Connecting the Time Series of Microwave Sounding Observations from
AMSU to ATMS for Long-Term Monitoring of Climate

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ABSTRACT

The measurements from the Microwave Sounding Unit (MSU) and the Advanced Microwave Sounding Unit-A (AMSU-A) on board NOAA polar-orbiting satellites have been extensively utilized for detecting atmospheric temperature trend during the last several decades. After the launch of the Suomi National Polar-orbiting Partnership (Suomi-NPP) satellite on 28 October 2011, MSU and AMSU-A time series will be overlapping with the Advanced Technology Microwave Sounder (ATMS) measurements. While ATMS inherited the central frequency and bandpass from most of AMSU-A sounding channels, its spatial resolution and noise features are, however, distinctly different from those of AMSU. In this study, the Backus–Gilbert method is used to optimally resample the ATMS data to AMSU-A fields of view (FOVs). The differences between the original and resampled ATMS data are demonstrated. By using the simultaneous nadir overpass (SNO) method, ATMS-resampled observations are collocated in space and time with AMSU-A data. The intersensor biases are then derived for each pair of ATMS–AMSU-A channels. It is shown that the brightness temperatures from ATMS now fall well within the AMSU data family after resampling and SNO cross calibration. Thus, the MSU–AMSU time series can be extended into future decades for more climate applications.

1. Introduction

Since the first launch of Television and Infrared Observation Satellite (TIROS-N) in 1978, microwave temperature sounding data have been used for both weather and climate applications. From 1978 to 2004, the National Oceanic and Atmospheric Administration (NOAA) launched eight satellites (NOAA-6–NOAA-12 and NOAA-14) carrying Microwave Sounding Unit (MSU) instruments. MSU had four channels for sounding atmospheric temperatures. Beginning in 1998, the MSU instruments were replaced by the Advanced Microwave Sounding Unit-A (AMSU-A) when NOAA-15–NOAA-19 were launched successively through 2009. AMSU-A contains 15 channels. Channels 3, 5, 7, and 9 have similar frequencies to the four MSU channels. Today, the Advanced Technology Microwave Sounder (ATMS) is flying on board the Suomi National Polar-orbiting Partnership (Suomi-NPP) satellite and will be also on board future U.S. Joint Polar Satellite System (JPSS) satellites, which are scheduled for launch in both 2017 and 2022. ATMS contains 22 channels. Channels 1–3 and 5–16 have the same central frequencies as the 15 AMSU-A channels.

Polar-orbiting satellites circle the earth in sun-synchronous orbits with different equator crossing times (ECTs). NOAA-6, -8, -10, -12, and -15 are the morning satellites with their ECT occurring at either 0530 or 0730 local time (LT). The satellites with ECT after 0930 LT are referring to midmorning satellites, such as NOAA-17, Meteorological Operation-A (MetOp-A) and MetOp-B,
whereas those after 1300 LT are afternoon satellites, such as TIROS-N, NOAA-7, -9, -11, -14, -16, -18, -19, and Suomi NPP. On all of these platforms, MSU, AMSU-A and ATMS provide the measurements of the global atmospheric temperature from the surface to the low stratosphere (MSU) and to the upper stratosphere at about 1 hPa (AMSU-A and ATMS) and can also be used for climate trend studies. Soon after the launch of Suomi NPP, an intensive calibration of the ATMS was carried out. The ATMS sensor data records have now reached a validated maturity level. For the JPSS program, both sensor data record (SDR) and environmental data record (EDR) products are evaluated at three maturity levels. The beta maturity level is made when the initial calibration is applied and the product is minimally validated, and may still contain significant errors (Weng and Zou 2013). At this level, the product is not appropriate for quantitative scientific publication, studies, or applications. The provisional maturity level is reached when the instruments are calibrated and the products are validated but incremental improvements are ongoing. The user community is encouraged to participate in the quality assurance and product validation processes. The validated maturity level is reached when the on-orbit sensor performance is characterized and calibration parameters are adjusted accordingly. The data are ready for use by the operational center and scientific publications. Overall, ATMS in-orbit performance is well characterized and its noise equivalent differential temperature (NEDT) meets the specification (Weng et al. 2013). The other ATMS features, such as channel specifications, bias characteristics, and impact of observation resolution on capturing tropical storm structures, were described in Weng et al. (2012, 2013). The scan biases related to ATMS sidelobes and possible antenna emission were quantified by Weng et al. (2013) using the ATMS pitch-over maneuver data. A postlaunch calibration of ATMS middle- and upper-tropospheric and stratospheric channels (i.e., channels 5–15) was carried out by Zou et al. (2014) using the global positioning system (GPS) radio occultation (RO) data. Preliminary assessments of the impact of ATMS data assimilation on hurricane track and intensity forecasts were reported in Zou et al. (2013).

The lifetime of a given MSU or AMSU-A is limited from a few years to more than 10 years. Fortunately, each of these satellites overlaps other satellites. For example, during the period of 1998–2006, the last MSU on board NOAA-14 operated as a backup, while the AMSU-A on the NOAA-15, -16, and -17 satellites became primary ones. The Suomi NPP ATMS has been operational since 2011, while AMSU-A on NOAA-15, -18, and -19 and MetOp-A and MetOp-B are still operating in a healthy condition. As such, MSU, AMSU-A, and ATMS will provide a continuous time series for more than 35 years, containing a wealth of information on global atmospheric temperature. Although the MSU, AMSU-A, and ATMS instruments are primarily designed for providing atmospheric temperatures on a daily basis for predicting atmospheric weather systems, they are also applicable of monitoring decadal climate changes of the atmospheric temperature because of the same channel frequencies from different sensors, the sensor stability, and high calibration accuracy.

To derive atmospheric temperature trends from the above-mentioned long-term MSU and AMSU-A data series, satellite-to-satellite cross calibration must be carried out (Grody et al. 2004; Christy et al. 2000; Zou et al. 2006). Using a well-calibrated MSU–AMSU-A data series, global warming ranging from 0.08 to 0.22 K per decade is detected in the lower troposphere represented by MSU channel 2 (53.74 GHz) (Christy et al. 1998, 2000, 2003; Mears et al. 2003; Mears and Wentz 2009; Vinnikov and Grody 2003; and Zou et al. 2009). In this study, the ATMS data are first resampled into AMSU-like data and an intersensor calibration is then carried out for merging ATMS data into the AMSU-A data family.

The Backus–Gilbert (B-G) inversion method (Kirsch et al. 1988; Caccin et al. 1992) is employed for the ATMS resampling purpose, which will be referred to as ATMS resample data. The B-G method solves an inverse problem that involves the integral equations. It can be viewed as an optimal linear interpolation filter in which the spatial resolution of the AMSU-A radiometer (i.e., the 3.3° beamwidth) and the antenna gain function of the ATMS radiometer are preserved, the sensor noise can be controlled, and the data-processing artifacts are minimized. Stogryn (1978) used the B-G method for estimating brightness temperatures from antenna temperatures measured by a conical-scanning satellite-borne radiometer system. Since the work by Stogryn (1978), the B-G algorithm was successfully applied to the Special Sensor Microwave Imager (SSM/I) satellite data (Poe 1990) to realize a spatial resolution enhancement of brightness temperature measurements from SSM/I (Poe 1990; Robinson et al. 1992; Farrar and Smith 1992; Sethmann et al. 1994; Long and Daum 1998).

While they all fly in sun-synchronous orbits, Suomi NPP, NOAA-18, MetOp-A, and NOAA-15 satellites have different ECTs. To collocate the data from any two different satellites during their overlapping period, Cao et al. (2004) proposed a simultaneous nadir overpass (SNO) method for intersatellite cross calibration. Yan and Weng (2008) used the SNO method for intersensor calibration between the Special Sensor Microwave Imager/Sounder (SSM/IS) and SSM/I. In this study, the
SNO method is used for the intersensor calibration between AMSU-A and ATMS. Since the SNO matched points from AMSU-A and ATMS only occur near the poles and the sample sizes since October 2011 are limited, the intersatellite calibration between AMSU-A and ATMS is still preliminary and will be further refined as more SNO data pairs are collected in the future.

This work describes in detail a set of intersensor calibration between ATMS and AMSU-A on board NOAA-18, MetOp-A, and NOAA-15. Section 2 provides a brief description of ATMS observations. The B-G method for optimally resampling the ATMS data to AMSU-A-like observations is briefly described in section 3. Differences resulting from the resampling within Hurricane Sandy are illustrated in section 4. Section 5 presents numerical results of intersensor calibration between ATMS on board Suomi NPP and AMSU-A on board NOAA-15, NOAA-18, and MetOp-A using

![Diagram](https://example.com/diagram.png)

**Fig. 1.** ATMS FOVs (circles) used for remapping into an AMSU-like FOV (light gray) for ATMS channels (a) 3–16 and (b) 1 and 2 FOVs. Magnitudes of B-G coefficients are indicated with colors. Integration time and satellite movement were taken into consideration.
the SNO method. Section 6 provides a summary and conclusions.

2. Differences of channel characteristics between ATMS and AMSU-A

ATMS is a total power cross-track radiometer, and it scans the earth within the range of $\pm 52.77^\circ$ with respect to the nadir direction. It has a total of 22 channels. The first 16 channels are primarily for temperature soundings from the surface to about 1 hPa ($\sim 45$ km) and are investigated in this study. The remaining channels, 17–22, are for humidity soundings in the troposphere from the surface to about 200 hPa ($\sim 12$ km) and are not included in this study.

The antenna beamwidth of ATMS is different from that of AMSU-A. All AMSU-A channels have a beamwidth of 3.3°. However, the ATMS channels 3–16 have a smaller beamwidth of 2.2° and that of ATMS channels 1 and 2 is 5.2°. The differences in the beamwidth between ATMS and AMSU channels result in a significant difference in the size of the field of view (FOV) between ATMS and AMSU (Weng et al. 2013). Another major difference between ATMS and AMSU-A arises from the scanning mode. Since AMSU-A scans the earth in a step-and-stare mode, there is no overlapping between neighboring FOVs in both cross-track and along-track directions. However, ATMS FOVs are overlapping because of its continuously scanning mode, which results in significant oversampling in both cross-track and along-track directions. A single FOV of either ATMS channel 1 or 2 overlaps partially with its neighboring four FOVs and four scan lines. A single FOV of any of the ATMS channels 3–16 overlaps with its three neighboring FOVs and three nearby scan lines.


To link ATMS observations with AMSU-A observations from all prior NOAA polar-orbiting satellites,
ATMS brightness temperatures are first resampled to the AMSU-A-like observations. Differences in FOVs between ATMS and AMSU-A are illustrated in Fig. 1. Specifically, Fig. 1a shows an AMSU-A FOV and its nearby $5 \times 5$ FOVs for ATMS channels 3–16, whereas Fig. 1b plots an AMSU-A FOV and its nearby $3 \times 3$ FOVs for ATMS channels 1 and 2. The integration time for each ATMS FOV and Suomi NPP satellite movement is taken into consideration in all the FOVs shown in Fig. 1. Thus, ATMS data from neighboring points at channels 3–16 can be convolved, whereas those at channels 1 and 2 must be deconvolved to AMSU-like FOVs. Note that in the current Suomi NPP ground processing system, the ATMS resample...
The following is a brief description of the B-G algorithm based on the work by Stogryn (1978). Specifically, the B-G algorithm is a process of finding a set of optimal weighting coefficients \( w \) so that the \( k \)th AMSU-like ATMS data, \( T^\text{AMS}_b(k) \), can be expressed as a linear combination of adjacent ATMS brightness temperatures:

\[
T^\text{BG}_b(k) = \sum_{i,j=-N_{ch}}^{N_{ch}} w(k+i,j) T^\text{ATMS}_b(k+i,j),
\]

where \( N_{ch} \) is a resample window size parameter and \( k = 1, \ldots, 96 \).

Assuming that the portion of the earth viewed by the AMSU-A antenna at the \( k \)th scan angle from the satellite altitude is \( A_k \), the brightness temperatures over the region of \( A_k \) observed by ATMS can also be expressed as

\[
T^\text{ATMS}_b(k+i,j) = \int_{A_k+i,j} G_k T^\text{BG}_b(k) dA,
\]

where \( G \) is the AMSU-A antenna gain function and \( dA \) is the elementary surface area on the earth. The contributions from the cosmic background radiation and possible contributions from the spacecraft itself are very small and neglected in Eq. (2).

By multiplying \( w(k+i,j) \) on both sides of Eq. (2) and taking the summation over \((k+i,j)\), we can obtain

\[
\sum_{i,j=-N_{ch}}^{N_{ch}} w(k+i,j) T^\text{ATMS}_b(k+i,j) = \int_{A_k} \left[ \sum_{i,j=-N_{ch}}^{N_{ch}} w(k+i,j) G_k \right] T^\text{BG}_b(k) dA.
\]

If the bracketed term in Eq. (3) were a delta function \( \rho(k_{ij} - k) \), that is,

\[
\sum_{i,j=-N_{ch}}^{N_{ch}} w(k+i,j) G_k = \rho(k_{ij} - k),
\]

then Eq. (3) would turn into Eq. (1). Thus, if the weighting coefficients could be derived so that the left-hand side of Eq. (4) approaches a delta function, Eq. (1) could serve an approximation of the exact solution when Eq. (4) is held true.

The B-G resampling algorithm searches for the optimal weighting coefficients by minimizing the following least squares problem:

\[
Q_0[w(k+i,j)] = \int_{A_k} \left[ \sum_{i,j=-N_{ch}}^{N_{ch}} w(k+i,j) G_k - F(k+i,j) \right]^2 dA,
\]

under the following constraint:

\[
\int_{A_k} \sum_{i,j=-N_{ch}}^{N_{ch}} w(k+i,j) G_k dA = 1,
\]

where the function \( F \) is chosen to be a constant \( 1/A_0 \) over some specified region \( A_0 \) (see Fig. 2) and 0 outside this region. The constraint [Eq. (6)] simply ensures a proper normalization of the results. Thus, if a scene with a uniform brightness temperature were viewed, then the brightness temperature derived from Eqs. (1) and (3) would be exactly the brightness temperature of the scene observed by an AMSU-A antenna.
While obtaining an estimate at the desired AMSU-A resolution, one would also like to minimize the noise variance for the estimate, $T_{BG}$. Assuming $O_{\text{ATMS}}$ is the error covariance matrix of the ATMS measurements, the noise variance for the estimate can be expressed as

$$\sigma_{BG}^2 = w^T O_{\text{ATMS}} w.$$  

Instead of minimizing $Q_0$ defined in Eq. (5), the following quantity is minimized:

$$Q(w) = Q_0(w) \cos \gamma + \sigma_{BG}^2 \beta \sin \gamma,$$

where $\gamma$ is a parameter whose value varied from 0 to $\pi/2$ and $\beta$ is simply a convenient scale factor that is chosen to

![Scatterplots of brightness temperature difference between resampled ATMS and AMSU-A data as a function of the resampled ATMS brightness temperature for ATMS channels 6–11. Outliers that are removed from cross calibration are indicated in red. ATMS channel numbers are indicated in each panel.](image-url)

Fig. 5.
make $Q_0$ and $\sigma_{BG}^2$ dimensionally the same but is otherwise arbitrary. When $\gamma$ is increased from 0 to $\pi/2$, less emphasis is placed on resolution and more emphasis is placed on noise reduction in the estimate of $T_b^{BG}$, which is the AMSU-like ATMS resample data.

The solution of the minimization problem [Eq. (8)] under the constraint [Eq. (6)] was provided in Stogryn (1978) and would give the best estimate in the minimum variance sense. The estimate represents the average brightness temperature within a specified region (i.e., the AMSU-A FOV) based on the available measurements of ATMS antenna temperatures.

The $\beta$ value is taken to be $\beta = 0.001$, which makes the two terms in Eq. (8) of similar magnitudes. Three different window sizes (e.g., 3, 5, and 7) are assigned to the window size parameter $N_w$. The value of $\gamma$ is determined by requiring that the constraint [Eq. (6)] is best satisfied, which results in $\gamma = 0.1$ for downscaling of ATMS channels 3–16, and $\gamma = 0.1 \times 10^{-3}$ for resolution enhancement of ATMS channels 1 and 2, when producing the ATMS resample ATMS data. It is also found that the best window size is three for ATMS channels 1 and 2 and five for ATMS channels 3–16.

There are 94 AMSU-A-like FOVs whose geographic locations are the same as ATMS FOVs 2–95. For each of the 94 AMSU-A-like FOVs into which the ATMS channels 1 and 2 data are mapped, there are nine B-G coefficients, $w(k + i, j)$, where $i$ represents the three nearby FOVs and $j$ represents the three nearby scan lines. The B-G coefficients for the two FOVs having the same scan angle with respect to the nadir are the same, namely, the B-G coefficients for the second ATMS FOV are the same as those for the 95th ATMS FOV, the third ATMS FOV are the same as those for the 94th ATMS FOV, etc.

The B-G coefficients for the conversion of the ATMS antenna temperatures to an AMSU-A-like FOV at nadir for channels 3–16 and channels 1 and 2 are also shown in Fig. 1. It is seen that the largest weighting coefficient is

| Table 1. Mean differences of brightness temperatures (K) from SNO data of Suomi ATMS (resample) and AMSU-A during the time period from 1 Jan 2012 to 31 Mar 2013. |
|-----------------------------|-----------------------------|-----------------------------|
| Channel | ATMS resample minus AMSU-A | Mean | Intercept | Slope |
| 1 | −0.25 | −0.22 | −0.0002 |
| 2 | 0.08 | −0.20 | 0.0015 |
| 3 | −0.35 | −0.01 | −0.0016 |
| 5 | 0.15 | −0.74 | 0.0039 |
| 6 | −0.29 | −4.66 | 0.0189 |
| 7 | 0.99 | 2.73 | −0.0077 |
| 8 | 0.70 | 5.12 | −0.0199 |
| 9 | −0.30 | 1.31 | −0.0074 |
| 10 | 0.58 | 2.29 | −0.0079 |
| 11 | 0.59 | 3.66 | −0.0141 |
| 12 | 0.60 | 3.06 | −0.0112 |
| 13 | 0.26 | 2.35 | −0.0092 |
| 14 | 0.18 | 1.61 | −0.0061 |
| 15 | 0.08 | 1.82 | −0.0070 |
| 16 | −0.05 | 1.95 | −0.0102 |

| Table 2. Mean, as well as the intercept and slope of linear regression of the differences of brightness temperature (K) between MetOp-A AMSU-A and NOAA-18 AMSU-A derived from SNO data found during the time period from 1 May 2007 to 31 Dec 2012. |
|-----------------------------|-----------------------------|-----------------------------|
| Channel | MetOp-A minus NOAA-18 | Mean | Intercept | Slope |
| 1 | 0.04 | 0.23 | −0.0009 |
| 2 | −0.04 | 0.51 | −0.0027 |
| 3 | 0.25 | 1.00 | −0.0034 |
| 4 | 0.16 | 1.29 | −0.0048 |
| 5 | 0.16 | 0.83 | −0.0029 |
| 6 | −0.03 | 0.36 | −0.0017 |
| 7 | −0.12 | 1.80 | −0.0087 |
| 8 | −0.14 | −0.13 | −0.0001 |
| 9 | −0.26 | 0.06 | −0.0015 |
| 10 | −0.35 | −0.04 | −0.0014 |
| 11 | −0.41 | −0.63 | 0.0010 |
| 12 | −0.35 | 0.08 | −0.0019 |
| 13 | −0.18 | −1.15 | 0.0041 |
| 14 | 0.03 | 0.27 | −0.0010 |
| 15 | 0.01 | 0.07 | −0.0003 |

| Table 3. Mean, intercept, and slope of linear regression of the differences of brightness temperature (K) between NOAA-15 AMSU-A and NOAA-18 AMSU-A derived from SNO data found during the time period from 1 Jan 2006 to 31 Dec 2011. |
|-----------------------------|-----------------------------|-----------------------------|
| Channel | NOAA-15 minus NOAA-18 | Mean | Intercept | Slope |
| 1 | −0.05 | −1.78 | 0.0085 |
| 2 | 0.04 | −1.83 | 0.0093 |
| 3 | 0.05 | −0.14 | 0.0009 |
| 4 | −0.25 | −1.66 | 0.0060 |
| 5 | −0.07 | 0.29 | −0.0015 |
| 6 | 0.04 | 1.21 | −0.0052 |
| 7 | 0.54 | 3.17 | −0.0019 |
| 8 | 0.23 | 0.02 | 0.0010 |
| 9 | 0.51 | 1.92 | −0.0066 |
| 10 | 0.49 | 2.12 | −0.0079 |
| 12 | 0.30 | 2.13 | −0.0081 |
| 13 | 0.38 | 3.12 | −0.0116 |
| 15 | 0.27 | 3.35 | −0.0150 |
given to the ATMS FOV in the center, which coincides with the ATMS resample. The farther away the FOVs are from the ATMS resample, the smaller the B-G weights are. The overlapping characteristics of ATMS ensure that such a weighted average approximates a realistic mapping of ATMS data onto the AMSU-A type of data.

4. Differences introduced by ATMS resampling within Hurricane Sandy

To examine the differences of brightness temperatures introduced by the resampling of ATMS data, we choose a hurricane case that often occupies several thousand kilometers with complicated small-scale features. Specifically, ATMS observations and their resample data are compared within Hurricane Sandy on 28 October 2012. This is the time when Sandy started to move northward from its initial westward movement in the Caribbean Sea on 22 October and a subsequent northward movement over the Bahamas before 28 October. Hurricane Sandy was the largest Atlantic hurricane on record, and made landfall near Atlantic City, New Jersey, on 30 October 2012.

Figure 2 shows the liquid water path (LWP) derived from ATMS channels 1 and 2 (Fig. 2a), the ice water path (IWP) derived from Microwave Humidity Sounder (MHS) channels 1 and 2, as well as brightness temperature observations of Advanced Very High Resolution Radiometer (AVHRR) infrared channel 4 (10.8 μm) within Hurricane Sandy at 0600 UTC 28 October 2012. Both MHS and AVHRR are on board NOAA-18. The sea level pressure (SLP) from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) fields is also plotted using contours at 5-hPa intervals. There were two rainbands north and west of the center of Hurricane Sandy, which was located at...
31.3°N, 73.7°W at 0600 UTC 28 October 2012. The values of both LWP and IWP exceeded 1.5 kg m⁻². Because of higher resolutions of MHS (~15 km) and AVHRR (~4 km) than ATMS channels 1 and 2 (~75 km), Hurricane Sandy's eye is better captured by the MHS-derived IWP and AVHRR infrared channel 4 than the ATMS low-frequency-channel-derived LWP. There were more liquid clouds than ice clouds in terms of spatial coverage. The southeast half of Hurricane Sandy was mostly under clear-sky conditions at this time. This allows the differences of brightness temperatures introduced by the resampling of ATMS data to be examined in both cloudy and clear-sky conditions.

The ATMS brightness temperature observations for channels 1 and 16 before (Figs. 3a,c) and after (Figs. 3b,d) the resampling within Hurricane Sandy at 0600 UTC 28 October 2012 are presented in Fig. 3. For clarity, the differences introduced by the resampling for channels 1 and 16 are overlapped with the resampled brightness temperatures in Figs. 3b,d (e.g., contours at 1-K intervals). Both channels 1 and 16 are located at the window regions of atmospheric oxygen absorption spectra. The ATMS channel 1 has the lowest center frequency at 23.8 GHz among the 16 ATMS temperature sounding channels. Microwave measurements at this window channel are still quite sensitive to clouds and water vapor emission. It is one of the two key channels used for physical retrievals of LWP and water vapor path (WVP) through an emission-based radiative transfer model (Greenwald et al. 1993; Weng and Grody 1994; Weng et al. 1997; Weng and Grody 2000; Wentz 1997; Weng et al. 2003). By comparing ATMS brightness temperature observations (Fig. 3a) with LWP (Fig. 2a), it is found that the measured brightness temperatures at 23.8 GHz are higher over hurricane rainbands, reflecting the contributions from cloud and water vapor emission.
The center frequency of channel 16 is 88.2 GHz, which is the highest among the 16 ATMS temperature sounding channels. Microwave measurements at this frequency are affected by both the emission and scattering of clouds. Over areas with ice clouds (Fig. 2b), the ATMS-measured brightness temperatures at 88.2 GHz (Fig. 3c) could be more than 25 K colder than those over their surrounding areas with liquid water clouds. The resampling of ATMS channel 1 data (Fig. 3a), which has a 5.2° beamwidth, to AMSU-A-like resolution with a 3.3° beamwidth (Fig. 3b) does enhance the observation resolutions. After resampling, the maximum brightness temperatures over cloudy areas become even larger, the minimum brightness temperatures over clear-sky streaks among clouds become even smaller, and the gradients of brightness temperatures near cloud edges become sharper. On the contrary, when ATMS channel 16 data (2.2° beamwidth) is resampled to AMSU-A resolution (3.3° beamwidth), the data resolution is reduced. Results in Fig. 3d confirm that the brightness temperatures after resampling become smoother. The maximum brightness temperatures over areas with liquid clouds become lower, and the minimum brightness temperatures over ice cloud areas become larger after resampling. As expected, positive and negative differences resulting from the resample are found over the minimum and maximum brightness temperatures areas, respectively.

Impacts of the resampling on ATMS temperature sounding channels are qualitatively similar to ATMS channel 16, but the differences introduced by the resampling in brightness temperatures are of much smaller magnitudes, as shown in Figs. 3e,f for ATMS channel 5. Impacts on other channels with higher peak weighting function altitudes become even smaller (figures omitted).
The standard deviations of brightness temperatures for ATMS channels 1–9 and 16 within the domain shown in Fig. 3 for Hurricane Sandy before ($\sigma_{\text{ATMS}}$) and after ($\sigma_{\text{BG}}$) the resampling are provided in Fig. 4. The differences of standard deviations between $\sigma_{\text{ATMS}}$ and $\sigma_{\text{BG}}$—that is $\Delta\sigma = \sigma_{\text{BG}} - \sigma_{\text{ATMS}}$—are also indicated in Fig. 4. It is seen that a resolution enhancement by the resampling corresponds to an increase of the standard deviations of ATMS channels 1 and 2 on the order of 0.4–0.8 K. A resolution reduction by the resampling for ATMS channels 3–16 corresponds to a decrease of the standard deviations of measured brightness temperatures within Hurricane Sandy. It is therefore concluded that the B-G resampling algorithm acts as a smoother for ATMS channels 3–16, and is capable of producing higher-resolution data from overlapping coarser-resolution ATMS data for ATMS channels 1 and 2. Differences in standard deviations introduced by the resampling decrease rapidly with the increase of channel number for ATMS temperature sounding channels.

5. Cross calibration between ATMS resample and AMSU-A data

The SNO points between Suomi NPP ATMS and NOAA-18 AMSU-A are identified during a 16-month period from 1 January 2012 to 31 March 2013 and are used for characterizing the relative biases between two instruments. In addition, AMSU-A data from NOAA-15, NOAA-18, and MetOp-A satellites are also collocated at SNO locations. The SNO points are found under the criteria of a spatial distance and temporal separation being less than 15 km and 60 s, respectively. These SNO points of Suomi NPP and NOAA-18 satellites are then used for deriving a linear regression function of the bias between the two data types (i.e., ATMS resample and AMSU-A data).
AMSU-A) as a function of the ATMS brightness temperature for each pair of ATMS–AMSU-A channels.

Figure 5 shows the SNO brightness temperature differences between Suomi NPP ATMS and NOAA-18 AMSU-A as a function of the ATMS resampled brightness temperature. Here, the AMSU-A channel number (e.g., channel 5) is compared with the corresponding ATMS channel number (e.g., channel 6). Outliers with
SNO differences between the two instruments (e.g., ATMS and AMSU-A) being more than one standard deviation are removed. Impact of rain-induced saturation on the resampling is thus mostly eliminated. The differences between ATMS resample and AMSU-A data after the quality control step agree in general within ±1 K, and the bias between two instruments is slightly scene dependent, which is probably due to the different non-linearity correction in the radiometric calibration.

The SNO data points after quality control are used for deriving an intersatellite bias offset through a linear regression for each channel:
\[ \mu_{\text{ch}} = \alpha_{\text{ch}} T_{b,\text{ch}} + \beta_{\text{ch}}, \]  

where the subscript \( \text{ch} \) indicates the ATMS channel number. Values of the slope \( \alpha_{\text{ch}} \) and the intercept \( \beta_{\text{ch}} \) of the regression [Eq. (9)] for all the paired channels between ATMS and AMSU-A from NOAA-18 are provided in Table 1.

A similar procedure for SNO cross calibration is also carried out between MetOp-A and NOAA-18, and between NOAA-18 and NOAA-15. The SNO points between MetOp-A and NOAA-18 are found during the time period from 1 May 2007 to 31 December 2012, and those between NOAA-15 and NOAA-18 are found during the time period from 1 January 2006 to 31 December 2011. The mean, as well as the intercept and slope of a linear regression of the differences of brightness temperature between MetOp-A AMSU-A and NOAA-18 AMSU-A derived from SNO points are provided in Table 2. Similar results for NOAA-15 and NOAA-18 are provided in Table 3.

Changes in brightness temperatures through the SNO cross calibration described above are illustrated in Figs. 6–9 for various ATMS and AMSU channels. Figures 6 and 7 provide brightness temperature observations at nadir within the area (2°S–2°N, 80°–100°W) over the tropical Atlantic Ocean under clear-sky conditions. The clear sky is defined by a LWP that is derived from AMSU-A channels 1 and 2, being less than 0.01 kg m\(^{-2}\) (Weng et al. 2003). Before SNO corrections, AMSU-A data at channels 6 and 7 from NOAA-15, NOAA-18, and MetOp-A and ATMS channels 7 and 8 from Suomi NPP display some significant biases with respect to each other. Some of the biases may be related to the diurnal effects of atmospheric temperature profiles. Figures 8 and 9 are similar to Figs. 6 and 7, except for a different area over the tropical Pacific Ocean. It is seen that the ATMS data have no systematic biases and can be well merged with the AMSU-A data series after cross calibration.

Figure 10 presents a time series of the brightness temperature bias at nadir between eight paired ATMS–AMSU-A channels (e.g., AMSU-A channel numbers 5–10 and 12 and 13) over oceans in clear-sky atmospheric conditions within a latitudinal zone of 30°S–30°N before and after SNO calibration. AMSU-A on board NOAA-18 was used as a reference. AMSU-A channels 11 and 14 are not shown in Fig. 10 because NOAA-15 AMSU-A channel 14 has not been working since October 2000, and AMSU-A channel 11 failed in April 2002 (Mo 2009). Because of the significant influences of orbital drift and surface emissivity on the accuracy of surface-sensitive measurements, the measurements by AMSU-A channels 1–4 and 15 are not considered in this study. It is seen that before SNO calibration, there exists a significant offset between ATMS resample data and AMSU-A data. After the SNO calibration, the intersatellite biases between ATMS resample data and AMSU-A data from NOAA-15 and MetOp-A are significantly reduced for all eight paired ATMS–AMSU-A channels. Similar results are obtained in the middle and high latitudes (figures omitted). It is reminded that MetOp-A AMSU channel 7 has been degrading in performance since 16 December 2008 (http://www.oso.noaa.gov/poesstatus/componentStatusSummary.aspx?spacecraft=2&subsystem=1) with noise exceeding specifications. This degradation in data quality of NOAA-15 AMSU-A channel 7 is clearly seen in the temporal evolution of the intersatellite biases shown in Fig. 10. The slow deterioration in measurement accuracy of NOAA-15 AMSU-A channel 6 (Mo 2009) was also seen from the intersatellite biases (Fig. 10). In addition, the effects of AMSU-A instrument aging and NOAA-15 satellite orbital drift are reflected in the intersatellite biases between NOAA-15 and NOAA-18 and can also be detected in stratospheric channels.

6. Summary and conclusions

The AMSU-A instruments have been on board NOAA and European meteorological satellites since 1998. They were replaced by the Advanced Technology Microwave Sounder (ATMS) on board Suomi-NPP as well as future Joint Polar Satellite System (JPSS) satellites. While allowing for improved applications of microwave temperature sounding measurements to numerical weather prediction, some modifications in ATMS’s channel frequency, data resolutions, beamwidth, and overlapping FOVs present new challenges for merging ATMS data with data from its predecessor heritage instruments AMSU-A and MHS combined.

This paper first applies the B-G method for converting the ATMS data to the ATMS resample data, which are AMSU-A-like observations. This work is required for extending the time series of microwave temperature sounding observations for the purpose of monitoring climate. A subpixel microwave antenna temperature simulation technique is employed for deriving a set of optimal weighting coefficients. An SNO matchup dataset for nadir pixels with criteria of simultaneity of less than 60 s and within a ground distance of 15 km is then generated for all overlaps of the ATMS resample and AMSU-A on board NOAA-18 from 1 January 2012 to 31 March 2013. The simultaneous and overlapping nature of these matchups eliminates the impact of orbital drifts and reduces weather-related impacts on the calibration. Finally, a combination of the B-G method with the SNO allows for better merging of ATMS data with AMSU-A data.
It is found that the availability of redundant information contained in different ATMS FOVs because of their overlapping features makes it possible to resample the ATMS observations into either a higher or a lower AMSU-A-like spatial resolution of the same center frequency. Although the SNO matchups are confined within a latitudinal band centered around 81° in both hemispheres because of the orbital geometry of polar-orbiting weather satellites, it is shown that the global ATMS resample data after SNO corrections are well merged to AMSU-A data from the NOAA-15, NOAA-18, and MetOp-A satellites. The intersatellite biases are very small among NOAA-15, NOAA-18, MetOp-A, and Suomi NPP.

The resampling of ATMS data into AMSU-A-like data is a critical step for linking the ATMS data to NOAA MSU–AMSU time series to create a long-term fundamental climate data record that could be used in climate monitoring, reanalyses, and forecasts. The present study will be substantiated as more ATMS data become available. We plan to continue the time series by merging the ATMS resample and the AMSU and MSU observations using the SNO technique. This study is limited to cross calibration between ATMS and AMSU.

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