases the new centre frequencies also improved the absolute bias relative to the NWP models and the inter-satellite biases.

The analysis was extended to MSU channel 3 (54.96 GHz).Large shifts, of up to 70 MHz, are evident for the earliest satellites (see Figure 5).The analysed frequency drifts for later satellites become progressively smaller. These analysed shifts are effective in reducing the departure variance as well as the seasonal variation in the departure variances. The absolute (observation minus NWP)and inter-satellite biases are also reduced significantly in most cases.

3.5 ATMS

The Advanced Technology Microwave Sounder (ATMS) replaces the AMSU /MHS instrument suite for the Suomi-NPP and subsequent JPSS instruments. The Suomi-NPP satellite was launched in September 2011.

Data from the ATMS instrument is already widely used in NWP data simulation systems (Bormann, 2013), and is generally of good quality. An inspection of first guess departures showed that cross-track striping effects are evident in the data, with amplitudes of ~0.1 K.This was found to be due to low frequency (1/f) noise in a low noise amplifier which resulted in gain fluctuations on a timescale comparable with the scan period (8/3 seconds).This type of noise is difficult to eliminate through calibration averaging. Although detecting this feature of the observations was not reliant on the use of NWP models, the effects became much more evident when the observations are shown as departures (see Figure 6).

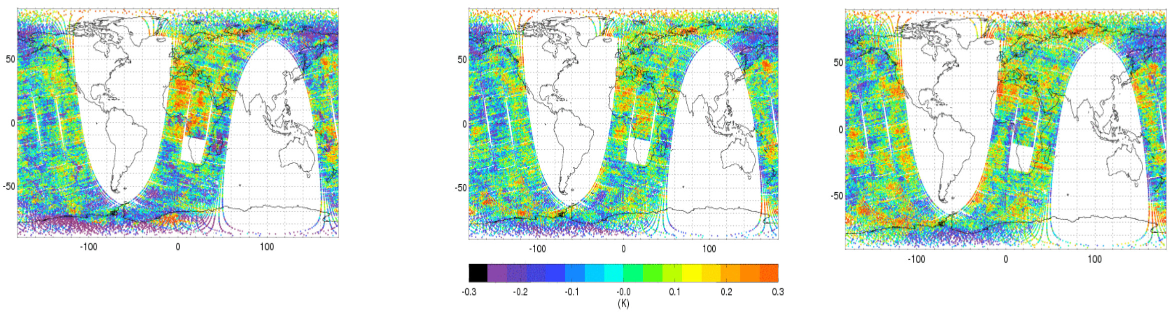

Figure 6: First guess departures, from the Met Office NWP model, for ATMS channels 7, 8 and 9 illustrating a striping effect due to 1/f noise in the ATMS low noise amplifier (reproduced from Doherty et al., 2012).

4. Summary and conclusion

NWP, reanalysis and climate applications of satellite data are generating increasingly demanding performance requirements on observations, not only in terms of random noise performance – but also in terms of the form and amplitude of the biases that inevitably affect all satellite observations at some level.

In addition to careful pre-launch testing there exists an array of approaches to characterise instruments post-launch to ensure pre-launch specifications are met. In recent years the value of NWP models, coupled with radiative transfer modelling, has been demonstrated through a number of Cal/Val campaigns for satellite sounding instruments. This type of validation now plays a central role in the post-launch assessment of satellite sounding observations, elucidating subtle biases at the level of a few tenths of a Kelvin, and complementing alternative approaches to Cal/Val. It is a reasonable working assumption that most new satellite sensors will exhibit complex, and often unique, bias characteristics. NWP-based validation, offering excellent spatio-temporal coverage and accuracy, will continue to provide quantitative assessments that drive the development of improved data processing and calibration schemes. Specific examples from studies on SSMIS, FY-3A and MSU/AMSU-A have been used to illustrate these points.

Perhaps the most important consequence of this type of investigation is that the specification, design and pre-launch calibration and testing of future instruments can be optimised to mitigate the risks of problems post-launch.

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