Assessment of the Long-Term Radiometric Calibration Stability of the TRMM Microwave Imager and the WindSat Satellite Radiometers

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Abstract— **The NASA's Global Precipitation Measurement (GPM) mission uses a constellation of international satellites with microwave radiometers, to provide the next-generation of global observations of precipitation. The GPM Intersatellite Calibration Working Group (aka XCAL) has the responsibility to perform the radiometric calibration process to normalize all radiometers to a common source, the GPM Microwave Imager, which serves as a radiometric transfer standard. Prior to the launch of GPM instrument on February 28, 2014, the Tropical Rainfall Measurement Mission (TRMM) Microwave Imager has been used as a proxy for the GMI to develop procedures and data analysis algorithms for inter-comparing two similar, but not identical, radiometers. In this regard, this paper assesses the long-term radiometric calibration stability of TMI relative to WindSat polarimetric radiometer. CFRSL conducted two independent inter-comparisons over oceans in XCAL year (July 2005 – June 2006) and CY 2011, and results are presented, which demonstrate deciKelvin relative stability over this greater than five-year period.**

Keywords— Global Precipitation Measurement (GPM); XCAL; microwave radiometry; radiometric calibration

I. Introduction

Inter-satellite radiometric calibration for microwave radiometers was started in June 1987, when the first Special Sensor Microwave Imager (SSM/I) on the DMSP-5D-2 (Defense Meteorological Satellite Program) F8 satellite was launched. With the launch of the operational SSM/I instruments from 1987 through 1997, the first formal multiyear calibration and validation (Cal/Val) effort was initiated, by the Space Sciences Division of the Naval Research Laboratory (NRL). This post-launch study established the absolute calibration and sensitivity of SSMI.

An important advantage in this inter-satellite calibration was that the SSM/I instruments were of identical design. In this case, the observed brightness temperatures in corresponding channels could be compared directly; however, as more satellites are launched with microwave radiometers of different designs (e.g. SSMIS, Advanced Microwave Scanning Radiometer (AMSR), TMI and WindSat), the inter-satellite radiometric comparison has become more complicated, and this constitutes the major challenge for the inter-satellite radiometric calibration. Thus, a consistent and qualitatively reliable transfer standard is required to develop procedures and data analysis algorithms for inter-comparing similar radiometers.

In March 2007, the Global Precipitation Measurement (GPM) Mission convened a microwave radiometer specialist workshop, which was the formation of the Inter-Satellite Radiometer Calibration Working Group (aka XCAL). The purpose of this ad hoc group was to converge on a set of basic approaches to meet GPM objective of single, internationally recognized effort to produce an inter-calibrated brightness temperature (Tb) data set. Ultimately, the transfer standard will be the GPM Microwave Imager (GMI), but for the present the TRMM Microwave Imager (TMI) fills this need [1].

Since the initial XCAL meeting seven years ago, the short-term stability of TMI has been verified by several researches, using complementary approaches [2]. This paper focuses on evaluating the long-term stability of inter-satellite radiometric calibration of TMI respect to WindSat. The CFRSL inter-satellite XCAL algorithm, known as the Double-Difference (DD) technique, is used to compare near-simultaneous clear-sky oceanic observations of two microwave radiometers (e.g. TMI and WindSat in this paper). Radiometric calibration biases between TMI and WindSat are presented for two one-year periods, XCAL year (July 2005 - June 2006) and CY 2011, which are separated by more than five years.

Since TMI is in a low inclination orbit and WindSat is in a near polar orbit, there are many near-simultaneous orbital intersections over a wide range of latitudes, to facilitate this inter-comparison. Thus, these radiometric comparisons are representative of all polar orbiting satellites, and can serve as a prototype for inter-satellite calibration of the GPM constellation.

TMI was launched in November 1997, on Tropical Rainfall Measurement Mission (TRMM) satellite. It measures radiances at 5 frequencies: 10.65, 19.35, 21.3, 37.0 and 85.5 GHz in both H-and V-polarization (except 21.3 GHz which only has V-pol). It's conical-scanning, with low inclination and in a non-sun synchronous orbit. TMI data used herein are the version 7 (v7) of the Level 1B Calibrated Tb product (i.e., TMI 1B11 v7). Over TRMM's lifetime, the TMI 1B11 have gone through multiple versions/improvements with the most recent, v7, in 2011. One of the major changes from v6 to v7 was the implementation of time-varying solar bias [3, 4].

WindSat, developed at the Naval Research Laboratory in Washington, DC, is a large-aperture, conically scanning polarimetric microwave radiometer, which consists of 22 channels of polarized brightness temperatures, operating in discrete bands at 6.8, 10.7, 18.7, 23.8, and 37.0 GHz. The 10.7, 18.7, and 37.0 GHz channels are fully polarimetric, while 6.8 and 23.8 GHz channels are dual polarized only (vertical and horizontal). WindSat radiometric calibration campaign has been believed to be an outstanding success, and excellent results have been published to provide high confidence in the brightness temperatures from WindSat Sensor Data Records (SDR) [5]. Only V- & H-pol measurements from the forward swath are used in this study. WindSat data product used herein are the version c214 of SDR for XCAL year, and c231 for 2011.

II. CFRSL XCAL ALGORITHM

CFRSL inter-satellite calibration algorithm compares two satellite radiometer observations, on a channel basis, for homogeneous earth scenes, that are collocated spatially and temporally [1]. In the simplest sense, if the corresponding channels of two radiometers, with identical design, were to make an observation over the earth at the exact same time and space, the difference in their Tb's should reflect the radiometric calibration bias between the instruments. Unfortunately, for radiometers of different designs, like TMI and WindSat, the situation is more complicated due to slightly different center frequencies, bandwidths and earth incidence angles. Thus, normalization between the radiometers is required. For the CFRSL XCAL algorithm, this normalization utilizes microwave radiative transfer theory to translate the measurement of one or the other to a common basis before comparison. This algorithm involves three steps in the normalization process to finally obtain simulated Tb's. A block diagram of this algorithm is shown in Fig. 1.

A. Gridding Process

The raw sensor Tb's are averaged spatially into 1° boxes, which are generated per orbit basis, for each sensor and each radiometer channel. For XCAL over oceans, which are presented in this paper, filters are used to select clear-sky homogeneous scenes. Because high Tb standard deviations within a box are indicative of nonhomogeneous environmental conditions, including weather fronts with rain and/or small island contamination, these boxes are removed when standard deviations exceed 2 and 3 K for vertical and horizontal polarizations, respectively. Further editing is applied at all frequencies based on the upper limits of Tb's expected from rain-free ocean; and a conservative land mask is also applied, to filter out possible Tb contamination from nearby land pixels.

B. Spatial and Temporal Collocation

To assure identical environmental conditions, the two radiometers are spatially collocated within a ±1 hour time window. The environmental parameters used are from the NOAA Global Data Assimilation System (GDAS), that are produced operationally every 6 hours. The surface environmental parameters are: pressure, sea surface temperature, and ocean surface wind speed; the atmosphere environmental parameters are： height profiles of pressure, temperature, specific humidity, and cloud liquid water.

C. Ocean Radiative Transfer Model (RTM)

When radiometers are of different designs, there might be significant differences in their radiances, which are caused by different frequencies or incidence angles; however, this does not necessarily constitute calibration errors. Therefore, the use of RTM allows the expected difference in the scene radiance (Tb's) to be determined.

The NASA XCAL RTM used in this paper requires environmental parameter inputs to simulate Tb's, as seen by the spaceborne radiometers, as shown in Fig. 2.

The most important characteristic of the RTM is that it accurately captures the dynamic change of the ocean scene Tb, resulting from differences in corresponding center frequency, bandwidth, EIA, polarization, and environmental parameters. Of the latter, sea surface temperature, wind speed, water vapor, and cloud liquid water are the most important.

The assumption is that the radiometers are stable, thus, the biases should be independent of time. This is verified by comparing collocations monthly over the two one-year periods (XCAL year and 2011). When the biases are correlated with any of the instrument, orbital or environmental parameters, calibration of the radiometer is considered flawed and must be corrected to eliminate the systematic trends, before the inter-satellite calibration performed.

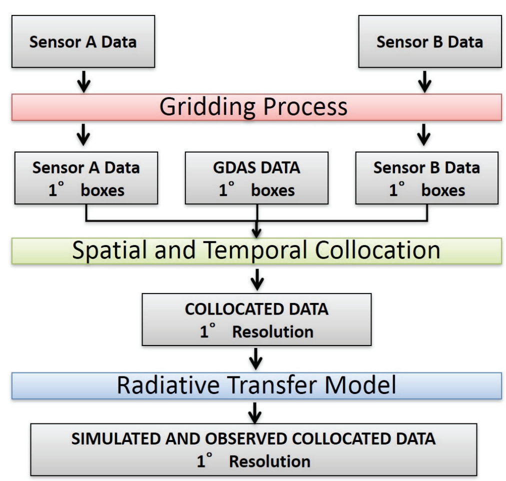

Fig. 1 Block diagram of CFRSL XCAL Algorithm.

For clear-sky oceanic scenes, the Tb is dominated by surface emission. The XCAL RTM uses an ocean surface emissivity module, which is based upon specular Fresnel reflection, that incorporates an ocean dielectric constant model and a wind-roughened ocean emissivity model, which uses empirical relationships. The ocean emissivity model requires sea surface temperature, wind speed, salinity, frequency, polarization and incidence angle as inputs. It calculates the isotropic ocean surface emissivity and ignores small wind direction effects, which were investigated and found to average to zero globally and have negligible effect on the derived Tb biases.

III. XCAL Doulble-difference Technique

The XCAL RTM is a state of the art for the physics associated with atmospheric and oceanic emissivity for the microwave window channels (<100 GHz); however, since the environmental parameter inputs derived from numerical weather models are not perfect, this results in Tb's with absolute Tb offsets. However, after using the Double-difference (DD) technique, these RTM errors are mostly common mode and usually cancel.

The Tb's averaged within a 1° box for a particular channel observed are WindSat (WS_{obs}) and TMI (TMI_{obs}). Next, the oceanic RTM (section II) is run, using the collocated environmental parameters and given sensor parameters (frequency, incidence angle and polarization), to produce the simulated Tb for WindSat (WS_{sim}) and TMI (TMI_{sim}). The expected Tb single difference is defined as WS_{sim} - TMI_{sim}, and the observed single difference is WS_{obs} - TMI_{obs}. The final step is to calculate the double difference (DD) as:

$$Tb_{bias} = DD = \left(WS_{sim} - TMI_{sim}\right) - \left(WS_{obs} - TMI_{obs}\right)$$

This DD difference essentially cancels out any absolute bias that may exist in the RTM, and represents the radiometric bias of TMI with respect to WindSat. Since WindSat is known to be well-calibrated and demonstrated to be self-consistent as reported by Jones et al. [5], this DD technique is a very robust procedure for assessing the TMI long-term biases.

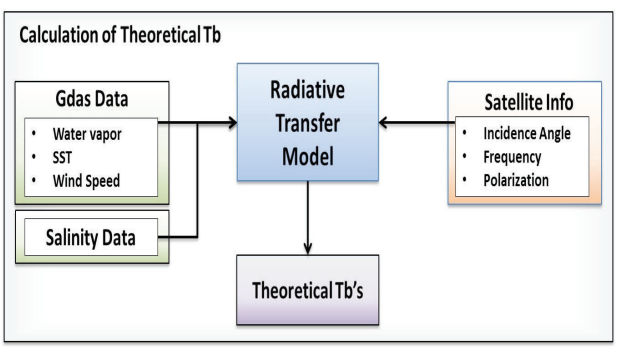

Fig. 2 Block diagram of RTM.

IV. Results

Two independent inter-comparisons over oceans for the XCAL year and 2011 are calculated and displayed in Table I (V-pol) and Table II (H-pol), for both periods. The mean and standard deviation of the Tb biases of TMI with respect to WindSat are given, along with the mean oceanic Tb of TMI at which they were observed. Also shown are the changes of the yearly averaged biases between XCAL year and 2011.

TABLE I. TMI-WindSat Double Differences For V-pol

	Mean (K)	Std. (K)	Change in Mean (K)	@Tb (K)
10 V	0.33 / 0.34	0.30 / 0.32	0.01	170 / 170
19 V	-0.50 / -0.35	0.59 / 0.61	0.15	199 / 200
22 V	-1.61 / -1.56	0.66 / 0.65	0.05	219 / 220
37 V	-3.188 / -3.185	0.583 / 0.585	0.003	214 / 214

Numbers before and after "/" represent XCAL year and 2011, respectively

TABLE II. TMI-WindSat Double Differences For H-pol

	Mean (K)	Std. (K)	Change in Mean (K)	@Tb (K)
10 H	-1.564 / -1.559	0.37 / 0.39	0.005	88 / 89
19 H	-2.78 / -2.60	0.8189/0.8190	0.18	132 / 133
37 H	-2.50 / -2.52	0.91 / 0.92	-0.02	152 / 153

Numbers before and after "/" represent XCAL year and 2011, respectively

It's surprising and encouraging to see that the radiometric biases of these two one-year periods, separated by more than a five-year interval, are almost identical. Except 19 H- and V-pol, the changes between the two periods of all the channels are much smaller than 0.1 K, which is the goal of the XCAL DD technique. Even in the worst case, 19 H-pol, the change 0.18 K is acceptable for GPM calibration purposes.

The DD biases for each channel were sorted various ways to assure that no systematic dependency existed (e.g., by month (seasonal), time of day (day/night), with latitude, and ascending/descending segments of the orbit). Thus, finding no such effects, results shown in Fig. 3 compare the monthly average bias time-series between XCAL year and 2011, for both V- and H-pol channels at 10 and 37 GHz. Since 10 and 37 GHz are the least and most atmosphere-affected frequencies, respectively, the comparisons of the monthly DD between the two periods are representative of all channels. The results are remarked similar in that monthly DD between XCAL year (red) and 2011 (blue) in 10 V- and H-pol are nearly equal.

Figure 4 shows the monthly DD of ascending passes for both XCAL year (red) and 2011 (blue) by channels. Similar to Fig. 3, the DD between these two periods match very well in all the channels except that 19 V- and H-pol channels that have relatively larger changes. However, the changes are still less than 0.2 K, which is quite acceptable. Also, the same patterns of the monthly DD are seen in descending passes.

At both north and south hemispheres, the monthly DD's of ascending and descending passes also show very good consistency between the XCAL year and 2011. In Fig. 5, the panel on the top shows the DD of ascending passes through north hemisphere at 10 V-pol channel. The variation range of this case is around 0.2 K which is quite satisfactory. The panel on the bottom shows that the monthly DD of descending passes

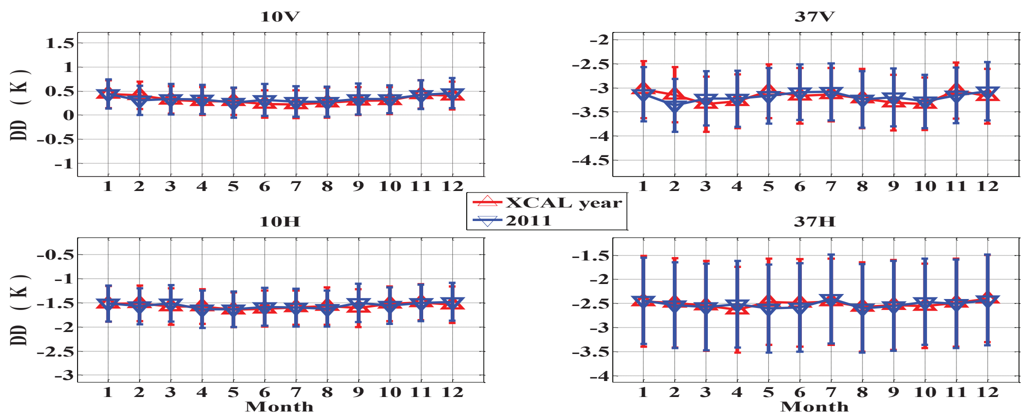

Fig. 3 Monthly average TMI-WindSat double difference bias time-series at 10 V-, 10 H, 37 V- and 37 H-pol channels, for XCAL year and 2011.

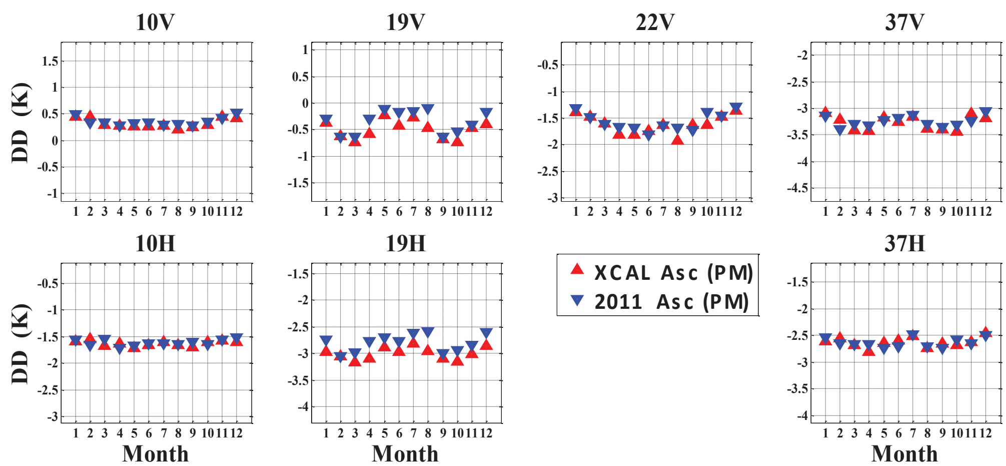

Fig. 4 Monthly average TMI-WindSat double difference bias of ascending passes at all channels, for XCAL year and 2011.

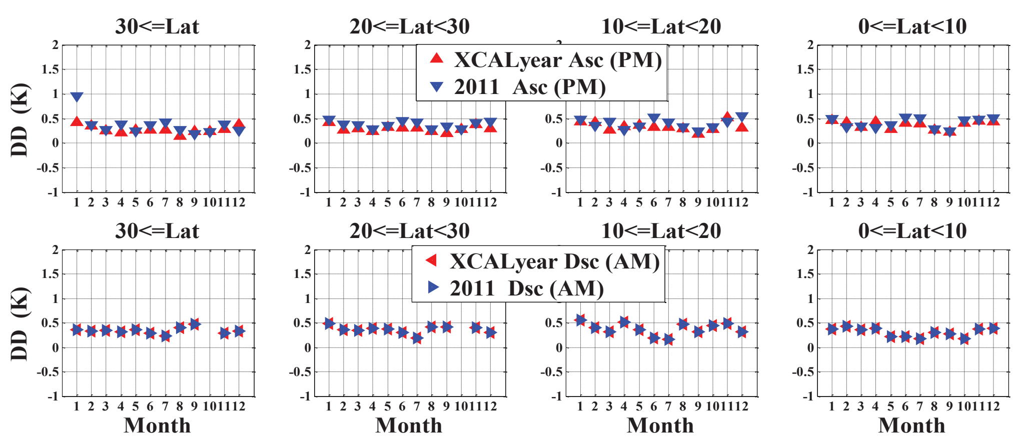

Fig. 5 Monthly average TMI-WindSat double difference of asc.(top) & dsc. (bottom) passes, through north hemisphere, at 10 V, for XCAL year and 2011.

at 10 V-pol channel are nearly equivalent between the two periods as well. The DD's of ascending and descending passes in the south hemisphere present similar results, which further verifies the long-term consistency of the inter-satellite radiometric calibration between TMI and WindSat.

V. CONCLUSION

This paper focuses on evaluating the long-term stability of the inter-satellite radiometric calibration, between TMI and WindSat, derived from data collected during the XCAL year and 2011. The double differences, which are the Tb biases between corresponding radiometers channels, are analyzed by: months, ascending/descending passes and latitude-based geolocation. These two one-year periods are separated by more than five years, which is very significant for evaluating the long-term consistency of TMI relative to WindSat.

The best case (10 V-pol) has an average change 0.01 K between these two periods, and this greatly exceeds the XCAL goal of 0.1 K. The change of the worst case (19 H-pol) is 0.18 K, which is slightly larger than the goal but still quite acceptable. The comparison of the monthly DD for TMI with respect to WindSat, between these two periods, reveals that the relative long-term stability of these two radiometers is excellent. Further, the biases are random errors, that exhibit no systematic dependence on any orbital or instrument parameter.

In addition, because of the excellent stability of these two data sets, separated by a period greater than 5 years on orbit, these results also validate the long-term consistency of the XCAL algorithm and DD technique to provide a very stable transfer standard (e.g. TMI or GMI) for calibration of the precipitation measuring constellation of satellite radiometers.

ACKNOWLEDGMENT

The authors gratefully acknowledge funding and logistical support from NASA's Precipitation Measurement Mission Program at Goddard Space Flight Center under sponsorship by NASA Headquarters Earth Sciences Division.

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