Semi-Annual Progress Report:

The Development of AMSU FCDR's and TCDR's for Hydrological Applications

Project Funding Period: May 1, 2010 – April 30, 2013

Reporting Period: May 1, 2011 – October 31, 2011

Principal Investigators: Ralph Ferraro and Huan Meng
NOAA/NESDIS/STAR/CoRP/Satellite Climate Studies Branch
College Park, MD

Scientific Staff: Wenze Yang, Chabitha Devaraj, Isaac Moradi
Cooperative Institute for Climate and Satellites (CICS), College Park, MD

Project Objectives:

This project will properly characterize the AMSU and MHS sensors to generate FCDR's from the Advanced Microwave Sounding Unit (AMSU); channels 1, 2, 3 and 15 on AMSU-A and all five channels on AMSU-B/MHS. We will then use an existing product generation system to generate TCDR's for hydrological cycle products like precipitable water, rain rate and snow cover. The generation of TCDR's is a necessary step to assess the accuracy of the FCDR's; similar results by multiple methods yield confidence and uncertainty estimates in the CDR's. By project completion, an 11-year (2000 – 2010) AMSU CDR is anticipated. The table below shows the sensors and years of operation that we will use in the project (note that NOAA-15 was placed into operation in 1998, however, there are some uncertainties in sensor health that might prevent us from generating CDR's for 1998 and 1999; additionally, several sensors have limited capability near the end of their data record).

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Year 1 Milestones:

From our original proposal, our milestones for the first year are to:
1. Acquire complete data set of AMSU level 1b for all NOAA-15 through N-19 and MetOp-A
2. Acquire and assemble data and metadata for all satellites
3. Organize and hold Water Cycle CDR workshop; factor in feedback to update proposal plan, including final selection of three viable AMSU calibration methodology
4. Begin SNO and RTM calibration; assess preliminary results
5. Begin asymmetry assessment
6. Implement L1 QC checks
7. Collaborate with other SDS projects
8. Present findings at scientific conferences

**Year 2 Milestones:**
10. Assess robustness of FCDR’s through TCDR generation and analysis
11. Assess the impact of orbital drift
12. Collaborate with other SDS projects
13. Present and publish the findings of this work

**Progress during the Reporting Period:**
Excellent progress continues to be made during the first six months of the second year of this project. Items 1 – 13 below (aligned with the milestones above) summarize our effort and results in this period.

1. Completed in the previous reporting period.

2. We have obtained the metadata information for all satellites from NESDIS/OSPO and the MSPPS project. We sifted through the records and compiled a file with information pertaining to our project such as sensor failure and restoration dates, calibration coefficients modifications, and geolocation processing changes etc. One year of sample metadata in NetCDF format has been generated following the guidelines by the CDR Program. This metadata framework will be finalized towards the end of this project, and the metadata will be included in the final delivery.

3. Completed on March 2 and 3, 2011 in College Park, MD. Expert feedbacks at the workshop helped to improve or confirm the methods we use for the development of CDR’s including cloud clearing method, RTM input data, and calibration approaches etc.

4. We continued the calibration work in this reporting period. Further discussions are in item 9 below.

5. An extensive study has been carried out on AMSU/MHS scan asymmetry; the results are shown in item 9.
6. We have found that AMSU/MHS level 1b data have many short and redundant files. These were removed from the data set to avoid skewed calibration. In addition, quality flags from level 1b files, such as geolocation error and brightness temperature out of range etc., are used to QC the data during calibration. These flags will also be included in the metadata.

7. We continue to collaborate with other SDS projects. See item 12 for further details.

8. See item 13 for a complete list of presentations and manuscripts in preparation.

9. We made significant progress with geolocation correction in the reporting period. The accuracy of geolocation is affected by errors such as satellite attitude errors (pitch, roll, and yaw offsets, or PRY), sensor mounting error, and satellite clock offset, etc. Geolocation error not only dislocates observations, it can also cause bias in sensor scan angle and satellite zenith angle which are important inputs for radiative transfer calculation. In this study, we have chosen to quantify geolocation error with the difference between ascending and descending brightness temperatures (ΔTb) along the shorelines. A perfect geolocation will lead to small ΔTb as a result of diurnal variations in the surface and atmospheric conditions. With the existence of geolocation error, however, ΔTb along the shorelines becomes the difference between land and ocean Tb’s. This difference is quite significant since it is related to the large difference between land and water emissivity in microwave frequencies, considering that land emissivity is very close to 1 while ocean emissivity is about 0.5. By setting appropriate ΔTb threshold and tuning satellite attitudes (PRY), we are able to derive the PRY corrections when the number of coastal pixels exceeding the threshold is minimized. Then the PRY correction is applied to calculate new latitude, longitude, sensor scan angle, and satellite zenith angle using a complex geolocation system. Three sets of geolocation correction are required for AMSU-A since the 4 window channels are on 3 different units: AMSU-A1-1, AMSU-A1-2, and AMSU-A2. Only one set of geolocation correction is needed for AMSU-B and MHS as all 5 channels are on the same unit and hence have the same geolocation error.

Our study shows that NOAA-15 AMSU-A2 (channels 1 and 2) has the largest geolocation error. Figure 1 shows that this unit is mounted about 1.2 degrees negative cross track, so that the instrument does not point to the satellite subpoint when the scan angle is zero. Other problems that we found in the level 1b data are as follows:

- MHS step angle is about 1+1/9 but instead 1+1/10 was used until August 2005. The difference can be up to 30 km for off-nadir pixels.
- The clock offset correction for NOAA-17 both AMSU-A and -B sensors has been turned off. The clock offset has a large impact on geolocation accuracy so that 1
second clock offset is roughly equal to 6 km along track geolocation error.

- NOAA-15 clock offset was not included in level 1b geolocation from satellite launch in 1998 to early 2001. This offset was sometimes more than 2 seconds and could shift data by about 12 km along track.
- The level 1b geolocation package failed to calculate Greenwich Hour Angle (GHA) for about 10 days at the beginning of 2004. Those data have a very large geolocation error with about 1-degree offset in longitude.
- Level geolocation data were in geocentric coordinates instead of geodetic coordinates before year 2007.

All the errors mentioned above have been corrected in this project. Figure 2 compares the ΔTb before and after geolocation correction for NOAA-15 AMSU-A 23.8 GHz.

**Figure 1.** Time series of the satellite attitudes for NOAA-15 AMSU-A 23.8 GHZ (channel 1). AMSU-A2 instrument is mounted about 1.2 degrees negative cross-track, so that the sensor does not point to the nadir when the scan angle is zero. The sensor has a small along track offset as well, about 0.5 degree.

**Figure 2.** Difference between ascending and descending brightness temperatures from NOAA-15 AMSU-A 23.8 GHz channel, (a) before correction; (b) after correction.
We further investigated issues related to scan bias in AMSU-A window channels. The efforts include: 1) tested several clear-sky screening schemes to examine their impact on scan bias characterization; 2) studied the effect of geolocation correction on scan bias; 3) compared the AMSU-A antenna pattern correction scheme developed NOAA/NESDIS with the ATOVS and AVHRR Processing Package (AAPP) scheme produced by European NWP Satellite Application Facilities (SAF), and concluded that the former generally outperforms the latter and hence is used for AMSU-A antenna pattern correction in this project; 4) compared several versions of vicarious cold reference (VCR) approaches and chose the one that is most suitable for characterizing scan bias; 5) developed the C code for generating AMSU-A FCDR including metadata; 6) one year of sample AMSU-A FCDR in NetCDF4 was generated with VCR correction; 7) effort is ongoing to adopt warm reference (VWR) for land calibration.

Figure 3 shows the impact of geolocation on scan bias. The most significant impact of geolocation error on scan bias characterization lies on the erroneous sensor scan angle. Sensor scan angle error will lead to a miscalculated brightness temperature because scan angle directly relates to the ratio between vertical and horizontal polarization. Among the 4 AMSU-A window channels, 50.3 GHz channel is least influenced by geolocation error (Figure 3c) while the other 3 channels (23.8, 31.4, and 89 GHz) suffer from 0.5 to 1.2 K of maximum bias caused by geolocation error (Figure 3a, b, and d).

Figure 4 compares various asymmetry characterization approaches under clear-sky over ocean from 60°S-60°N. These approaches are characterizations using All (all data), Low (a subgroup of data with low precipitable water or PW, low wind speed, and low SST), MPV (most probable value, i.e. a narrow range of data with prevailing PW, wind speed, and SST), and two versions of VCR. The VCR approach is widely used to investigate sensor bias and stability for surface channels. The original VCR approach used third degree polynomial to calculate the coldest brightness temperature. This method is highly sensitive to noise at the low end of brightness temperature and can produce erratic across scan bias patterns. To reduce the sensitivity of the VCR, we modified it to a quadratic polynomial and adjusted the sampling range. The new VCR result is more smooth and comparable to those from other approaches. The thorough study on the scan bias characterization method will help us to develop a sound correction scheme.

We continued the work on characterizing the AMSU-B/MHS cross-track asymmetry for the window channels (89 and 150/157 GHz) during the reporting period. We have included the antenna pattern correction for AMSU-B/MHS channels for conversion of antenna temperature to brightness temperature based on the method and the coefficients provided by AAPP since this is the only approach available. We further
Figure 3. Comparison of cross-scan bias with and without geolocation correction for NOAA-15 AMSU-A at (a) 23.8 GHz, (b) 31.4 GHz, (c) 50.3 GHz, and (d) 89 GHz. The observed data are under clear sky and over tropical and subtropical oceans from 30°S-30°N from year 2008.

Figure 4. Average differences between the simulated and the observed Tb’s using VCR V6 (red line), VCR V4 (blue line), All (red dot), Low (black dot line) and MPV (black dash line) for NOAA-15 AMSU-A at (a) 23.8 GHz, (b) 31.4 GHz, (c) 50.3 GHz, and (d) 89 GHz. The observed data are under clear sky and over oceans from 60°S-60°N from year 2004.
investigated the channel asymmetry patterns using stratification of different environmental conditions. The results show that while 89 GHz is highly sensitive to surface parameters, 150/157 GHz channel is sensitive to both the surface and the atmospheric conditions such as water vapor. In the tropical and subtropical ocean where there is abundant water vapor, the surface is essentially masked out for this channel. Since the complex surface is a major source of difficulty in window channel calibration, the sensitivity of 150/157 GHz to water vapor is an advantage to our CDR effort. Figure 5 and Figure 6 show the scan bias of the 89 and 150/157 GHz channels respectively for low wind speed and low PW (Figure 5) and for low wind speed and high PW (Figure 6). The stratification results indicate that different approaches are required for the characterization of the scan bias of the two channels.

![Figure 5](image1.png)  
**Figure 5.** Average scan bias observed in 2008 NOAA-18 MHS channels 1 and 2 with low wind speed, low precipitable water, and different ranges of sea surface temperature (SST).

![Figure 6](image2.png)  
**Figure 6.** Average scan bias observed in 2008 NOAA-18 MHS channels 1 and 2 with low wind speed, high precipitable water, and different ranges of sea surface temperature (SST).

We also implemented the correction technique described in the NOAA-KLM User Guide for NOAA-15 AMSU-B instrument to correct for the onboard Radio Frequency
Interference (RFI). This RFI was caused by material mismatch in the S-band antennas that damaged certain parts and compromised the electrical path. We investigated the effects of RFI in the NOAA-15 AMSU-B sensors by analyzing the scan bias over tropical and subtropical ocean under clear-sky before and after the RFI correction for all the channels. Figure 7 presents the results of NOAA-15 AMSU-B scan bias characterization from 2001. It is noticed that the observed asymmetry before RFI correction was higher in channels 2 and 4 as expected, and this effect was significantly reduced after the correction. NOAA-17 also has minor onboard RFI and is corrected with the same processing system.

**Figure 7.** Average scan bias observed in 2001 NOAA-15 AMSU-B channels 1 and 2 before and after RFI correction.
10. Not started yet; will be worked in the second half of year 2.

11. Not started yet; will be worked in the second half of year 2.

12. We continue to work closely with our colleagues at NOAA/NESDIS (C. Zou, PI) and Colorado State University (C. Kummerow, PI) on their AMSU (sounding channels) and SSM/I CDR efforts. W. Yang from our project attended the GPM Intersatellite Calibration (X-Cal) Working Group meeting in July and gave a presentation about the AMSU/MHS CDR project. The SSM/I CDR team is actively involved in the X-Cal effort. W. Yang also had a very productive visit to the SSM/I CDR team in July 2011 through a NOAA student exchange program. M. Sapiano from the SSM/I team visited us in September 2011 and gave a seminar about their CDR effort. We also continue to acquire PATMOS-x data from A. Heidinger.

13. The following presentations were given and publications written during the reporting period:


- W. Yang - Development of AMSU-A Fundamental CDR’s. GSICS users’ workshop, Oslo, Norway, September, 2011.

- C. Devaraj - Characterizing scan bias in Advanced Microwave Sounding Unit-B
(AMSU-B) and Microwave Humidity Sounder (MHS). CICS-UMD seminar, September 2011.

- I. Moradi - Geolocation Correction for NOAA POES Passive Microwave Instruments. ESSIC seminar, University of Maryland, College Park, MD, October, 2011.

Papers in preparation


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1. Acquire complete data set of AMSU level 1b for all NOAA-15 through N-19 and MetOp-A
2. Acquire and assemble data and metadata for all satellites
3. Organize and hold Water Cycle CDR workshop; factor in feedback to update proposal plan, including final selection of three viable AMSU calibration methodology
4. Begin SNO and RTM calibration; assess preliminary results
5. Begin asymmetry assessment
6. Implement L1 QC checks
7. Collaborate with other SDS projects
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Year 2 Milestones:
2. Assess robustness of FCDR’s through TCDR generation and analysis
3. Assess the impact of orbital drift
4. Collaborate with other SDS projects
5. Present and publish the findings of this work

**Progress during the Reporting Period:**

We continue to make excellent progress during the last six months of the second year of this project. All milestones from Year 1 are essentially achieved with minor tasks to complete such as acquiring a short period of ancillary data due to data availability issue. Items 1 – 5 below (aligned with the Year 2 milestones) summarize our effort and results in this period.

**Milestone 1.** Some components of the system for generating FCDR have not been finalized yet, especially inter-satellite calibration. The components that have been developed are described below.

We have finished the geolocation correction for all AMSU-A, AMSU-B, and MHS sensors aboard the NOAA POES satellites (NOAA-15 to -19). The correction algorithm is schematically explained in Figure 1.

The results show that NOAA-15 AMSU-A2 sensor is mounted about 1.2 degrees negative cross track, and about 0.5 degree positive along track. NOAA-16 AMSU-A1 and -A2 are mounted about 0.5 degree positive along track, and NOAA-18 AMSU-A2 is mounted more than 1 degree positive along track. Table 1 gives the average geolocation error and the Local Zenith Angle (LZA) error caused by geolocation problem for the AMSU/MHS sensors.

A new geolocation dataset has been developed for MW instruments aboard NOAA POES satellites. The new dataset includes latitude, longitude, scan angle, and local zenith angle. This dataset will be used throughout the project for scan asymmetry, bias correction and inter-calibration.
Our geolocation correction method cannot be applied to MetOp-A data as the geometry of the MetOp-A orbit is different from NOAA satellites and our method introduces some extra geolocation error. In addition, our investigations show that the MetOp-A geolocation error is rather small, less than a few kilometers, and does not introduce large error in scan bias or LZA.

We have also finished AMSU-A scan bias characterization and correction. In addition, the possible reasons for the bias were investigated and the result summarized in Yang et al., 2012. AMSU-A scan bias is characterized by taking the difference between the observed brightness temperatures (Tb) and simulated Tbs over low and mid-latitude oceans (60°S-60°N) under clear sky. The difference is adjusted across scan line by its nadir value so there is no systematic difference at nadir. The bias is asymmetric relative to the nadir, and there
is little difference between ascending and descending nodes. The asymmetry pattern is stable through several years of data examined, but varies noticeably for different satellites. The asymmetry appears to be a result of sensor errors especially polarization related issues. By introducing the vicarious cold reference (VCR) approach and stratifying at the most probable value (MPV) level, the cross-scan asymmetry of AMSU-A window channels from these approaches is illustrated in Fig. 2. A third method, vicarious hot reference (VHR), was also adopted to characterize cross-scan asymmetry in the Amazon region (Fig. 3) and provides a reference bias point over radiometrically warm land.

Two approaches are used to correct cross-scan bias: one is based on the characterization of the bias at cold end (Fig. 2) and warm end (Fig. 3), i.e., two-point correction; and the other uses three-point correction by adding the bias at MPV. The corrected Tbs are shown in Fig. 4 for the four AMSU-A channels. Little residual bias is observed for all observations and the individual reference points, i.e. MPV, VCR, and VHR (not shown).

Figure 2. Mean difference between the simulated brightness temperature and the observed under clear-sky over ocean in mid- and low-latitude for NOAA-15 AMSU-A (a) 23.8, (b) 31.4, (c) 50.3 and (d) 89 GHz. Results are for all observation (All), most probable value stratification (MPV), and vicarious cold reference (VCR). The mean bias is relative to nadir.
Figure 3. Mean difference between simulated and observed NOAA-15 AMSU-A brightness temperatures at 23.8, 31.4, 50.3 and 89 GHz over Amazon and under clear sky.

Fig. 4. Similar to Fig. 2 after the three-point bias correction.
The scan bias in MHS window channels (89 GHz and 157 GHz) is characterized by comparing the observed and the simulated Tbs over ocean under clear sky. The simulation is performed with CRTM and two sets of reanalysis data as input, i.e. ERA-interim and CFSR. It is important to point out that the resolution of ERA-interim is about 0.7 degree and CFSR 0.5 degree. Figure 5 compares the cross-scan bias derived with the two sets of data. It is observed that there is a clear concave shaped scan dependence in the two channels when ERA-interim data is used as input while the concavity is significantly reduced in 89 GHz and essentially non-existent in 157 GHz when CFSR data is used with CRTM. The systematic concave shaped bias appears to be a bias introduced by the mismatch of scale between the reanalysis data grid and the satellite field-of-view (FOV). MHS FOV sizes range from 16 km x 16 km at nadir to 26 km x 52 km at limb and are more comparable to the scale of CFSR than to ERA-interim. The scale induced bias is more pronounced at 89 GHz than at 157 GHz, possibly because the latter is more sensitive to water vapor and does not have as much influence from the surface as the former. From the study on AMSU-A scan bias, it is clear that certain biases, such as polarization related errors, are aggravated by the polarized surface and suppressed by the depolarizing atmosphere.

![Figure 5](image.png)

Figure 5. Mean difference between observed Tb from 2008 NOAA-18 MHS channels and CRTM simulations with ERA-interim and CFSR data as input.

The MHS window channels data are further stratified by wind speed and water vapor. The left-right pairwise differences of the stratified data are displayed in Fig. 6, where low humidity is 0.0-2.5 cm, high humidity 4.0-7.0 cm; and low wind speed 0.0-3.0 m/h, most probably value (MPV) wind: 3.0-7.0, high wind 7.0-12.0 m/h. The figure shows that, for both channels, the sensor has the highest scan asymmetry over calm ocean with dry atmosphere. Calm ocean acts as a specular surface that has strong polarization which indicates again that the scan asymmetry is related to polarization. Dry atmosphere minimizes the depolarization effect from water vapor and allows considerable contributions from polarized ocean surface, hence inducing larger bias as a result of polarization related problems. The NEAT of these channels are 1 K. Figure 6 shows that the cross-scan asymmetry is less than NEAT even in the worst scenario for both channels.
Figure 6. Asymmetry observed in 2008 NOAA-18 MHS channels for low and high humidity (pw) stratification cases for different ranges of wind speed.

We started working on the scan asymmetry for AMSU-B/MHS water vapor channels. Previous studies show that the scan asymmetry for AMSU-B/MHS water vapor channels is expected to be very small, less than NEΔT. Therefore, in the first step we will investigate the difference between $T_b$ of left (pixels number 1 to 45) and right (pixels number 46 to 90) sides of the scan lines to confirm the conclusions from the previous studies.

Throughout the history of POES and MetOp satellites, there have been three pairs of satellites that overlap with each other in orbit due to orbital drift: NOAA-15 and -16 (Aug 08), NOAA-17 and MetOp-A (Apr, May 09), and NOAA-18 and -19 (Sept 09). These overlapping pairs of satellites/periods will first be investigated during inter-calibration. SNO and Double Difference are two approaches we will employ for this purpose. Once inter-calibration is completed, we will develop a 11-year FCDR for the AMSU-A window channels and all the AMSU-B/MHS channels.

**Milestone 2.** MSPPS products are used to demonstrate the robustness of the AMSU-A asymmetry correction method. The improvement is evident in the products when the asymmetry correction is applied. Figure 7 compares two MSPPS products, cloud liquid
water (CLW) and emissivity at 31.4 GHz, before and after the asymmetry correction. Before correction, the asymmetry effect is clearly seen in the CLW image (Fig. 7a) with drier atmosphere at the left edge of the swath and wetter at the opposite edge, which makes the cloud system unrealistic. For instance, compared to the uncorrected CLW image, the corrected version has a much more coherent cloud structure above the vast ocean area at mid- and high-latitudes of Southern Hemisphere (Figure 7b). The corrected 31.4 GHz emissivity (Figure 7d) also exhibits much improvement in its cross-scan symmetry than the original (Figure 7c). This is most noticeable in the 15°N to about 37°N latitude bands where the lower emissivity is asymmetric at the two limbs in the original image but becomes comparable after correction. In summary, asymmetry correction makes the angular distribution much more symmetric and realistic. It is worth noting that the CDR asymmetry cross-scan approach outperforms the current operational correction approach used in MSPPS, which is essentially a one-point correction. The significant reduction in asymmetry in the MSPPS products proves that the bias correction scheme for AMSU-A window channels is very effective.

Figure 7. Geographical distribution of cloud liquid water (upper panels) and land surface emissivity at 31.4 GHz (lower panels), derived through MSPPS. Images (a) and (c) are the original products; and (b) and (d) are with asymmetry correction. For clarity, the 31.4 GHz emissivity is shown over the continent of Africa instead of the entire globe.

Milestone 3. The effect of orbital drift on cross-scan bias is examined by comparing the
bias from different time periods. Figure 8 shows the cross-scan bias in the NOAA-15 AMSU-A window channels from years 2000, 2004, and 2008 along with the bias in the same channels from NOAA-16, NOAA-18, and MetOp-A. While there is noticeable difference in bias patterns from different satellites, there is minimal bias change with NOAA-15 from the different years, even though there is about 2.5 hours drift in NOAA-15’s equator crossing time during the eight years. Based on this observation, we conclude that the impact of orbital drift on cross-scan bias is negligible.

Figure 8. Cross-scan bias in mid- and low-latitude mean observed brightness temperatures at NOAA-15, 16, 18 and MetOp-A (M02) AMSU-A (a) 23.8, (b) 31.4, (c) 50.3 and (d) 89 GHz over ocean under clear-sky. Results are calculated using a whole month of data in the years listed in the figure legend.

**Milestone 4.** We continue to work closely with our colleagues at NOAA/NESDIS (C. Zou, PI; A. Heidinger, PI). Some of our geolocation correction results were shared with Zou’s group when they investigated similar issues. The outcome from our geolocation study can be applied to the sensors they work with in their future study. At our request, Heidinger provided one month of PATMOS-x data from 2010 to use in our study on scale impact from reanalysis data. I. Moradi from our project attended the GPM Intersatellite Calibration (X-Cal) Working Group meeting in November and gave a presentation about the AMSU/MHS CDR project.
**Milestone 5.** The following presentations were given and publications submitted during the reporting period:

**Presentations:**


**Papers submitted:**
