Correcting geolocation errors for microwave instruments aboard NOAA satellites

Isaac Moradi, Huan Meng, Ralph Ferraro, and Stephen Bilanow

Abstract

Microwave (MW) satellite data are widely used as input in the Numerical Weather Prediction (NWP) models and also in other applications like climate monitoring and reanalysis. MW satellite data are prone to different problems including geolocation errors. MW data do not have a fine spatial resolution like visible and infrared data, therefore the accuracy of their geolocation cannot be easily determined using the normal methods such as superimposing coastlines on the satellite images. Currently, no geolocation correction is performed on data from MW instruments aboard the satellites in the NOAA Polar Operational Environmental Satellite (POES) program. However, geolocation error can be a significant source of bias in satellite measurements. In this study, we investigated and corrected the geolocation errors of the observations from the Advanced Microwave Sounding Unit (AMSU) and Microwave Humidity Sounder (MHS) aboard NOAA-15 to -19. We used the difference between ascending and descending observations along the coastlines to quantify the geolocation error in terms of the satellite attitude (Euler angles), i.e. pitch, roll, and yaw. New geographical coordinates and scan/local zenith angles were calculated using new attitudes. The results show that NOAA-15 AMSU-A2 sensor is mounted about 1.2 degrees cross-track, and about 0.5 degree negative along-track. NOAA-16 AMSU-A1 and -A2 are mounted about 0.5 degree negative alongtrack, and NOAA-18 AMSU-A2 is mounted more than 1 degree negative alongtrack.

Index Terms

Geolocation, microwave remote sensing, NOAA, satellite, navigation

I. Introduction

Microwave (MW) satellite data play a very important role in weather forecasting and also in climate monitoring and assessment. Microwave data are widely used to derive a variety of hydrological products including precipitation [1]–[4], precipitable water [5], [6], snow cover [1], tropospheric humidity [7], cloud liquid water [8], deep convective clouds [9], and land surface emissivity [10]. The primary motivation of this work was to develop corrections to geolocation of the microwave sounders that will contribute to the creation of more accurate time series for the development of a long-term climate data record from microwave satellite data [11]. Geolocation errors are one of...
the main sources of uncertainty in the MW satellite data and have serious effects on intercalibrating, validating, and retrieving geophysical variables from satellite data.

Some potential sources of the geolocation errors are i) satellite clock offset which is the difference between the satellite clock and UTC; ii) systematic misalignment of the instrument so that the nadir position does not point to the subsatellite point and/or the scanning is not perpendicular to the velocity direction, iii) the time dependent satellite attitude (pitch, roll and yaw) errors, iv) inaccuracy in the ephemeris data that are used to predict the satellite position, and v) instrument modelling errors such as the step angle of the instrument. MW data do not have fine spatial resolution like visible and even infrared data. For instance, the Advanced Microwave Sounding Unit-A (AMSU-A) aboard the National Oceanic and Atmospheric Administration (NOAA) satellites has a spatial resolution of about $48 \times 48$ km at nadir that increases towards the limbs. Therefore, the accuracy of their geolocation cannot easily be determined using simple methods such as superimposing coastlines on the satellite images. The number of published materials about correcting geolocation errors for MW data is very limited. Poe et al. [12] investigated the SSMI/S geolocation accuracy using partial derivatives of the radiometer data. They derived angular and time offsets that are the main cause of the geolocation error and reported that the correction will reduce the inaccuracy of the SSMI/S geolocation to less than 4–5 km. Purdy et al. [13] investigated the WindSat geolocation and pointing accuracy using a combination of coastline matchup technique and scan bias analysis. They reported an accuracy of 0.5° for the pointing knowledge and 5 km for the geolocation. Initial evaluation of the geolocation accuracy of NOAA-15 data using cross-correlation between AMSU-B Channel 1 and AMSU-A Channel 7 showed a small misalignment between the two channels [14].

One of the most important sources of the MW data comes from the satellites operated by NOAA. Currently, no geolocation correction is performed on the data from MW instruments aboard the satellites in the NOAA Polar Operational Environmental Satellite (POES) series. In this study, we investigate and correct the geolocation errors of measurements from AMSU-A, -B and Microwave Humidity Sounder (MHS) aboard NOAA-15 to -19. This study focuses on the correction of satellite attitude errors, clock offset, as well as sensor misalignment. To the best of the authors’ knowledge the current study is the first attempt that investigates and corrects the geolocation errors of the microwave data from the NOAA satellites.

II. INSTRUMENTS AND ORBITAL DATA

A. satellite instruments

The NOAA satellites are near-polar orbiting (98.7 degree inclination) platforms which use Earth and Sun sensors for primary attitude control. AMSU-A, -B and MHS are cross-track scanning instruments. AMSU-A scans thirty contiguous scenes in eight seconds in a stepped-scan fashion; antenna steps and stops at each beam position for a short time. The antenna beam width, instantaneous field of view (IFOV), is a constant 3.3° (at the half power beam-width). AMSU-A has 15 channels on two separate modules: two lowest channels are on AMSU-A2 and the remaining thirteen channels are on AMSU-A1. AMSU-A1 itself has two antenna systems to minimize the front-end
radio frequency (RF) loss and a constant 3.3° antenna beam width [15]. Channels 3–5 and 8 are on AMSU-A1-2 and Channels 6, 7, and 9–15 are on AMSU-A1-1.

AMSU-B and MHS are a cross-track scanning five-channel microwave radiometer. The instruments have an IFOV of 1.1°, and a swath width of approximately 2300 km with 90 scan positions. Their footprint size, defined with respect to the half power beam width, is approximately 16 × 16 km at nadir but increases toward the edge of the scan. The AMSU-B/MHS IFOV is smeared out as the sensor and satellite move during integration time. Therefore, the foot-print size defined with respect to the effective FOV (EFOV) is 27 × 16 km [16]. The Microwave Humidity Sounder (MHS) is very similar to AMSU-B, but the MHS step angle is 1.1° (0.1 recurring) while the AMSU-B step angle is 1.1°. All AMSU-B and MHS channels are on the same module and are expected to have the same geolocation error. Therefore, we only investigated the geolocation errors of the first AMSU-B and MHS channel, i.e. 89.0 GHz. Since there are three modules on AMSU-A, we studied Channel 1 for AMSU-A2, Channel 3 for AMSU-A1-2 and Channel 15 for AMSU-A1-1. The satellite attitude and sensor mounting errors of these channels can be applied to the channels on the same module. The characteristics of AMSU and MHS sensors that are important for geolocation are reported in Table I. The FOV plus dead time (FDT) is the time that antenna spends to scan the current spot and then step to the next spot. Dead time is the non-integration time required for reflector slewing and/or transferring of data. Note that for MHS the IFOV is 1.1° but the step angle, separation between adjacent beam positions, is 1.1°.

In this study we used NOAA Level 1b (L1b) data that are raw but quality controlled. L1b data are geolocated and calibration information have been appended but have not been applied. This definition of level-1b is just for data from the NOAA POES satellites and is not valid for the satellite data from other agencies like the National Aeronautics and Space Administration (NASA) and The European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) [15].

B. Orbital data

The first step of geolocation is to estimate the satellite position and velocity state vectors. These vectors describe the position and velocity of a satellite at a given time. The state vectors (plus a few other essential parameters) are usually reported once or twice per day using satellite orbital elements (ephemeris data). The ephemeris data are propagated using an ephemeris model to predict the satellite state vectors at the scanning time.

In this study, we used the Two-Line Element (TLE) data that are developed by the North American Aerospace Defense Command (NORAD). The TLE format was developed by NORAD to transmit satellite orbital elements. The name TLE comes from the fact that the ephemeris data are stored in two lines. The ephemeris data are normally computed once or twice per day and are propagated using a propagation model through the rest of the day or the day after that. The accuracy of the prediction degrades with time and it is not suggested to extend the prediction more than 24 hours from the time of the orbital elements [17]. The propagation model predicts the future satellite position velocity state vectors using current state vectors and other ephemeris parameters. The user is required to use Simplified General Perturbations (SGP) orbit propagator with the TLE data to get accurate orbital predictions.
The models simulate perturbations resulting from the effect of the Earth’s shape, atmospheric drag, solar fluxes and gravitational effects from other celestial objects like sun and moon [18]. The SGP model is for the objects close to the Earth, orbital period less than 225 minutes. There is another version of SGP called Simplified Deep Space Perturbations (SDP) that can be used for object further away from the earth, orbital period greater than 225 minutes [19].

The Information Processing Division (IPD) of the Office of Satellite Data Processing and Distribution (OSDPD) of NESDIS/NOAA uses 4-line ephemeris data and the Advanced Earth Location Data System (AELDS) for geolocating the POES satellite data. The difference introduced by the ephemeris data expected to be very small. For example, Poe and Conway [17] reported a difference of 1.5 km, with the maximum difference occurring between subsatellite latitudes, between subsatellite points calculated using ephemeris data from Space Surveillance Center (SSC) and Naval Space Surveillance System (NAVSPASUR). We also found that the difference between the new and L1b coordinates is less than 1 km, on average. This difference can be attributed to either the ephemeris data and propagation model (as those are the only known differences between the two methods) or other unknown sources of error.

III. QUANTIFYING GEOLOCATION ERROR

In microwave frequencies the radiative transfer (RT) equation is clear-sky conditions (nonscattering media) can be written as [20]:

$$T_b = \varepsilon_s \tau_s T_s + \int_z T d\tau + \tau_s \int_\Omega \left\{ \rho_s^\Omega \left( \int T d\tau^\Omega + \tau_s^\Omega \hat{T}_c \right) \right\} d\Omega$$

(1)

where, $T_b$ is the brightness temperature measured by the sensor, $\varepsilon_s$ and $\tau_s$ are the surface emissivity and atmospheric transmittance for the entire column from the surface to the satellite, respectively, $T_s$ is the surface physical temperature, $T$ and $\tau$ are the atmospheric temperature and the atmospheric transmittance, respectively, $\varepsilon_s$ and $\rho_s$ are, respectively, the surface emissivity and bidirectional reflectance in the direction $\Omega$, $\tau_s^\Omega$ is the atmospheric transmittance at the top of the atmosphere, and $\hat{T}_c$ is cosmic background temperature (2.73 K). $T_b$, $\varepsilon_s$, $\tau_s$, and $\rho_s$ depend on frequency and the local zenith angle. The first term on the right-hand side of Equation 1 is the contribution from the surface (either land or sea), the second term is the atmospheric contribution due to emission, and the last term is the reflected radiation. In the window channels, like AMSU-A Channels 1, 2, 3, and 15 and AMSU-B/MHS Channel 1, $\tau_s$ is very close to unity. So that the atmospheric contribution and the reflected radiation are very small compared to the surface contribution, hence Equation 1 can be simplified as $T_b = \varepsilon_s T_s$.

In microwave frequencies the difference between land ($\varepsilon_L$) and sea emissivity ($\varepsilon_S$) is very large, $\varepsilon_L$ is about 0.9 but $\varepsilon_S$ is about 0.5, on average. This translates to a very large difference between land and ocean $T_b$'s. For instance, if we assume a physical temperature of 270 K for both land and ocean; satellite $T_b$ will be about 243 K over land and 135 K over ocean. If the satellite data are correctly geolocated then the difference between ascending and descending $T_b$’s ($\Delta T_b$) will be very small which is a function of the diurnal variation of the physical temperature, surface emissivity, and environmental conditions. The temporal variation of $\varepsilon$ is negligible, especially on daily basis, compared to the difference between $\varepsilon_L$ and $\varepsilon_S$. 
Any sensor mounting (pointing offset), ephemeris or timing error shifts the coastline locations shown from ascending and descending orbits in different directions. For positive roll or roll-alignment errors, geolocation is shifted to the west for ascending passes, and to the east for descending passes. For positive pitch or pitch-alignment errors, geolocation is shifted south for the ascending passes and north for the descending passes. Note that positive roll and positive pitch are defined, respectively, in negative cross-track and negative along-track directions. Along-track ephemeris and timing errors can cause the same effect as a pitch attitude or pitch alignment offset. The errors in pitch and roll are highlighted on the $\Delta T_b$ maps. For instance the effect of 2° pitch and roll errors on the $\Delta T_b$ maps along the Australian shorelines are shown in Figure 1. We first partitioned the data into ascending and descending, next binned the data into a grid of 0.1 by 0.1 degree, then for each bin we computed: $\Delta T_b = T_{b_{\text{asc}}} - T_{b_{\text{desc}}}$. The grid resolution was chosen to balance the accuracy of geolocation error quantification and consumption of computer resources. The regions along the shorelines that are land during ascending and water during descending show warm $T_b$’s and vice versa. Analyzing the effects of pitch and roll shifts on $\Delta T_b$’s (see Figure 1) demonstrates the following associations: (i) positive roll offset causes warm (positive) $\Delta T_b$ on west coasts, and cold (negative) $\Delta T_b$ on east coasts, Figure 1(a), (ii) positive pitch offset causes warm (positive) $\Delta T_b$ on south coasts, and cold (negative) $\Delta T_b$ on north coasts, Figure 1(b). The effects for yaw errors are more complicated to describe since they vary with position in the scan. Positive yaw errors cause positive along-track (pitch-like) errors on the left side of the swath, negative along-track errors on the right side of the swath, and negligible errors near the center of the scan. The combined error effects on the difference maps depend on where along the scan the samples are collected for the northbound and southbound passes. Near to where the subsatellite ascending and descending ground tracks intersect there is little effect to the $\Delta T_b$ from yaw errors. However, over areas where different parts of the scan sample the same North or South coast, the $\Delta T_b$ is affected. Since the sensitivity to yaw effects is weaker, it is solved for last and is less accurate, as discussed further later in this paper.

The correction algorithm is based on minimizing number of pixels along the coastlines where $\Delta T_b$ is greater than a threshold (30 K). The threshold needs to be greater than the daily range of the land surface temperature (around 20 K) plus the small effect of the diurnal variation of the surface emissivity. We only utilized the pixels whose distance from the shorelines was less than 150 km. Although geolocation errors are introduced by the satellite attitude and sensor mounting errors; they can be corrected in the same way using satellite attitude rotation matrix. The correction algorithm is schematically explained in Figure 2 and is summarized in the following:

i. set the attitude (pitch, roll, yaw) to zero and geolocate one day of data
ii. partition the data into ascending and descending, then bin them into grids of 0.1°, after that make the difference map and count number of pixels (Np) along the coastlines where $T_b$ is greater than the threshold
iii. if Np is zero then write out the data and go to the next day, otherwise go to the next step to correct the geolocation
iv. add/subtract a small value to pitch and repeat steps 2 and 3 using new pitch value until Np is minimized
v. repeat steps 2 to 4 for roll and yaw
vi. geolocate the data using the new values for pitch, roll, and yaw and write out the new geolocation data and go to the next day

The sensitivity analysis of geolocation to the satellite attitude is shown in Figure 3. The plots are created using one AMSU-A swath file, therefore we have 30 FOVs where the scan angle starts from 1.6° for the nadir spots (beam positions 15 and 16) and increases by 3.3° towards the edges of the scan (beam positions 1 and 30). Any pitch offset shifts the scanlines alongtrack independent of the scan angle. Since the satellite is moving while recording the data, the scanlines are not exactly perpendicular to the velocity direction. Therefore there is a very small dependency between the pitch effect and scan angle. Overall, the impact of 1° pitch error is about 15 km along-track. Pitch and timing error have the same influence on the location of spots on the ground, both shift the scanlines alongtrack. However, the pitch effect depends on the satellite altitude but the timing effect depends on the satellite velocity. For NOAA POES satellites, 3.3° pitch error has an effect equal to 8 s timing error. Roll has the same angular impact on nadir and off-nadir beam positions; e.g., if roll offset is 3° then all the spots will be shifted 3° in the cross-track direction. However the actual displacement on the Earth’s surface is a function of the beam position. The same angular roll error of 3° causes about 45 km shift for the nadir beam positions and up to 150 km for the outermost beam positions, see Figure 3(b). Roll directly affects local zenith angle (LZA, θ). LZA is very important for radiative transfer calculations because optical path length is scaled by 1/\cos(θ). It is worthwhile to mention that in addition to the local zenith angle, other terms like satellite zenith angle and earth incidence angle are also used for θ. The yaw effect increases from nadir to off-nadir beam positions, see Figure 3(c). In fact, yaw does not affect the subsatellite point at all. The effect of one degree yaw offset corresponds to more than 20 km shift at the edges of the scans.

IV. Results

In this section, first the NOAA level-1b geolocation problems that we found are discussed. Then, the satellite attitudes and sensors mounting offsets are discussed. Finally, the error analysis results for this study are explained.

A. Level 1b Geolocation Problems

The problems explained in this section are operational (software and human related issues) rather than satellite instability or sensor mounting errors. NOAA has used some nominal values for the satellite attitudes to geolocate L1b data, e.g. 0.2° for the yaw offset of NOAA-15 AMSU-A. According to NOAA Preprocessing Center [21] these values are implemented based on users feedback. We used these values in our calculations for this section to make sure that the difference between NOAA L1b and the new geolocation data is not introduced by different attitudes. After geolocating L1b data using the new method, we calculated the distance between the two sets of coordinates (original L1b and the new one) and then averaged this distance over the swath file. The differences between the two methods are shown in Figure 4 for different satellites. We applied a 5-day moving average to smooth the data so that the overall agreement between the methods can be seen. As shown in Figure 4, the average offset between the two methods is about 2 km until July 6, 2006 and then decreases to about 0.7–1.5 km, averaging about 1.5
km for AMSU-A, and about 0.8 km for AMSU-B and MHS after July 2006. The reason for this discrepancy is
that AELDS switched from geocentric to geodetic subsatellite point on July 6, 2006, while we used geodetic nadir
for the entire period. The NOAA platforms are designed to point their Z axis toward geodetic nadir using the
Earth Sensor Assembly (ESA), but AELDS assumed geocentric nadir pointing. The geocentric subsatellite point is
defined as the intersection of the Earth’s surface with the vector that points from the Earth’s center to the satellite
but the geodetic subsatellite point is the intersection of the Earth’s surface with the vector that is perpendicular to
the Earth ellipsoid and points to the satellite. After July 2006, the only known difference between the two methods
is that different ephemeris data are used to calculate the satellite position and velocity vectors. NOAA uses 4-line
ephemeris data to estimate the satellite state vectors and we used 2-line ephemeris data. The offset is consistent with
Poe and Conway [17] who reported that different ephemeris sources introduce less than 1.5 km shift in subsatellite
point.

At the beginning of 2004, the offset between L1b and new geolocation data, see Figure 4, is very large, up
to 75 km. One of the swaths for January 1, 2004 is shown in Figure 5. The swath Tb’s are plotted using L1b
geolocation data in Figure 5(a), and new geolocation data in Figure 5(b). Obviously, L1b geolocation data are
displaced relative to the shorelines. Further investigations showed that for about 5 days at the beginning of 2004,
the level-1b longitudes were about one degree wrong. The reason for this large offset was that AELDS failed to
correctly calculate Greenwich Hour Angle (GHA) (see Appendix A) when it crossed the year [21]. GHA directly
affects longitudes. There is also a noticeable offset, up to 10 km, between the two methods in 2001. We did not
have access to the AELDS package to investigate the reasons for this large offset.

Another problem in L1b data is that NOAA has used $1.1^\circ$ for the NOAA-18 MHS step angle until August 5,
2005 (daynumber 217) while the correct value is $1.1(1)^\circ$. This caused up to a 30 km error for the most off-nadir
beam positions but the error is smaller for the nadir beam positions. In this study we used $1.1(1)^\circ$ for the MHS
step angle and corrected the entire dataset.

NOAA-17 clock offset correction was unintentionally turned off in the AELDS package since the launch date for
both AMSU-A and -B but not for the other sensors like AVHRR. Therefore, the time used to geolocate NOAA-17
data can be up to 600 ms wrong. We obtained the clock drift files from NOAA and interpolated the data following
NOAA’s standard method. The clock drift information was then added to level-1b to geolocate the data. The clock
offset values for different satellites are shown in Figure 6. NOAA updates the satellite clock offsets infrequently.
The clock offsets are interpolated based on a constant daily drift rate until 2007, then constant clock offsets are
used. NOAA aims to keep the clock offset less than 1 second so that when the clock offset goes beyond 1 second,
they command and correct the satellite clock. However, there were cases, in early years, where the clock offset was
more than 2 seconds. NOAA incorporated the clock offsets since December 15, 2000 for NOAA-15 and March 16,
2006 for NOAA-18, see Figure 6. As mentioned before, NOAA-17 AMSU-A and AMSU-B L1b data are based on
uncorrected scanning time. We incorporated the clock offsets for all the satellites in our analysis.

Clock offset and pitch have the same effect on the image geolocating and both shift the scanlines along-track.
Therefore, any inaccuracy in the satellite clock will affect the estimated pitch offset. Figure 7 shows NOAA-17
attitudes before and after correcting the satellite clock offset. NOAA-17 clock offset changed from about −300 ms in 2005 to about 600 ms in 2007. In Figure 7 this error is translated into pitch error. Therefore, before correcting the satellite timing for the clock offset there is a jump, more than 0.3°, in estimated pitch error during the years 2006-2007. After incorporating the clock offset the jump is removed so that pitch varies less than 0.1°. Although both pitch and timing error shift the scanlines alongtrack, they have different effects on LZA. Timing error does not affect LZA as the timing error, in fact, affects the satellite position rather than the viewing geometry. On the other hand, pitch affects the viewing geometry. Figure 8 shows the effect of 1.1° pitch error on LZA. The effect is negligible for off-nadir beam positions but significant (about 0.4°) for the most nadir beam positions. This LZA offset is introduced by 1.1° pitch error which is equal to about 2.5 s in timing error. In other words, if we have a timing error of 2.5 s and take it as a pitch offset then calculated LZA will be about 0.4° wrong for the most nadir beam positions. In this study, we first corrected the satellite timing for the clock offset using NOAA clock-offset tables, then interpolated the ephemeris to calculate the satellite position and velocity vectors. Since NOAA does not frequently update the clock-offset tables, we expect that some timing error is left even after taking into account the satellite cloak-offset. However, this timing error is expected to be very small compared to the original clock offsets. Consequently, the LZA error introduced by the remaining timing error is estimated to be negligible even for the most nadir beam positions. Obviously, the remaining timing error introduces some variations in the pitch values. The timing error has always been a concern for geolocating satellite data. For example, Poe and Conway [17] reported a geolocation inaccuracy resulted from the error in the spacecraft position as a consequence of a time shift up to 2.0 seconds in the archived SSMI data.

B. Instrument Attitude

The attitudes normally explain the status and stability of the satellite. In our case, however, the satellite attitudes (i.e. pitch, roll, and yaw) cannot be separated from the other error sources such as sensor mounting error. Therefore we refer to all the error sources as instrument attitude rather than satellite attitude. The instrument attitude includes satellite attitude, sensor mounting error, timing error, and uncertainty in the ephemeris data. The last error is estimated to be negligible, less than 2 km. Besides, the timing error is also estimated to be very small since we corrected the scanning time for the clock offsets. Sensor misalignment is a constant error so that the sensor/antenna does not exactly point to the subsatellite point when the scan angle is zero. The satellite attitude offsets are dynamic but are expected to be small since the platform is kept level to the local horizon to within about 0.2 degrees, which is essentially perpendicular to the local geodetic nadir [15].

Figure 9 shows the temporal variation of the attitudes for NOAA-15 AMSU-A (Channels 1, 3, and 15) and AMSU-B Channel 1. The main feature of the NOAA-15 attitudes is that roll and yaw are very stable but pitch has a notable fluctuation. The reason is that any clock offset and error in the ephemeris data or propagation model is translated into pitch. The timing error and any error related to the satellite state vectors have the same effect as pitch on the geolocation. The current method is unable to distinguish the difference between pitch and other related errors. However, since all these errors have the same effect on geolocation, they can be treated as pitch
error and corrected in the same manner. It was discussed earlier in this paper that the main difference between pitch and timing error is that unlike timing error, pitch affects LZA. However the fluctuation in the NOAA-15 pitch is within ±0.2°, as shown in Figure 9. If we assume that this variation is caused by timing error rather than pitch, then the related error in LZA will be less than ±0.1° for the sub-nadir beam positions and negligible for the off-nadir beam positions. All the NOAA-15 AMSU-A Channels have the same pattern for pitch. Pitch is greater for AMSU-A Channel 1 than for Channels 3 and 15. Before 2000, the pattern of pitch for AMSU-B is slightly different from AMSU-A but then they almost follow each other. This may be because of the noise in the AMSU-B data as later NOAA introduced correction algorithms for AMSU-B. The AMSU-B pitch varies between 0° and 0.4° before 2002 and then becomes more stable. The pitch values for AMSU-A channels are also more stable after 2002. About 0.4–0.5° of pitch error for AMSU-A channels may be because of the sensor misalignment since the AMSU-B pitch is very small after 2002. The roll is about 1.2° for NOAA-15 AMSU-A Channel 1. This large error in roll is caused by a sensor misalignment rather than satellite attitude error. The values shown in the attitudes figures are in fact what we add to compensate for the attitudes errors. In other words, the attitudes errors have a different sign than the values that are shown in the figures. For instance the roll error for NOAA-15 AMSU-A2 is about −1.2°, so we have to add 1.2° to remove that error. On average, a 1° error in roll translates to about a 15 km displacement on the Earth’s surface at nadir and increases towards the edges of the scan. Roll offset directly affects the scan angle. Therefore the new scan angle for AMSU-A2 data is the nominal value plus 1.2°. AMSU-A FOV is 3.3°, therefore all the pixels are shifted about 1/3 of a pixel in the scan direction towards the right-side of the scan. Roll is very small for the other three NOAA-15 channels. The yaw values are very small for all AMSU-A and AMSU-B Channels. The main inconsistency between AMSU-A and -B is a rise in AMSU-B yaw after 2008 but the range of this change is smaller than methodological uncertainty. The methodological uncertainty is estimated to be about ±0.1°. The standard deviation of the mean, vertical bars in the attitudes’ plots, is a good estimate for the uncertainty due to random noise in the sampling, however it is difficult to quantify the overall uncertainty due to other error sources.

NOAA-16 attitudes are shown in Figure 10. First of all, the patterns for all AMSU-A and AMSU-B channels are very similar. Pitch has a small fluctuation less than ±0.2°. The mean value for pitch is greater for AMSU-A than AMSU-B. It is likely that about 0.4–0.5° of the AMSU-A pitch error is introduced by sensor mounting error or a systematic timing error. However, a systematic timing error for such a long-period is unlikely as the satellite clock has been updated a few times during that period. All AMSU-A channels show a small roll error that can be attributed to the sensor mounting. This error is about −0.2 to −0.3° for Channel 1, 0.4° for Channel 3, and over 0.2° for Channel 15.

The instrument attitudes for NOAA-17 AMSU-A and -B are shown in Figure 11. NOAA-17 AMSU-A1 (Channels 3-15) failed on October 28, 2003 because of a surge current caused by a solar event. Therefore the attitudes are not shown for those channels. For Channel 1, the pitch varies between −0.6 to −0.3° but roll and yaw are very small. As we explained before, a trend in pitch indicates uncertainty either in the satellite timing or in ephemeris data. The ephemeris error is estimated to be less than 2 km. Therefore the timing errors are expected to be the
main reason for the pitch variations. NOAA-17 AMSU-B shows a roll error of about \(-0.3^\circ\) that can be attributed to the sensor mounting error.

Figure 12 shows the attitude errors for NOAA-18 AMSU-A and MHS. AMSU-A Channel 1 has a large pitch offset between \(-1\) to \(-1.4^\circ\). As the other channels do not show such a large pitch offset, we attribute this to a sensor misalignment. The pitch fluctuations are similar between AMSU-A and MHS channels, however there are some small differences, less than methodological uncertainties, between the channels.

Figure 13 shows the attitudes for NOAA-19 AMSU-A Channels 1, 3, and 15 and MHS Channel 1. NOAA-19 AMSU-A Channels 3 and 15 show a similar pattern for pitch with a steep trend (about \(0.8^\circ\)) in 2009. This trend can not be attributed to the satellite attitude or timing error as AMSU-A Channel 1 and MHS do not show the same trend. The reason may be related to the instrument scan motor or the reflector misalignment since these parts operate independently for AMSU-A-1, AMSU-A-2, and MHS. Electronic disorders could also introduce such an inconsistency between the instruments. However, it is difficult to investigate the actual reasons behind this inconsistency.

Figure 14 shows the sample difference maps before and after geolocation correction for NOAA-15 AMSU-A Channel 1 over Australia and Mediterranean Sea. For the corrected maps, we first calculated the attitudes using Australian coastlines, then calculated the geodetic coordinates of each beam position using new attitudes, and the SGP model. After that, we separated ascending and descending data and binned them separately into grids of 0.1 degree using new corrected geolocation data. Finally, the difference maps were created as the difference between ascending and descending grids. It is obvious that cold and warm coastal patterns introduced by geolocation errors are removed after correction over both Australia and Mediterranean Sea. Since we used the attitudes derived using Australian coastlines to correct the data over Mediterranean region, this demonstrates that the region used to derive the attitude corrections does not have any effect on the attitudes.

C. Error Analysis

We conducted 3 different tests for the error analysis: (i) adding a fixed geolocation error to L1b data and trying to retrieve it using the current method, (ii) conducting a 3D minimization and comparing the results with 1D minimization, (iii) investigating the impact of tuning order on the calculated attitudes.

For the first test, we added a fixed error of \(-0.4^\circ, 0.8^\circ,\) and \(0.2^\circ\) to roll, pitch and yaw, respectively. This was implemented in the processing package in a way to act like an extra sensor misalignment error. We expected to retrieve these values as the difference between the corresponding attitudes before and after adding the errors. The values that we retrieved were, on average, \(0.37^\circ, -0.76^\circ,\) and \(-0.10^\circ\) for roll, pitch, and yaw respectively. Standard deviations of the differences between the two set of the attitudes, taken as the uncertainty in the retrievals, were \(0.00^\circ, 0.01^\circ,\) and \(0.03^\circ\) for roll, pitch, and yaw, respectively. Obviously the method is able to derive both pitch and roll with a good accuracy but the retrieved values for yaw are subject to some uncertainties. This is expected since yaw does not affect all the beam positions and mainly affects off-nadir beam positions. However, the yaw uncertainties are still less than the methodological uncertainty. One reason for a larger uncertainty in yaw
could be the overlap between adjacent orbits so that when we bin the data, Tb’s from different beam positions are mixed up and averaged. Since the yaw effect depends on the beam positions, after averaging different beam positions, the yaw error is averaged and canceled out. However since we make the difference maps on a daily basis and there is almost no overlap between adjacent orbits over Australia, negligible averaging is done over different beam positions in the scan. The overlap between the adjacent orbits starts from about $\pm 35^\circ$ for NOAA POES satellites but Australia extends from $-10^\circ$ to $-40^\circ$. So there is a very small overlap over South Australia that is negligible.

For the second test, i.e. 3D vs. 1D minimization, we used NOAA-18 AMSU-A Channel 1 data and iterated the algorithm over pitch (-2.5 to 0), roll (-1.5 to 1.5), and yaw (-1.5 to 1.5) and tuned all the angles together. We call this test 3D minimization since all the three angles, i.e. pitch, roll, and yaw, are tuned at the same time. In fact, we iterated the algorithm over the given ranges and calculated the index, number of pixels along the coastlines where $\Delta T$ is greater than the threshold, for each set of pitch, roll, and yaw. 3D minimization has the benefit that all the angles are tuned together but it is computationally very expensive. The main purpose was to show that there is one set of pitch, roll, and yaw values that minimizes the index. The results for the 3D minimization are shown in Figure 15. The plots shown in Figure 15 are, from bottom to top, for yaw equal to $0^\circ$, $-1^\circ$ and $1^\circ$, respectively. In summary, the plots show that there is always one solution or one set of pitch, roll and yaw values that minimizes the number of pixels outside the threshold. Therefore, a 1D minimization always yields the same solution as the 3D because there is only one optimal solution.

Figure 15 also shows that the shape of the surface almost does not depend on yaw but the surface is shifted along the z-axis (number of pixels) for different yaw values. So the estimated values for the pitch and roll offsets do not depend on yaw. Therefore, we can set yaw to any value and tune either pitch or roll, then use the best estimates of pitch and roll to estimate yaw. As we explained before, it is better to first tune pitch and roll and then yaw since the index (number of pixels) is not as sensitive to yaw.

The tuning order may be conducted in 6 different combinations. The tuning order is important if there is any dependency among the attitudes. Pitch and roll are mathematically independent since pitch affects the along-track and roll the cross-track directions. Yaw introduces both along-track and cross track shifts but its along-track effect is more dominant. In addition, yaw has a negligible effect on the nadir beam positions that increases toward the limbs, see Figure 3. The 3D minimization results indicated that yaw does not affect pitch and roll. Therefore we mainly focus on examining the effect of pitch on roll and yaw as well as roll on pitch and yaw. We already know that pitch and roll are independent, so the effect of one on the other should be very small. However we would like to quantify the effects. We examined 3 cases: pitch/roll/yaw (hereafter PRY), roll/yaw/pitch (hereafter RYP), and no angle update (hereafter NAU). For the first and second cases, PRY, and RYP, we estimated the first angle, then used the estimated value while tuning the second angle and so on. For the NAU case, we estimated the first angle but did not use the estimated value to optimize the second angle and so on. In other words, we set two of the angles zero and estimated the third one. These combinations are enough to investigate the effect of one parameter on the others. In fact we are mainly interested to finding out the effect of pitch and roll on yaw. The difference between
PRY and RYP shows the effect of pitch on roll, pitch on yaw, as well as roll and yaw together on pitch. Since yaw is very small, the latter shows the effect of roll value on estimating pitch. Likewise, the difference between the PRY and NAU attitudes shows the effect of pitch on roll, and also pitch and roll together on yaw. As an explanation, in the PRY case, roll is estimated after tuning pitch, but in the RYP case, roll is estimated while pitch is set to zero. Therefore the difference between roll values from PRY and RYP shows the effect of pitch on estimating roll. The conclusion is only valid if pitch value is large enough. In this case pitch is about $0.7^\circ$, roll is about $1.2^\circ$, and yaw is almost $0.1^\circ$ for NOAA-15 Channel 1. Therefore none of these tests can reveal the effect of yaw on the other two angles. We already showed in the 3D minimization that yaw values do not affect pitch and roll.

The average differences between PRY and NAU was $0.00^\circ, 0.01^\circ, 0.07^\circ$ for pitch, roll and yaw, respectively, for NOAA-15 AMSU-A Channel 1. The standard deviations for pitch, roll and yaw, respectively, were $0.00^\circ, 0.01^\circ$, and $0.03^\circ$. In this case, pitch values are the same since, in both cases, roll and yaw are set to zero when pitch is tuned. As we expected, the effect of pitch on roll is negligible since the two are independent. The effect of pitch and roll on yaw is about $0.1^\circ$. This effect is introduced by $1.2^\circ$ roll error and about $0.5 - 0.7^\circ$ pitch error. Therefore, we expect that the effect of pitch and roll errors on estimating the yaw error is negligible for the other channels. In addition this bias is still less than methodological uncertainties.

The averages (standard deviations) of the differences between PRY and RYP for NOAA-15 AMSU-A Channel 1 are $0.06 (0.04), 0.02 (0.01), and 0.08 (0.02)$ for pitch, roll and yaw, respectively. This test shows that the effect of pitch on roll is negligible. The effect of $0.5 - 0.7^\circ$ pitch error on the estimated value for yaw is less than $0.1^\circ$. As we expected, the effect of pitch on roll and roll on pitch is negligible, in both cases the effect is less than $0.05^\circ$. In summary, pitch and roll have some effect on yaw but the effect is estimated to be less than $0.1^\circ$. This bias is less than methodological uncertainty which in most cases is estimated to be about $\pm 0.1^\circ$.

V. Conclusion

Microwave satellite data are used to retrieve a variety of hydrological products including precipitation rate, total precipitable water, snow cover, tropospheric humidity, precipitable water and cloud liquid water. MW data are prone to different errors such as geolocation, calibration, and scan biases. In this study we investigated and corrected the geolocation errors of the data from the microwave instruments (AMSU-A, -B, and MHS) aboard the satellites in the NOAA POES program. The spatial resolution of the MW data is very coarse so that the accuracy of their geolocation can not be easily determined using simple methods like superimposing coastlines on the satellite data. The main purpose of this work was to develop a long-term climate data record from microwave satellite data [11]. Currently, no geolocation correction is performed on data from MW instruments aboard the NOAA satellites.

We used the difference between ascending and descending observations along the coastlines to quantify the geolocation error in terms of the satellite attitude, i.e. pitch, roll, and yaw, then calculated the new geographical coordinates and scan/local zenith angles using the new attitudes. The main findings of this study are as follows: NOAA-15 AMSU-A2 sensor is mounted about $1.2^\circ$ off cross-track, and about $0.5^\circ$ off negative along-track, NOAA-16 AMSU-A1 and -A2 are mounted about $0.5^\circ$ off negative alongtrack, and NOAA-18 AMSU-A2 is mounted more
than 1° off negative alongtrack. The new geolocation represents a significant improvement over the NOAA L1b in consistency as well as attitude adjustments by channels. The accuracy of the new dataset is estimated to be within ±2 km, ±0.1° error in the attitudes.

Because smoothing with an effectively long time constant was applied to reduce the noise, it is noted that relatively shorter period variations in pitch, roll, or yaw are not captured by design. Analysis of pointing errors for the Tropical Rainfall Measuring Mission (TRMM) satellite [22] when using similar attitude control aboard showed short term attitude variations on typically the order ±0.05°, but occasionally as large as 0.2 to 0.4° when Sun interference is encountered in the Earth Sensor Assembly. It is also noted that systematic seasonally changing latitude dependent errors could be expected from systematic Earth horizon radiance variations. On TRMM these showed up in roll, on the order of 0.05 degrees, but for the NOAA polar orbiter geometry these effects would be expected to show up mainly in pitch. Analyzing such shorter term and ascending/descending and latitude dependent error sources is beyond the scope of this study. One of the main restrictions of this study was that very few references are available about the NOAA aboard attitude control performance.

APPENDIX

GEOLOCATING SATELLITE DATA

The main scope of this appendix is to briefly explain the geolocation process for the satellite data. The relations explained in this appendix are mostly based on geocentric coordinate systems. In this study we calculated all the quantities including subsatellite point, latitude and LZA in geodetic system. However geodetic system requires sophisticated calculations that cannot be explained here.

The first step in geolocation is to calculate the satellite state vectors using TLE data and a propagation model. The satellite state vectors are first defined in an Earth-Centered Inertial coordinate system (ECI). In this system, see Figure 16, the $Z_{ECI}$ axis points along the spin axis of the Earth. The $X_{ECI}$ axis points from the Earth’s center to the vernal equinox, at the intersection of the Earth’s equatorial plane and the ecliptic plane of the Earth’s orbit around the Sun. The $Y_{ECI}$ Axis is in the Earth’s equatorial plane perpendicular to $X_{ECI}$ Axis. For this discussion the Earth’s spin axis is considered as “true-of-date” and we ignore the detailed effect on the inertial coordinate definition of the Earth’s spin axis precession and nutation over time. The Earth-Centered, Earth-Fixed (ECEF) is similar to ECI but the x-y plane is rotated so that x-axis points to the Greenwich meridian. ECEF rotates with the Earth, therefore coordinates of a point fixed on the Earth does not change. The relation between ECI and ECEF coordinate systems are shown in Figure 16. The following equations are used to convert from ECI to ECEF coordinate system:

\[
X_{ECEF} = X_{ECI} \cos(G) + Y_{ECI} \sin(G) \quad (2a)
\]

\[
Y_{ECEF} = Y_{ECI} \cos(G) - X_{ECI} \sin(G) \quad (2b)
\]

\[
Z_{ECEF} = Z_{ECI} \quad (2c)
\]
where, $G$ is the Greenwich Sidereal Hour angle, the angle between Greenwich meridian and vernal equinox, that is a function of time. The ECEF is used to project the satellite position to the Earth’s surface and geolocate the satellite data. In a geocentric coordinate, latitude ($\phi$) and longitude ($\lambda$) of the subsatellite point are defined as follows, see Figure 16:

$$\tan \phi = \frac{Z}{\sqrt{X^2 + Y^2}}$$  \hspace{1cm} (3a)

$$\tan \lambda = \frac{Y}{X}$$  \hspace{1cm} (3b)

In the geocentric system, the subsatellite point is defined as the intersection of the vector that points from the satellite position to the Earth’s center. But in the geodetic system, the subsatellite point is defined the intersection of the vector that is originated from the satellite position and is normal to the Earth’s surface. Moreover, the geocentric latitude is defined as the angle between the vector that points from the spot location to the earth’s center and the equatorial plane, but the geodetic latitude is defined as the angle between the normal vector to the Earth’s surface at the spot location and the equatorial plane.

The local zenith and scan angles are very important for radiative transfer calculations as they directly effect the optical path length and also the computations for the polarized components of the outgoing radiance received by the sensor. The scan angle is the angle between the nadir pointing vector, i.e. the vector that points to the subsatellite point, and the local pointing vector, see Figure 16. The new scan angle is simply the nominal scan angle plus the roll offset. The local zenith angle (LZA), also known as satellite zenith angle and earth incidence angle, is defined as the angle between the satellite antenna boresight direction and normal to the Earth’s surface at the spot location, see Figure 16(b), and can be calculated as follows:

$$\cos (\theta) = \frac{-R \cdot \hat{n}}{\|R\| \|\hat{n}\|}$$  \hspace{1cm} (4)

The surface normal can be calculated by taking the gradient of the Earth’s ellipsoid:

$$\hat{n} = < \frac{x}{a^2}, \frac{y}{a^2}, \frac{z}{b^2} >$$  \hspace{1cm} (5)

where, $x$, $y$, and $z$ are ECEF coordinate system, $a$ and $b$ are respectively the semi-major (equatorial) and semi-minor (polar) axes of the Earth’s ellipse. NOAA uses World Geodetic Survey 1972 (WGS-72), therefore $a = 6378.135 \text{ km}$ and $b = 6356.75052 \text{ km}$.

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