Special Sensor Microwave Imager (SSM/I) Intersensor Calibration Using a Simultaneous Conical Overpass Technique

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ABSTRACT

A new intersensor calibration scheme is developed for the Defense Meteorological Satellite Program Special Sensor Microwave Imager (SSM/I) to correct its scan-angle-dependent bias, the radar calibration beacon interference on the F-15 satellite, and other intersensor biases. The intersensor bias is characterized by the simultaneous overpass measurements with the F-13 SSM/I as a reference. This sensor data record (SDR) intersensor calibration procedure is routinely running at the National Oceanic and Atmospheric Administration and is now used for reprocessing all SSM/I environmental data records (EDR), including total precipitable water (TPW) and surface precipitation. Results show that this scheme improves the consistency of the monthly SDR’s time series from different SSM/I sensors. Relative to the matched rain products from the Tropical Rainfall Measuring Mission, the bias of SSM/I monthly precipitation is reduced by 12% after intersensor calibration. TPW biases between sensors are reduced by 75% over the global ocean and 20% over the tropical ocean, respectively. The intersensor calibration reduces biases by 20.6%, 15.7%, and 6.5% for oceanic, land, and global precipitation, respectively. The TPW climate trend is 1.59% decade$^{-1}$ (or 0.34 mm decade$^{-1}$) for the global ocean and 1.39% decade$^{-1}$ (or 0.63 mm decade$^{-1}$) for the tropical ocean, indicating related trends decrease of 38% and 54%, respectively, from the uncalibrated SDRs. Results demonstrate the large impacts of this calibration on the TPW climate trend.

1. Introduction

The history of environmental satellite measurements now spans several decades, which is relatively sufficient...
long record of consistent measurements from multiple similar sensors is extremely important in generating CDRs for climate change research and analysis. However, the long-term multiple SSM/I measurements are not accurate enough to be directly applied in climate-related studies. The uncertainty caused by simply stitching multiple SSM/I datasets together as a CDR arises from instrument offsets, instrument degradation, signal interference, satellite orbital drift, missing data, etc. In addition, when these Defense Meteorological Satellite Program (DMSP) instruments were originally designed, the instrument calibration was mainly focused on their weather and environment applications, and their long-term performance stability has not been thoroughly assessed to date. Therefore, different SSM/I sensors have to be carefully calibrated to a reference satellite or a stable reference system in order to produce consistent and high quality CDRs for climate analysis and reanalysis. The calibrated SSM/I datasets computed by Remote Sensing Systems (RSS) are now available online (http://www.ssmi.com/ssmi). Another set of the calibrated SSM/I data computed by the research group led by Prof. C. Kummerow at Colorado State University (CSU) can also be found online (http://rain.atmos.colostate.edu).

Previous studies based on the Microwave Sounding Unit (MSU), which is carried on board the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites, show that the atmospheric tropospheric temperature warms up within a range of 0.08–0.21 K decade\(^{-1}\) (Christy et al. 2003; Grody et al. 2004; Wentz and Schabel 1998; Prabhakara et al. 2000; Zou et al. 2006, 2009). The MSU intersensor calibration also has a prominent impact on the temperature climate trend not only by increasing our confidence in the estimation of climate trends, but also by improving the consistency of temperature trends at the surface and in the troposphere (Zou et al. 2009; Mears and Wentz 2005). The most recent study indicates a trend of 0.2 K decade\(^{-1}\) for the global tropospheric temperature (Zou et al. 2009).

Intersensor calibration between SSM/I and SSMIS is also progressing well and is geared toward climate applications. The SSM/I anomaly due to the antenna field-of-view intrusion by the spacecraft and the glare suppression system was successfully corrected (e.g., Colton and Poe 1999). The SSM/I measurements are calibrated with respect to the radiative transfer simulations over oceans (Hilburn and Wentz 2008) and the well-calibrated SSM/I data reduce the discrepancy between the observed precipitation trend and the climate model prediction (Wentz et al. 2007). Recently, the observational anomalies of the first SSMIS on board the F-16 satellite were investigated and found to be caused by solar illumination on the SSMIS warm calibration target and antenna reflector emission (Kunkee et al. 2008; Yan and Weng 2008, 2009).

Several approaches have been commonly used for satellite intersensor calibrations, including 1) intercomparison between satellite and ground-based measurements, 2) comparison with clear-sky radiative transfer model simulations, 3) analysis of two overlapping sensor measurements at nearly simultaneous temporal and spatial locations, and 4) matching up the statistical properties of two sensor measurements at selected spatial scales. The simultaneous nadir overpass (SNO) technique was developed at NOAA/National Environmental Satellite, Data, and Information Service (NESDIS) (Cao et al. 2007) and has been used for MSU and AMSU temperature retrievals (Zou et al. 2006; Iacovazzi and Cao 2007, 2008; Iacovazzi et al. 2009). A similar simultaneous conical overpass (SCO) technique is developed for conically scanning instruments and the preliminary results show that the SCO calibration scheme can effectively remove biases between SSM/I or SSMIS sensors (Yan and Weng 2006, 2008; Weng et al. 2009; Yang et al. 2009).

For DMSP satellites, the intersensor calibration can be performed at either antenna temperature \(T_a\) or brightness temperature \(T_b\). The data record of satellite \(T_b\) measurements is called the sensor data record (SDR). Here, \(T_a\) is the effective blackbody temperature of the radiance on the feedhorn, while \(T_b\) is the calibrated effective blackbody temperature of the radiance on the antenna reflector. The conversion of \(T_a\) to \(T_b\) is performed to conduct the antenna pattern correction (CPA) in correcting the incomplete radiometric coupling between the reflector and feedhorn and the cross-polarization coupling between channels and sidelobe contamination (Colton and Poe 1999). It is recommended that the calibration of the radiometric measurements during the National Polar-orbiting Operational Environmental Satellite System (NPOESS) era should be conducted at \(T_b\) level. Therefore, this study presents the process involved with the SSM/I SDR intersensor calibration technique. The impacts of this scheme on the SSM/I-derived total precipitable water (TPW) and surface precipitation trends are also investigated.

2. Methodology and dataset

The SSM/I measurements are available at five frequency channels with vertical (V) and horizontal (H) polarization, except at the water vapor channel: that is, 19 (V, H), 22 (V), 37 (V, H), and 85 (V, H) GHz. The DMSP SSM/I datasets have been archived at Colorado State University (CSU) and NOAA/National Climatic Data Center (NCDC). The 1987–92 SSM/I datasets are in the Wentz format and the Wentz decoding procedures
were applied (Wentz 1988, 1991, 1993), while the 1993–2006 SSM/I data are the NOAA temperature data record (TDR) products. The description of the TDR products can be found in the NOAA documentation (Akunuri et al. 2009; NOAA/NCDC 2009). The 1987–99 SSM/I data from CSU and the 2000–06 datasets from NOAA are used in this study. The $T_a$ to $T_b$ conversion is based on the method discussed in Colton and Poe (1999).

Figure 1 displays the time series of rain-free monthly mean $T_b$ at 37V GHz from valid SSM/I measurements over the 60°S–60°N oceanic areas. It is obvious that SSM/I instruments provide a continuous measurement averaged over the oceanic region since July 1987; however, brightness temperature trends from different sensors are quite different. The $T_b$ biases of all overlapped SSM/I sensors shown in the bottom panel of Fig. 1 indicate that the bias varies with time and different SCO pairs by as much as ±1.2 K, while their mean absolute intersensor $T_b$ bias against the F-13 is 0.39 K. This large bias among different sensors demonstrates that the SSM/I SDRs and their derived environmental data records (EDRs) from the existing calibrations may not be suitable for climate studies. Thus, the calibration efforts for all SSM/I sensors must be conducted in order to generate unbiased and high quality CDRs for climate change analysis and trend studies.

Fortunately, the SSM/I measurements during their overlapping periods provide an alternative way of checking their consistency and of selecting a reference frame for the SSM/I intersensor calibrations. Figure 2 shows the local equatorial crossing times of the SSM/I sensors at their ascending nodes. It is evident that F-13 and F-14 have more overlapping time periods with other SSM/I sensors. Either one is naturally an ideal candidate as a reference satellite. However, F-13 has the longest data record and the smallest change in equatorial crossing time due to satellite orbit drift. Although we cannot prove that F-13 is absolutely accurate as the reference satellite, we use F-13 as the reference for the SSM/I cross-sensor calibration because of the stable F-13 $T_b$ time series in Fig. 1 and its water vapor products (see Fig. 11). In addition, a sensitivity study was conducted in the SSM/I $T_a$ intersensor calibration process using F-13 as the reference satellite, in which we assumed that F-13 was not taken as the absolute reference; instead, an F-13 $T_a$ bias was optimized to minimize the mean absolute intersensor bias.

**Fig. 1.** (top) Time series of oceanic rain-free monthly $T_b$ (K) at SSM/I 37V GHz during the period 1987–2006. (bottom) Time series of the SSM/I intersensor bias of oceanic rain-free monthly $T_b$ at the 37V GHz during the period 1987–2006 for any overlapped sensors. The mean absolute bias (K) against F-13 is shown at the bottom-left corner.

**Fig. 2.** The local equatorial crossing times (h) of available DMSP satellites with SSM/I instruments on board for ascending node, except for F-08 for the descending node since it is 12 h out of phase with the others.
bias (not discussed in this paper). Results show that the optimized $F_{-13} T_{b}$ bias is small so that the choice of $F_{-13}$ as the reference satellite in the SSM/I intersensor calibration is reasonable. Therefore, $F_{-13}$ is finally selected as the reference satellite. However, we plan to investigate the stability of the $F_{-13}$ sensor and its calibration in our continued efforts to improve the SSM/I-based CDRs, once the information is available.

The SSM/I measurements from a pair of the DMSP satellites are matched when they are simultaneously overpassing local areas, typically at high latitudes. These measurements are called the SCO pairs defined in details in section 3c. They are supposed to be identical if the sensors with the same incidence and azimuth angles are all well calibrated. Figure 3 shows the locations of the SCO pairs over the North and South Poles used in this study. However, a bias between two different SSM/I sensors normally exists due to many factors such as instrument calibration, instrument degradation, sources of interference to signals, satellite orbital drift, and incidence and azimuth angles. The bias between the SCO pairs should be removed in order to generate consistent SDRs, EDRs, and CDRs. We do not explicitly correct any possible error due to different sensor incidence and azimuth angles, although this bias should be very small in this study due to the SCO pair selection procedure to be discussed in section 3c. The data quality control of the SCO pixels described in section 3c is one of the key procedures in the calibration process. A double-difference technique (DDT) will be applied for SSM/I datasets if there is no direct interception between $F_{-13}$ and another satellite $A$ ($S_A$). In this case a third satellite ($S_B$), which has abundant SCOs with both $F_{-13}$ and $S_A$, will be used as a transfer radiometer to intercompare $F_{-13}$ and $S_A$. In this study, as discussed in section 3c, $F_{-14}$ is applied as the transfer radiometer between $F_{-13}$ and $F_{-15}$ for SCO over a water surface. It should be pointed out that the SCO-based bias correction scheme could not remove the biases that have a spatial variation.

SSM/I measurements from the $F_{-08}$, $F_{-10}$, $F_{-11}$, $F_{-13}$, $F_{-14}$, and $F_{-15}$ satellites during 1987–2006 are applied in this study, while only SSM/I data during 1990–2006 are used in the trend analysis. The SSM/I-based TPW and precipitation retrievals are derived from the NOAA heritage algorithms (Weng and Grody 1994; Ferraro et al. 1996). Since the Tropical Rainfall Measuring Mission (TRMM) rainfall products have been regarded by the science community as the most accurate precipitation measurements from satellite remote sensing (Yang and Smith 2008; Yang et al. 2008; Wolff and Fisher 2008, 2009; Yamamoto et al. 2008; Kummerow et al. 2000), three official TRMM rain products are utilized to demonstrate the impacts of the SSM/I SDR calibration on rain retrievals. These TRMM rain products are 2A12, the TRMM Microwave Imager (TMI) rain-only algorithm (Olson et al. 2006; Yang et al. 2006; Kummerow et al. 1996, 2001); 2A25, the TRMM precipitation radar (PR) rain-only algorithm (Iguchi et al. 2000); and 2B31, the combined TMI–PR rain algorithm (Haddad et al. 1997). In addition, the multisatellite blended TRMM rain algorithm, 3B42 (Huffman et al. 2007), is included in the analysis. The 2A12 rain product includes the TRMM orbital instantaneous rain retrievals at the TMI footprint scale of $10 \, \text{km} \times 10 \, \text{km}$, while both the 2A25 and 2B31 rain products are at the TRMM PR pixel resolution of $5 \, \text{km} \times 5 \, \text{km}$. The 3B42 rain product is at $3\,\text{h}^{\frac{1}{4}}$ grid resolution. A significance test on the trend analysis is conducted following the method discussed by von Storch and Zwiets (1999).

In addition, only the TRMM rain data that temporally match up with the SSM/I measurements at the orbital $0.5^\circ \times 0.5^\circ$ scale are used in the rain assessment study.
Thus, the TRMM TMI swath is applied for 2A12, while the TRMM PR swath is used for both 2A25 and 2B31. To mitigate the sampling issue, we conduct the assessment and intercomparison study for the monthly rainfall with the TRMM products at \( 5^\circ \times 5^\circ \) grid resolution.

3. SSM/I SDR intersensor calibration

a. Scan-angle-dependent bias

The SSM/I scan-angle-dependent bias was previously reported by Colton and Poe (1999) as being due to the antenna field-of-view intrusion by the SSM/I spacecraft near the beginning of the scan, and the glare suppression system near the end of the scan. The spacecraft intrusion and the glare suppression system have the least impact on SSM/I at its scan central position, so a measurement at this position can be regarded as an accurate reference. This bias is sensor dependent and varies at different channels and satellite orbit orientations, and must be removed prior to the SSM/I SDR intersensor bias corrections.

As an example, Fig. 4 shows the scan-angle-dependent bias at 37 GHz averaged from all available SSM/I measurements of oceanic rain-free pixels inside 60°S–60°N against the scan central position for all SSM/I sensors at the 37-GHz (top) vertical and (bottom) horizontal polarizations.

![Fig. 4. The mean scan-angle-dependent \( T_b \) bias (K) of oceanic rain-free pixels inside 60°S–60°N against the scan central position for all SSM/I sensors at the 37-GHz (top) vertical and (bottom) horizontal polarizations.](image)

**b. RADCAL beacon interference on F-15 22V GHz**

RADCAL, a system of instruments on board the DMSP F-15 spacecraft, consists of redundant C-band transponders with unique antennas, Doppler transmitters operating at 150 and 400 MHz, and deployable antennas. The purpose of the RADCAL C-band transponder-antennas is to provide a signal source for ground-based C-band radar interrogation and tracking, while the primary purpose of the Doppler transmitters and antennas is to determine satellite positions for comparison with the radar data. A secondary purpose of the Doppler systems is to support the Coherent Electromagnetic Tomography (CERTO) experiment. RADCAL has been operational since 14 August 2006 and considerably affects the F-15 SSM/I and Special Sensor Microwave Temperature-2 (SSMT-2) sensor data. In particular, the 150-MHz beacon produces considerable increases in brightness temperatures at 22 GHz (G. A. Poe et al. 2006, unpublished manuscript).

Since the RADCAL beacon interference on F-15 22V-GHz channel is steady, an initial correction algorithm is applied to remove the interference. Figure 5 exhibits the SSM/I F-15 \( T_a \) error at 22V GHz due to the RADCAL beacon interference on 30 August 2006 as a function of scan position for the ascending and descending nodes (Yan and Weng 2006). The errors are based on the mean differences between the global SSM/I observations and the radiative transfer model simulations under oceanic cloud-free conditions. A polynomial function is applied to fit the error curves; then, this error is subtracted from the raw \( T_a \) at 22V GHz:

\[
T_a(\text{err}) = a_0 + a_1 X + a_2 X^2 + a_3 X^3 \quad \text{and} \quad (1)
\]

\[
T_a(\text{cal}) = T_a(\text{obs}) - T_a(\text{err}). \quad (2)
\]

In Eq. (1), \( X \) is the scan position, and the coefficients of \( a_0, a_1, a_2, \) and \( a_3 \) are given in Table 1. The fitted lines are

\[ -0.5 \text{ K are seen at SSM/I high-frequency channels. In addition, there are also prominent bias differences for ascending and descending nodes. During the calibration processes, the five-scan position-weighted average bias curve is applied so that possible noise associated with the scan positions is minimized. A linear interpolation scheme is used to estimate the bias at any pixel position of an SSM/I high-frequency channel that is not collocated with the position of the low-frequency channel. Finally, the seasonal variability of the bias patterns is analyzed. Results indicate a small seasonal change in the scan-angle-dependent bias patterns, but this seasonal variation is not considered in this study. A detailed analysis and the complete bias table will be available in a NOAA technical report to be published in the near future. \]

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\]

\[
T_a(\text{cal}) = T_a(\text{obs}) - T_a(\text{err}). \quad (2)
\]

In Eq. (1), \( X \) is the scan position, and the coefficients of \( a_0, a_1, a_2, \) and \( a_3 \) are given in Table 1. The fitted lines are
overlapped in Fig. 5 to clearly show the fitting applied for this study. This correction of the F-15 RADCAL beacon interference is applied before the scan-angle bias correction. However, G. A. Poe et al. (2006, unpublished manuscript) indicate an increased RADCAL interference during Earth shadow, resulting in an approximately 1.3-K increase in the vicinity of the maximum interference at beam position 25. This effect is apparent for the descending orbits that enter Earth’s shadow for part of the year due to Earth’s elliptical orbit and leads to a clear impact on EDRs, especially TPW, during Earth shadow. This Earth shadow effect on TPW is small for global or tropical ocean averages, while it could create a notably artificial spatial variation at regional scales, especially when the time in Earth shadow increases considerably during summer 2007. In addition, the RADCAL interference also affects the F-15 85-GHz channels at a lesser degree. Since only 4 months of F-15 datasets affected by the RADCAL interference were involved in this study, their impact on the 85-GHz channels should not substantially change the results from this study. Therefore, we do not discuss the influence of the interference during Earth shadow and its impact on the 85-GHz channels in this paper. However, we plan to further investigate these issues through our continued efforts to improve the SSM/I and SSMIS data quality at NOAA/NESDIS.

c. SCO technique for linear SDR intersensor bias correction

The physical principle of the SCO technique in intersensor calibration studies is primarily based on the assumption that simultaneous measurements at a location from two different sensors of the same design should be highly correlated. If one sensor is regarded as a reference, the other can be calibrated to this reference. The skill of the SCO technique requires minimization of the measurement differences caused by noninstrumental factors. Thus, the SCO differences between two different sensors are primarily due to instrumental errors, which should be removed during the post launch calibration processes.

Many experiments with different SCO constraints are conducted for an optimal result. All possible SCO pairs are first quality controlled for the same orbital node (e.g., ascending or descending) and similar pixel positions. A spatial distance ($D_d$) of 3 km between the SCO pair is used to ensure that at least the footprints of two SSM/I instruments are overlapped by 75%–90%. A reasonable time difference ($D_t$) between two sensors is required to lead to a reliable analysis. Figure 6 displays the mean bias, standard deviation, and the SCO pair samples against different time criterion at 22V GHz.

TABLE 1. The $T_a$ correction coefficients used in Eq. (1) for the RADCAL beacon interference error at F-15 SSM/I 22V GHz.

<table>
<thead>
<tr>
<th>Satellite status</th>
<th>Coef</th>
<th>1</th>
<th>2–37</th>
<th>38–62</th>
<th>63–64</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ascending node</td>
<td>$a_0$</td>
<td>10.011 36</td>
<td>9.607</td>
<td>2.2655</td>
<td>4.780 03</td>
</tr>
<tr>
<td></td>
<td>$a_1$</td>
<td>0</td>
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<td>$-3.7596 \times 10^{-1}$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$a_2$</td>
<td>0</td>
<td>$-1.2794 \times 10^{-3}$</td>
<td>$1.5069 \times 10^{-4}$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$a_3$</td>
<td>0</td>
<td>$-1.2039 \times 10^{-4}$</td>
<td>$2.1233 \times 10^{-5}$</td>
<td>0</td>
</tr>
<tr>
<td>Descending node</td>
<td>$a_0$</td>
<td>10.286 97</td>
<td>9.989</td>
<td>28.191</td>
<td>5.406 14</td>
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<td></td>
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<td>0</td>
</tr>
<tr>
<td></td>
<td>$a_3$</td>
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<td>$-7.877 \times 10^{-5}$</td>
<td>$-6.8437 \times 10^{-5}$</td>
<td>0</td>
</tr>
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<td>9.798</td>
<td>28.578</td>
<td>5.05</td>
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<tr>
<td></td>
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<td>$-8.52 \times 10^{-1}$</td>
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<tr>
<td></td>
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<tr>
<td></td>
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<td>$-6.8086 \times 10^{-5}$</td>
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</table>
between F-13 and other SSM/I sensors over water surfaces. It is evident that the bias and standard deviation vary slightly with different time criteria, except for the F-13/F-11 bias, which increases dramatically when the time difference is less than 2 min due to the increase in the uncertainties with limited samples. Similar results exist for other channels. Over land (figure omitted), the SCO bias difference is very small with the different time criteria (0.5, 1, and 2 min). However, the bias increases considerably when the time difference is greater than 5 min. Thus, in general, the 2-min criterion is used and the SCO samples are enough for the analysis of the intersensor bias correction. In addition, the samples over inhomogeneous background conditions are eliminated by applying the standard deviation ($\sigma$) of nine neighboring pixels surrounding a candidate SCO pair. The SCO pair is taken as a good one if $\sigma$ is less than 2 K for a homogeneous surface. Features similar to those for the water surface are found for SCO pairs over ice and coastal surface types, except that $\sigma$ less than 5 K is used for coastal areas. Finally, the absolute $T_b$ difference ($|\Delta T_b|$) of an SCO pair should be less than 10 K. Only about 1% (0.06%) of the oceanic (continental) SCO pairs were excluded with this criterion.

After careful analysis of the SCO pairs using F-13 as a reference satellite, the criteria for collecting high-quality SCO pairs are defined as follows:

- $\Delta d \leq 3$ km,
- $\Delta t \leq 2$ min,
- $\sigma \leq 2$ K (5 K for coast case),
- and $|\Delta T_b| \leq 10$ K.
In addition, the same orbital nodes and similar scan positions (less than three scan positions difference) are also required. The bias distribution with the SCO time differences is inspected to eliminate any potentially large bias caused by small samples of the SCO pairs that were not well distributed.

All SCO pixels are sorted into four categories based on surface type (i.e., water, land, ice, and coast) to avoid the contamination caused by mixing these surface types and were carefully analyzed accordingly. As an example, Fig. 7 presents the SCO $T_b$ bias [$T_b(F-13) - T_b(F-14)$] at 37V GHz against their interception time difference over the water background. It is evident that 2059 SCO pixels are well distributed around the exact interception time ($\Delta t = 0$) between F-13 and F-14. The statistical mean bias is $-0.58$ K with a standard deviation of 0.60 K. Since it is difficult to find many exactly simultaneous measurements between any two SSM/I sensors, the statistical mean bias of the SCO pixels with nearly simultaneous measurements is a reliable choice for obtaining the bias between these two sensors. Similar processes are conducted for all other SSM/I channels to estimate the intersensor bias coefficients between F-13 and other SSM/I satellites.

Due to the limited SCO pixels between F-13 and F-15 over water surfaces, a DDT approach is utilized to estimate the $T_b$ bias, that is, using F-14 (which has better overlaps with both F-13 and F-15) as a transfer radiometer to connect them so that subtraction of the $T_b$ bias between F-15 and F-14 from that between F-13 and F-14 results in the $T_b$ bias $T_{b,F-13-F-15}$ because the F-14 effect is literally cancelled out from the double difference

$T_{b,F-13-F-15} = T_{b,F-13-F-14} - T_{b,F-15-F-14}$.

Please be advised that the DDT can only be applied when there are insufficient good-quality SCO pixels between two SSM/I sensors so that a third sensor must be used as a transfer radiometer. Finally, no bias correction is applied with F-08 because there are no reliable SCO pixels between F-08 and F-13 and there are insufficient F-08–F10 match-ups to apply a DDT. Additional efforts are planned at NOAA/NESDIS to produce a calibrated F-08 dataset in the near future. The final intersensor bias correction coefficients and standard deviations for F-10, F-11, F-13, F-14, and F-15 using F-13 as the reference satellite are listed in Table 2.

4. Calibration impacts on SSM/I SDR

With the continuously increasing time span of environmental satellite measurements, the satellite remote sensing derived EDRs are becoming more important in climate-related studies. Since the climate trends of meteorological parameters are small compared to the natural variability in the system, improvements in satellite remote sensing datasets will be important for use in quantifying climate trends. After implementation of the SDR intersensor calibration procedure as discussed in section 3, the trends from all SSM/I SDR time series are now more consistent.

Figure 8 shows the time series of SSM/I oceanic rain-free monthly mean intersensor calibrated $T_b$ and their intersensor bias at the 37V-GHz channel. When compared to Fig. 1, it is apparent that the new time series has a considerably improved consistency among these SSM/I sensors, with the intersensor bias reduced dramatically. The variation of the intersensor biases with time and different overlapping SSM/I sensors is only around ±0.5 K, indicating a 58% decrease of the bias after intersensor calibration. We use the mean absolute bias to summarize how calibration offsets affect the consistency of the monthly $T_b$ time series among different sensors. This parameter is the average absolute monthly $T_b$ biases, which highlights the spread, as opposed to the grand-average offsets captured by a simple average of the monthly biases. The mean absolute bias after calibration is only 0.20 K, indicating a mean absolute bias deduction of 49%. Similar results are found for other SSM/I channels. The mean absolute $T_b$ bias against F-13 before and after the SDR intersensor calibration and the percentage change for each channel are summarized in Table 3. The averaged deduction of the mean absolute bias with the SDR calibration is about 30%. Therefore, these results demonstrate that the newly developed SSM/I SDR intersensor calibration scheme is very useful and can substantially improve the
The improved consistency of the SSM/I SDRs should lead to a more reliable SDR trend analysis. Since F-08 is not included in the processing of the SSM/I SDR intersensor bias corrections using F-13 as the reference satellite, F-08 is not involved in the trend analysis. Thus, the trend analysis throughout this paper is only based on SSM/I measurements from the time period 1990–2006.

Figure 9 presents the time series of the SSM/I oceanic rain-free monthly $T_b$ before and after intersensor SDR calibration at the 37V-GHz channel. The SSM/I $T_b$ time series before calibration presents a standard deviation ($\sigma$) of 0.49 K and a linear trend of $-0.12$ K decade$^{-1}$ at the 2.5% significance level. After calibration, the monthly $T_b$ time series has the same mean value, but much smaller $\sigma$ (0.32) and larger trend ($-0.32$ K decade$^{-1}$) at the 0.1% significance level. Similar analyses are conducted for other channels and the results are summarized in Table 4. It is obvious that SDR intersensor calibration using F-13 as the reference satellite will not substantially change the averaged monthly $T_b$, but will lead to a more consistent time series among multiple SSM/I sensors with a mean reduced...

![Oceanic Rain-Free Monthly Mean $T_b$](image1)

![SSM/I Intersensor Bias of Oceanic Rain-Free Monthly Mean $T_b$](image2)

**Fig. 8.** As in Fig. 1, but for the SDR intersensor-calibrated $T_b$ (K).
The mean absolute intersensor bias of the oceanic rain-free monthly mean brightness temperature $T_b$ for SSM/I F-10, F-11, F-13, F-14, and F-15 using F-13 as the reference satellite. Here, $T_{b,\text{Raw}}$ (K) and $T_{b,\text{Cal}}$ (K) are for before and after the SDR intersensor calibration, respectively. The bottom row shows the percentage change from before to after the calibration.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$T_{b,\text{Raw}}$ (K)</th>
<th>$T_{b,\text{Cal}}$ (K)</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19V</td>
<td>0.45</td>
<td>0.23</td>
<td>-49</td>
</tr>
<tr>
<td>19H</td>
<td>0.28</td>
<td>0.23</td>
<td>-18</td>
</tr>
<tr>
<td>22V</td>
<td>0.74</td>
<td>0.43</td>
<td>-42</td>
</tr>
<tr>
<td>37V</td>
<td>0.39</td>
<td>0.20</td>
<td>-49</td>
</tr>
<tr>
<td>37H</td>
<td>0.94</td>
<td>0.51</td>
<td>-12</td>
</tr>
<tr>
<td>85V</td>
<td>0.58</td>
<td>0.52</td>
<td>-35</td>
</tr>
<tr>
<td>85H</td>
<td>0.80</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$a$ of 21.4% for all channels. The most important impact of this calibration is its role in changing the $T_b$ trend considerably at every SSM/I channel; that is, the trend magnitudes are reduced by 37.1%, 72.2%, 74.1%, and 77.3% for channels 19V, 37H, 85V, and 85H GHz, respectively, while they increase by a larger percentage at 19H, 22V, and 37V GHz because the original trend was small.

5. Impacts of SSM/I intersensor calibration on TPW and precipitation

$a$. TPW analysis

The TPW and precipitation products are two of many meteorological variables retrieved from SSM/I measurements using the NOAA heritage retrieval package (Sun and Weng 2008). Although there are discrepancies between different TPW and precipitation algorithms, the oceanic TPW and precipitation estimates based on satellite passive microwave measurements are considered to be robust retrievals (Sohn and Smith 2003; Ebert and Manton 1998). Therefore, they are used to demonstrate the intersensor calibration impacts on the SSM/I-based EDRs. Figure 10 presents the monthly TPW intersensor bias over the global ocean and the tropical ocean between any two overlapped SSM/I sensors on board F-10, F-11, F-13, F-14, and F-15 for before and after the intersensor SDR calibration. The relatively large TPW intersensor biases before calibration are obvious, especially between F-10 and F-11 and between F-10 and F-13 that have large biases of -1.5 mm over the global ocean and -3.0 mm over the tropical ocean. The averaged absolute TPW intersensor biases are 0.358 and 0.264 mm for the global and tropical oceans, respectively. After the intersensor calibration, the amplitude of the associated TPW intersensor biases is only about ±0.10 mm over the global ocean and ±0.50 mm over the tropical ocean, showing a dramatic bias reduction from before calibration. By the same token, the mean absolute TPW biases are only about 0.089 and 0.209 mm, respectively. Thus, SSM/I intersensor calibration has a large positive impact on the TPW retrievals with a resultant decrease of the mean absolute intersensor bias by 75% over the global ocean and 20% over the tropical ocean.

We have demonstrated that the newly developed SSM/I SDR intersensor calibration scheme improves the consistency of the multisensor SSM/I measurements and associated EDRs. Figure 11 presents the TPW trend analysis over both global and tropical oceans before and after the SDR intersensor calibrations for F-10, F-11, F-13, F-14, and F-15. The key statistics are also shown in

![Figure 9](image-url)
It is apparent that the improved TPW consistency among different SSM/I sensors results in a reliable trend analysis. Prior to the intersensor calibration, the mean TPW, standard deviation, and trend are at 21.30 mm, 0.67 mm, and 0.54 mm decade\(^{-1}\) for the global ocean and 44.80 mm, 1.57 mm, and 1.35 mm decade\(^{-1}\) for the tropical ocean, respectively. The corresponding values after the intersensor calibration are only about 21.60 mm, 0.40 mm, and 0.34 mm decade\(^{-1}\) over the global ocean and 45.30 mm, 1.24 mm, and 0.63 mm decade\(^{-1}\) over the tropical ocean. The trend is at the 0.1% significance level for all cases. The mean TPW is increased by 1% with the calibration; however, the TPW standard deviation and trend are decreased by 40% and 38% over the global ocean and 21% and 54% over the tropical ocean, respectively. The impacts of the TPW mean absolute intersensor bias and trend from the SDR calibration are summarized in Table 5.

Therefore, this study illustrates the importance of the SSM/I intersensor calibration in TPW climate-related studies. Although uncertainties, especially at detailed horizontal distributions in TPW retrievals based on passive microwave measurements, exist, the different TPW algorithms are generally in agreement with each other (Sohn and Smith 2003). The TPW retrieval error should be smaller compared with the error associated with the uncalibrated \(T_b\).

The 0.34 mm decade\(^{-1}\) (or 1.59% decade\(^{-1}\)) of the global oceanic TPW trend in this study agrees well with the analysis of Trenberth et al. (2005) at 0.40 ± 0.09 mm decade\(^{-1}\) (or 1.3 ± 0.3% decade\(^{-1}\)) from the 1988–2003 period and the results of Wentz et al. (2007) at 0.354 ± 0.114 mm decade\(^{-1}\) (or 1.2 ± 0.4% decade\(^{-1}\)) over the 1987–2006 period. Our results also indicate that the TPW trend is 1.39% decade\(^{-1}\) for the tropical ocean inside the 20° latitude zonal belts.

### b. Precipitation analysis

Since precipitation is one of the most important climate variables and has a relatively large retrieval uncertainty with satellite measurements (e.g., Yang and Smith 2008; Smith et al. 1998), any impacts of the intersensor calibration on precipitation should be carefully assessed. Here, we demonstrate the important impacts of the SDR intersensor calibration on precipitation using the NOAA heritage rain retrieval algorithm (Weng and Grody 1994; Ferraro et al. 1996; Sun and Weng 2008; Sun et al. 2009).

Figure 12 presents a comparison of the monthly mean rain rates from F-14 SSM/I measurements during December 2006 before and after intersensor calibration. It is evident that the monthly mean rainfall distributions before and after the calibrations are in very good agreement due to the fact that the calibration impacts on each panel of Fig. 11.
precipitation are relatively small compared to the magnitude of the retrieved precipitation. The overall mean (conditional mean, i.e., without 0 rain-rate pixels) rain rates are 1.00 (2.63) and 0.40 (4.80) mm day$^{-1}$ over ocean and land, respectively. The rain-rate difference after the SDR calibration and before calibration is generally less than $-0.2$ mm day$^{-1}$ with a conditional mean of $-0.07$ mm day$^{-1}$ over ocean, and is less than 0.4 mm day$^{-1}$ with a conditional mean of 0.09 mm day$^{-1}$ over land. With the intersensor calibration, precipitation from the heritage rain algorithm consistently produces less oceanic rainfall and more continental precipitation.

Fig. 10. Time series of monthly TPW intersensor bias (mm) for any overlapped SSM/I sensors on board F-10, F-11, F-13, F-14, and F-15. Different SSM/I pairs are marked by different symbols. (left) Before and (right) after SDR intersensor calibration. (top) The global ocean and (bottom) the tropical ocean (20$^\circ$S–20$^\circ$N). The averaged absolute TPW intersensor bias (mm) is shown in the bottom-left corner of each panel.

Fig. 11. Time series of monthly TPW (mm) derived from F-10, F-11, F-13, F-14, and F-15 SSM/I measurements. Different symbols are used for different SSM/I satellites. (left) Before and (right) after SDR intersensor calibration. (top) The global ocean and (bottom) the tropical ocean. The overlapped heavy dashed line is the linear fitting curve based on the least absolute deviation method. The key stats of trend (mm decade$^{-1}$), t-test significance (%), mean TPW (mm), and standard deviation (mm) are listed at the bottom of each panel.
rainfall (Fig. 12, bottom). Thus, it indicates that the calibration impacts on precipitation are relatively small on a monthly scale.

Figure 13 illustrates the horizontal distributions of the monthly mean rain rate at $5^\circ \times 5^\circ$ grid scale after the intersensor calibration for F-14 SSM/I measurements in December 2006, as well as from the matched TRMM 3B42, 2A12, 2A25, and 2B31 measurements. It is apparent that the monthly rainfall distribution pattern from the heritage rain algorithm is highly consistent with TRMM measurements, although some detailed differences exist; for example, NOAA rainfall over land is greater than TRMM rainfall. Due to the decreased reliability of rainfall from passive microwave measurements over land, only oceanic rain retrievals are used in the following intercomparison.

Further intercomparison of the December 2006 oceanic precipitation at $5^\circ \times 5^\circ$ grid resolution from the NOAA heritage rain algorithm with the F-14 SSM/I measurements before and after the SDR intersensor calibration and from the TRMM facility algorithms (e.g., 2A12, 2A25, and 2B31) is demonstrated in Fig. 14. Note that intercomparison at higher spatial scales would lead to large uncertainties because of the uneven sampling match-up issues; so that only the monthly $5^\circ \times 5^\circ$ grid scale is applied in the intercomparison study. It is shown that both monthly precipitation before and after the intersensor calibration has good agreement with the TRMM official rain products. There is a very small difference in the mean precipitation before and after the calibration. If we treat the TRMM rain products as the “truth,” the correlation coefficients are almost the same, while the relative biases of precipitation after calibration are reduced by 14%, 9%, and 15% against 2A12, 2A25, and 2B31, respectively. These results provide robust examples of the important impacts on precipitation retrievals with the SSM/I SDR intersensor calibration.

Table 5. Intercomparison summary of TPW mean absolute intersensor bias (mm) and trend (% decade$^{-1}$) before and after the SSM/I intersensor calibration and their associated percentage changes.

<table>
<thead>
<tr>
<th>Mean absolute intersensor bias</th>
<th>Trend</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPW (mm)</td>
<td>Before calibration</td>
</tr>
<tr>
<td>Global ocean</td>
<td>0.358</td>
</tr>
<tr>
<td>Tropic ocean</td>
<td>0.264</td>
</tr>
</tbody>
</table>

where the rain retrieval from passive microwave measurements has the largest error. The corresponding mean absolute biases are 0.068, 0.446, 0.107, and 0.098 mm day$^{-1}$, respectively. After the cross calibration, the mean absolute biases are 0.054, 0.376, 0.1, and 0.098 mm day$^{-1}$, resulting in deductions of the biases by about 20.6%, 15.7%, 6.5% and 0%, respectively. This small impact on the tropical rainfall is expected due to the relatively small magnitude of the SDR calibration and will not affect the rain intensity considerably when precipitation is already strong in the tropics. Some statistics on variations of the precipitation mean absolute bias due to the SDR calibration are summarized in Table 6.

### 6. Discussion and conclusions

A new NOAA/NESDIS SSM/I SDR intersensor calibration scheme is developed for climate studies. This calibration scheme is built on the SCO technique, which collects observations at the same time and location from two SSM/I sensors that have an overlapping time period. The SCO intersensor calibration scheme requires an SSM/I sensor to be the reference radiometer so that other sensors can be calibrated against this reference sensor. We have selected F-13 as a reference sensor because of its most stable local equatorial crossing time and because it has the most interceptions with other satellites.

The SSM/I scan-angle-dependent bias is analyzed by comparing the mean oceanic rain-free $T_b$ at each scan position against its central position. Results show a maximum bias of $-2.5$ K for high-frequency channels and $-1.75$ K for low-frequency channels near the end of the scan due to the glare suppression system, and a notable bias of $-0.5$ K near the beginning of the scan caused by the SSM/I spacecraft intrusion. This scan-angle-dependent bias varies with the orbital ascending and descending nodes, as well as the seasons. In addition, a statistical method is developed in an early effort to remove the RADCAL beacon interference on the F-15 22V-GHz channel. Both the scan-angle-dependent bias and the 22V-GHz channel interference have to be removed prior to any SSM/I SDR intersensor bias corrections. The impacts of the RADCAL interference on the
85-GHz channel and its increased interference during the Earth shadow period are not discussed in this study. This issue will be considered in our continued calibration efforts.

Because of the important influence of surface background on satellite passive microwave radiance, the surface inhomogeneity has a huge impact on the collected SCO pixels. To eliminate maximally the impacts of the surface inhomogeneity on the SCO pixels, a tight quality control procedure was developed so that the bias of the SCO pixels for two overlapped SSM/I sensors would be mainly caused by the sensor differences. In addition to the same satellite orbital nodes and similar scan positions, the SCO criteria are set as $\Delta d \leq 3$ km, $\Delta t \leq 2$ min, $\sigma \leq 2$ K, and $|\Delta T_b| \leq 10$ K for three surface categories (i.e., water, land, and ice surface types), while $\sigma \leq 5$ K is used for coastal situations. Notably, when there are not enough high quality SCO pixels between

![Fig. 12. The F-14 SSM/I-based monthly mean rain rate (mm day$^{-1}$) at 0.5° × 0.5° grid scale for December 2006 (top) before and (middle) after SDR intersensor calibration. (bottom) The rain-rate difference between after and before calibration.](image-url)
two sensors, a third satellite that has good SCO pixels with both of these two sensors is utilized as the transfer radiometer to create the desired SCO pixels (This process is normally referred as the DDT.). Therefore, the current NOAA/NESDIS SSM/I SDR intersensor calibration scheme has two major components: 1) removal of the scan-angle-dependent bias and the RADCAL beacon interference error on F-15 22V GHz after 15 August 2006 and 2) removal of the intersensor bias against the reference satellite (F-13) over different surface types. (Because of the lack of useful SCO pixels against F-13, F-08 is not applied in the SDR intersensor calibration.)

FIG. 13. Monthly mean rain rate (mm day$^{-1}$) at 5° × 5° grid scale for December 2006 from the F-14 SSM/I and the matched TRMM measurements. (top) After SDR intersensor calibration. The bottom four panels are for the F-14-matched TRMM 3B42, 2A12, 2A25, and 2B31 results respectively.
Results demonstrate that the newly developed SSM/I SDR intersensor calibration scheme substantially improves the consistency of the monthly mean oceanic rain-free $T_b$ time series for all sensors, in terms of 58% reduced maximum intersensor bias, 30% declined mean absolute bias, and 21% decreased standard deviation. In addition, as we expected, the intersensor calibration has little impact on the mean rain-free oceanic monthly $T_b$; however, it displays a dramatic influence on the climate trend of the monthly $T_b$ series. Because of the consistency of the $T_b$ series for all SSM/I sensors, the SDR’s climate trend becomes more reliable. The SDR’s climate trend over ocean varies from $-2.70$ to $0.36$ K decade$^{-1}$ before the intersensor calibration and from $-0.44$ to $0.09$ K decade$^{-1}$ after the calibration, resulting in a percentage change of 37% at the 19V-GHz channel, and more than 70% at other channels.

The TPW and precipitation are taken as examples to demonstrate the impacts of the SSM/I SDR intersensor calibration on the associated EDRs and CDRs. The F-14 SSM/I measurements during December 2006 were applied to illustrate the differences in the precipitation retrievals before and after the intersensor calibration. The NOAA heritage rain algorithm is used in this analysis. The SSM/I SDR intersensor calibration leads to a systematic deduction of oceanic precipitation with an overall change of $-2.7\%$ and a systematic continental rainfall increase with a mean difference of $1.7\%$. The resultant oceanic precipitation retrievals after the intersensor calibration improve their comparisons with the matched official TRMM rain products from the TMI, PR, and TMI–PR combined algorithms by reduced biases of $14\%$, $9\%$, and $15\%$, respectively.

The most important impact on TPW and precipitation from the SSM/I SDR intersensor calibration is that the resultant monthly TPW and precipitation show a dramatically improved consistency among all sensors, indicating that the EDRs and CDRs with the intersensor-calibrated SSM/I measurements are more suitable for climate-related studies. In general, the maximum TPW intersensor bias from before to after the calibration changes from $-1.5$ to $\pm 0.1$ mm for the global ocean and from $-3$ to $\pm 0.5$ mm for the tropical ocean, resulting in 75% and 20% deductions of the mean absolute intersensor bias, respectively. The corresponding TPW standard deviations are also decreased by 40% and 21%.

![Fig. 14. Intercomparison of monthly mean rain rate (mm day$^{-1}$) at $5^\circ \times 5^\circ$ grid scale for December 2006 from the F-14 SSM/I and the F-14-matched TRMM (left) 2A12, (middle) 2A25, and (right) 2B31. (top) TRMM and the uncalibrated SSM/I precipitation, and (bottom) TRMM and the SDR intersensor-calibrated SSM/I precipitation. The key stats are listed in the bottom-right corner of each panel. The $\Delta$ bias presents the percentage change of the bias from before to after intersensor calibration.](image-url)
The TPW climate trends after the intersensor calibration are 0.34 mm decade\(^{-1}\) (or 1.59% decade\(^{-1}\)) for the global ocean and 0.63 mm decade\(^{-1}\) (or 1.39% decade\(^{-1}\)) for the tropical ocean, showing trend decreases of 38% and 54% from before the calibration, respectively. The TPW trend with the intersensor-calibrated SSM/I measurements are in a good agreement with previously published results.

The impacts of calibration on precipitation retrievals are relatively small in comparison with TPW but are still important. The standard deviation of the monthly oceanic precipitation is generally reduced by 10%, and mean absolute rainfall intersensor biases are also decreased by 20.6%, 15.7%, 6.5%, and 0% for ocean, land, global, and tropical ocean datasets, respectively.

Overall, this study provides robust evidence that the cross-sensor calibration has some impact, resulting in more consistent SDRs, EDRs, and CDRs. The SSM/I SDR intersensor calibration can potentially improve climate-trend studies.

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**TABLE 6.** Intercomparison summary of precipitation mean absolute intersensor bias (mm day\(^{-1}\)) and trend (% decade\(^{-1}\)) before and after the SSM/I intersensor calibration and their associated percentage changes.

<table>
<thead>
<tr>
<th></th>
<th>Mean absolute intersensor bias</th>
<th>Before calibration</th>
<th>After calibration</th>
<th>Change (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ocean</td>
<td>0.068</td>
<td>0.054</td>
<td>-20.6</td>
<td></td>
</tr>
<tr>
<td>Land</td>
<td>0.446</td>
<td>0.376</td>
<td>-15.7</td>
<td></td>
</tr>
<tr>
<td>Global</td>
<td>0.107</td>
<td>0.100</td>
<td>-6.5</td>
<td></td>
</tr>
<tr>
<td>Tropical ocean</td>
<td>0.098</td>
<td>0.098</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
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