The Version-6 Calibration of SSM/I

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1. Introduction

The Special Sensor Microwave Imagers (SSM/I) are a series of 6 satellite radiometers that have been in operation since 1987. These satellite sensors measure the natural microwave emission coming from the Earth’s surface in the spectral band from 19 to 85 GHz. These emission measurements contain valuable information on many important climate variables including winds over the ocean, the moisture and rain in the atmosphere, sea ice, and snow cover. However, the extraction of this information from the raw satellite measurements is a complicated process requiring considerable care and diligence. The first step in the process is the generation of Fundamental Climate Data Records (FCDR) of the sensor measurements in term of antenna temperatures (T_A) and brightness temperatures (T_B). It is absolutely essential that proper satellite inter-calibration methods be employed when producing these SSM/I FCDRs.

Since the first SSM/I was launched in 1987, Remote Sensing Systems (RSS) has been providing SSM/I data to the research and climate communities. The most current RSS dataset is called Version 6 and is generally recognized as the most complete and accurate SSM/I FCDR available. The V6 T_A and T_B are currently being used at about 20 institutions worldwide. This document describes the calibration procedure that is used to convert the raw SSM/I sensor counts that are sent down from the spacecraft to fully calibrated T_A and T_B.

This document assumes the reader in familiar with the SSM/I from both a hardware standpoint and an analysis standpoint. The following references provide ample information in these two areas: Hollinger et al. 1987; Wentz 1988, 1991, 1993, 1997; Colton and Poe, 1999; Hilburn and Wentz, 2008.
2. **Unadjusted Antenna Temperature**

In computing the unadjusted SSM/I antenna temperature \( T_A \), the basic assumption is that the radiometer output voltage is linearly related to the input power at the mixer/preamplifier. Nonlinear effects such as imperfections in the square-law detector and the IF amplifier compression are assumed to negligible. Under these assumptions, the \( T_A \) is given by [Wentz, 1991]

\[
T_A = \frac{(T_{Ah} - T_{Ac}) C + T_{Ac} C_h - T_{Ah} C_c}{C_h - C_c}
\]  

(1)

The terms \( C_c, C_h, \) and \( C \) are the radiometer counts (i.e., output voltage) when the radiometer is looking at the cold calibration target, the hot calibration target, and the earth scene, respectively. The temperatures \( T_{Ac} \) and \( T_{Ah} \) are the effective temperatures of the cold and hot calibration targets. Equation (1) is simply expressing the assumption that the radiometer counts vary linearly as the scene temperature varies from \( T_{Ac} \) to \( T_{Ah} \).

One difficulty is accurately specifying \( T_{Ac} \) and \( T_{Ah} \). For example, the cold target is a mirror pointing towards cold space, which has a temperature of 2.73 K. However, if the mirror is not a perfect reflector or if the cold measurement is receiving radiation from other sources (i.e., spill-over effects), the true value for \( T_{Ac} \) will be greater than 2.73 K. The specification of \( T_{Ah} \) is even more difficult. In this case, one must infer \( T_{Ah} \) from thermistor readings attached to the hot target. The thermistors are embedded into the hot load, and there will be some error in using these readings to estimate the effective surface temperature of the hot load. Thermal gradients over the extent of the hot load will also cause problems (SSM/I has only 3 thermistors).

In computing the unadjusted \( T_A \), we use a relatively simple model for \( T_{Ac} \) and \( T_{Ah} \). The cold temperature is assumed to be 2.7 K for the 19, 22, and 37 GHz channels. For the 85 GHz channels, a value of 3.2 K is assumed. At 85 GHz, the Rayleigh-Jeans approximation to the Planck equation begins to break down. A common technique for handling this problem is to use a somewhat larger value for \( T_{Ac} \) to compensate for the slight non-linearity between spectral radiance and brightness temperature that occurs at the higher microwave frequencies. Accordingly, we use a value of \( T_{Ac}=3.2 \) K at 85 GHz.

For the hot load temperature, we use the following

\[
T_{Ah} = T_h + \xi (T_p - T_h)
\]  

(2)
The temperature $T_h$ is the average of the 3 thermistor readings and the temperature $T_p$ is the reading from the single thermistor on the SSM/I drum plate facing the hot load. The coefficient $\xi$ is a value derived from prelaunch thermal-vacuum measurements and its value is 0.01 [Hollinger et al., 1987]. For the F13 SSM/I, only hot-load thermistor 2 is used for $\bar{T}_h$ because the other 2 thermistors displayed considerable noise [Colton and Poe, 1999].

Noise in $C_c$ and $C_h$ is reduced by averaging measurements from adjacent scans. We use a time window of ±12 seconds centered on the scan being processed. If there are no data gaps, this time window will include 7 A/B scan pairs. For the 19-37 GHz channels, calibration counts are only collected during the A scan. For 85 GHz, calibration counts are collected for both the A and B scans. For each scan, 5 calibration measurements are taken of the cold target and another 5 for the hot target. Thus our ±12 seconds time window provides 35 cold counts and 35 hot count for each of the lower-frequency channels. At 85 GHz, there are twice as many count values. This is a sufficient number of samples to reduce the noise in the calibration counts to an acceptable level. In equation (1), $C_c$ and $C_h$ represent average values over 7 scans. The same type of scan averaging is also done for the hot load thermistor readings, but this has little effect.

3. Along-Scan Correction

One of the first SSM/I calibration problems that was detected was an along-scan error [Wentz, 1991]. Towards the end of the Earth scan, the cold calibration mirror began to intrude into the field of view of the feedhorn. As a result, the $T_A$ measurements exhibit a systematic roll-off of about 1K at the end of the scan.

To find a correction for the along-scan error, the first step is to remove variations due to changing incidence angle and wind direction. If not accounted for, these two effects can introduce spurious signals into the derivation of the along-scan correction. The adjusted $T_A$, denoted by a single prime, is given by

$$T'_{Aij} = T_{Aij} - \frac{\partial T_A}{\partial \theta_{cia}} (\theta_{cia} - 53.25^\circ) - f_{rm}(\phi_i)$$

where we have now introduced the subscripts $i$ and $j$ to denote the channel number and satellite number, respectively. The channel number goes from $i=1$ to 7 and corresponds to 19V, 19H,
22V, 37V, 37H, 85V, and 85H, respectively. The satellite number goes from \( j = 1 \) to 6 and corresponds to F08, F10, F11, F13, F14, and F15, respectively. These subscripts have this same definition through this document. The term \( T_{\text{Aij}} \) is the unadjusted \( T_{\text{A}} \) discussed in Section 2.

The first term in (3) is intended to normalize the antenna temperatures to a constant incidence angle for 53.25°. The derivative of \( T_{\text{A}} \) w.r.t. the Earth incidence angle \( \theta_{\text{eai}} \) is estimated from the \( T_{\text{A}} \) values. The v-pol derivative is fairly invariant for ocean, rain-free scenes, having a typical value of +2 K/deg. The h-pol derivative is more sensitive to the variation in atmospheric absorption due to water vapor and clouds, and its values can typically range from -1 K/deg for clear dry scenes to +1 K/deg for cloudy wet scenes. The v-pol minus h-pol difference exhibited by the \( T_{\text{A}} \)s at the various frequencies is a good indicator of the atmospheric absorption, and a relative simply algorithm can be used to estimate \( \partial T_{\text{A}} / \partial \theta_{\text{eai}} \). The second term in (3) corrects for wind direction effects. The argument \( \phi_{r} \) is the relative angle between the wind direction and the SSM/I azimuth look direction. NCEP values for wind speed and direction along with the azimuth angle of the SSM/I observation are used to compute the change in antenna temperature just due to wind direction [Wentz, 1992]. This component is then subtracted from \( T_{\text{A}} \). The adjustments for incidence angle and wind direction are only done for ocean observations. The resulting \( T_{\text{Aij}}' \) is then the isotropic (no wind direction effects) \( T_{\text{A}} \) at an Earth incidence angle of 53.25°.

Our model for the along-scan error is

\[
T_{\text{Aij}}' = \left(1 - \Psi_{ij}(\omega)\right)T_{\text{Aij}}'' + \Psi_{ij}(\omega)T_{\text{Ac}}
\]  

(4)

where the observed \( T_{\text{A}} \) on the left-hand side is the weighted sum of the \( T_{\text{A}} \) coming from the Earth \( T_{\text{Aij}}'' \) and the \( T_{\text{A}} \) coming from the cold mirror \( T_{\text{Ac}} \), which we assume to be 2.7 K for the lower frequency channels and 3.2 for 85 GHz, as discussed above. The weight factor \( \Psi_{ij}(\omega) \) is a function of the scan angle \( \omega \), which represents 64 scan positions for the 19 through 37 GHz channels and 128 scan positions for the 85 GHz channels. The \( T_{\text{A}} \) corrected for along-scan errors is then given by inverting (4).

\[
T_{\text{Aij}}'' = \frac{T_{\text{Aij}}' - \Psi_{ij}(\omega)T_{\text{Ac}}}{1 - \Psi_{ij}(\omega)}
\]  

(5)
The derivation of $\Psi_\omega (\omega)$ is essentially an averaging process. $T'_{\omega ij}$ values for ocean, rain-free observations are averaged into cell position bins (i.e. $\omega$-bins) and into $1^\circ$ latitude zones from 50S to 50N. If we did not use latitude zones and simply averaged all observations into $\omega$-bins, then the average latitude for the $\omega$-bins would vary considerably across the scan. For example, the SSM/I right-most cell is also the north-most cell as the satellite approaches the poles. The $\omega$-bin for this cell will have a higher average latitude than the left-most cell. Since all the SSM/I channels are sensitive to water vapor and since water vapor has a strong latitudinal variation, spurious features would occur due to non-uniform latitude sampling. By pre-averaging into $1^\circ$ latitude bins, this effect is greatly mitigated. We experimented with other methods to find the along-scan correction such as making $1^\circ$ latitude/longitude $T_A$ maps, calculating the change in $T_A$ with latitude, and then making a correction. This method gave essentially the same results, but was more complicated. Using the $10^\circ$ pre-averaging method is sufficient.

All available observations are used to find the ($\omega$, latitude)-bin averages. For example for F13, which has the longest operational period, 10 years of observations are averaged. These averages are denote by $\overline{T'_{\omega ij}}_{\omega, \text{lat}}$. The pre-averages are then averaged over the 10 zones as follows:

$$\overline{T'_{\omega ij}} = \frac{\sum_{\text{lat}=1}^{10} n_{\text{lat}} \overline{T'_{\omega ij}}_{\omega, \text{lat}}}{\sum_{\text{lat}=1}^{10} n_{\text{lat}}}$$  \hspace{1cm} (6a)

$$\overline{T'_{Aij}} = \frac{\sum_{\omega} \sum_{\text{lat}=1}^{10} n_{\text{lat}} \overline{T'_{Aij}}_{\omega, \text{lat}}}{\sum_{\omega} \sum_{\text{lat}=1}^{10} n_{\text{lat}}}$$  \hspace{1cm} (6b)

Equation (6a) represents a properly averaged $T_A$ binned according to just scan angle, and (6b) is $T_A$ properly averaged over the entire scan. We define the scan correction $\Psi_\omega (\omega)$ such that its average over $\omega$ is zero, and hence according to equation (4) the scan-average $T_A$ is $T''_{Aij}$, which is the same as $\overline{T'_{Aij}}$ equation (6b), i.e., $T''_{Aij} \leftarrow \overline{T'_{Aij}}$. The $\omega$-bin average for the uncorrected $T_A$ is $T'_{Aij}$ in equation (4) and $\overline{T'_{Aij}}_{\omega}$ in equation (6a), i.e., $T'_{Aij} \leftarrow \overline{T'_{Aij}}_{\omega}$. Then, inverting (4) to yield $\Psi_\omega (\omega)$ and applying the two substitutions just given results in
In this way, tables are made for each satellite $j$ and each channel $i$ that gives $\Psi_{ij}(\omega)$ for the 64 cell positions for the lower frequencies and for the 128 cell positions for the higher frequencies. Figure 1 show $\Psi_{ij}(\omega)$ for all satellites and all channels. The color coding used to display the 7 different channels is given in Table 1 below. Table 1 also gives the color coding for figures to be presented later in which the colors denote the 6 different SSM/I.

$$\Psi_{ij}(\omega) = \frac{\langle T'_{ij} \rangle - \langle T''_{ij} \rangle_{\omega}}{\langle T''_{ij} \rangle - T_{sc}}$$

(7)

Figure 1. The along-scan correction that is applied to the SSM/I $T_A$. To show these results in terms of a value indicative of the $T_A$ adjustment, $\Psi_{ij}(\omega)$ has been multiplied by 200K. The adjustment has the effect of increasing $T_A$ at the end of the scan to compensate for the intrusion of the cold mirror into the field of view. The 7 colors correspond to the 7 channels as indicated in Table 1. The 85 GHz channels show a saw-tooth pattern presumably due to a small mismatch in the integration timing.
Table 1. Color coding for figures displaying 7 channels or 6 SSM/I.

<table>
<thead>
<tr>
<th>black</th>
<th>red</th>
<th>green</th>
<th>blue</th>
<th>magenta</th>
<th>cyan</th>
<th>orange</th>
</tr>
</thead>
<tbody>
<tr>
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<td>19H</td>
<td>22V</td>
<td>37V</td>
<td>37H</td>
<td>85V</td>
<td>85H</td>
</tr>
<tr>
<td>F08</td>
<td>F10</td>
<td>F11</td>
<td>F13</td>
<td>F14</td>
<td>F15</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Color coding for figures displaying the 11 inter-satellite overlap periods.

<table>
<thead>
<tr>
<th>black</th>
<th>red</th>
<th>green</th>
<th>blue</th>
<th>magenta</th>
<th>cyan</th>
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<th>black</th>
<th>red</th>
<th>green</th>
<th>blue</th>
</tr>
</thead>
<tbody>
<tr>
<td>F08</td>
<td>F08</td>
<td>F10</td>
<td>F10</td>
<td>F10</td>
<td>F11</td>
<td>F11</td>
<td>F11</td>
<td>F13</td>
<td>F13</td>
<td>F14</td>
</tr>
<tr>
<td>F10</td>
<td>F11</td>
<td>F11</td>
<td>F13</td>
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<td>F14</td>
<td>F15</td>
<td>F14</td>
<td>F15</td>
<td>F15</td>
<td>F15</td>
</tr>
</tbody>
</table>

4. Inter-Satellite Calibration

4.1. Observed \( T_A \) Differences among the 6 SSM/I

The next step in the calibration procedure is to inter-calibrate the 6 SSM/I. To do this, we first make global maps of \( T_{Aij}' \)' for each SSM/I. The \( T_A \) maps represent a 5-day (pentad) average of SSM/I observations within a 1° latitude/longitude cell. Separate maps are made for observations taken during the morning portion of the orbit and the evening portion. For these maps, \( T_A \) is normalized to an incidence angle of 53.25°, wind direction effects are removed, and the along-scan correction is applied (i.e., we use the double-prime \( T_A \)).

Inter-satellite differences are then computed. Table 2 shows the various combinations of satellite overlaps. There are a total of 11 types of overlaps. For each type of overlap, the difference of the satellite-2 \( T_{Aij}' \)' minus the satellite-1 \( T_{Aij}' \) is found. These inter-satellite \( T_A \) differences are only found if for a given pentad both satellites have observed the same latitude/longitude cell during the same portion of the orbit (i.e. evening or morning). Figure 2 shows the inter-satellite \( T_A \) differences averaged over latitude and longitude for the evening case. Figure 3 show analogous results from the morning case. The 11 different satellite overlap cases are shown by a different color, as indicated in Table 2. (Colors can be reused for the later overlap cases because they are separate for the earlier cases.) Our inter-calibration analysis for Version 6 was done in 2006, thus there are no inter-comparisons after this mid-2006. For the lower frequency channels (19-37 GHz) the inter-satellite \( T_A \) differences for the most part lie between -1 K and +1 K. However at 85 GHz, larger differences can be seen.
Figure 2. The SSM/I $T_A$ differences for 11 overlap periods. Each overlap period is shown in a different color with the color coding given by Table 2. The 7 frames show the 7 channels going from 19V at the top to 85H at the bottom in the order indicated in Table 1. These results are for the evening portion of the orbit.
Figure 3. Same as Figure 2 except these results are for the morning portion of the orbit.
4.2. Error Model for Inter-Satellite $T_A$ Differences

Much time was spent analyzing the results in Figure 2 and 3. In addition to averaging over all latitudes for the morning and evening cases, we also reviewed zonal results for which the $T_A$ differences are stratified according to 3 latitude zones: south of 20S, 20S-20N, and north of 20N. Our objective is to find an error model as simple as possible that will explain the inter-satellite $T_A$ differences. After considerable trial and error analyses, we selected the following error model:

\[
\Delta T_{Aij} = A_{ij}(\varphi) + B_{ij}(\varphi) \cos \left( \frac{2\pi t}{t_{year}} \right) + C_{ij}(t) + \alpha_{ij} \left( T_{k} - \langle T_{k} \rangle \right) + \beta_{ij} (t - t_{0}) - \frac{1}{2} \eta_{i} \]

where $\Delta T_{Aij}$ is to be subtracted from $T_{Aij}^{*}$ to obtain the desired calibrated $T_A$. We will now explain each term in equation (8).

The function $A_{ij}(\varphi)$ is called the inter-satellite zonal offset with the angle $\varphi$ specifying the position of the satellite in its orbit; $\varphi$ equals 0° at the satellite’s south-most position, 90° at the equatorial ascending node, and so on. $A_{ij}(\varphi)$ expresses the $T_A$ difference that is found among the 6 SSM/I. To establish an absolute channel level, we required the following:

\[
\sum_{j=3}^{6} \sum_{\varphi} A_{ij}(\varphi) = 0 \]

which is requiring $A_{ij}(\varphi)$ be zero when averaged over the 4 later SSM/I's and over $\varphi$. This requirement has the effect of establishing an absolute $T_A$ calibration reference that is consistent with the average unadjusted $T_A$ calibration for F11 through F15. The SSM/I on F13 is used as the reference for the $\varphi$ variation by requiring $A_{ij}(\varphi)$ to be a constant value independent of $\varphi$.

Figure 4 shows $A_{ij}(\varphi)$. For most cases, the inter-satellite offsets are nearly constant over the orbit ($\pm$ 0.2 K), but for certain satellites and certain channels the intra-orbit variation can be significant. For this reason, the inter-satellite offset is modeled as a function of the satellite position angle $\varphi$. 

10
The function $B_{ij}(\phi)$ is a very small term ($< 0.1$ K), except for F10. It models the seasonal variation of the inter-satellite offset and is only included because comparisons of the F10 SSM/I to the other SSM/I (particularly the 85H channel) showed this term is important for F10. The seasonal variation is specified by the cosine term where $t$ is the time for the observation (hours), and $t_{\text{year}}$ is the length of the solar year. $B_{ij}(\phi)$ for F08 and F13 are set to 0. For F13, F14, and F15, $B_{ij}(\phi)$ is assumed to be constant (i.e., no variation with $\phi$) and never exceeds 0.07K for these 3 satellites. Figure 5 shows $B_{ij}(\phi)$.

Function $C_{ij}(t)$ models slow time variations in the inter-satellite offsets. Only 3 SSM/I have this term: F10, F11, and F13. For the other SSM/I, $C_{ij}(t)$ is zero. Figure 6 shows $C_{ij}(t)$ for F10, F11, and F13. Treating the F11 SSM/I are a reference, we saw obvious slow time variations of the F10 T_A relative to F11. The F13 T_A relative to F11 also shows a slow time variation but only during the first year of F13 operation. During the last four years of the F11-F13 over-

**Figure 4.** The inter-satellite zonal offset $A_{ij}(\phi)$ plotted versus satellite position angle $\phi$. The colors denote the 7 SSM/I channels as indicated in Table 1.
lap, the $T_A$ difference shows no obvious variation with time. Because the SSM/I F10 exhibits relatively large calibration errors in many respects, presumably due to it anomalous orbit, we assign the observed F10-F11 time-varying error to F10, with one exception. The F11-F10 $T_A$ difference for 37H shows a very slow monotonic increase going from about -0.2K in 1992 to +0.1K in 1999. As it turns out, a completely separate analysis looking at histograms of wind speed retrievals from F11 shows a slight shift of the left edge of the histograms (i.e., the position of the histogram for wind=0) over the life of F11. The shift was in the positive direction and very closely mimics the observed F11-F10 $T_A$ difference at 37H, which is the primary wind speed channel. So we decided to assign this small component of the time variation to F11. Otherwise F11 seemed very stable, and we assume the remaining part of the time variation is due to problems with F10.

**Figure 5.** The amplitude of seasonal variability of inter-satellite offset $B_i(\phi)$ plotted versus satellite position angle $\phi$. The colors denote the 7 SSM/I channels as indicated in Table 1.
**Figure 6.** Slow time variations $C_{ij}(t)$ in the inter-satellite offsets. Only 3 SSM/Is (F10, F11, and F13) showed relative time drifts. Colors denote the 7 SSM/I channels as indicated in Table 1.

The F13-F11 $T_A$ differences are harder to explain. In general, F13 seems to be stable and well calibrated. During most of the F11 and F13 overlap period, the two SSM/I track each other very well. It is just the first year after launch that the F13-F11 $T_A$ differences show a slow time variation. It does not have the signature of a diurnal feature. We elected to assign the problem to F13 assuming it was some sort of early mission stabilization. The size of the correction is small being 0.1-0.2 K as is shown in Figure 6.

The $\alpha$-term in equation (8) is based on our satellite calibration work done for the Microwave Sounding Unit (MSU). The term $\bar{T}_h$ is the hot load temperature defined in Section 2, and $\langle \bar{T}_h \rangle$ is the mission-averaged value of $\bar{T}_h$. The MSU and the Advanced MSU (AMSU) are atmospheric profilers that measure air temperature in different layers of the atmosphere. Much work has gone into doing inter-satellite calibration for the series of MSU/AMSU that starts in 1979. One finding from the MSU investigations is that inter-satellite offsets are correlated with the hot-load temperature [Christy et al., 2000; Mears et al., 2003]. It is not clear why such a correlation exists, but possibly it is related to non-linearities in the radiometer response function. We include
this term, which is called the ‘target factor’, in our SSM/I error model to see if it could explain some of the observed inter-satellite $T_A$ variation. Table 3 gives the values for $\langle T_s \rangle_j$ and $\alpha_j$. For the MSU analyses [Mears et al., 2003], several sensors had $\alpha$ values of 3%. However, for SSM/I the largest $\alpha$ value is 1% for the F15 85V channels, and for the most part $\alpha$ is well below the 1% level. This suggests the target-factor effect is not as serious of a problem for SSM/I as it is for MSU. There were so many other problems with the F10 SSM/I, we did not attempt to compute a target factor, and $\alpha$ is set to 0 for F10.

Table 3. The mission-average hot-load temperature and the target factor $\alpha$.

<table>
<thead>
<tr>
<th></th>
<th>F08</th>
<th>F10</th>
<th>F11</th>
<th>F13</th>
<th>F14</th>
<th>F15</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle T_s \rangle_j$ (K)</td>
<td>264.1232</td>
<td>307.5306</td>
<td>278.0409</td>
<td>291.4749</td>
<td>304.4429</td>
<td>301.4340</td>
</tr>
<tr>
<td>19V $\alpha$</td>
<td>-0.0029</td>
<td>0</td>
<td>-0.0037</td>
<td>0.0046</td>
<td>0.0008</td>
<td>0.0041</td>
</tr>
<tr>
<td>19H $\alpha$</td>
<td>0.0021</td>
<td>0</td>
<td>-0.0013</td>
<td>0.0030</td>
<td>0.0009</td>
<td>0.0016</td>
</tr>
<tr>
<td>22V $\alpha$</td>
<td>-0.0003</td>
<td>0</td>
<td>-0.0002</td>
<td>0.0053</td>
<td>0.0024</td>
<td>0.0056</td>
</tr>
<tr>
<td>37V $\alpha$</td>
<td>-0.0080</td>
<td>0</td>
<td>0.0007</td>
<td>0.0042</td>
<td>0.0009</td>
<td>0.0065</td>
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<tr>
<td>37H $\alpha$</td>
<td>-0.0088</td>
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<td>85V $\alpha$</td>
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<td>0.0048</td>
<td>0.0053</td>
<td>0.0078</td>
</tr>
</tbody>
</table>

The last term is equation (8) is intended to remove natural diurnal variability. The SSM/I views the earth in the early-to-mid morning (5:30 am to 10:00 am) and in the evening (5:30 pm to 10:00 pm). The major contributor to the diurnal signal seen during these periods is clouds, which are drying off in the morning and moistening in the evening. An analysis of the TRMM microwave radiometer observations, which views the Earth through the entire diurnal cycle, indicates that to first order, the change in the antenna temperature can be modeled as a linear decrease in the morning and a linear increase in the evening, with the magnitude of the slope being the same. This slope (K/hour) is denoted by $\beta_i$ in (8). The plus sign for this term is for morning observations and the minus sign is for evening observations. The time $t_0=70200$ is the typical time for the evening equator crossing (i.e., 7:30 pm).
The other term $\eta_i$ in the diurnal model is the typical $T_A$ difference at 7:30 am minus 7:30 pm. To find this term, we first normalize the observations from all the SSM/Is to 7:30 am and 7:30 pm using the $\beta_i$ term. Then we find a change in water vapor $V$ and liquid cloud water $L$ that best explains the observed 7:30 am minus 7:30 pm difference in $T_A$. The values found are -0.2 mm and + 0.005 mm for vapor and cloud, respectively. Using typical global values for the derivatives $\partial T_A/\partial V$ and $\partial T_A/\partial L$, a fixed value for $\eta_i$ is found for each channel. Table 4 gives the values for $\beta_i$ and $\eta_i$. Note when finding inter-satellite $T_A$ differences, the $\eta_i$ term cancels out.

<table>
<thead>
<tr>
<th></th>
<th>19V</th>
<th>19H</th>
<th>22V</th>
<th>37V</th>
<th>37H</th>
<th>85V</th>
<th>85H</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$ (K/hour)</td>
<td>0.049</td>
<td>0.080</td>
<td>0.029</td>
<td>0.101</td>
<td>0.197</td>
<td>0.091</td>
<td>0.238</td>
</tr>
<tr>
<td>$\eta$ (K)</td>
<td>0.02</td>
<td>0.04</td>
<td>-0.07</td>
<td>0.21</td>
<td>0.41</td>
<td>0.21</td>
<td>0.57</td>
</tr>
</tbody>
</table>

4.3. Derivation of Coefficients in Error Model

The first step in deriving the coefficients in the error model is to perform a least squares minimization for the 6 overlap periods for F11 through F15 (see Table 2). The quantity that is minimized is the inter-satellite difference. For example for the F13-F11 overlap, the $T''_{A14} - T''_{A13}$ is minimized. All 6 overlaps are done simultaneously and there are 153 coefficients found for each channel. For each satellite there are 36 coefficients for $A_y(\phi)$, one for $\alpha_y$, and one for $B_y$. ($A_y(\phi)$ is specified at 10° increments and for these 4 satellites $B_y$ is assumed independent of $\phi$.) These 38 coefficients times 4 satellites gives a total of 152. There is one additional coefficient $\beta_i$ that is the same for all satellites. During the minimization, we apply the constraint specified by equation (9), the constraint $B_{i2}(\phi)=0$, and reasonable smoothing to constrain on the 36 elements of $A_y(\phi)$. After finding the 153 coefficients and applying the correction to the $T_A$, the final step in calibrating F11 through F15 is to find the slowly varying time function $C_y(t)$ for F11 and F13. This is done by simply taking the time series of the inter-satellite differences, assigning a difference to a particular satellite as discussed above, and apply appropriate smoothing.

Once the F11 through F15 SSM/I have been fully calibrated, we calibrate F10 keeping the F11 through F15 calibration fixed. The last 1.5 years of F10 is excluded because of problems
that begin to develop with F10. Our major objective is to obtain a good calibration for F10 during the earlier part of its mission so that we can use it to connect F08 with F11. Hence we thought it best to exclude the last part of F10 from the derivation of the calibration coefficients.

For F10, we use the same type of least-squares minimization. In this case there are 3 types of overlaps (F11, F13, F14) and number of coefficients found is 72: 36 for $A_{i2}(\varphi)$ and 36 for $B_{i2}(\varphi)$ ($\alpha_{i2}$ is set to 0 as discussed above). After finding the 72 coefficients and applying the correction to $T_A$, we find $C_{i2}(t)$ by using F11 as a reference. For the time period before F11, $C_{i2}(t)$ is set to a constant value equal to its value during the early part of the F10-F11 overlap.

The last step is to calibrate F08 for which there are two overlaps: one with F10 and a brief overlap with F11. For F08, $B_{i1}(\varphi)$ is constrained to be zero, and 37 coefficients are found: 36 for $A_{i1}(\varphi)$ and one for $\alpha_{i1}$. This completes the derivation of the coefficients in the error model. The error model is then subtracted from $T_{ij}^*$ to obtain the fully corrected (triple-prime) $T_A$:

$$T_{ij}^{**} = T_{ij}^* - \Delta T_{ij}$$

5. Correction to the Earth Incidence Angle

Except for the diurnal term, the error model given by (8) is similar for the evening portion (pm) of the orbit and the morning portion (am). For most channels and satellites the dependence of the offset on the satellite position angle $\varphi$ is small. Also the am-pm $\alpha$ target factor is similar (and small). Most of the contribution of the target factor is due to the seasonal variability of the hot load temperature. For a given day, the am versus pm difference of the hot load temperature is relatively small. Thus a good approximation for the am minus pm $T_A$ difference is

$$\Delta T_{ij,am} - \Delta T_{ij,pm} \approx 2 \beta_i (t - t_0) - \delta_i$$

where just the diurnal term remains. The diurnal variation is mostly due to the atmosphere which is evidence in Table 4 by the fact that at 37 GHz the h-pol term is twice the v-pol. A well-known method to remove the atmospheric influence from radiometer measurements is to use the following linear combination of polarizations:

$$T_{Ax} = T_{A37h} - 2T_{A37v}$$

16
where we have introduce the subscript $x$, which replaces the channel subscript $i$, and denotes what we call the ‘x-polarization’. Using this polarization in (11) gives

$$\Delta T_{Axj,am} - \Delta T_{Axj,pm} \approx 2 \beta_x (t - t_0) - \delta_x$$

(13)

and Table 4 shows that the value for $\beta_x$ and $\eta_x$ is very small.

We thus expect the am/pm difference of $T''_{Axj}$ to be very small if our error model is sufficient. The triple-prime $T_A$ supposedly has all calibration problems removed and using x-pol should eliminate diurnal features. However, when am/pm $T''_{Axj}$ is plotted versus time, we see obvious oscillations with fixed periodicities, particularly for F10. We think the most likely explanation for these features is an error in specifying $\theta_{eia}$. The SSM/I flies on a Defense Meteorological Satellite Program (DMSP) spacecraft. Our knowledge of the DMSP spacecraft is limited, but we think the attitude control system is based on a horizon sensor. There is no attitude information given with the SSM/I science on ephemeris data. We have no values of roll, pitch, or yaw to reference. Supposedly, the DMSP spacecraft flies a geodetic mission with the horizon sensor keeping the spacecraft nadir pointing perpendicular to the Earth’s geoid. Given no attitude information, we must simply assume geodetic geometry when computing $\theta_{eia}$. Some error between our assumed geodetic $\theta_{eia}$ and the true $\theta_{eia}$ is to be expected, particularly for the F10 DMSP which was in an anomalous orbit with a relatively high eccentricity due to a partial launch failure.

The x-pol is very sensitive to incidence angle. A $1^\circ$ change in $\theta_{eia}$ produces about a -4 K change in $T_{Ax}$. We transform the time oscillations in $T''_{Axj}$ to time oscillation in $\theta_{eia}$ using a typical $\partial T_{Ax}/\partial \theta_{eia}$ derivative value of -4.23 K/deg. The resulting incidence angle error $\Delta \theta_{eia}$ is then modeled as

$$\Delta \theta_{eia,j} = D_j(t) \sin \varphi$$

(14)

where $D_j(t)$ is a slowly varying function of time. This model is the simplest that would produce the observed am/pm differences in $T''_{Axj}$. Figure 7 shows $D_j(t)$ for each of the 6 SSM/I. The oscillations with fixed periodicities discussed above are clearly evident. $\Delta \theta_{eia,j}$ is to be subtracted from the geodetic $\theta_{eia}$. 
Figure 7. Amplitude $D_j(t)$ of the Earth incidence angle error for each SSM/I.
We note that the x-pol $T_A$ is also sensitive to wind speed variations. However, it is difficult to imagine diurnal features in wind speed that would be large enough and would have the periodicities that we are seeing in Figure 7. Incidence angle error is a much more likely cause.

6. A Small Final Adjustment to the F10 $T_A$

The oscillation in Figure 7 exhibited by F10 has a fixed period of 122 days, which is the same period exhibited by the orbit’s angle of perigee and eccentricity (see Figure 4 in Wentz [1991]). As a final (and very minor) measure after applying all the corrections discussed above including the correction to $\theta_{\text{dia}}$, we do a harmonic analysis just for F10 to see if there is any residual error correlated with a 122-day period. The harmonic analysis is based on the $T_A$ difference of F10 relative to F11. The following residual was found:

$$\Delta T_{A_{i,j},122} = G_1 \sin \phi \sin \frac{2\pi t}{t_{122}} + G_2 \cos \phi \cos \frac{2\pi t}{t_{122}}$$

where $t_{122}$ is 122 days in terms of hours. The $G$ coefficients are given in Table 5 and none exceed 0.2 K. $\Delta T_{A_{i,j},122}$ is subtracted from $T^\prime_{A_{i,j}}$ as a final correction to F10. To avoid adding a fourth prime to $T_A$, we redefine the triple-prime $T_A$ to include this final little adjustment.

<table>
<thead>
<tr>
<th></th>
<th>19V</th>
<th>19H</th>
<th>22V</th>
<th>37V</th>
<th>37H</th>
<th>85V</th>
<th>85H</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_1$ (K)</td>
<td>0.09</td>
<td>0.02</td>
<td>0.02</td>
<td>0.03</td>
<td>0.07</td>
<td>0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>$G_2$ (K)</td>
<td>0.13</td>
<td>-0.03</td>
<td>0.16</td>
<td>0.18</td>
<td>-0.05</td>
<td>0.02</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

7. Fully Corrected Antenna Temperatures

Inter-satellite $T_A$ differences for the fully corrected $T^\prime_{A_{ij}}$ are then computed for the 11 overlaps periods. The procedure is the same as described in Section 4.1. Figures 8 (evening) and 9 (morning) show the results. As compared to Figures 2 and 3, the inter-satellite $T_A$ differences are greatly reduced. Note that when normalizing the $T_A$ to an incidence angle of $53.25^\circ$ as prescribed by equation (3), the corrected incidence angle is now used.
Figure 8. SSM/I $T_A$ differences for 11 overlap periods after applying all the corrections. Each overlap period is shown in a different color with the color coding given by Table 2. The 7 frames show the 7 channels going from 19V at the top to 85H at the bottom in the order indicated in Table 1. These results are for the evening portion of the orbit.
Figure 9. Same as Fig. 8 except these results are for the morning portion of the orbit.
8. **Comparison of Morning and Evening $T_A$**

It is also informative to look at the morning minus evening $T_A$ difference for a given SSM/I. As mentioned above the $T_A$ maps are partitioned into the evening portion (pm) of the orbit and the morning portion (am). Am-pm $T_A$ differences are found but only if for a given pentad there is an observation of the same latitude/longitude cell for both the morning and evening. These $T_A$ difference are then averaged over all latitudes and longitudes and plotted versus time. Figure 10 show the results for $T_{Ag}^{\prime \prime}$, which is the $T_A$ before applying the corrections (8), (14), and (15). The most obvious features are the oscillations in incidence angle error for F10 and to a lesser extent for F13. Figure 11 is the same as Figure 10 except all corrections have been applied. There are still some unexplained features, but the major oscillations have been removed.

9. **RADCAL Beacon Correction for F15**

On 14 August 2006, a radar calibration (RADCAL) beacon was activated on F15. This radar interfered with the SSM/I, primarily the 22V channel. We apply a correction to the F15 22V channel to mitigate the RADCAL interference [Hilburn and Wentz, 2008; Hilburn 2009]. This correction is given by

$$\Delta T_{A,\text{radcal}} = H(\omega) \Gamma(\bar{T}_h)$$

$$\Gamma(\bar{T}_h) = c_0 + c_1 \bar{T}_h + c_2 \bar{T}_h^2$$

where $\Delta T_{A,\text{radcal}}$ is to be subtracted from the $T_A$ measurement. The term $H(\omega)$ is a table of 64 values corresponding to the SSM/I scan position and is shown in Figure 12. The coefficients $c_0$, $c_1$, and $c_2$ are 79.8977, -0.518557 K$^{-1}$, and 8.51691e-4 K$^{-2}$, respectively. At the extremes, if $\Gamma(\bar{T}_h)$ falls below 1, it is set to 1; if it exceeds 3.5, it is set to 3.5. This correction is applied starting with F15 orbit 34478.
Figure 10. The am minus pm $T_A$ differences for the 6 SSM/I. Each SSM/I is shown in a different color with the color coding given by Table 1. The 7 frames show the 7 channels going from 19V at the top to 85H at the bottom in the order indicated in Table 1. These results are before applying the $T_A$ and incidence angle corrections.
Figure 11. Same as Fig. 10 except the $T_A$ and incidence angle corrections have been applied.
10. Version 6 Mean Channel Level Compared to Version 5

After completing the V6 calibration, we compared the overall mean level of each channel (averaged over all satellites and all times) with the previous V5 calibration. We found small offsets of the order of 0.1 K, or less. The V6 minus V5 offsets are shown in Table 6. The principle reason these version offsets occur is that the V5 overall calibration was based on an average of all 6 SSM/I, whereas the V6 overall calibration is based on just the last 4 SSM/I, as prescribed by equation (9). The V6 calibration is much more extensive than that done for V5 and represents a major step forward, particularly with regards to inter-calibrating the 6 SSM/I. However, there are reasons for not changing the overall absolute level of the 7 channels. The main reason is that V5 datasets were in wide use, and the users did not want a change in the absolute level. So the V6-V5 channel offsets are subtracted from the $T_A$ to bring V6 into alignment with V5. Note that the same channel offsets are added to all 6 SSM/I and this adjustment has no effect on relative calibration. With this adjustment, the overall mean channel level is more indicative of the average of all 6 SSM/I. This is a very small adjustment, and Users not wanting to implement this final normalization are free to add back in the values in Table 6.
### Table 6. The difference in the overall mean channel level for V6 compared to V5.

<table>
<thead>
<tr>
<th>Channel</th>
<th>V6-V5 channel offsets (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19V</td>
<td>-0.11</td>
</tr>
<tr>
<td>19H</td>
<td>-0.01</td>
</tr>
<tr>
<td>22V</td>
<td>-0.03</td>
</tr>
<tr>
<td>37V</td>
<td>-0.12</td>
</tr>
<tr>
<td>37H</td>
<td>-0.05</td>
</tr>
<tr>
<td>85V</td>
<td>-0.07</td>
</tr>
<tr>
<td>85H</td>
<td>0.00</td>
</tr>
</tbody>
</table>

#### 11. Computation of Earth Brightness Temperature

Antenna temperature is a measure of radiant power entering the feedhorn. It is computed by integrating the brightness temperature environment over the gain pattern of the SSM/I parabolic reflector and feedhorn assembly. About $\frac{3}{4}$ of the surrounding environment consists of cold space at a temperature near 2.7 K and the remaining $\frac{1}{4}$ is the Earth, which has a brightness temperature $T_B$ between 100 and 300 K, depending on the scene. Thus, the antenna temperature is biased low relative to the Earth $T_B$. In addition, some Earth scenes are very polarized, particularly the oceans, and the antenna gain pattern tends to mix polarizations. As a result, the antenna temperature is not as polarized at the Earth $T_B$.

These two effects are commonly characterized by the antenna spillover $\delta$, which is the fraction of power coming from cold space, and the polarization leakage $\chi$, which is the fraction of polarization mixing, and the integration over the field of view is approximated by [Wentz, 1991]

$$T_{Ap} \approx \left(1 - \delta_p\right)\frac{T_{Bv} + \chi_pT_{Bh}}{1 + \chi_p} + \delta_p T_{Bc}$$  \hspace{1cm} (17)$$

where subscript $p$ denotes polarization (either $v$ or $h$), $T_{Bc}$ is the brightness temperature of cold space, and $T_{Bv}$ and $T_{Bh}$ are the Earth $v$-pol and $h$-pol brightness temperatures. The spillover $\delta$ and leakage $\chi$ can be derived in an optimum way by first defining $T_{Bv}$ and $T_{Bh}$ to represent an average over some prescribed areal extent on the Earth (we use the 3-dB footprint), and then fitting (17) to the antenna temperature coming from the exact integration. This fitting procedure was done for the F08 antenna patterns [Wentz, 1991], and the results are shown in Table 7.
Field antenna pattern measurements were made for each SSM/I. These measured patterns are different for the different SSM/I. However, when we used these separately measured antenna patterns (i.e., different $\delta, \chi$ for different SSM/I), the inter-satellite offsets became larger. We concluded that most of the difference exhibited by the different set of antenna patterns is due to measurement error, and that in fact the antennas for the 6 SSM/I were more alike that suggested by the field measurements. In view of this, we use the F08 $\delta, \chi$ values for all SSM/I. The intersatellite offsets that we do see are probably in part due to the $\delta, \chi$ values being different for the different sensors, but not as different as suggested by the field measurements.

For 19, 37, and 85 GHz, there are two equations for (17): one for $T_{Av}$ and the other for $T_{Ah}$, in two unknowns: $T_{Bv}$ and $T_{Bh}$. These equations are easily inverted to yield $T_{Bv}$ and $T_{Bh}$. At 22 GHz, there is only v-pol for SSM/I, and the following approximation is used

$$T_{B22v} = 1.01993T_{A22v} + 1.994$$

(18)

See Wentz [1991] for details on the derivation of (18).
**12. References**


13. Appendix A. Software for Applying the Calibration Procedures

The following Fortran subroutine performs the mathematical operations described in the document for doing the inter-satellite calibration and incidence angle correction.

```fortran
subroutine ssmi_v06_calibration(isat,itime87,zang,hltemp, ta_offset,thtcor) implicit none   integer(4), parameter :: nsat=6   integer(4), parameter :: nch= 7   integer(4), intent(in) :: isat,itime87   real(4), intent(in) :: zang,hltemp   integer(4) istart,ich,i1,i2,j1,j2   real(4) cosang,ta_offset(nch),thtcor   real(4) thotavg(nsat),alpha(nsat,nch),acoef(36,nsat,nch),bcoef(36,nsat,nch)   real(4) ccoef_f13(432,nch),ccoef_f10(432,nch),gcoef1(nch),gcoef2(nch)   real(4) thtcor_tab(2000,nsat)   real(4) dta_v05(nch)   real(4) ang,a1,a2,b1,b2,brief,ccoef,pentad,xyear,sinpent,cospent,sinzang,coszang   data dta_v05/ -0.106, -0.014, -0.031, -0.116, -0.046, -0.067, 0.001/   data istart/1/
```

---

```fortran
---
```
if(istart.eq.1) then
  istart=0

open(3,file='o:\ssmi5\v06\calibrate\v6_cal_coefs.dat',status='old',access='sequential',form='binary')
read(3) thotavg !mission average hot load temperature
read(3) alpha !target factors
read(3) acoef
read(3) bcoef
read(3) ccoef_f13
read(3) ccoef_f10
read(3) gcoef1
read(3) gcoef2
close(3)

open(3,file='o:\ssmi5\v06\calibrate\v6_eia_correction.dat',status='old',access='sequential',form='binary')
read(3) thtcor_tab
close(3)
endif

sinzang=sind(zang)
coszang=cosd(zang)
ang=(360.d0*itime87)/(365.25d0*86400.d0)
cosang=cosd(ang)
pentad=0.5 + itime87/438300.d0
sintpent=sind(360.*(pentad/24.1))!122 day period
cospent=cosd(360.*(pentad/24.1))!122 day period

if(zang.lt.0 .or. zang.gt.360) stop 'zang oob in fd_ta_adjustment2, pgm stopped'
brief=zang/10.
if(brief.gt.35.999) brief=35.999
j1=1+brief
j2=j1+1
b1=j1-brief
b2=1.-b1
if(j1.eq.0) j1=36
if(j2.eq.37) j2=1

if(isat.eq.3) then
  xyear=1987 + itime87/31557600.d0
  ccoef= -0.472002 + 0.062637*(xyear-1992) - 0.000454*(xyear-1992)**3 + 0.2505
TA_OFFSET = TA_OFFSET + CCoeff
endif

if(isat.eq.4) then
  BRIEF = PENTAD-577
  if(brief.lt.0.00) brief = 0.00
  if(brief.gt.430.99) brief = 430.99
  I1 = I1 + brief
  I2 = I1 + 1
  A1 = I1 - brief
  A2 = 1.0 - A1
  DO ich = 1, NCH
    CCOEFF = A1*CCOEFF_F13(I1, ich) + A2*CCOEFF_F13(I2, ich)
    TA_OFFSET (IICH) = TA_OFFSET (IICH) + CCOEFF
  ENDDO
endif

if(isat.eq.2) then
  BRIEF = PENTAD-361
  if(brief.lt.0.00) brief = 0.00
  if(brief.gt.430.99) brief = 430.99
  I1 = I1 + brief
  I2 = I1 + 1
  A1 = I1 - brief
  A2 = 1.0 - A1
  DO ich = 1, NCH
    CCOEFF = A1*CCOEFF_F10(I1, ich) + A2*CCOEFF_F10(I2, ich)
    TA_OFFSET (IICH) = TA_OFFSET (IICH) + CCOEFF + gcoef1(IICH)*sinzang*sinpent + gcoef2(IICH)*coszang*cospent
  ENDDO
endif

TA_OFFSET = TA_OFFSET - DTA_V05 ! normalize to V5 channel levels

brief = PENTAD-1
I1 = I1 + brief
I2 = I1 + 1
A1 = I1 - brief
A2 = 1.0 - A1
if(I1.LT.1 .OR. I2.GT.2000) STOP 'error in sat_offsets, pgm stopped'
THTCOR = (A1*THTCOR_TAB(I1,ISAT) + A2*THTCOR_TAB(I2,ISAT))*SINZANG

RETURN
END

The generation of the SSM/I $T_A$ datasets has gone through six major improvements (i.e., version changes), starting with Version-1 in 1988 [Wentz, 1988]. The primary emphasis of Version-1 was data compression. In the late 1980s and early 1990s, the only access to SSM/I $T_A$ datasets was 6250 bpi tapes stored at NESDIS. There were 4 tapes/day and users were required to pay $175/tape. These large volumes and costs essentially made the SSM/I $T_A$ datasets unavailable to the research community. As part of a Small Business Innovation Research (SBIR) program, RSS developed a technique for compacting the SSM/I $T_A$ (no information lost) onto monthly Exabyte™ tapes. This provided an affordable means for institutions to obtain a complete dataset of SSM/I observations. Nearly all of the SSM/I scientific research during this early phase utilized these “Compact Tapes”.

Version-2 implemented a more user-friendly format, more accurate geolocation, and an along-scan correction for the antenna temperatures [Wentz, 1991]. Version-3 extended the data set to include the second SSM/I launched in December 1991 [Wentz, 1993]. This was the first version to include intersatellite calibration coefficients for matching the F08 and F10 SSM/I sensors.

In 1997, Version-4 was released. At this point four SSM/I sensors had been launched (F08, F10, F11, and F13), and two more would soon go into space. It was becoming apparent that this series of six SSM/I was playing a very important role in climate monitoring. Thus, we did a more careful intersatellite calibration that included diurnal variability and intra-orbit calibration variability. Also, further refinements were made to the SSM/I pointing geometry to achieve better geolocation. Version-4 was the mainstay for several years, being replaced by Version-5 in 2002.

Version-5 was relatively short lived due to subtle calibration problems that caused small spurious trends in the climate retrievals (the SSM/I record had become long enough at this point to detect such errors). The problem was due to subtle correlations in our derivation of the ‘target factors’ for the F10 and F14 SSM/I. Like the Microwave Sounding Unit (MSU), some of the SSM/I exhibit errors that are correlated with the hot-load target temperatures, and we removed these errors using the “target multiplier” approach [Mears et al., 2003]. These problems, along
with their solutions, are discussed in Wentz et al. [2007]. Application of the solutions described herein provided the current V6 SSM/I $T_A$ and $T_B$ dataset.

The primary validation of the V6 $T_A$ and $T_B$ datasets is through their resulting geophysical retrievals. For example, one of the most critical requirements for an CDR dataset is that it be free of spurious long-term trends. Validation of this requirement can be obtained by analyses of the resulting geophysical retrievals. Comparison of the wind speeds retrieved from the V6 $T_B$ with buoys and scatterometers indicates a trend error of 0.05 m/s/decade at the 95% confidence level over the 1987 to 2006 time period [Wentz et al., 2007]. The standard error on the water vapor trend (1987-2006) is 0.2% per decade [Wentz and Schabel, 2000]. With respect to precipitation, when diurnal effects are removed, the agreement among different SSM/I is 3% [Hilburn and Wentz, 2008b]. Note that some of this 3% difference is probably due to residual geophysical effects such as ‘beamfilling’ rather than $T_B$ intercalibration error. Still, 3% is the best inter-sensor precipitation agreement yet achieved from any SSM/I $T_B$ dataset.

Further validation is obtained from our users. Our SSM/I V6 $T_A$ and $T_B$ datasets are in use at about 20 institutions including the National Snow and Ice Data Center (NSIDC), the NASA Goddard Global Modeling and Assimilation Office (GMAO), Global Precipitation Climatology Project (GPCP), EUMETSAT, Max-Planck Institute for Meteorology, and the Remote Sensing Technology Center of Japan. The V6 geophysical products (wind/vapor/cloud/rain/ice) are freely available on the web through the sponsorship of NASA’s REASoN and MEaSUREs programs. Approximately 40 users consistently download the RSS V6 geophysical products on a daily-to-weekly basis in addition to about 4000 occasional users. The feedback we receive from this broad user community has helped to identify problems in the past and provides us with more confidence that the V6 SSM/I V6 $T_A$ and $T_B$ datasets represent a highly accurate climate data record.