Semi-Annual Progress Report:

The Development of AMSU FCDR's and TCDR's for Hydrological Applicati ons

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

Reporting Period: May 1, 2012 – October 31, 2012

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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).

Satellite	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
NOAA-15	May	X	X	X	X	X	X	X	X	X	X	X	X
NOAA-16			Sep	X	X	X	X	X	X	X	X	X	X
NOAA-17					Jun	X	X	X	X	X	X	Dec	
NOAA-18								May	X	X	X	X	X
MetOp-A									Oct	X	X	X	X
NOAA-19												Feb	X

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:

1. Complete eleven-year FCDR (2000 – 2010) for three production paths
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

Year 3 Milestones:

1. Generate final FCDR's and TCDR's for 11-years (2000 – 2010); potentially expand back to 1998 if feasible.
2. Archive FCDR's and TCDR's at NCDC
3. Distribute TCDR's to scientific programs such as PMM, GEWEX and CEOS
4. Present and publish the findings of this work

<u>Progress during the Reporting Period</u>:

We continue to make progress towards the creation of AMSU-A and AMSU-B/MHS FCDR's and TCDR's during the first six months of the third year of this project. All milestones from Year 1 and most from Year 2 have been completed. Items 1 – 4 below (aligned with the Year 3 milestones) summarize our effort and results in this period.

Milestone 1. Some components of the system for generating FCDR are still under development. The components that have been completed 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), and a new dataset corrected for geolocation errors has been generated. The dataset includes latitude, longitude, local zenith angle, and sensor scan angle. The methodology for the geolocation correction is published in Moradi et al., 2012.

A method has been developed for the characterization, correction and verification of the cross scan asymmetry of AMSU-A window channels (Yang et al., 2012). This method utilizes a three-point correction approach: vicarious cold reference (VCR), most probable

value (MPV), and vicarious hot reference (VHR). It was successfully applied to 23.8 GHz and 31.4 GHz channels. However, since the coldest brightness temperatures (Tb) at the 50.3 GHz and 89 GHz channels generally occur over land in the polar regions, VCR does not represent the lower limit of the Tb dynamic range. To overcome this problem, much similar to using the Amazon area for scan bias correction at the warm end, targeted areas in Antarctica and Greenland were chosen to characterize and then correct bias at the cold end. Figure 1 presents the pentad means of the cross scan surface temperatures which are retrieved using AMSU-A brightness temperatures including the 50.3 GHz. The curve that used VCR (red) in the asymmetry correction for the 50.3 GHz channel shows more cross scan variation than the one that used polar data (blue) for correction. Figure 2 shows the correction curves for four beam positions from NOAA-15 AMSU-A window channels, where different methods were used for the characterization of 23.8 and 31.4 GHz channels from those used for 50.3 GHz and 89 GHz channels as discussed above.

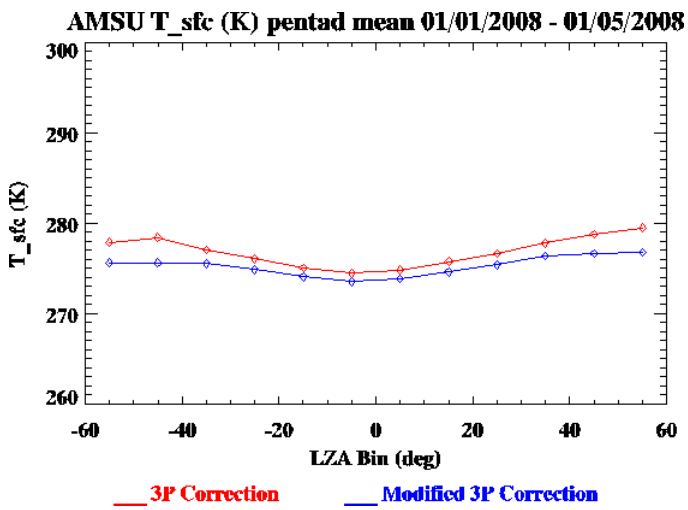

Figure 1. Pentad mean of surface temperature (Ts) vs. local zenith angle (LZA) from Jan 1-5, 2008.Ts is a level-2 product and retrieved using brightness temperatures (Tb) at 23.8, 31.4, and 50.3 GHz. The red curve uses Tb's that are corrected using the 3-point method: VCR, MPV, and VHR. The blue curve uses modified 3-point method where the 50.3 GHz is corrected using polar data, MPV, and VHR.

The asymmetry of the AMSU-B and MHS channels were investigated using the differences between the brightness temperatures of right and left sides of the scan. The differences

were averaged over the tropical region (ocean for channels 1 and 2, and global for channels 3-5). The results for NOAA-15 AMSU-B are shown in Fig. 3. Note the NEΔT specification for both AMSU-B and MHS frequencies is 1 K. As shown in Fig. 3, all the channels have a small scan asymmetry close or less than the NEΔT early on but started to exhibit sensor degradation as time progressed. By 2009, all channels had scan asymmetry that exceeded the NEΔT. For instance, the asymmetry in channel 4 is more than 2 K in 2002, about 6 K in 2005, and 12 K in 2009. The asymmetry plots for NOAA-16 (not shown) also reveal serious degradation issues in the water vapor channels (channels 3-5). However, the asymmetry of NOAA-16 window channels (channels 1 and 2) is within NEΔT throughout the years.

Likewise, the asymmetry of the rest of the AMSU-B and MHS sensors (onboard NOAA-17, -18, -19 and Metop-A) is less than 1 K for all the channels in the study period with only one exception - Metop-A channels 4 and 5 display clear asymmetry that is not caused by sensor degradation (Fig. 4).

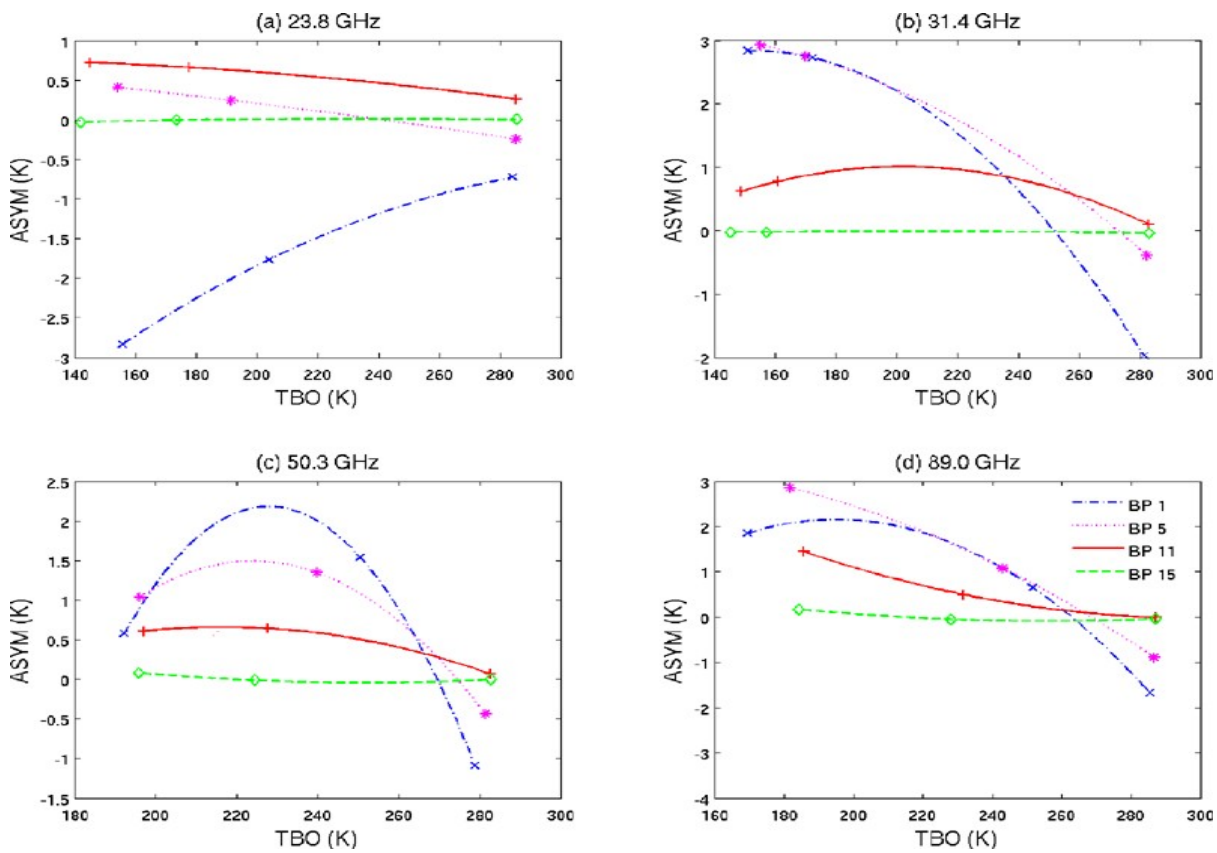

Figure 2. Cross-scan asymmetry (ASYM) as a function of observed brightness temperature (TBO) for NOAA-15 AMSU-A (a) 23.8, (b) 31.4, (c) 50.3 and (d) 89 GHz. For each channel and beam position (BP), the ASYM-TBO relationship is developed at three reference points. For 23.8 and 31.4 GHz, the three points are: vicarious cold reference (VCR), most probable value (MPV) and vicarious hot reference (VHR), with VCR denoting the lowest TBO, and VHR the highest TBO. For 50.3 and 89 GHz, the reference point of VCR is replaced by observations and simulations in polar land areas. Note only 4 out of 30 beam positions are shown for each channel.

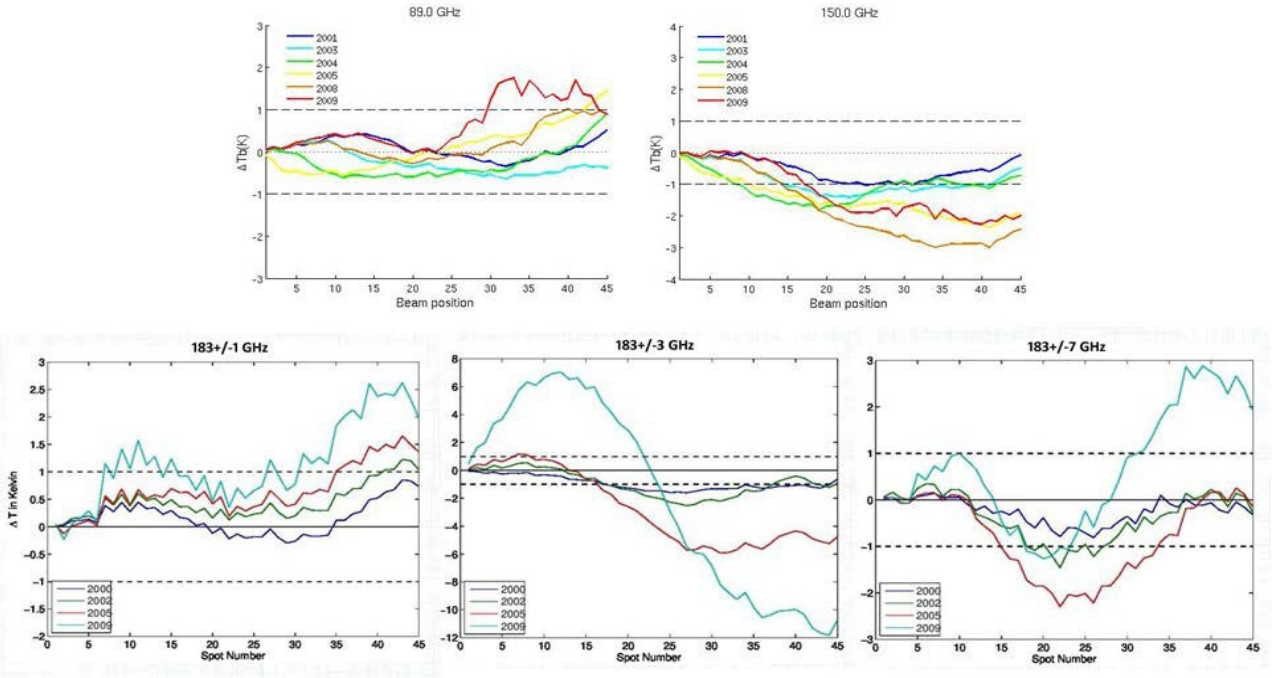

Figure 3. Cross-scan asymmetry of NOAA-15 AMSU-B channels

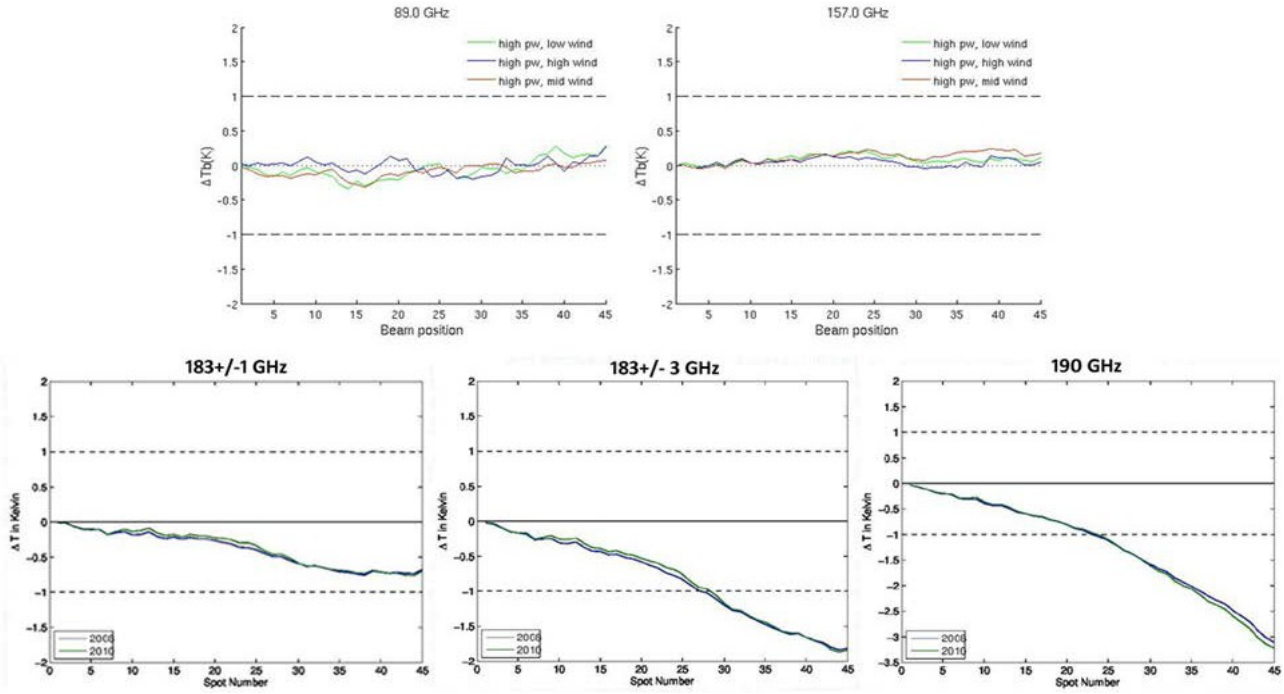

Figure 4. Cross-scan asymmetry of Metop-A MHS channels

Inter-satellite calibration for AMSU-A window channels was started in this period, beginning with the global simultaneous nadir overpass (SNO) method. Most SNO events occur in polar regions. However, global SNO can occur when two satellites take the same equatorial overpass time because of orbital drift. Figure 5 shows the three pairs of satellites that had global SNO during certain periods from 2000 to 2010: NOAA-15 and NOAA-16, NOAA-17 and Metop-A, and NOAA-18 and NOAA-19. For AMSU-A global SNO, the criteria for collocated data are less than 50 s and 50 km apart. One exception is NOAA-18 and -19 for which the distance limit is 75 km due to the scarcity of global SNO data. Figure 6 presents the geographical distribution of the 23.8 GHz Tb difference from the global SNO collocated data set. The Tb differences are generally within 3 K with the extreme values mostly along the coast or in the polar regions.

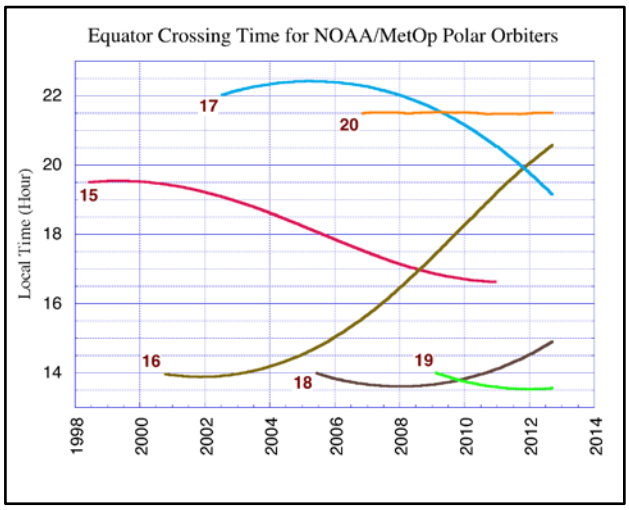

Figure 5. Equatorial crossing times (LST) for NOAA-15 through NOAA-19, as well as MetOp-A (20). This is for ascending nodes.

While global SNO allows direct comparison of the observations from two sensors onboard different satellites, the approach is limited to a short time period when the satellites meet due to orbital drift. Polar SNO, on the other hand, provides the means to compare sensors onboard different satellites throughout the sensors' operational lives. The limitation of the polar SNO method is that it only represents sensor differences in certain part of the measurement dynamic range, usually at the lower end. Figure 7 shows the time series of SNO data at the four AMSU-A channels between NOAA-15 and the other satellites, i.e. NOAA-16 to -19 and Metop-A. Figure 7(a) and (b) reveal that NOAA-17 channel-1 and -2 appear to have some quality issues between April 2006 and February 2008. In addition, further study is required to explain the cycles in the NOAA-15/-16 and NOAA-15/-18 time series.

Inter-satellite calibration is also carried out for AMSU-B and MHS sensors using global SNO data (Figure 8). As shown in the figure, the Tb difference between the different satellite pairs is a function of frequency. Most Tb differences are less or close to 2 K. The only exception is channel 5 between NOAA-15 and -16 which is as large as 5 K.

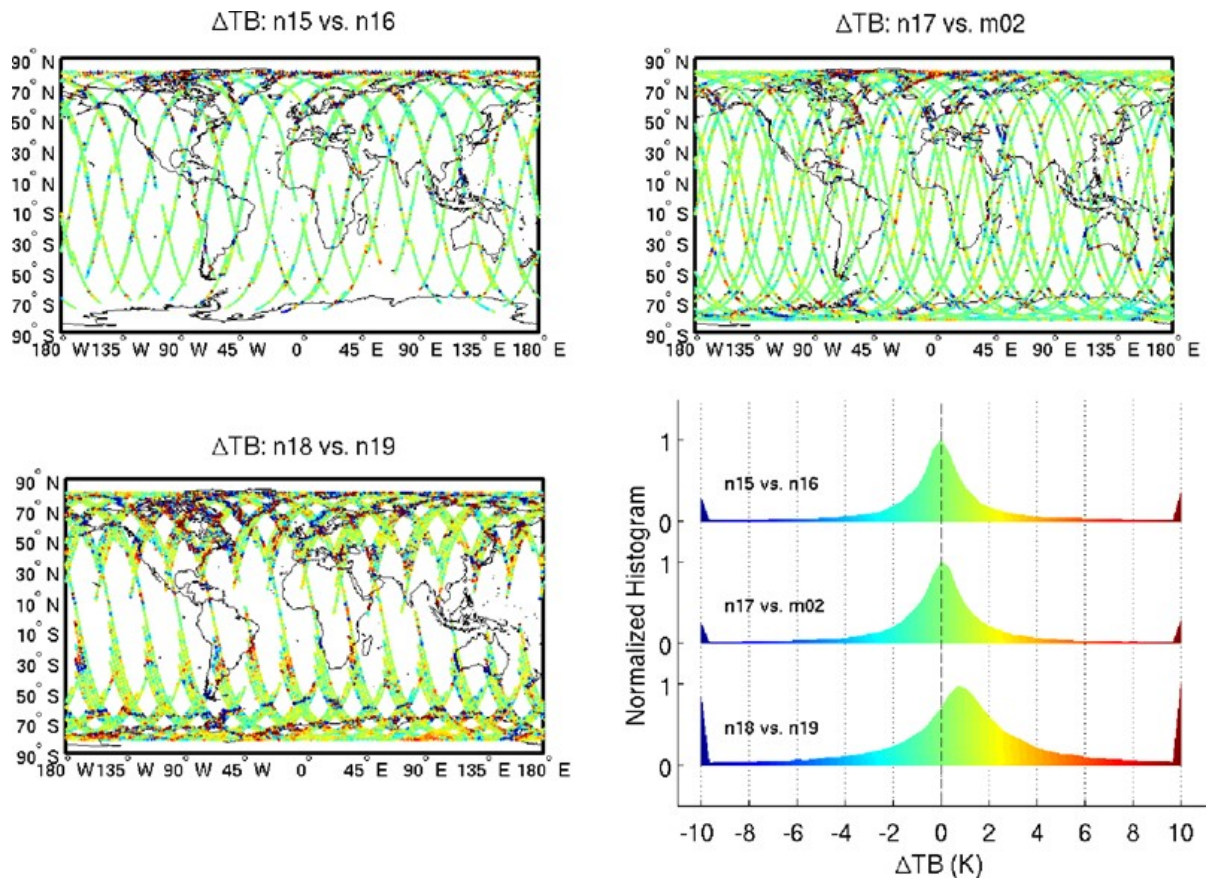

Figure 6. Geographical distribution of the 23.8 GHz brightness temperature difference when global SNO's occurred. SNO is defined as observations from two satellites that are less than 50 s and 50 km apart (the NOAA-18 and -19 pair uses a distance limit of 75 km).

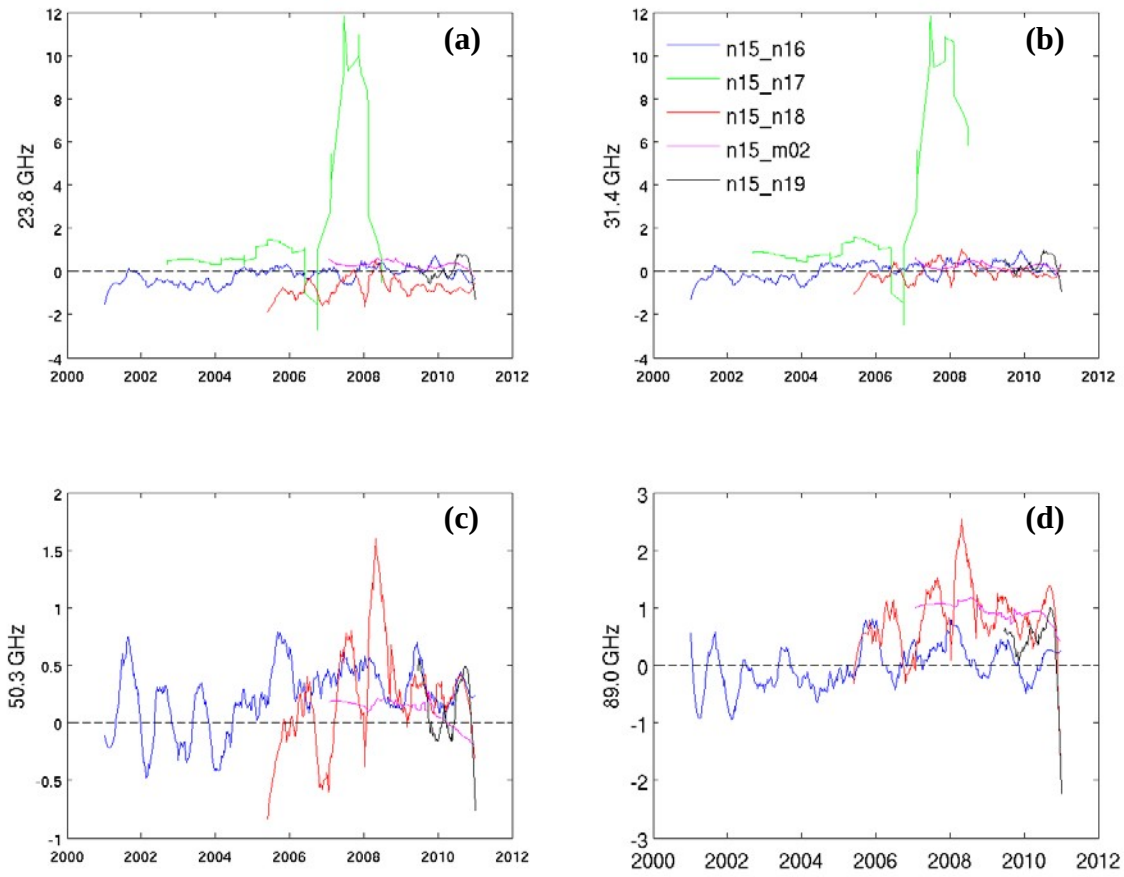

Figure 7. Time series of brightness temperature differences of SNO pairs between AMSU-A onboard NOAA-15 and NOAA-16 through NOAA-19 and Metop-A, (a) 23.8, (b) 31.4, (c) 50.3 and (d) 89 GHz.

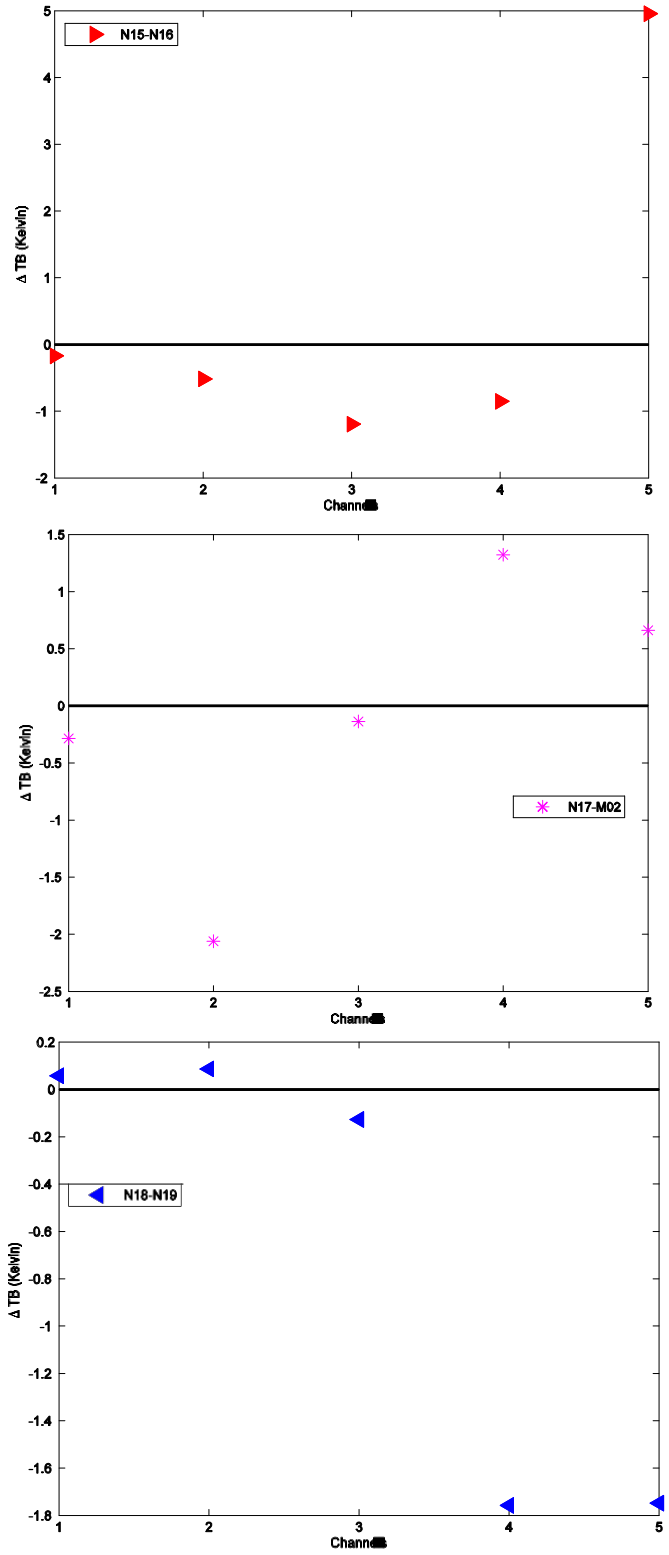

Figure 8: Inter-satellite calibration of AMSU-B and MHS sensors using global simultaneous nadir observations.

Milestone 2. This task is pending the completion of Milestone 1.

Milestone 3. A beta data set was generated and made available to the public during this period. The set is composed of 2008 NOAA-18 AMSU-A window channels Tb and MHS all channels Tb as well as some ancillary variables. The data include geolocation correction and cross-scan bias correction (for AMSU-A). The next beta data set will include level-2 products as a test TCDR set.

Milestone 4. The publications and presentations from this reporting period are listed below.

Publications:

Yang, W., H. Meng, R. Ferraro, I. Moradi, C. Devaraj, Cross scan asymmetry of AMSU-A window channels: characterization, correction and verification. IEEE Transactions on Geoscience and Remote Sensing, doi:10.1109/TGRS.2012.2211884.

Moradi, I., H. Meng, R. Ferraro, S. Bilanow, Correcting geolocation errors for microwave instruments aboard NOAA satellites. IEEE Transactions on Geoscience and Remote Sensing. In print.

Presentations:

Moradi, I., H. Meng, R. Ferraro, W. Yang, C. Deveraj, Climate Data Records from Microwave Satellite Data: A New High Quality Data Source for Reanalyses, 4th WCRP International Conference on Reanalyses, Silver Spring, Maryland, USA, May 7-11, 2012.

Yang, W., H. Meng, R. Ferraro, I. Moradi, C. Devaraj, The Development of AMSU-A Fundamental CDR's, GPM Xcal meeting, Ann Arbor, MI, Jul 11-12, 2012.

Yang, W., H. Meng, R. Ferraro, I. Moradi, C. Devaraj, Cross scan asymmetry of AMSU-A window channels: characterization, correction and verification, CALCON meeting, Logan, UT, Aug 26-30, 2012

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Reporting Period: May 1, 2013 – October 31, 2013

Principal Investigators: Ralph Ferraro[1] and Huan Meng[1]

Scientific Staff: Wenze Yang[2], Isaac Moradi[2], Jim Beauchamp[2], Tom Smith[1]

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College Park, MD
[2]Cooperative Institute for Climate and Satellites (CICS), College Park, MD

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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).

Satellite	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
NOAA/15	May	X	X	X	X	X	X	X	X	X	X	X	Sep
NOAA/16			Sep	X	X	X	X	X	X	X	X	X	X
NOAA/17					Jun	X	X	X	X	X	X	Dec	
NOAA/18								May	X	X	X	X	X
MetOp/A									Oct	X	X	X	X
NOAA/19												Feb	X

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 NOAA-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
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Year 2 Milestones:

1. Complete eleven-year FCDR (2000 – 2010) for three production paths
2. Assess robustness of FCDR's through TCDR generation and analysis
3 Assess the impact of orbital drift
4. Collaborate with other SDS projects
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Year 3 Milestones*:

1. Continue the development of AMSU and MHS FCDR and TCDR.
2. Generate AMSU and MHS FCDR beta data sets and distribute to scientific programs such as PMM, GEWEX and CEOS
3. Present and publish the findings of this work

Year 4 Milestones

1. Generate final FCDR's and TCDR's for 11 years (2000 – 2010); potentially expand back to 1998 if feasible.
2. Archive FCDR's and TCDR's at NCDC
3. Present and publish the findings of this work

<u>Progress during the Reporting Period</u>:

We continue to make progress towards the creation of AMSU-A and AMSU-B/MHS FCDR's and TCDR's during the first half of the forth project year. All milestones from Year 1 to Year 3 have been completed. Items 1 – 3 below (aligned with the Year 4 milestones) summarize our effort and results in this period.

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* Year 3 funding has been divided into two years due to a NCDC approved project extension and lack of full funding in Year 3.

Milestone 1. In the previous reporting period, we established the threshold for standard deviation (STD) of brightness temperature difference (ΔTb) in order to achieve homogeneity for simultaneous nadir overpass (SNO). We also identified warm target contamination as a serious issue for the SNO data. Building on these results, we adopted Zou's (Zou et al., 2006, 2009, 2010, and 2011) Sequential Adjusting Process (SAP) to inter-calibrate AMSU-A window channels and mitigate warm target contamination. SAP was originally developed and applied to create AMSU-A sounding channels FCDR's. Its basic procedure includes the following steps:

i. Generate intermediate SNO data set, which includes 142 variables for each SNO events
ii. Calculate SNO coefficients (α, β, a0, a1)
iii. Set δR_{N15} (= 0) and μ_{N15}, calculate δR_k *and* μ_k , k = 1 to 5
iv. Generate Level-1c radiances for all six satellites using recalibration coefficients
v. Compute tropical ocean mean brightness temperature (Tb) difference (ΔTb) time series for available overlapping pairs
vi. Change the value of μ_{N15} and repeat steps 3, 4, and 5
vii. Stop when the summation of root mean square of ΔTb is at the minimum

Figure 1 illustrates the process to iteratively search for μ_{N15}. Parameters δR_k *and* μ_k are calculated by setting μ_{N15} from -25 to 25 (sr m^2 cm^{-1})(mW)$^{-1}$ (step iii above). Then a set of level 1c radiance over the tropical ocean is generated, and compared with that of NOAA-15. Each satellite pair would reach a minimum STD of ΔTb. The minimum averaged STD of ΔTb is selected.

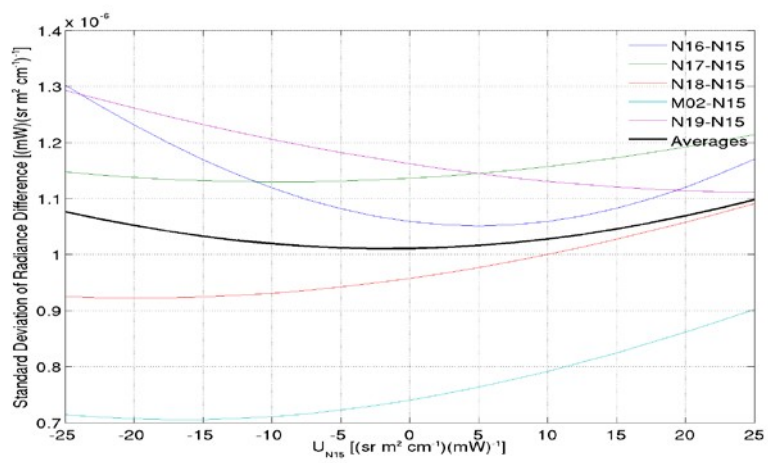

Figure 1. Iterative search for μ_{N15} of 23.8 GHz channel.

Table 1 lists the optimal μ and δR for each satellite and each window channel after μ_{N15} is determined from the iterative process. It is noted that inter-calibrated μ is rather different from the prelaunch μ.

Table 1. Optimal μ and δ*R*.

		N15	N16	N17	N18	M02	N19
μ	**Ch1**	-2.90860	-7.75889	-10.30357	0.54319	-3.12837	0.09178
	Ch2	1.05310	-2.15364	-3.06236	3.79401	-4.42838	-0.79372
	Ch3	-1.98488	-2.46439	-1.69333	-1.77138	-3.13583	-1.12520
	Ch15	-3.98007	-6.70802	-6.35800	-5.85813	-6.16404	-5.65483
δ*R*	**Ch1**	0.000E+00	-4.505E-07	-7.846E-07	1.389E-06	-6.149E-07	-4.975E-07
	Ch2	0.000E+00	1.064E-07	6.151E-08	2.861E-07	-1.104E-07	3.753E-07
	Ch3	0.000E+00	-1.311E-06	-2.104E-06	9.705E-06	-5.078E-06	-4.291E-06
	Ch15	0.000E+00	1.191E-05	-1.983E-06	-4.071E-05	-1.029E-04	-5.833E-05

The optimal μ and δ*R* are applied to calculate inter-calibrated brightness temperatures for all satellites and all years. Figure 2 and 3 respectively show the time series of nadir-only mean Tb over the tropical ocean before and after the correction.

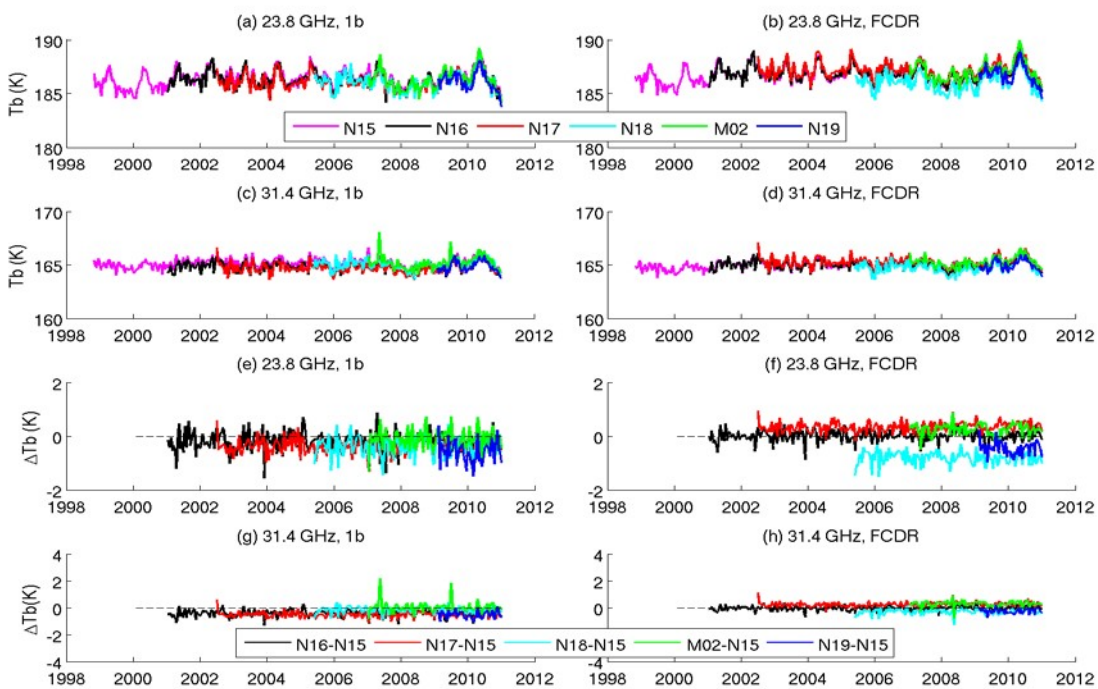

Figure 2. Tropical ocean mean Tb and ΔTb for 23.8 and 30.4 GHz channels. Left panels display the values before correction, while right panels are after correction.

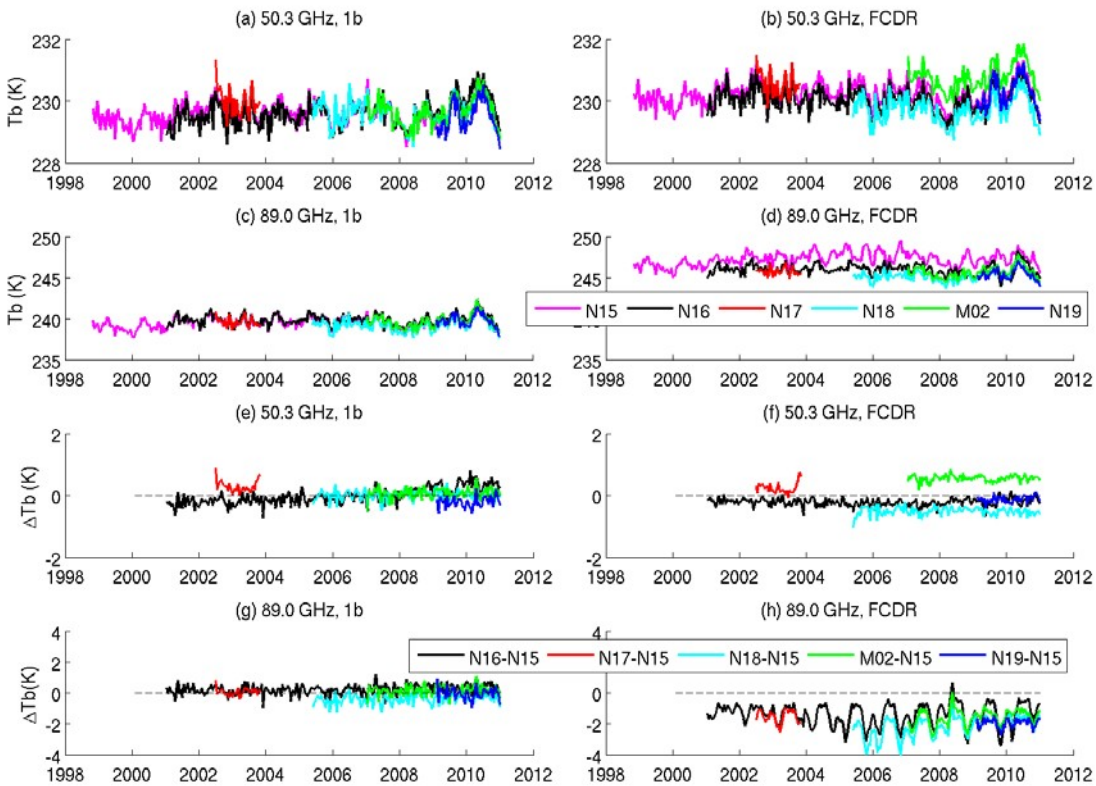

Figure 3. Similar to Figure 2, but for 50.3 and 89.0 GHz channels.

The inter-calibration minimizes the impact of warm target contamination as a result of orbital drift and nonlinearity in the calibration coefficients. Table 2 shows the comparison of the STD of ΔTb calculated from Figure 2(e)-(h) and Figure 3(e)-(h). The reduction in STD is approximately 50% for all satellites and all channels with the exception of 89.0 GHz. NOAA-15 89.0 GHz appears to suffer from frequency shift. Consequently, correction performed using NOAA-15 as reference results in increased STD for the 89.0 GHz channel. Further development is ongoing to appropriately correct this channel.

Table 2. Tropical Ocean STD of ΔTb

	Before				After			
Channel	23.8	31.4	50.3	89	23.8	31.4	50.3	89
N16-N15	0.374	0.263	0.267	0.315	0.217	0.193	0.125	0.716
N17-N15	0.285	0.217	0.191	0.225	0.19	0.191	0.171	0.411
N18-N15	0.386	0.259	0.168	0.337	0.238	0.196	0.129	0.647
M02-N15	0.37	0.384	0.167	0.328	0.215	0.207	0.107	0.518
N19-N15	0.424	0.276	0.174	0.374	0.262	0.186	0.115	0.296

It is worth mentioning that NOAA-16 50.3 GHz displays an upward trend before correction due to bias drift. The trend was carefully removed with an added term in the SAP correction (Zou and Wang, 2011).

AMSU-A inter-calibrated Tbs have been generated following the SAP method with the exception of NOAA-15 89.0 GHz. Since the inter-calibration method also corrects off-nadir measurements, we will perform asymmetry correction to the inter-calibration data in the next reporting period, which will create the final FCDR's and consequently the final TCDR's. It is noted that the asymmetry correction method for AMSU-A window channels has been developed in the previous years of the project. Figure 4 shows a flowchart of the AMSU-A window channel FCDR and TCDR processing system including the top level program and the most important programs in each subsystem:

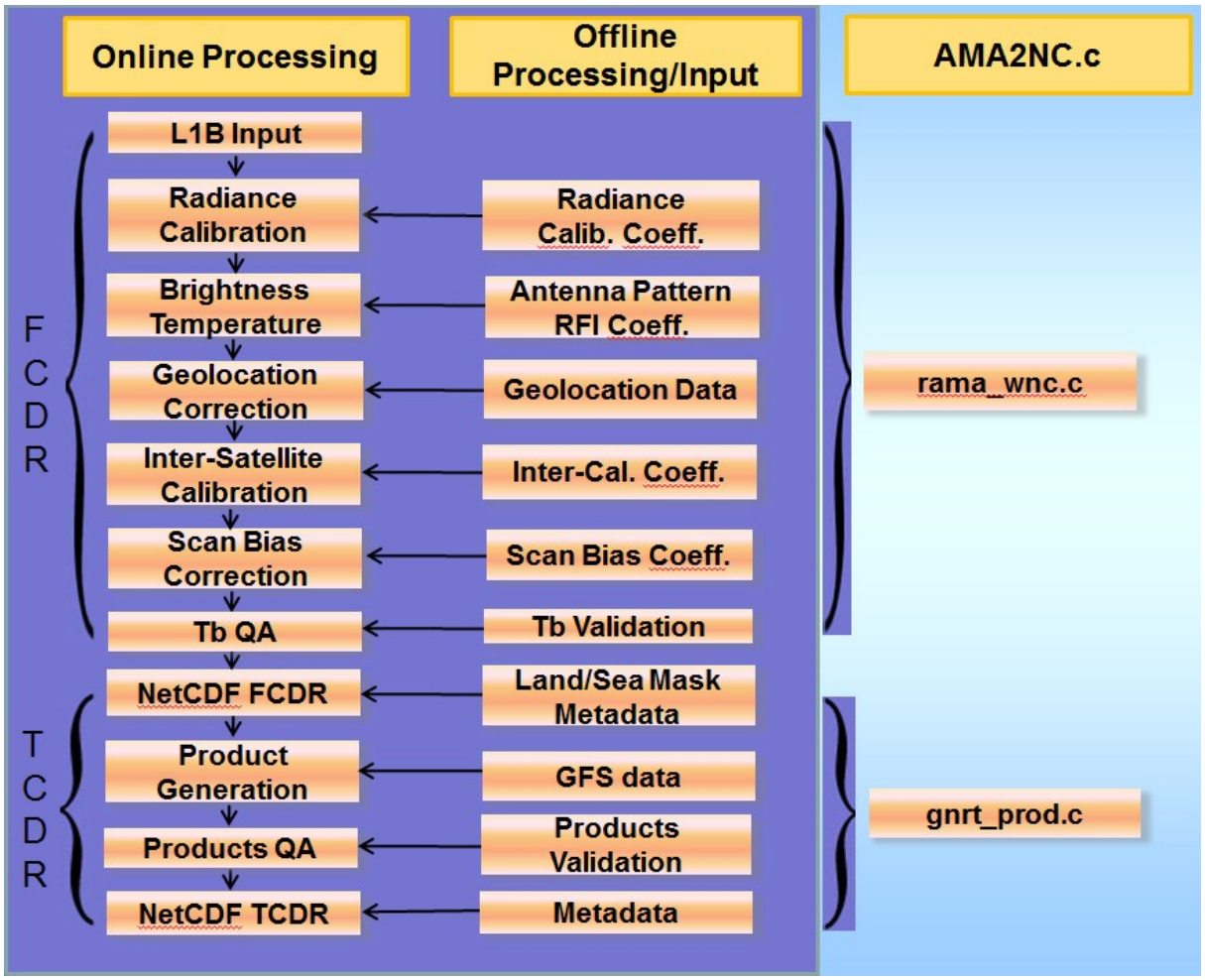

Figure 4. AMSU-A window channels FCDR and TCDR processing system

The inter-calibration of AMSU-B and MHS water vapor channels was conducted using a two point generic method that uses area averaged tropical brightness temperatures (latitude band from -25° to +25°) as the warm point and the polar averaged (latitude < -75°) brightness temperatures as the cold point. Then the daily averaged values were used for inter-comparison. A linear relation was developed between the TB's from the reference satellite as the independent variable and the target satellite as the dependent variable. The relations are defined for each year separately to account for the sensor drift.

Figure 5 shows the daily averaged polar and tropical TB's from NOAA15 AMSU-B Chan 1 versus corresponding observations from NOAA17 AMSU-B Chan 1 and Figure 6 shows the same scatterplots for MetOp-A MHS Chan 1 versus NOAA-18 MHS Chan 1. The lower range indicates the observations from the polar region and the upper range shows the tropical data. The calibration coefficients were calculated as: TB_TARGET = A x TB_REFERENCE + B and the coefficients are presented in Table 3.

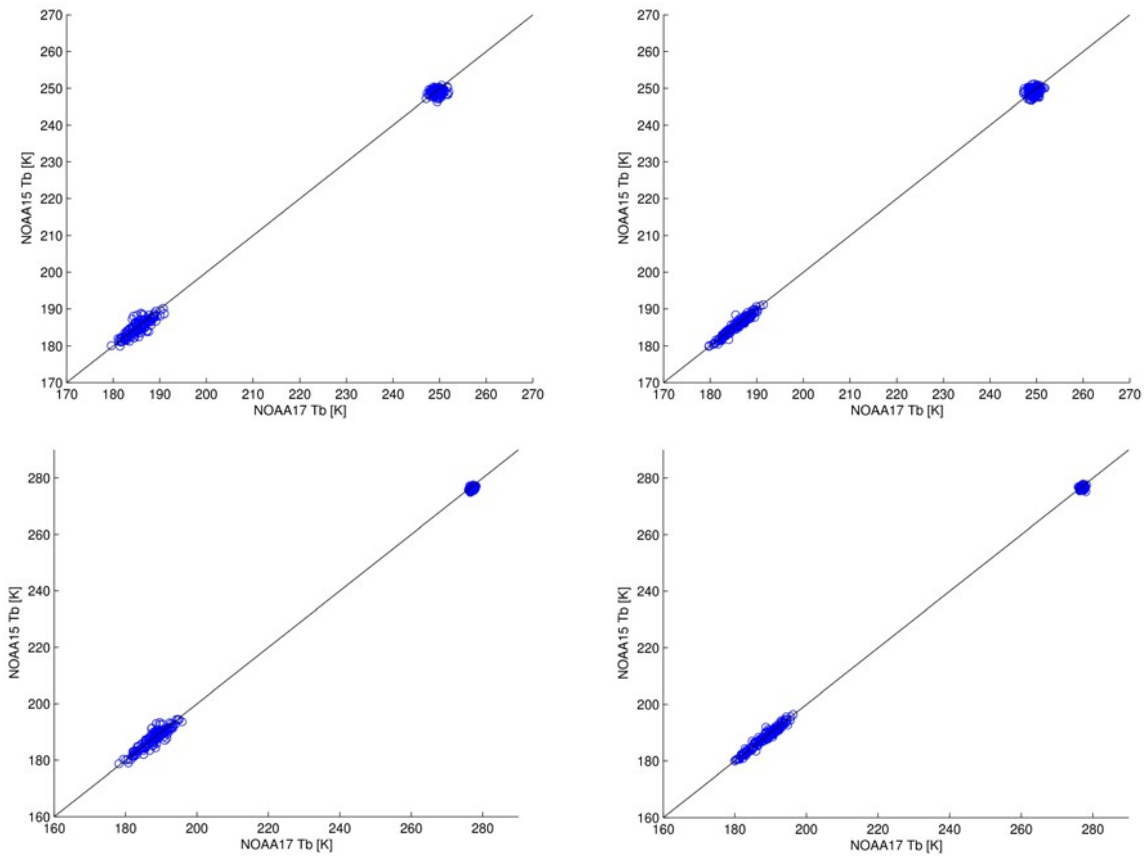

Figure 5. Observations from NOAA-15 AMSU-B Chan 1 versus observations from NOAA-17 AMSU-B Chan 1 (top) and Channel 2 (bottom), left 2007, right 2009.

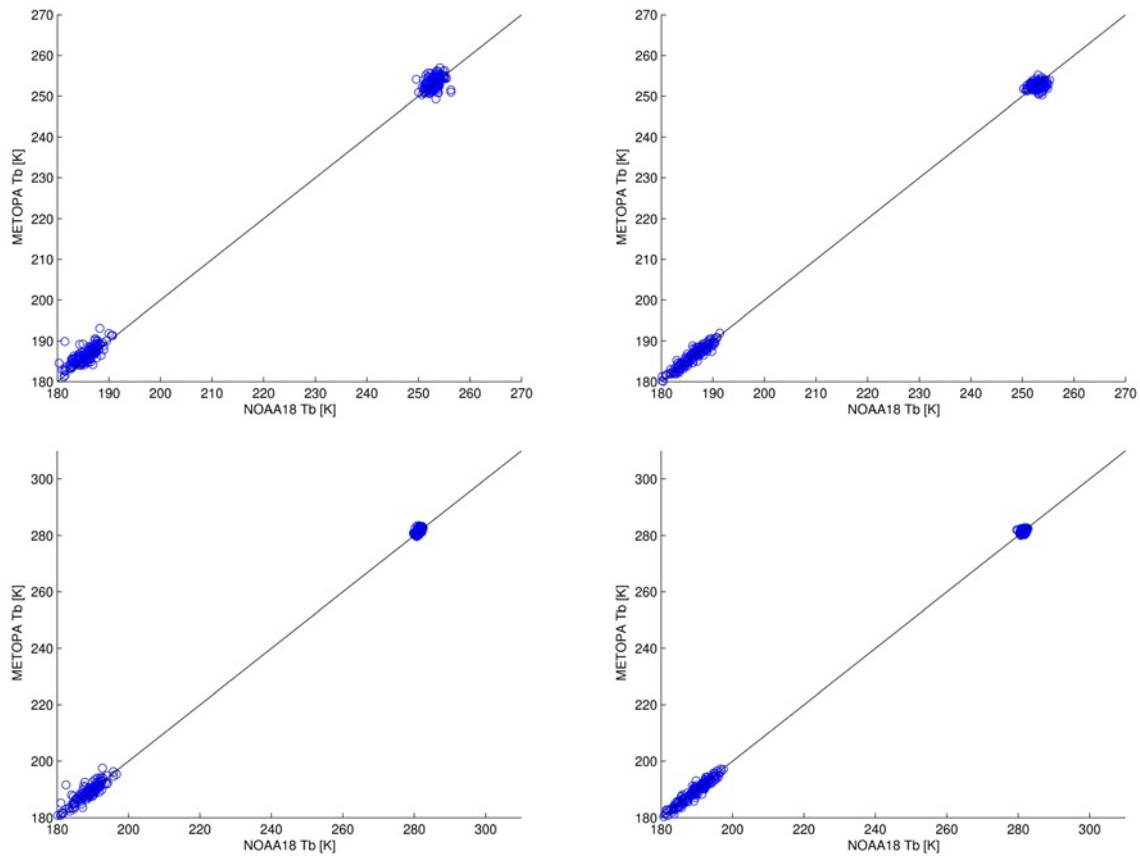

Figure 6. Observations from MetOp-A MHS Chan 1 versus observations from NOAA-18 MHS Chan 1 (top) and Channel 2 (bottom), left 2007, right 2009.

Table 3. Slope (A) and intercepts (B) for the regression fits for AMSU-B/MHS channel 1 and channel 2 (as presented in Figures 5 and 6). This is the case for using all data, both clear and cloudy sky.

Satellite	Reference Satellite	Channel	A	B	Year
NOAA-15	NOAA-17	1	0.9951	0.5631	2007
NOAA-15	NOAA-17	1	0.9983	0.1533	2009
NOAA-15	NOAA-17	2	0.9938	0.9363	2007
NOAA-15	NOAA-17	2	0.9948	0.8370	2009
MetOp-A	NOAA-18	1	0.9850	3.7000	2007
MetOp-A	NOAA-18	1	0.9907	1.8754	2009
MetOp-A	NOAA-18	2	1.0001	-0.1068	2007
MetOp-A	NOAA-18	2	1.0025	-0.6744	2009

The effect of clouds on the inter-calibration coefficients was investigated by filtering clouds using TB differences. The idea is that because of the lapse rate in atmospheric temperature,

the lower channels have larger TB than the higher peaking channels. Therefore, in clear-sky conditions the TBs of lower channels are warmer than the TBs of higher channels. In the case of clouds, the relation is changed which can be used as a filter to remove cloud contaminated pixels. Figure 7 shows the distribution of the TB's for different MHS channels in the presence of a relatively deep convective cloud. The cloud filters defined using TB differences are shown in Figure 8.

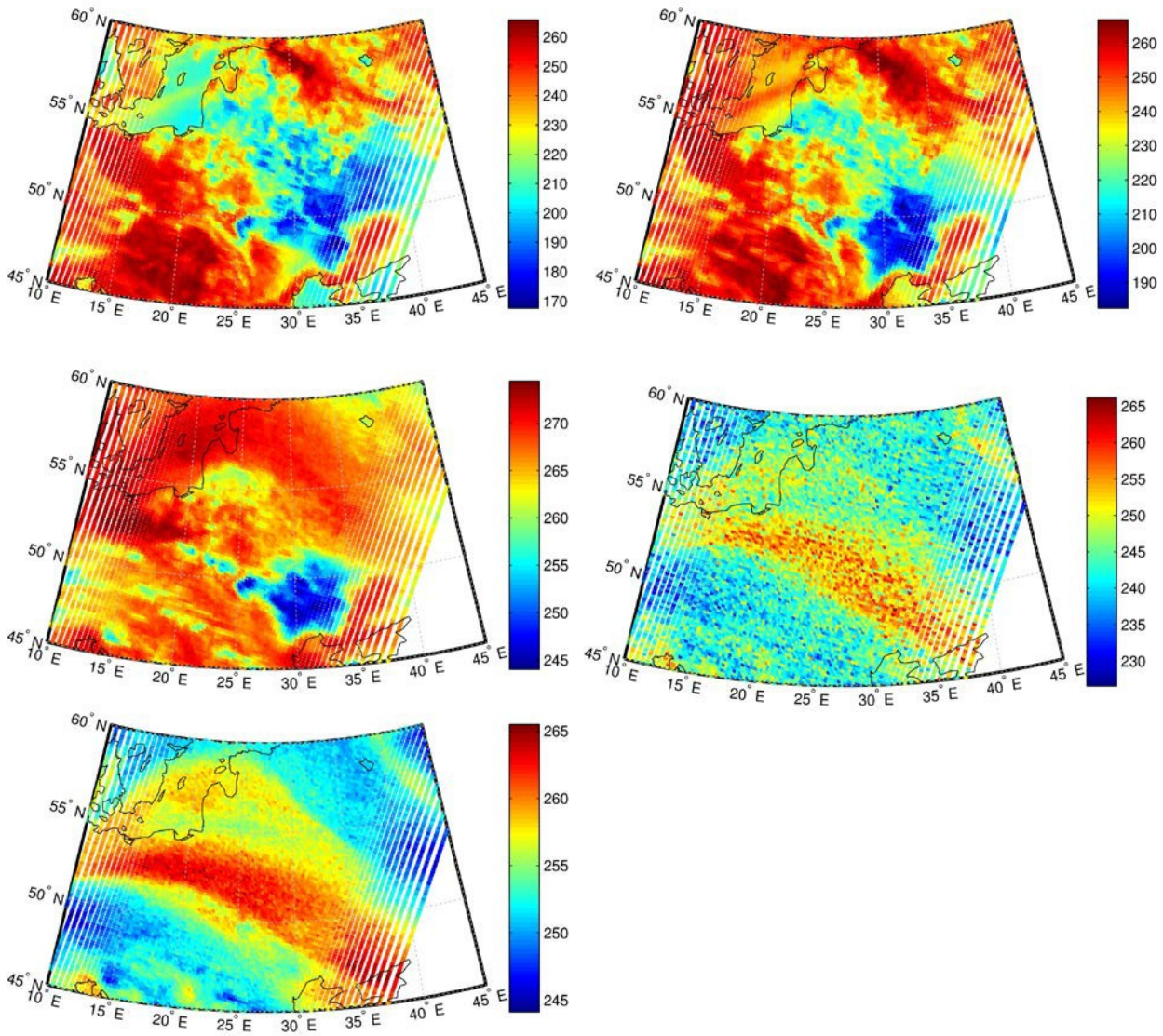

Figure 7: Brightness temperatures from different MHS Channels, Channels 1 to 5, from left to right then top to bottom. The plots indicate the upper-level channels are less sensitive to clouds than the lower channels.

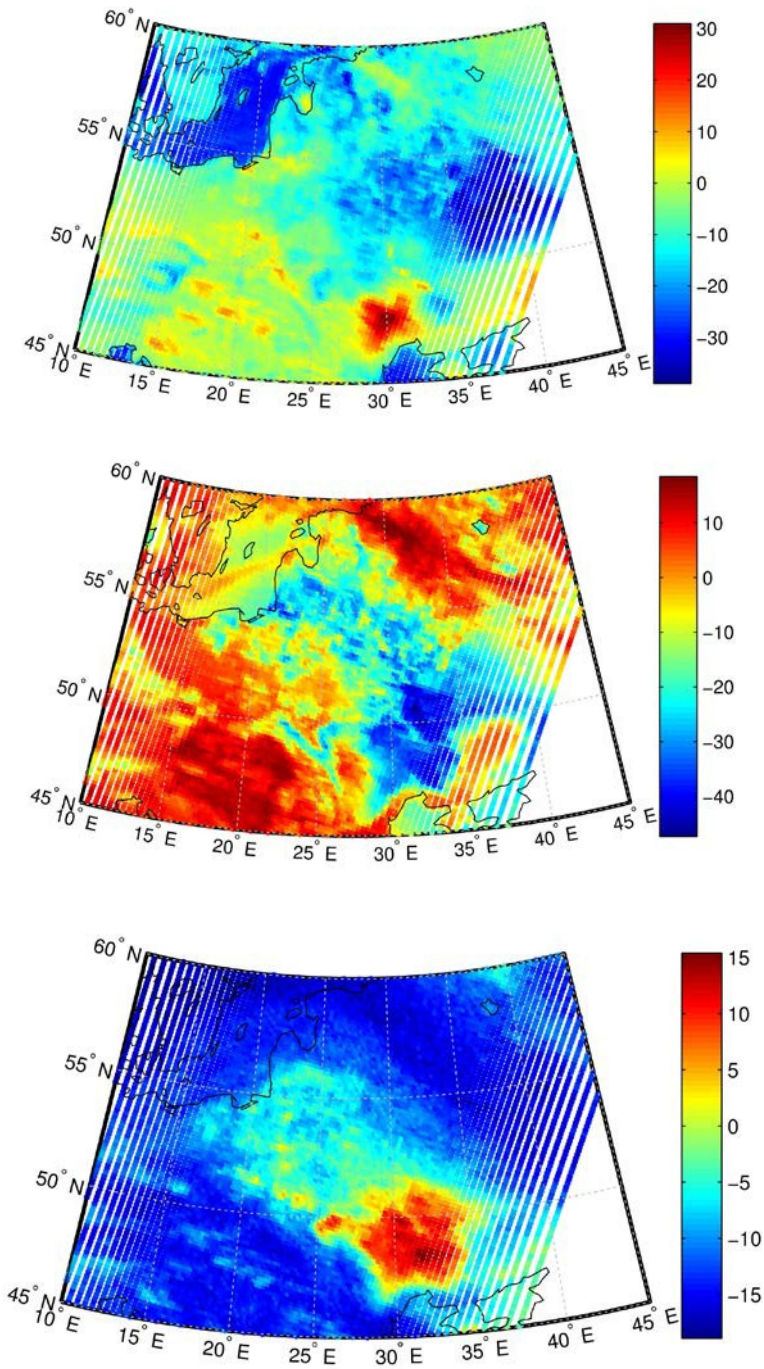

Figure 8: Cloud Filters defined using brightness temperature differences. (top) Chan 1 minus Chan 2, (middle) Chan 2 – Chan 5 and (bottom) Chan 3 – Chan 5.

It was found that because of the dry atmosphere in the polar region it is very difficult to apply the TB difference technique to the observations from the polar region. The effect of

surface emissivity becomes important in the polar region and it obscures the cloud effects. Besides, MW observations are only sensitive to deep-convective clouds which are not present in the polar region. Therefore, it was decided that it is not necessary to apply the cloud detection techniques to the polar observations. However in the tropical region the TB's from the window channels can be affected by the deep convective clouds. We tested two different filters: channel 3 – channel 4 and channel 5 minus channel 2 as the cloud filters. The statistics (percentage of the observations affected by the clouds) are shown in Figure 9. The statistics show that the Chan3-Chan4 is only able to detect a small percentage of the clouds as those channels peak very high in tropical region and are also very similar because of high relative humidity. It was already expected that water vapor channels are not very sensitive to clouds since those channels normally peak high and are only affected by over-shooting clouds. Therefore, based on the analysis of the impact of clouds on different channels, it was decided to apply the Chan5 – Chan2 filter to the observations from the window channels and then inter-calibrate the target and reference satellites' observations.

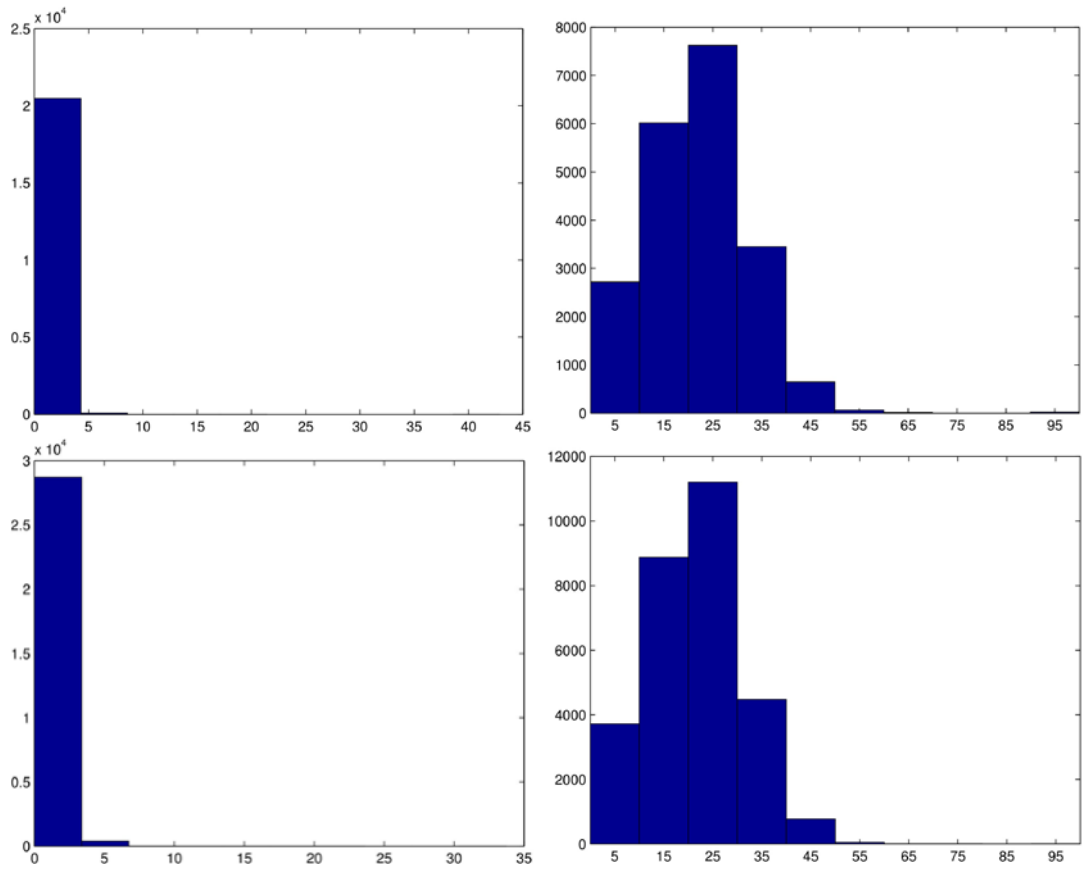

Figure 9: Histograms of he percentage of clouds (x-axis) based on different cloud filters (Ch 5 – Ch2; left and Ch4 – Ch5; right)over the tropical region for MetOp-A (top) and N-18 (bottom). The percentages are for individual swaths within the tropical zone for the entire period of record for the two satellites.

A complete set of AMSU-B/MHS beta data in NetCDF4 format has been generated that includes geolocation correction and inter-calibration as described above. A summary of the processing system used for the generation of these products is shown in Figure 10.

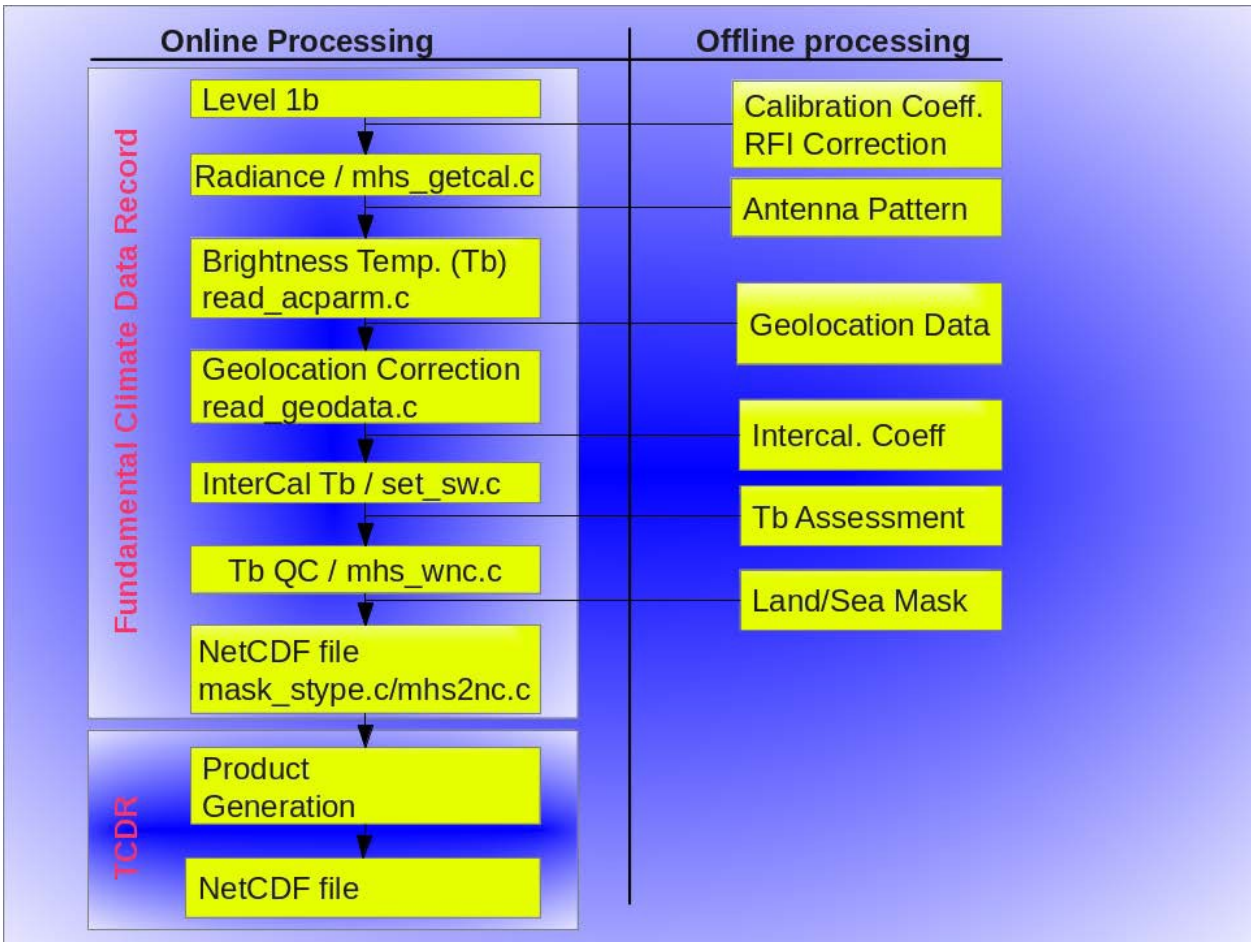

Figure 10. AMSU-B/MHS window channels FCDR and TCDR processing system

Milestone 2. The final FCDR's and TCDR's will be delivered to NCDC to be archived in the second half of this project year.

Milestone 3. The presentations from this reporting period are listed below.

Presentations:

Ferraro, R., H. Meng, W. Yang, I. Moradi, The Development of AMSU FCDR's and TCDR's for Hydrological Applications, CDR PI meeting, Asheville, NC, Jul 30 – Aug 1, 2013.

Yang, W., H. Meng, R. Ferraro, Inter-Calibration of AMSU-A Window Channels, EUMETSAT/AMS Conference, Vienna, Austria, Sep 16-20, 2013.

Semi/Annual Progress Report:

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

Project Funding Period: May 1, 2010 – October 31, 2014

Reporting Period: November 1, 2013 – April 30, 2014

Principal Investigators: Ralph Ferraro[1] and Huan Meng[1]

Scientific Staff: Wenze Yang[2], Isaac Moradi[2], Jim Beauchamp[2], Tom Smith[1]

[1]NOAA/NESDIS/STAR/CoRP/Satellite Climate Studies Branch
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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).

Satellite	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
NOAA/15	May	X	X	X	X	X	X	X	X	X	X	X	Sep
NOAA/16			Sep	X	X	X	X	X	X	X	X	X	X
NOAA/17					Jun	X	X	X	X	X	X	Dec	
NOAA/18								May	X	X	X	X	X
MetOp/A									Oct	X	X	X	X
NOAA/19												Feb	X

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 NOAA-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:

1. Complete eleven-year FCDR (2000 – 2010) for three production paths
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

Year 3 Milestones*:

1. Continue the development of AMSU and MHS FCDR and TCDR.
2. Generate AMSU and MHS FCDR beta data sets and distribute to scientific programs such as PMM, GEWEX and CEOS
3. Present and publish the findings of this work

Year 4 Milestones

1. Generate final FCDR's and TCDR's for 11 years (2000 – 2010); potentially expand back to 1998 if feasible.
2. Archive FCDR's and TCDR's at NCDC
3. Present and publish the findings of this work

<u>Progress during the Reporting Period</u>:

We continue to make progress towards the creation of AMSU-A and AMSU-B/MHS FCDR's and TCDR's during the second half of the forth project year. All milestones from Year 1 to Year 3 have been completed. Items 1 – 3 below (aligned with the Year 4 milestones) summarize our effort and results in this period.

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* Year 3 funding has been divided into two years due to a NCDC approved project extension and lack of full funding in Year 3.

Milestone 1.

Previously, we have chosen the Integrated Microwave Inter-Calibration Approach (IMICA) developed by Zou et al. (2006, 2009, 2010 and 2011) as our inter-satellite calibration method for AMSU-A window channels. Since IMICA is very sensitive to the quality of input data, several sets of corrections have been performed using the approach to achieve satisfactory outcome. As a result, the optimal parameters μ and δR have been updated to produce a new set of inter-calibrated AMSU-A window channel FCDR for all satellites from 2000 to 2010. NOAA-15 was selected to be the reference satellite for inter-calibration except for channel 89 GHz (see discussion below). To illustrate the effect of the corrections, the nadir-view brightness temperatures over the tropical ocean are extracted. This region is selected to avoid strong diurnal variation and the impact of sea ice. Figure 1 and 2 compare the time series of brightness temperatures and their differences before and after the corrections.

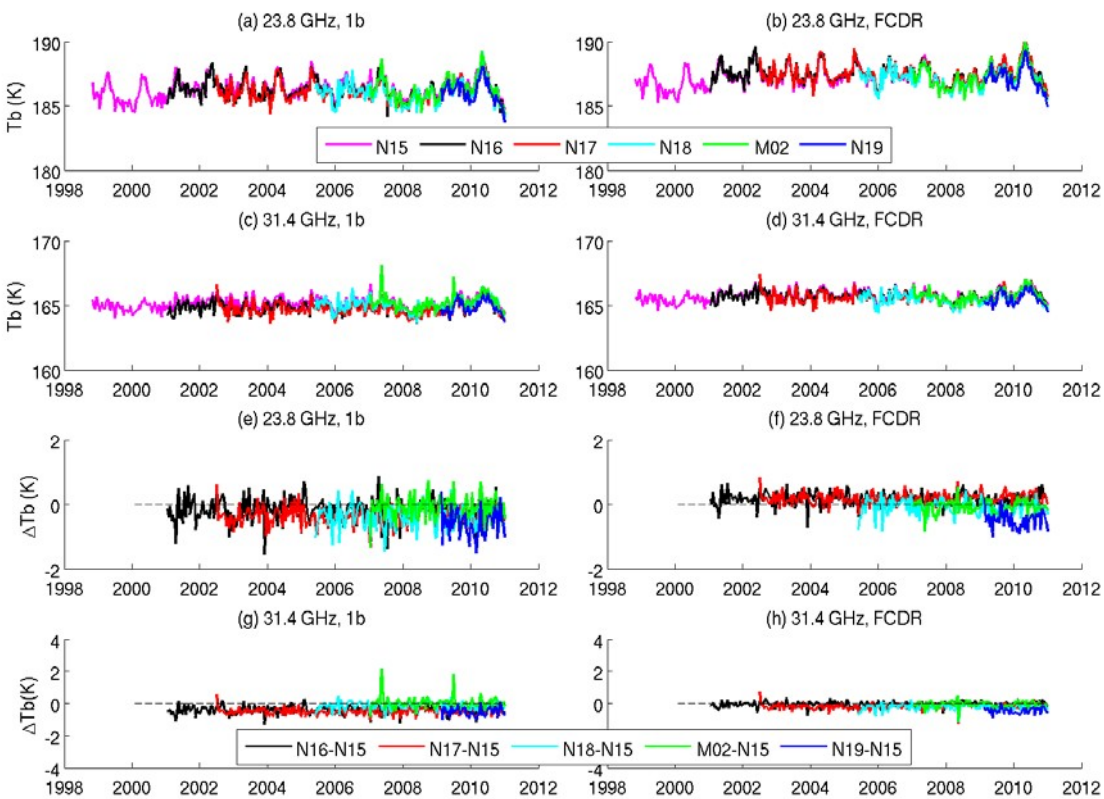

Figure 1. Tropical ocean mean brightness temperature (Tb) and difference (ΔTb) for the 23.8 and 30.4 GHz channels. Left panel shows the values before correction, while the right panel is after correction.

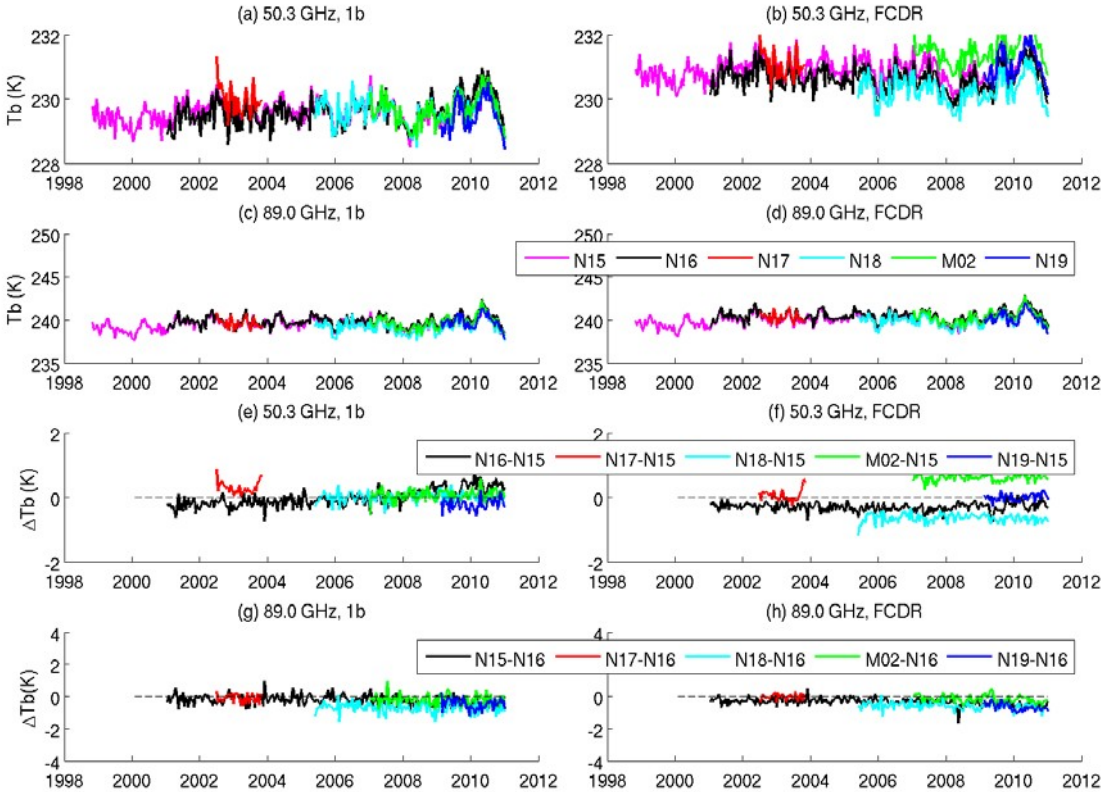

Figure 2. Similar to Figure 1, but for the 50.3 and 89.0 GHz channels.

The inter-calibration minimized the impact of the various biases such as warm target contamination. The corrected brightness temperatures, labeled as FCDR in the figures, exhibit better agreement among satellites than the operational level-1b data. The comparison of the STD of ΔTb calculated from Figure 1(e)-(h) and Figure 2(e)-(h) shows that the improvement of these channels is approximately 50%, as shown in Table 1.

Table 1. Tropical Ocean STD of ΔTb

	Before				After			
Channel	23.8	31.4	50.3	89	23.8	31.4	50.3	89
N16-N15	0.374	0.263	0.267	0.315	0.217	0.193	0.126	0.227
N17-N15	0.285	0.217	0.191	0.225	0.191	0.191	0.171	0.132
N18-N15	0.386	0.259	0.168	0.337	0.239	0.197	0.130	0.242
M02-N15	0.37	0.384	0.167	0.328	0.215	0.207	0.108	0.227
N19-N15	0.424	0.276	0.174	0.374	0.263	0.187	0.115	0.208

It is noted that NOAA-15 89 GHz channel appears to suffer from frequency shift. Therefore, NOAA-16 was used as the reference satellite to inter-calibrate other satellites for this channel.

We have developed the approach for asymmetry correction in this project previously. The correction coefficients for all satellites were generated during this reporting period. The results confirmed our previous conclusion that the asymmetry pattern is stable for each satellite during its operating period, but rather different among satellites.

With the completion of the scan asymmetry and inter-satellite correction as well as geolocation correction, a complete set of AMSU-A window channels FCDR data set has been created which covers the entire period from launch to the end of 2010 for each of the six satellites, namely, NOAA-15 to NOAA-19 and MetOp-A.

The AMSU-A TCDR products, including total precipitable water, cloud liquid water, sea ice concentration, land surface temperature, and land surface emissivity (for 23.8, 31.4, and 50.3 GHz), have also been generated using the Microwave Surface and Precipitation Products Systems (MSPPS). Besides the calibrated brightness temperature, this system also requires some input data from the Global Forecast System (GFS). Modifications were made to the original near real-time processing system to meet the need of re-processing for TCDR. In addition, a draft C-ATBD for the AMSU-A FCDR was completed during this reporting period.

The inter-calibration of AMSU-B and MHS water vapor and window channels was conducted using area averaged values from tropical region (latitude band from -25° to +25°) as well as Antarctica (latitude < -75°). The initial inter-calibration was based on calculating inter-calibration coefficients in annual basis using brightness temperatures averaged over tropical region as well as Antarctica. The effect of land and ocean on the inter-calibration, especially the effect of stronger diurnal variation over land, was investigated by separating land and ocean brightness temperatures over tropical region, then calculating the inter-calibration coefficients. It was found that the inter-calibration coefficients are slightly different for land and ocean which can be explained by the diurnal variation of brightness temperatures over land. Figure 3 shows an example of differences between collocated brightness temperatures for two different satellites over land and ocean. Therefore, the inter-calibration was limited to tropical oceans to avoid the effect of diurnal variation. Since during winter, Antarctica is only covered by ice and snow, therefore we average all the data over Antarctica and no land/ocean mask is applied. Besides, our previous study also showed that the results slightly depend on the cloud screening, therefore the inter-calibration is limited to only clear sky conditions. We also found that the annual averages are not enough for inter-calibration since there might be short term changes in the data that cannot be taken care of using annual coefficients. In the new version, we calculate the coefficients on a monthly basis, and then interpolate them to calculate the daily values of inter-calibration coefficients. Therefore, the inter-calibration process can be explained as follows: (1) data are averaged over tropical oceans and

Antarctica, (2) one month of data from both regions are used to make the scatter-plots between reference and target satellites, (3) monthly inter-calibration coefficients are calculated then interpolated, (4) the coefficients are applied to level-1b data to calculate the inter-calibrated brightness temperatures.

The results were tested using area averaged values over different latitude bands. The inter-calibrated brightness temperatures are normally consistent over tropical oceans but there are some differences for other zones which can be explained by the different overpass time for different satellites.

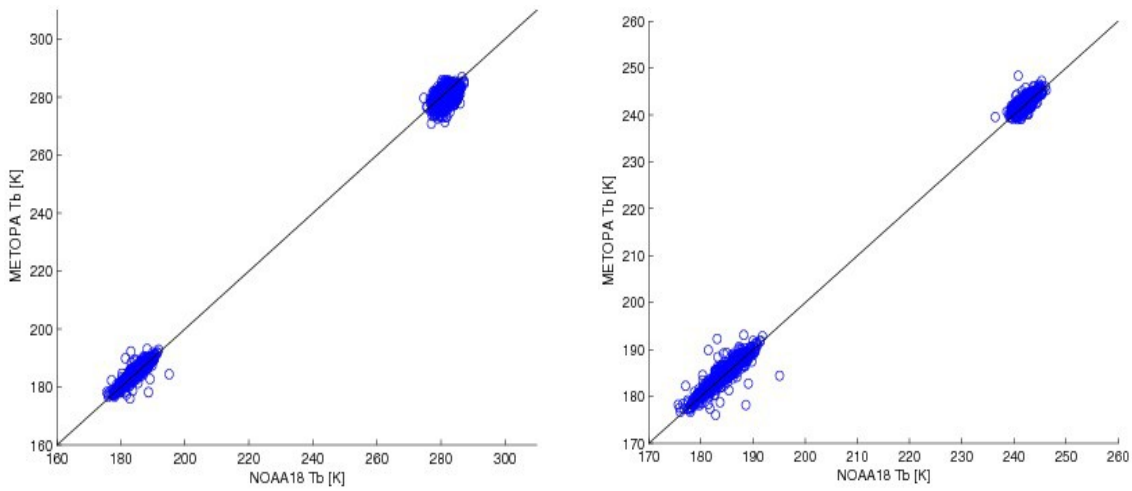

Figure 3: Brightness temperatures for MetOp-A versus NOAA-18 averaged over tropical region as well as Antarctica: (left) over land, and (right) over ocean.

After having initially calculated level-Beta brightness temperature using annual inter-calibration coefficients, the same calculations were made based on monthly coefficients. These monthly values were first cubic-spline interpolated to daily in order to smooth month to month transitions and fill periods where monthly coefficients could not be determined. These interpolated daily values were then applied to level-1b data to create NetCDF4 format level-Beta data for MetOp-A (2007 – 2010) and NOAA-16 (2002 – 2009). In addition, a draft Climate Algorithm Theoretical Basis Document (C-ATBD) for AMSU-B/MHS FCDR has been completed.

A number of analyzes were also performed to detect and guide the development of methods to minimize biases between the satellite brightness temperature records. One of the studies was to evaluate the daily cycle of satellite measurements using satellite data and reanalysis temperatures at several surface and upper-air levels from ERA-interim data. The ERA surface temperature daily cycle was found to be unreliable, due to the use of lower-boundary SST that does not resolve the daily cycle. Upper-air ERA temperatures gave more physically reasonable estimates of the daily cycle which are potentially useful

for comparison to satellite data daily cycles. Preliminary evaluations suggest no serious problems with the satellite diurnal cycles at the upper-air levels.

In addition, biases for records of several years in length were evaluated using regional averages from different satellite sources and different frequencies. Regions include ocean and land areas, for global, tropical, and extra tropical areas. Comparing different corrected measurements can reveal problems with the correction approaches. Problems can include discontinuities from changes in instrument calibration, orbital drift, or improper screening of suspect radiances. As a result of this testing changes to calibration were developed and the re-calibrated data were tested to evaluate results. Figure 4 shows an example comparison. It displays tropical ocean-area averages of brightness temperatures at AMSU-B 89 GHz from NOAA-18 and MHS 89 GHz from MetOp-A where NOAA-18 is the reference satellite. The MetOp-A brightness temperatures are shown unadjusted and with calibration adjustment (beta4). Note that the calibration adjustment tends to minimize differences from the comparison NOAA-18 brightness temperatures.

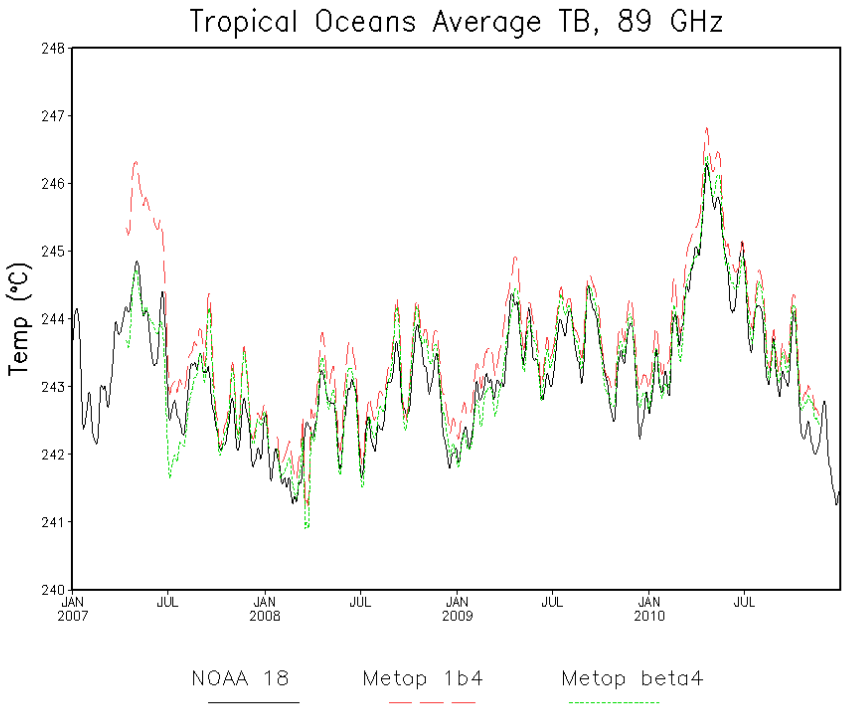

Figure 1. Tropical ocean-area 89 GHz brightness temperature averages from NOAA-18 AMSU-B and MetOp-A MHS.

Milestone 2. The draft AMSU-A C-ATBD and a set of AMSU-A FCDR were delivered to the CDR Program. We have received positive feedback on the C-ATBD. The final FCDR's and TCDR's will be delivered once the CDR Program is ready for the transition.

Milestone 3. The manuscript and presentations from this reporting period are listed below.

Publication

Yang, W., H. Meng, and R. Ferraro, 2014, Inter-Calibration of AMSU-A window channels. IEEE Transactions on Geoscience and Remote Sensing, to be submitted.

Presentations:

Ferraro, R., H. Meng, W. Yang, I. Moradi, The Development of AMSU FCDR's and TCDR's for Hydrological Applications, CDR PI meeting, Asheville, NC, Jul 30 – Aug 1, 2013.

Ferraro, R., Passive Microwave Satellite Precipitation Time Series: A Historical Perspective and Future Challenges, Precipitation Data and Applications Workshop, Asheville, NC, Dec 3-4, 2013.

Ferraro, R., H. Meng, W. Yang and I. Moradi, The Development of AMSU FDR's and TCDR's for Hydrological Applications, 2014 GSICS Research and Data Working Group Meeting (presented remotely), Darmstadt, Germany, Mar 24-28, 2014.

Moradi, I. and R. Ferraro, Inter-calibration and validation of observations from modern satellite microwave humidity and temperature sounders, The 13th Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment, Pasadena, CA, Mar 24-27, 2014.

Yang, W., H. Meng, R. Ferraro, Inter-Calibration of AMSU-A Window Channels, EUMETSAT/AMS Conference, Vienna, Austria, Sep 16-20, 2013.