On-Orbit Absolute Calibration of the
Global Precipitation Mission Microwave Imager

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ABSTRACT

The Global Precipitation Mission (GPM) Core Observatory was launched on February 27, 2014. One of the principal instruments on the spacecraft is the GPM Microwave Imager (GMI). This paper describes the absolute calibration of the GMI antenna temperature (TA) and Earth brightness temperature (TB). The deep-space observations taken on May 20, 2014, supplemented by nadir viewing data, are used for the TA calibration. Data from two backlobe maneuvers are used to determine the primary reflector’s cold space spillover, which is required to convert the TA into TB. The calibrated GMI observations are compared to predictions from an ocean radiative transfer model (RTM) using collocated WindSat ocean retrievals as input. The mean difference when averaged globally over 13 months does not exceed 0.1 K for any of the 9 channels from 11 to 89 GHz. The RTM comparisons also show that there are no significant solar intrusion errors in the GMI hot load. The absolute accuracy of the GMI TA and TB measurements is about 0.1 K and 0.2 K, respectively.

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1. Introduction

The Global Precipitation Mission (GPM) Core Observatory was launched on February 27, 2014. One of the principal instruments on the spacecraft is the GPM Microwave Imager (GMI). GMI is the follow-on instrument for the Tropical Rainfall Measuring Mission (TRMM) microwave (MW) imager TMI, which provided continuous and stable observations for 17 years, until its scheduled end of mission in April 2015 (Wentz, 2015). The combination of GMI and TMI provides the potential to acquire three decades of extraordinarily stable MW observations.

In addition to providing information on precipitation, over the oceans GMI provides a full suite of environmental parameters including sea-surface temperature (T_s), wind speed (W), columnar water vapor (V), and columnar cloud liquid water (L). The literature has many examples of the importance of these variables to climate research (Wentz and Schabel 2000; Wentz et al. 2000; Trenberth et al. 2005; Chelton and Wentz 2005; Mears et al. 2007, Wentz et al. 2007). Three decades of these essential climate variables will provide a unique contribution to climate change research.

Climate applications are very demanding when it comes to sensor calibration. Here, we take a critical look at GMI on-orbit performance during the first year of operation (March 2014 through March 2015). Typical climate applications require accuracies of about 0.1 to 0.2 K in the estimate of the Earth’s MW brightness temperature (T_B).

GMI represents a significant advancement in satellite MW imagers. The pre-launch characterization of the sensor was the most extensive ever and is thoroughly documented in a 221-page GMI Calibration Data Book (GCDB) with an additional 25 appendices (Draper 2015). GMI is the first MW imager to employ both external and internal calibration systems. This dual calibration provides the means, for the first time, to measure the non-linear response of the electronics.
in orbit. The external hot-load, used for the warm-end calibration, was carefully designed to eliminate problems due to solar intrusion and thermal gradients.

In addition to the well-designed, well-characterized sensor, GPM conducted several orbital maneuvers during the first year of operation that play an essential role in our analysis. These orbital maneuvers include the:

1. Deep-space maneuver for which the primary reflector and cold mirror view cold space.
2. Backlobe maneuver for which the backlobe of the primary reflector sees the Earth.
3. Nadir maneuver for which the primary reflector views the Earth at zero incidence angle.

Our long-standing method of calibrating satellite MW imagers is to use an ocean radiative transfer model (RTM) as a reference (Meissner and Wentz 2004; Meissner and Wentz 2012; Wentz and Meissner 2015). This gives us a common reference for all sensors. Rather than using purely empirical offsets, the calibration to the RTM is done by adjusting physical parameters such as the hot-load temperature and the antenna pattern. For the purpose of doing geophysical retrievals one important requirement is that the measurements agree with the RTM used to develop the retrieval algorithm, and our RTM calibration method accomplishes this. However, the question of absolute calibration has always been an issue. Until GMI, the uncertainty in characterization of the MW imagers was so large that we had considerable freedom (1 to 2 K) in adjusting the sensor parameters to match the observations to the RTM. This has changed with the advent of GMI and its orbital maneuvers. The absolute calibration can now be done using solely the GMI observations collected during the three maneuvers. The RTM comparisons can then be used to evaluate the cold space calibration at warmer Earth temperatures.

2. Channel Set and Required Data Sets

GMI operates at 8 frequencies from 11 to 183 GHz. Our analysis only considers the 5 lower channels: 10.6, 18.7, 23.8, 36.6, and 89.0 GHz. At all of these frequencies except 23.8 GHz,
both vertical polarization (v-pol, V) and horizontal polarization (h-pol, H) observations are taken. At 23.8 GHz, there are only v-pol observations. This set of 9 channels is denoted by: 11V, 11H, 19V, 19H, 24V, 37V, 37H, 89V, and 89H.

The GMI data used herein are the V03C-Base-RSS data files obtained from NASA Goddard Precipitation Processing System (PPS) (GPM Science Team 2014). Unless otherwise noted, the calibration parameters we use are the same as reported in the GCDB. The ocean retrievals from the NRL WindSat on Coriolis, the Advanced Microwave Scanning Radiometer (AMSR-2) on GCOM-W1, the Tropical Rainfall Measuring Mission Microwave Imager (TMI), and the Special Sensor Microwave Imager/Sounders (SSMIS) on DMSP platforms are downloaded from Remote Sensing System (RSS) (www.remss.com). Two SSMIS are used in this study: one flying on the F16 spacecraft and the other on F17. All of these ocean retrievals are available as RSS Version-7 products. The sea-surface temperature dataset comes from the NOAA SST operational product (Reynolds et al., 2002a; Reynolds et al., 2002b). For wind direction, we use the National Center for Environmental Prediction (NCEP) Global Data Assimilation System 6-hourly wind fields (NOAA/NCEP 2000).

Much of the analysis is performed in terms of radiometer counts. To provide a more meaningful description of the sensitivities being considered, we note that between 35 and 45 counts is equivalent to a change of 1 K in antenna temperature (T_A). Using a value of 40 counts = 1 K provides a simple means to translate counts to antenna temperature.

### 3. Antenna Temperature Equation

The antenna temperature is computed from

\[ T_{40} = T_c + x(T_h - T_c) - 4x(1-x)T_{NL} \]  

\[ x = \frac{C_e - C_c}{C_h - C_c} = \frac{\Delta T_e}{\Delta T_h} \]  

\[ 1 \]  

\[ 2 \]
\[ T_A = T_{A0} - g(\alpha) - h(\alpha)(T_{\text{intru}} - T_{A0}) \]  

where \( C_e, C_c, \) and \( C_h \) are the Earth, cold, and hot counts, and \( T_c \) and \( T_h \) are the temperatures for cold space and the hot load. We have introduced the abbreviated notation \( \Delta C_{ec} \) and \( \Delta C_{hc} \) for the two count differences that govern \( T_A \). The earth-cold count difference \( \Delta C_{ec} \) will play a central role in this paper. Equation (1) accounts for the small non-linearity in the radiometer output voltage relative to power coming into the feedhorn. This non-linearity is characterized in terms of the temperature \( T_{NL} \), which has a typical value between 0.0 and 0.5 K, depending on the channel. Equation (3) provides a correction for errors related to the scan position and consists of two components: a fixed component \( g(\alpha) \) that is a function of the scan angle \( \alpha \), and an intrusion component that is proportional to the difference between the intrusion temperature \( T_{\text{intru}} \) and the antenna temperature \( T_{A0} \). The proportional factor is \( h(\alpha) \). The derivation of this along-scan correction is further discussed in Section 11. The hot-load temperature \( T_h \) is computed from an array of precision thermistors with correction for the thermal coupling with the hot-load tray (Draper 2015) and is further discussed in Section 10.

It is customary to use the Rayleigh Jeans approximation to Planck’s law at MW frequencies. The error due to the approximation can be made negligible by adding a small offset to the true cosmic microwave background temperature of 2.73K. This modified cold-space temperature is called the Planck equivalent temperature \( T_{B,\text{space}} \). The cold-space temperature \( T_c \) in (1) is the same as \( T_{B,\text{space}} \) except at the two lower frequencies of 11 and 19 GHz. Section 9 shows that there is a small amount of earth radiation leaking into the cold mirror observation during normal operation. To account for this, 0.2 and 0.1 K are added to \( T_{B,\text{space}} \) at 11 and 19 GHz. Table 1 gives \( T_{B,\text{space}} \) and \( T_c \).
4. Magnetic Susceptibility Error

Soon after launch, an analysis of the radiometer counts collected during the deep-space maneuver revealed systematic errors correlated with the ambient magnetic field that consists of the Earth magnetic field and a second component from the spacecraft and sensor such as the magnetic reed switches on launch restraint (Draper 2015). The analysis clearly showed that the GMI receiver electronics are affected by the magnetic field. The magnetic susceptibility error (MSE) is modeled as (Draper 2015, Draper et al. 2015)

\[ C(\alpha) = C_0(\alpha) - R(\alpha)B_E^T - \Gamma(\alpha) - \Delta C_k \] (4)

where \( C(\alpha) \) are the radiometer count values after removing the MSE and \( C_0(\alpha) \) are the counts coming from the sensor. The term \( B_E \) is the Earth’s magnetic field vector in the spacecraft frame of reference, with the x-axis in the direction of spacecraft velocity for zero yaw, and the z-axis in the direction opposite to the spacecraft nadir for zero pitch. \( R(\alpha) \) is the rotation matrix for the spinning GMI sensor, and \( S \) is the electronics susceptibility vector: a constant to be found. The adjustments due to the spacecraft/sensor magnetic fields are represented by \( \Gamma(\alpha) \) and \( \Delta C_k \). The subscript \( k = c, h, e \) denotes the segment of the scan during which the feedhorn views the cold-sky reflector, the hot load, and the primary reflector, respectively. In normal operation, the primary reflector views the Earth, and hence we use the subscript \( e \). The term \( \Gamma(\alpha) \) is defined so that its mean value when averaged over the range of \( \alpha \) for any of the 3 sub-scans (\( c, h, \) or \( e \)) is zero, and \( \Delta C_k \) is the overall count bias for the \( k^{th} \) sub-scan.

The term \( \Gamma(\alpha) \) is found using about 4 months of on-orbit count measurements. When averaged over several months, the term \( R(\alpha)B_E^T \) in (4) averages to zero due to the variable scan-
ning geometry. For the cold and hot sub-scan, $\Gamma(\alpha)$ is found by simply averaging the counts into $\alpha$-bins and then subtracting out the average value for all cells in the sub-scan being considered.

$$\Gamma(\alpha) = \langle C_0(\alpha) - \bar{C}_{0k} \rangle$$ (6)

where the brackets indicate a 4-month average and $\bar{C}_{0k}$ is the count average of all scan positions for the $k^{th}$ sub-scan. The calculation of $C_o(\alpha)$ for the Earth counts is more complicated because there are other factors (antenna-induced biases and scan-edge intrusions) that vary along the scan. The method for removing these other influences and isolating $C_o(\alpha)$ is discussed in Section 11. The values for $C_o(\alpha)$ are given in the GCDB.

To find the susceptibility vector $S$, we use the observations from the deep-space maneuver. During this maneuver, both the primary reflector and the cold mirror viewed cold space simultaneously. Hence, the counts for the primary reflector $C(\alpha_e)$ and the counts for the cold mirror $C(\alpha_c)$ should be the same. Taking the difference of the Earth and cold counts as given by (4) and assuming $C(\alpha_e) = C(\alpha_c)$, gives

$$S_0 + \left[ R(\alpha_e) - R(\alpha_c) \right] B_e S^T = C_0(\alpha_e) - C_0(\alpha_c) - \Gamma(\alpha_e) + \Gamma(\alpha_c)$$ (7)

$$S_0 = \Delta C_e - \Delta C_c$$ (8)

where the right-hand side is known and the unknowns are the three components of $S$ and the bias term $S_0$. Note that because the bottom row of the rotation matrix is independent $\alpha$, the 3$^{rd}$ component of $S$ has no effect on (7). In other words, $S_3$ has the same effect on all counts and hence does not affect $C_e - C_c$. One can simply set $S_3$ to zero with no effect on calibration.

The deep-space maneuver occurred on May 20, 2014, between 13.65 and 16.8 hours GMT. In this maneuver the spacecraft is pitch 55$^\circ$ away from the Earth, and both the mainlobe and backlobe of the primary reflector view cold space. The cold mirror also views cold space during the first part of its scan segment (first 10 cold samples) except for 19 GHz which has a small
amount of Earth contamination even at the beginning of the scan. This determination of the 19 GHz Earth contamination is based on observing the change in cold counts as the spacecraft went from normal operation to the deep space orientation. If only the first 5 observations of the cold scan are used, the 19 GHz Earth contamination is 0.07 K and 0.24 for v-pol and h-pol, respectively. These values are subtracted from $C_e$ to obtain a value indicative of a true cold space observation. For the other channels, we just average the first 10 observations in the cold scan and no other correction is necessary.

There are two orbits of deep-space observations (5947 scans), and for each scan there are 221 Earth scan positions $\alpha_e$. To avoid earth contamination in $C_e$, we discard the first and last 20 scan positions (see Figure 1). The 5947 scans x 181 scan positions gives 1,076,407 simultaneous linear equations corresponding to (7), from which $S_0$ and the first two components of $S$ ($S_1$ and $S_2$) are estimated via least squares. As discussed in Section 7, a mild constraint is put on the estimation to maintain consistency between the spillover values obtained from the two backlobe maneuvers.

The values for $S_0$, $S_1$, and $S_2$ are given in Table 2 for each channel being considered here. Figure 1 shows earth minus cold count difference $\Delta C_{ec}$ as measured during the deep-space maneuver as a function of scan position and scan number before removing the MSE. Figure 2 show $\Delta C_{ec}$ after removing the MSE. The fact that the simple 3-parameter model ($S_0,S_1,S_2$) is so effective in removing the error is rather remarkable and clearly shows the effect is due to the changing magnetic field, as discovered by Draper shortly after launch [Draper 2015, Draper et al, 2015].

Figure 2 also shows (1) Earth contamination in $C_e$ at the scan edges and (2) a zone of minimum $\Delta C_{ec}$ between scan positions 50 and 100. These zonal effects are mostly independent
of the spacecraft position in orbit (i.e., scan number), and hence due not appear to be related to
the MSE. We intrepret the zone of mininum $\Delta C_{ec}$ as ‘true’ deep-space observations minimally
affected by radiation from the Earth.

5. Determination of the bias in $\Delta C_{ec}$ from Deep-Space Observations

Figure 3 shows $\Delta C_{ec}$ averaged over scan positions 50 through 100 plotted versus spacecraft
position in orbit (scan number). Two complete orbits are shown. For this figure we apply the
dynamic part of the MSE ($S_1$ and $S_2$), but do not remove the bias ($S_0$) because we want to exam-
ine the bias in $\Delta C_{ec}$. We see biases ranging from 0 to 0.4 K depending on channel. Figure 3 also
shows the Earth contamination in $C_e$ as predicted by the on-orbit simulation using the method-of-
moments (MoM) antenna patterns as discussed in Section 7. This prediction is useful for mar k-
ing those times during the deep-space maneuver that the Earth field of view was over ocean ver-
sus land. The transition from ocean to land is marked by an increase in the predicted $C_e$ contam-
ination, which is about 0.1 K at 7 GHz and less for the higher frequencies. If the dominate por-
tion of the Earth contamination comes from $C_c$ rather than $C_e$, the ocean-land transitions would
have the opposite sign. Thus these transitions provide a means to determine which contamina-
tion is dominate. If both $C_c$ and $C_e$ are equally contaminated, then the transitions will not appear
and there will be no bias to remove.

The 11V $\Delta C_{ec}$ timseries resembles the predicted $C_e$ contamination, but the 11H $\Delta C_{ec}$ does
not. The other channels show no obvious ocean-land transition except for 24V, which hints at an
ocean-land transition of the opposite sign, indicating $C_c$ is the domiminate contamination. The
predicted Earth contamination in $C_e$ was also computed using a different set of antenna patterns:
the physical optics model (PO). The PO model gave about twice the Earth contimination, which
is not at all supported by the observations.
To determine the bias in $\Delta C_{ec}$, we first look at its 2nd Stokes component: vertical minus horizontal polarization, which we expect to be zero for deep space observations. These biases range from about -0.1 to 0.2 K, depending on channel and are shown in Table 3. We also give the results obtained from the nadir maneuver discussed in the next section. Removing the $\Delta C_{ec}$ 2nd Stokes bias will affect the 2nd Stokes $T_A$, and we want to verify that any correction will not adversely affect the nadir observations. The nadir-observed 2nd Stokes $T_A$ is given in Table 3 for land and ocean. Except at 89 GHz, we found that a good compromise to reduce in 2nd Stokes bias in the deep-space observations, the nadir ocean observations, and the nadir land observations is to simply average the biases for these 3 types of observations and assume the error is in $C_e$. Table 3 shows the results after removing the bias in this manner. The 2nd Stokes biases are now all at the 0.05 K level or smaller, except for the deep-space 11 GHz bias, which is 0.07 K. We think some (maybe all) of this is real Earth contamination of the 11V, and as such is real and should not be removed as a $\Delta C_{ec}$ bias. At 89 GHz, the deep-space 2nd Stokes bias is -0.11 K while the nadir ocean and land results show no appreciable bias. For this case the 2nd Stokes bias is removed by assuming the error is in the cold counts $C_c$ rather than $C_e$. In this way, the bias for deep-space is removed with little effect on the ocean and land results, both of which are at the warm end of the calibration range and hence are insensitive to $C_c$.

The 1st Stokes component of $\Delta C_{ec}$ before bias removal is shown in Table 4. The 1st Stokes is defined as the sum of v-pol and h-pol divided by 2 (i.e., the average). At 24 GHz, there is no h-pol and results for just v-pol are shown. As discussed above, at 19, 37, and 89 GHz we see no evidence of Earth contamination (i.e. no obvious ocean-land transitions), and we simply remove all the observed bias in the 1st Stokes $\Delta C_{ec}$. At 11 GHz (24 GHz), we see some evidence of contamination in $C_e$ ($C_c$) and do not remove all the observed bias because some of it appears to be
real contamination. A small positive offset of 0.12 K is left at 11 GHz, and a small negative offset of -0.03 K is left at 24 GHz. The second row in Figure 3 shows the ΔC_{ec} after the 1st and 2nd Stokes bias removal. The Earth contamination in 11V is now quite obvious, and the 11V ΔC_{ec} timeseries appears to be positioned properly with a small positive offset.

Table 5 summarizes the results of this section. It gives the count offsets \( b_c, b_e, \) and \( b_{ec} \) for the cold counts and earth counts.

\[
\Delta C_e = \pm b_e + \kappa b_{ec}
\]

\[
\Delta C_e = \pm b_e + (\kappa - 1) b_{ec}
\]

where the plus (minus) sign applies to v-pol (h-pol). Equation (4) is then used to remove the count bias. For the 2nd Stokes offsets \( b_c \) and \( b_e \), we are able to separate the observed ΔC_{ec} bias into a cold-count bias and an earth-count bias because we have results for cold space, moderate ocean, and warm land. For the 1st Stokes offset \( b_{ec} \), we only have cold space results and cannot tell how much of the ΔC_{ec} bias is due to \( C_c \) versus \( C_e \). Thus, we have introduced the additional parameter \( \kappa \) that specifies the \( C_c \) versus \( C_e \) partitioning, and this parameter then becomes a degree of freedom that is discussed in later sections.

6. Nadir Observations

On December 8, 2014, between 20.8 and 23.9 hour GMT, the GPM spacecraft was pitched 48.45° towards the Earth so that the Earth incidence angle \( \theta_i \) at the center of the scan was near zero. We call this the nadir maneuver and use these nadir observations to evaluate the consistency between the v-pol and h-pol T_A. For near-nadir observations, the 2nd Stokes T_B can be well approximated by

\[
T_{Bq} \equiv T_{Bv} - T_{Bh} = b \theta_i^2 \cos 2\gamma + c W \cos 2(\varphi_v - \varphi_w)
\]
The first term accounts for small (< 5°) departures of θ_i from zero, where γ is the polarization rotation angle. The second term is the influence of wind direction on the 2nd Stokes T_B, where W and ϕ_w are the wind speed and direction and ϕ_v is the direction of the v-pol vector. The b coefficients are estimated from ocean RTM to be 0.022, 0.021, 0.020, and 0.013 K for 11, 19, 37, and 89 GHz, respectively. The c coefficients also come from the RTM and are 0.1038, 0.1304, 0.1582, and 0.0671 K/m/s, respectively.

The polarization rotation angle γ accounts for the fact that the GMI-referenced v-pol and h-pol vectors are, in general, rotated relative to the Earth v-pol and h-pol vectors, and γ is the degree of rotation. For example, the observations near the center of the scan all have their v-pol vector pointing forward in the general direction of the spacecraft motion. For the observations to the left or right of center, this v-pol vector corresponds to Earth-reference h-pol vector and hence γ = ± 90°. The wind direction effect at nadir is such that T_B is larger when the wind direction is aligned with the polarization vector (Etkin et al 1991). The wind speed and direction come from the NCEP 6-hour wind fields collocated to the GMI observation.

Letting T_Aq,mea denote the GMI near-nadir 2nd Stokes measurement, we define the T_A nadir anomaly to be

\[
\Delta T_{Ag} = T_{Ag,mea} - (1 - \eta)[b \theta_i^2 \cos 2\gamma + c W \cos 2(\phi_v - \phi_w)]
\]

(12)

where 1 – η accounts for the antenna spillover effect discussed in the next section. Since (12) is removing the θ_i and wind direction effects, \( \Delta T_{Ag} \) should ideally be zero. Figure 4 shows histograms of \( \Delta T_{Ag} \). To construct these histograms, we only used the observation cells that are close to nadir (scan positions 107 through 115), which limits the incidence angle to a maximum of 4°. Histograms are done separately for land and ocean observations. Table 3 gives the mean values for the histograms for ocean and land separately. Figure 4 also shows the histogram of \( \Delta T_{Ag} \)
when the wind direction correction is not applied. Clearly, wind direction plays an important
role for nadir observations, and if not accounted for produces anomalous results.

The small biases in the 2nd Stokes nadir $T_A$ are interpreted as biases in $\Delta C_{ec}$, as discussed in
the previous section. They could also be due to a difference between the v-pol and h-pol antenna
spillover value or in $\Delta C_{hc}$, but these factors would have a different effect on the three types of
observations (deep-space, ocean, and land). In view of the fact that a small adjustment in $\Delta C_{ec}$
reduced the 2nd Stokes error to the 0.05 K level simultaneously for deep-space, ocean, and land,
we conclude this is an appropriate approach.

7. Calculation of GMI Antenna Spillover

During normal operation of GMI (spacecraft pitch = 0°), the antenna temperature measured
by the sensor can be expressed by

$$T_A = (1 - \eta) T_{B,earth} + \eta T_{B,space}$$ (13)

where $T_{B,earth}$ is the gain-weighted Earth brightness temperature and $\eta$ is called the cold-space
spillover. To determine $T_{B,earth}$ given the GMI $T_A$ measurement, the spillover component must
be removed. The specification of $\eta$ has always been a major challenge for satellite microwave
radiometers. It is very difficult to measure directly in antenna chambers or on antenna ranges.
Analyses of previous satellite MW radiometers indicate that errors of 1% in $\eta$ are common, and
this equates to 2 K errors in recovering $T_{B,earth}$ (Wentz 2013). In view of the uncertainty in the
knowledge of $\eta$, the adjustment of this parameter has traditionally been our primary means to
bring overall agreement between the satellite measurements and the RTM.

For GMI, we no longer allow $\eta$ to be a degree of freedom. Rather we directly compute it
from the data acquired during the backlobe maneuver. This greatly constrains the calibration
process. There were two backlobe maneuvers on May 20, 2014 and December 9, 2014. To ac-
complish these maneuvers, the spacecraft is put into an inertial hold mode, for which the space-
craft pitch relative to the Earth varies from $0^\circ$ to $360^\circ$ around the orbit. At the point in the orbit where the pitch = $180^\circ$, the backlobe points directly down at the Earth, and all the power in the backlobe is subtended by the Earth. At the same time, the mainlobe views cold space. Given the measured antenna temperature and the Earth’s brightness temperature, one can estimate $\eta$.

In a more detailed expression, the antenna temperature measured by GMI is given by integrating the scene v-pol and h-pol brightness temperatures, $T_{Bv}$ and $T_{Bh}$, weighted by the gain pattern over $4\pi$ steradians (Piepmeier et al 2008).

$$T_{Av} = \int d\Omega \left[ \left( T_{Bv} \cos^2 \phi + T_{Bh} \sin^2 \phi \right) |G_{vv}|^2 + \left( T_{Bv} \sin^2 \phi + T_{Bh} \cos^2 \phi \right) |G_{hh}|^2 - T_{Bq} \Re\left( G_{vv} G_{hv}^* \right) \sin 2\phi \right]$$

(14)

where $T_{Bq}$ is the 2nd Stokes $T_B$, $G_{vv}$ is the co-pol complex gain amplitude, and $G_{hv}$ is the cross-pol complex gain amplitude. The angle $\phi$ is the rotation angle between the antenna-referenced polarization basis and the Earth-based polarization basis. The h-pol $T_{Ah}$ is given by switching the $v$ and $h$ subscripts in (14). The $T_A$ measurements taken during the back-lobe maneuver show very little polarization signature, with the v-pol minus h-pol differences being about 0.1 K or less. In view of this and the need to simplify the analysis, we assume that v-pol and h-pol backlobe patterns are the same. We can then use the sum of the v-pol and h-pol measurements to calculate a single spillover for each frequency, independent of polarization. Assuming the v-pol and h-pol gain patterns are the same, (14) simplifies to be

$$T_{Av} + T_{Ah} = \int d\Omega \left[ \left( |G_c|^2 + |G_s|^2 \right) \left( T_{Bv} + T_{Bh} \right) - 2S_2 \Re\left( G_c G_s^* \right) \sin 2\phi \right]$$

(15)

The $\sin 2\phi$ term is found to be very small (0.04K) and is set to zero. Thus, the characterization of the backlobe gain reduces to specifying the co-pol and cross-pol gain magnitudes $|G_c|^2$ and $|G_s|^2$. In addition to simplifying the problem, using the sum of v-pol and h-pol (i.e., the 1st Stokes $T_B$) reduces the sensitivity of the calculation to the details of polarization rotation in the back-
lobe. The integral (15) is partitioned into the portion that is subtended by the Earth (i.e., the backlobe portion) and the remaining portion that sees cold space.

\[ T_{av} + T_{Ah} = 2T_{B, space} (1 - \eta_{bl}) + \int \omega \left( |G_v|^2 + |G_h|^2 \right) (T_{B, v} + T_{B, h}) \]  

(16)

\[ \eta_{bl} = \int \omega \left( |G_v|^2 + |G_h|^2 \right) \]  

(17)

where \( \eta_{bl} \) is the backlobe spillover, and we make use of the normalization property that the gain integrated over \( 4\pi \) steradians is unity.

The prelaunch specification of the GMI antenna gain pattern was based on a hybrid method using both near-field feedhorn measurements and theoretical modeling as described in the GCDB. Two models are were used: a physical optics (PO) model utilizing theoretical feed patterns and a method-of-moments (MoM) model using feed patterns measured by a near-field range. Although the spillover fraction differs when directly computed from each model, the backlobe spillover analysis is rather insensitive to the choice of model. We assume that the gain terms in (14) and (15) can be represented by PO or MoM patterns with a simple scaling factor \( \mu \) applied.

\[ T_{av} + T_{Ah} = 2T_{B, space} (1 - \mu \hat{\eta}_{bl}) + \mu \int \omega \left( |\hat{G}_v|^2 + |\hat{G}_h|^2 \right) (T_{B, v} + T_{B, h}) \]  

(18)

\[ \eta_{bl} = \int \omega \left( |\hat{G}_v|^2 + |\hat{G}_h|^2 \right) \]  

(19)

where the top hat indicates the gain is either from the PO or MoM model and the gain is the average value of the v-pol and h-pol model gain. One can then solve for \( \eta_{bl} \)

\[ \eta_{bl} = \frac{T_{av} + T_{Ah} - 2T_{B, space}}{T_{B, eff} - 2T_{B, space}} \]  

(20)
Equation (21) shows the PO and MoM gain patterns are only being used as a weighting function to specify the effective Earth brightness temperature $T_{B,\text{eff}}$ seen by the backlobe. Even though the PO and MoM patterns have significantly different amplitudes, the calculation of $\eta_{bl}$ is essentially the same ($\Delta \eta = 0.0001$) for the two patterns.

The backlobe spillover $\eta_{bl}$ corresponds to that portion of the backlobe that is subtended by the Earth when the sensor is pitched 180°. During normal operation (pitch = 0°), the portion of the antenna pattern seeing cold space is $\eta_{bl}$ plus an additional annulus $\eta_a$ that extends from the Earth’s limb to the region corresponding to $\eta_{bl}$. Both the PO and MoM patterns indicate the power received by this region is very small, being about 0.2% or less of the total power. We use the PO values to account for this power, as shown in Table 6, and the total cold sky spillover that is used for normal operation is

$$\eta = \eta_{bl} + \eta_a$$

This then gives the spillover value that is to be used in (13) to remove the contribution of cold space during normal operation.

An on-orbit simulator is used to find $T_{B,\text{eff}}$. The simulator performs the full $4\pi$ gain integration for each GMI observation taken during the backlobe maneuver. The scene brightness temperatures $T_{Bv}$ and $T_{Bh}$ come from the ocean RTM when the integration pixel is over the ocean. The $T_B$ for land pixels is simply set to 275 K. The pitch = 180° point of interest is in the open ocean, so the specification of the land pixels is not that important. The ocean RTM requires sea-surface temperature ($T_S$), wind speed ($W$), wind direction ($\phi_w$), columnar water vapor ($V$), columnar liquid cloud water ($L$), and rain rate ($R$). $T_S$ comes from the NOAA SST operational product (Reynolds et al., 2002a; Reynolds et al., 2002b), and $\phi_w$ comes the NCEP 6-hour wind
fields. The remaining environmental parameters ($W, V, L,$ and $R$) come from other satellite MW radiometers that are coincident with the GMI observation. The collection of satellites used includes WindSat, AMSR-2, TMI, F16 SSMIS, and F17 SSMIS, all of which have been inter-calibrated. The satellite closest in time is used, with the typical time difference between it and GMI being about 1 hour.

Given $T_{B,\text{eff}}$, $\eta_{bl}$ is computed according to (20) for each GMI observation over the orbit segment for which the spacecraft pitch is between 177° and 183°. A simple average of all these values is then taken, and these values appear in Table 6 along with the annulus spillover $\eta_a$, and the total spillover $\eta$. Separate values for $\eta_{bl}$ are shown for the two maneuvers, and the consistency between the two maneuvers is at the 0.15 K level assuming a $T_A$ of 200 K. The average of these two maneuvers is used for $\eta$. Table 6 also shows the value of $\eta$ predicted by the PO model and the MoM model. Except for 24 GHz, the PO values are close to the values we derive: 0 to 0.2 K for $T_A = 200$ K. For 24 GHz there is no h-pol $T_A$ measurement, and we set $T_{Ah}$ equal to $T_{Av}$. For the other frequencies that have both polarizations the difference between $T_{Ah}$ and $T_{Av}$ is 0.1 K or less. So setting $T_{Ah}$ to $T_{Av}$ is a reasonable approximation, but it may partly explain the larger discrepancy in $\eta$ at 24 GHz (0.39 K). The MoM $\eta$ values are much larger, and we consider the MOM values spurious.

The satellite yaw for the first (second) backlobe maneuver was 0° (180°), and as a consequence magnetic susceptibility correction has opposite signs for the two maneuvers. We found the difference between the $\eta_{bl}$ calculations for the two maneuvers fairly sensitive to $S_l$. When doing the least-squares estimation of $S_0$, $S_1$, and $S_2$, we put a mild constraint on $S_l$ to keep the consistency of $\eta_{bl}$ between the two maneuvers near the 0.2 K level. This constraint had very lit-
tle impact on the quality of fit of (7) to the deep-space data. Also, by averaging the two maneuvers, the sensitivity to $S_I$ is greatly reduced.

For several reasons, we did not use the backlobe method to compute a spillover for 89 GHz. First, as discussed at the end of this section, our method requires the noise diodes for calibration when the pitch is at 180°, and there are no noise diodes at 89 GHz. Also the PO model predicts the spillover is very small (0.2%) at 89 GHz spillover, and the deep-space maneuver results discussed in Section 5 show little biases at 89 GHz (see Table 5). Thus we use the simpler method of adjusting the spillover to agree with the RTM. The required adjustment is very small: we needed to increase the PO $\eta$ value of 0.00194 to 0.00235, which is equivalent to a change of 0.08 K for $T_A=200$ K. This again suggests the PO model is providing a very accurate estimate of the true spillover.

To further evaluate the method of computing spillover, (18) is used to compute $T_{Av}+T_{Ah}$ for an extended portion of the backlobe maneuver. This simulated $T_{Av}+T_{Ah}$ is then compared to the measured value in Figure 5 (May 20 maneuver) and Figure 6 (December 9 maneuver). The importance of using timely collocations from other satellites to specify the Earth TB is shown by Figure 5. On May 20, 2014, a fairly strong South Pacific storm shown in Figure 7 had rapidly developed at the 180° pitch location. The GMI backlobe observed the storm at 23°S, 194°E at 17.3 hours GMT. The high winds, vapor, and rain in the storm produce brightness temperatures considerably warmer than typical for that location. Both the simulated and measured $T_A$ show this increase at the storm location.

The December 9 maneuver shows the effect of land. Land observations are only encountered away from the 180° pitch point, and hence do not affect the spillover calculations. Howev-
er, they do provide a good test for the simulation. As Figure 6 shows, the simulation models the
effect of the Aleutian Islands very well. The islands are seen as a small uptick in $T_A$.

There is very good agreement between the simulated and measured $T_A$ over the range of
pitch from 108° to 216° (144° to 252°) for the May 20 (December 9) maneuver. The pitch ranges
for the two maneuvers are different because the spacecraft yaw for the first maneuver was 0° and
that for the second maneuver was 180°. This agreement, particularly with regards to modeling
weather and land features, provides confidence in the spillover results. As the maneuver departs
further from the 180° point, the backlobe begins to leave the Earth and the agreement degrades
because the calculation of $T_A$ becomes much more sensitive to the detailed shape of the PO or
MoM patterns. Towards the end of the maneuver, the main lobe resumes viewing the Earth and
$T_A$ abruptly increases.

One complication of doing the spillover computation is that the GMI cold mirror views the
Earth, rather than cold space, at the 180° pitch point. Thus the standard cold-mirror/hot-load cal-
ibration cannot be used. Instead, we use the count difference of the hot load with noise diode
minus hot load without noise diode, $C_{hn} - C_h$, to specify the radiometer gain $G$:

$$T_{A0} = T_h - (C_h - C_c)G$$

(23)

$$G = \frac{\Delta T_N}{C_{hn} - C_h}$$

(24)

where $\Delta T_N$ is the excess temperature produced by the noise diode. There is some uncertainty in
specifying $\Delta T_N$ simply as a function of the physical temperature of the noise diode. A better ap-
proach is to specify $\Delta T_N$ so that the gain $G$ is the same as the standard cold-mirror/hot-load gain
while the cold mirror is still seeing cold space, i.e. before the pitch exceeds about 55°.

$$\Delta T_N = \left\langle \frac{C_{hn} - C_h}{C_h - C_c} (T_h - T_c) \right\rangle + a \left( T_R - \langle T_R \rangle \right)$$

(25)
The brackets denote a 12-minute average done right before the cold mirror ceases to have a clear view of cold space. The second term in (25) accounts for the change in $\Delta T_N$ due to the physical temperature of the noise diode that varies during the course of the maneuver. The receiver temperature $T_R$ is used to model the temperature variation. The sensitivity coefficient $a$ is found from the $\Delta T_N$ versus $T_R$ plots in the GCDB. Combining (24) and (25), one see that the gain $G$ for the 12-minute initialization period is standard cold-mirror/hot-load gain $(T_h - T_c)/(C_h - C_c)$.

When computing $T_{A0}$ from (23), the counts offsets given by (9) and (10) must be applied. We found that the specification of $\kappa$ mattered little. Three cases were run for $\kappa = 0$ (all the error is in $C_c$), $\kappa = 1$ (all the error is in $C_e$), and $\kappa = 0.5$ (equal error in $C_e$ and $C_c$). The choice of $\kappa$ had a negligible effect on $\eta$ (0.00004 or less) because $T_A$ for the backlobe measurements, which is 9 K or less, is very close the temperature of cold space (2.7 K), and changing $C_e$ versus $C_c$ has essentially the same effect. This is fortunate because it allows us to determine $\eta$ without having to be concerned with specifying $\kappa$.

For the December 9 maneuver the spacecraft transitions immediately from normal operation to the backlobe maneuver. However, the May 20 backlobe maneuver is preceded by a deep-space maneuver lasting over 3 hours. We did not want to use a gain initialization period that was 4 hours before the 180° pitch point because $\Delta T_N$ could have significant variation over this long of a time period that is not captured by (23). Instead, we the choose initialization period to be the 12 minutes right before the spacecraft transitioned from the deep-space maneuver to the backlobe maneuver, which occurred at 16.8 GMT.

8. **GMI Antenna Temperatures Compared to the RTM**

In this section we compare the GMI $T_A$ measurements with simulated $T_A$ from the ocean RTM. The simulated v-pol antenna temperature is given by
The h-pol $T_A$ is also given by (26), but with the $v$ and $h$ subscripts reversed. Equation (27) is the same as (13) except that we explicitly show the polarization mixing, which is represented by the cross-polarization coefficient $\chi$. The spillover $\eta$ comes from the backlobe analysis discussed in Section 7. Equation (26) is an often used approximation for the full $T_A$ integral equation as depicted by (14).

The coefficient $\chi$ is found by integrating the cross-pol gain over the antenna pattern

$$\chi = \int_{\Omega_o} |G| d\Omega$$  \hspace{1cm} (27)

where $\Omega_o$ is the solid angle of integration. It is typical to reference $\chi$ to an integration over just the mainlobe (more specifically over a solid angle 2.5 times larger than the 3-dB beamwidth). However, there is additional polarization mixing outside the mainlobe that should be considered. Table 7 gives $\chi$ values for $\Omega_o$ equal to 2.5 times and 25 times the 3-dB beamwidth (BW). We use the 25BW values for our analysis. The results are nearly identical for the PO and MoM patterns. For a given frequency, there are very small differences between the $v$-pol and $h$-pol patterns, and we use the average values, as shown in Table 7.

The specification of the Earth brightness temperatures $T_{Bv}$ and $T_{Bh}$ in (26) is done in the same way as described for the backlobe analysis in Section 7. The only differences are (1) rainy observations are excluded, and (2) a collocation window of 1-hour and 25-km is used. Separate calculations are done using WindSat, TMI, and AMSR-2 to specify the environmental parameters $W$, $V$, $L$, and $R$. Table 8 shows the mean values of $T_A-T_{A,rtm}$ averaged over the 13 months of collocation and averaged over the world’s oceans. The first 5 rows in Table 8 show various results using the WindSat retrievals. Rows 1 and 2 show results using the method-of-moments
spillover and the physical optics spillover, respectively, and with no offsets applied to the counts, i.e., no bias removal. The MoM biases are quite large (2 K), and as mentioned earlier the MOM spillover appears to be spurious. The PO results show much better agreement between the GMI $T_A$ and the RTM, with differences of the order of 0 to 0.3 K. When (9) and (10) are used to remove the bias in $C_c$ and $C_e$, the $T_A - T_{A, rtm}$ difference is further reduced (rows 3, 4, and 5). We show results for $\kappa = 0$ (all the error is in $C_c$) and $\kappa = 1$ (all the error is in $C_e$). The choice of $\kappa$ can make a 0.1 to 0.2 K difference depending on channel. We also show results of an optimum choice of $\kappa$, where we use $\kappa = 1$ at 11 GHZ, and $\kappa = 0.5$ for all other channels. The bottom two rows show the TMI and AMSR-2 $T_A - T_{A, rtm}$ using this optimum $\kappa$.

We think WindSat is probably the best calibrated sensor that is collocated with GMI, and the WindSat $T_A - T_{A, rtm}$ biases do not exceed 0.1K. The WindSat ocean retrievals have been thoroughly validated by us and many others (Wentz 2012; Meissner et al. 2011; Mears et al. 2015; De Biasio and Zecchetto 2013; Huang et al. 2014; Wentz 2015) against buoy measurements, GPS vapor measurements, and geophysical retrievals for other satellites. WindSat has proven to be a very stable sensor. Comparisons of WindSat SST and winds with ocean buoys and WindSat vapor with GPS-derived vapor show no obvious evidence of drift. Comparisons with TMI also verify the stability of WindSat (Wentz 2015). We use a tight 1-hour GMI-WindSat collocation window to avoid diurnal issues.

The high level of agreement between the GMI $T_A$ and the RTM is due in part to some adjustments made to the RTM based on an early analysis of GMI observations. This is discussed by Wentz and Meissner (2015). For example, at 37 and 89 GHz, the atmospheric absorption was decreased to match the 2\textsuperscript{nd} Stokes GMI observation. This decrease in absorption brought the model closer to laboratory measurements. Other small changes were made related to vapor and
wind sensitivities, but there were no adjustments to force the 1\textsuperscript{st} Stokes RTM to match GMI. See Wentz and Meissner (2015) for the details.

9. Cold-Sky Mirror

Cold calibration observations are taken during the portion of the scan during which the cold-sky mirror is seen by the feedhorn. At this point in the scan, the cold mirror is between the underlying feedhorn and the primary reflector above. A problem that has occurred with previous MW imagers is that the feedhorn sees a small amount of radiation coming from the primary reflector around the outer edge of the cold mirror. This effect is called cold-mirror spillover. The MW imagers AMSR-E and AMSR-2 have a cold-mirror spillover near 0.4\% (i.e. 0.4\% of the cold calibration observation comes from the Earth). When specifying the temperature of cold-space $T_c$ in (4), this Earth radiation needs to be considered, and $T_c$ will have a value greater than the Planck-equivalent $T_{B,\text{space}}$.

To examine this problem for GMI, we make geographic maps of the cold counts. When doing the mapping, the latitudes and longitudes of where the main reflector is looking at the time of the cold observations are used. Anomaly $C_c$ maps are then made averaging over 13 months (March 2014 through March 2015) and subtracting the zonal average (average over all longitudes) for 1\degree latitude bands. Figure 8 shows the resulting $C_c$ anomaly maps for each GMI channel being considered. Any significant cold-mirror spillover will manifest itself as a contrast between the cold oceans and the warmer continents. For the 11 and 19 GHz, a careful inspection reveals South America and Australia, but these features are very faint. The largest features in Figure 8 are due to gain variations in $C_c$ that persist even after averaging for 13 months. The GMI cold-mirror spillover features are much less distinct than those observed with AMSR-E and AMSR-2. It is clear that for GMI cold-mirror spillover is a very small problem. Still, there is a little Earth radiation leaking in, and $T_c$ is a little greater than the minimum value given by $T_{B,\text{space}}$. 

23
Since the ocean $T_B$ (average of v-pol and h-pol) is about half way between 0 K and the land $T_B$, the average Earth contamination for land and ocean is about 1.5 times the ocean-land contrast shown in Figure 8.

Since some continents show up and others do not, the estimate of the land-ocean contrast is uncertain. We use an approximate value of 0.1 K for 11 GHz. For 19 GHz, for which the features are fainter, we use half this value. This gives an increase of 0.15 K and 0.075 K for the increase in $T_c$ due to Earth contamination ($T_A \approx 200$), and the corresponding cold-mirror spillover values are 0.08% and 0.04%. The GCDB predicts the spillover values of 0.17% and 0.04%. The GCDB also predicts some additional contamination coming from the spacecraft, and we slightly increase the contamination values to 0.2 and 0.1 K, which are the values shown in Table 1. If we assume the error in $T_c$ is 0.06 K, then according to (1) the error in the v-pol and h-pol $T_A$ is 0.03 and 0.04 K, respectively.

The deep-space analysis in Section 5 does not show Earth contamination in $C_c$ at 11 and 19 GHz. This is probably because of the different pointing geometry of the cold mirror and the fact that we only use the first part of the cold scan for the deep-space analysis.

10. Hot Load

Hot calibration observations are taken during the portion of the scan during which the hot load is seen by the feedhorn. At this point in the scan, the hot load is between the underlying feedhorn and the primary reflector above. A problem with previous MW imagers has been large thermal gradients in the hot load. Due to these gradients, the effective temperature of the hot load, as seen by the feedhorn, is not well represented by the precision thermistors that are attached to the hot load. The thermal gradients are mostly due to the varying sun-spacecraft geometry that occurs over every orbit. At some points in the orbit the sun either directly shines or
reflects into the hot load, thereby producing the thermal gradients (Twarog et al., 2006). Nearly all previous MW imagers experience this problem to one extent or the other (Wentz, 2013).

These hot-load problems can be seen by making plots of measured-minus-predicted $T_A$ anomalies, $T_A - T_{A,\text{rtm}}$, versus the sun’s azimuth angle $\phi_{\text{sun}}$ and zenith angle $\theta_{\text{sun}}$ as measured in the spacecraft coordinate system for which the z-axis points up away from nadir and the x-axis is the spacecraft velocity vector. The $T_A$ anomalies are denoted by:

$$\Delta T_A = T_A - T_{A,\text{rtm}}$$  \hspace{1cm} (28)

where $T_A$ comes from (1) and $T_{A,\text{rtm}}$ is computed as described above. Figure 9 shows $\Delta T_A$ plotted versus $\phi_{\text{sun}},\theta_{\text{sun}}$. To produce this figure, we use ocean retrievals from three MW images: WindSat, AMSR-2, and TMI for the period from the beginning of the GMI mission March 4, 2014 through March 31, 2015. Using just one satellite would not capture the full extent of the $\phi_{\text{sun}},\theta_{\text{sun}}$-space seen by GMI. For a given imager and a given channel, there are small overall biases in $\Delta T_A$ as listed in Table 8. In Figure 9, these small biases are removed to more clearly show features just related to the sun angles. We see no evidence at all that the GMI hot load has an error associated with the sun angle. The 89 GHz images do show features reaching 0.5 K, but we attribute this to mismodeling of the radiative properties of clouds at 89 GHz. It is an RTM problem, not a sensor problem. Clouds strongly affect the 89 GHz observations, and factors such as air temperature, cloud height, and drop size distribution play a much stronger role than at the lower frequencies. Errors on the order of 0.5 K are probably to be expected. Note there are few observations for sun azimuth angles between 350° and 360°, and that is why the results look noisy in this region. Comparing Figure 9 to similar figures for other MW imagers shows how well the GMI hot load is performing (Wentz 2013; Wentz 2015).
The algorithm for computing $T_h$ from the thermistor values is given in the GCDB. The algorithm first performs a simple average of either 4 or 5 thermistors, depending on channel, and then does a correction that accounts for the temperature difference between the hot-load temperature and the hot-load tray temperature. In view of the results shown here, we see no need to adjust this $T_h$ value coming from this algorithm.

### 11. Along-Scan Biases

For the Earth sub-scan, the derivation of the along-scan correction terms and $g(\alpha)$, $h(\alpha)$, and $\Gamma(\alpha)$ in (3) and (4) is also based on the measured-minus-predicted $T_A$, anomalies $\Delta T_A$. In this case, $\Delta T_A$ is binned and averaged according to the scan angle $\alpha$ rather than $\phi_{sun}, \theta_{sun}$. $\Delta T_A(\alpha)$ is found from a 4-month average of ocean observations (March through June 2014). The average value of $\Delta T_A(\alpha)$ for all $\alpha$ is subtracted out, thereby making $\Delta T_A(\alpha)$ an unbiased correction that does not affect the absolute calibration of GMI. This along-scan anomaly is then partitioned into a count anomaly $\Gamma(\alpha)$ resulting from the spacecraft/sensor fixed magnetic field, an additive portion $g(\alpha)$ that most likely comes from the antenna sidelobes and backlobe, and a multiplicative term $h(\alpha)$ due to the intrusion of the cold-sky mirror at the end of the Earth scan. The method for partitioning the three terms is given in the GCDB. We have verified that extending data from March 2014 through March 2015 has no appreciable effect on $\Delta T_A(\alpha)$. That is to say, the along-scan anomaly is stable with time. We refer the reader to the GCDB for more information of the along-scan biases.

### 12. Mission and Closure Plots

Next we present what we call mission plots because they provide a summary of the entire GMI mission. These plots show the anomaly $\Delta T_A$ plots versus orbit number and intra-orbit position $\omega$, which is the angular position of the spacecraft relative to its southern-most position. Hence $\omega = 0^o, 90^o, 180^o,$ and $270^o$ correspond the minimum latitude near $60^o$S, the equator as-
cending nodes, the maximum latitude near 60°N, and the equator descending node. Figure 10 shows the results. For the lower frequencies from 11 to 37 GHz, the variation of $\Delta T_A$ is mostly within ±0.2 K. At 89 GHz there is higher variability due to clouds as already discussed in Section 10. We see no residual MSE or other problems, at least at the 0.1 - 0.2 K level.

As a final consistency check, we do a closure analysis, which is the same as the mission plots except that the environmental parameters $W$, $V$, and $L$ used to compute $T_{A,rtm}$ come directly from the GMI ocean retrieval algorithm. Thus, colocation is no longer a problem, and we have a value of $T_{A,rtm}$ for every GMI observation over the ocean, thereby giving us a full uninterrupted set of $\Delta T_A$ anomalies. Since there are only three retrievals for the 9 channels, there is no guarantee that $\Delta T_A$ will be zero. A single anomalous channel will be quite apparent. With previous MW imagers this closure analysis proved effective in detecting small problems (Wentz 2013).

Figure 11 shows the results for GMI. There is slight zonal banding at the ±0.1 K level, but this is likely due to small inconsistencies in the retrieval algorithm not being a perfect inverse of the RTM, particularly with respect to the 70 K variation in 24V $T_A$ due to changing water vapor. The larger, cloud-related features in the 89 GHz images are similar to those shown in the previous section and again are attributed to RTM problems. We see no evidence of sensor calibration problems with GMI.

13. Conclusion

GMI’s only significant calibration problem appears to be its susceptibility to the ambient magnetic field. Fortunately the deep-space observations provide the means to characterize and remove the magnetic susceptibility error (MSE), both its variable part and its bias. The nadir observations give us additional calibration points for the 2nd Stokes $T_A$ at ocean and land temperatures. This allows us to precisely calibrate the $\Delta C_{ce}$ term in the $T_A$ equation (1). The other terms in the $T_A$ equation are the cold space temperature $T_c$, the hot load temperature $T_h$, and the hot mi-
nus cold count difference $\Delta C_{hc}$. With respect to $T_c$, we did detect a small amount of cold-mirror spillover (0.2 K at 11 GHz, 0.1 K at 19 GHz), but this was expected based on pre-launch analyses. With respect to $T_h$, we found no evidence of sun intrusion into the hot load. There could be an overall bias in $T_h$, but the fact that the 1st Stokes GMI $T_A$ matches the RTM to better than 0.1 K suggests any bias in $T_h$ must be small. We were not able to examine $\Delta C_{hc}$, but again the RTM comparisons indicate any bias in $\Delta C_{hc}$ must be around the 0.1 K level. We conclude that the accuracy of the GMI $T_A$ is near 0.1 K, which is typical of the discrepancies shown in our various analyses. None of our analyses showed discrepancies larger than 0.2 K.

The second part of the calibration problem is the specification of primary reflector’s cold-space spillover $\eta$, which is needed to convert $T_A$ to $T_B$. The backlobe maneuvers provided the means to directly compute $\eta$ rather than relying on pre-launch measurements. The agreement between $\eta$ derived from the backlobe maneuvers and the ones computed from the physical optics antenna pattern is 0.1 to 0.2 K ($T_A$ =200 K), except for 24V which is somewhat higher (0.4 K). The agreement between $\eta$ for the two maneuvers is at the 0.15 K level, and by averaging the two maneuvers, the sensitivity of $\eta$ to the MSE is greatly reduced. We conclude the error in specifying $\eta$ is about 0.1 K. Hence the total error in estimating the Earth brightness temperature, the sum of the $T_A$ and $\eta$ errors, is estimated to be about 0.2 K. This error estimate is support by the WindSat RTM comparisons, for which the globally averaged $T_A - T_{A,rtm}$ does not exceed 0.1 K.

GMI marks a milestone in satellite microwave radiometry. GMI is the first microwave imager that has been independently calibrated (i.e., without resorting to the RTM) to an absolute accuracy approaching 0.1 K. Furthermore, the inclusion of the noise diodes, which measure the radiometer’s non-linearity, directly provides the means to maintain this calibration over the full range of $T_B$ from the cold oceans at 80 K to the hot deserts at 300 K. By establishing reference
temperatures for the oceans and for stable land targets such as the Amazon rainforest, GMI’s
precision calibration can be extended both forward and backward in time to create highly accu-
rate multi-decadal records of our planet’s changing climate as seen in the microwave spectrum.
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help they provided during the course of this investigation.
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### Tables

**Table 1.** Planck equivalent temperature and cold mirror temperature (K).

<table>
<thead>
<tr>
<th></th>
<th>11 GHz</th>
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<th>24 GHz</th>
<th>37 GHz</th>
<th>89 GHz</th>
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<tbody>
<tr>
<td>Planck Equivalent Temperature $T_{B,\text{space}}$</td>
<td>2.74</td>
<td>2.75</td>
<td>2.77</td>
<td>2.82</td>
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<td>Cold Mirror $T_c$</td>
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<td>2.85</td>
<td>2.77</td>
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**Table 2.** Count bias $S_0$ (counts) and magnetic susceptibility vector components $S_1$ and $S_2$ (counts/microteslas).

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<thead>
<tr>
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<th>11V</th>
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<th>19V</th>
<th>19H</th>
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<th>37H</th>
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<tr>
<td>$S_0$</td>
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<td>10.78</td>
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<td>-0.4991</td>
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<td>-0.0567</td>
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**Table 3.** Bias in the 2nd Stokes component of $\Delta C_{ee}$ and $T_A$ (K).

<table>
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<th>11 GHz</th>
<th>19 GHz</th>
<th>37 GHz</th>
<th>89 GHz</th>
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</thead>
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<tr>
<td><strong>Bias in $\Delta C_{ee}$</strong></td>
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<tr>
<td>Deep-Space</td>
<td>0.204</td>
<td>0.053</td>
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<td>Ocean</td>
<td>0.092</td>
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<td>Land</td>
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<td>-0.077</td>
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<td><strong>After Bias Removal</strong></td>
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</tr>
<tr>
<td>Deep-Space</td>
<td>0.069</td>
<td>-0.049</td>
<td>0.033</td>
<td>-0.001</td>
</tr>
<tr>
<td>Ocean</td>
<td>-0.051</td>
<td>0.039</td>
<td>-0.023</td>
<td>0.043</td>
</tr>
<tr>
<td>Land</td>
<td>-0.026</td>
<td>0.015</td>
<td>-0.012</td>
<td>-0.025</td>
</tr>
</tbody>
</table>

**Table 4.** Bias in the 1st Stokes component of $\Delta C_{ee}$ (K).

<table>
<thead>
<tr>
<th></th>
<th>11 GHz</th>
<th>19 GHz</th>
<th>24 GHz</th>
<th>37 GHz</th>
<th>89 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bias in 1st Stokes $\Delta C_{ee}$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 GHz</td>
<td>0.263</td>
<td>0.118</td>
<td>9.70</td>
<td>0.076</td>
<td>0.049</td>
</tr>
<tr>
<td><strong>After Bias Removal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24 GHz</td>
<td>0.118</td>
<td>0.000</td>
<td>-0.033</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

24 GHz is just v-pol, not 1st Stokes. Small residual biases at 11 and 24 GHz are intentional.
Table 5. Offsets to cold and earth counts that are subtracted to debias the counts.

<table>
<thead>
<tr>
<th></th>
<th>11 GHz</th>
<th>19 GHz</th>
<th>24 GHz</th>
<th>37 GHz</th>
<th>89 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_c$</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.86</td>
</tr>
<tr>
<td>$b_e$</td>
<td>2.76</td>
<td>2.33</td>
<td>0.00</td>
<td>-1.16</td>
<td>0.00</td>
</tr>
<tr>
<td>$b_{ec}$</td>
<td>6.00</td>
<td>5.44</td>
<td>11.00</td>
<td>2.84</td>
<td>1.66</td>
</tr>
</tbody>
</table>

Table 6. Spillover computed from backlobe maneuver and theoretical models.

<table>
<thead>
<tr>
<th></th>
<th>11 GHz</th>
<th>19 GHz</th>
<th>24 GHz</th>
<th>37 GHz</th>
<th>89 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_{bl}$, 2014 May Maneuver</td>
<td>0.0410</td>
<td>0.0387</td>
<td>0.0252</td>
<td>0.00353</td>
<td></td>
</tr>
<tr>
<td>$\eta_{bl}$, 2014 Dec. Maneuver</td>
<td>0.04096</td>
<td>0.03976</td>
<td>0.02598</td>
<td>0.00422</td>
<td></td>
</tr>
<tr>
<td>$\eta_{bl}$, Avg. both Maneuver</td>
<td>0.04102</td>
<td>0.03927</td>
<td>0.02561</td>
<td>0.00388</td>
<td></td>
</tr>
<tr>
<td>Annulus $\eta_a$</td>
<td>0.00169</td>
<td>0.00149</td>
<td>0.00081</td>
<td>0.00014</td>
<td></td>
</tr>
<tr>
<td>Total spillover $\eta$</td>
<td>0.04271</td>
<td>0.04076</td>
<td>0.02642</td>
<td>0.00402</td>
<td>0.00235*</td>
</tr>
<tr>
<td>PO model spillover</td>
<td>0.04269</td>
<td>0.04158</td>
<td>0.02448</td>
<td>0.00397</td>
<td>0.00194</td>
</tr>
<tr>
<td>MoM model spillover</td>
<td>0.05575</td>
<td>0.05944</td>
<td>0.03385</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

*89 GHz spillover comes from a direct adjustment to the RTM

Table 7. Cross-polarization coupling.

<table>
<thead>
<tr>
<th></th>
<th>11 GHz</th>
<th>19 GHz</th>
<th>24 GHz</th>
<th>37 GHz</th>
<th>89 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi$, 2.5BW</td>
<td>0.00241</td>
<td>0.00206</td>
<td>0.00140</td>
<td>0.00106</td>
<td>0.00135</td>
</tr>
<tr>
<td>$\chi$, 25BW</td>
<td>0.00290</td>
<td>0.00235</td>
<td>0.00167</td>
<td>0.00120</td>
<td>0.00145</td>
</tr>
</tbody>
</table>

Table 8. $T_A - T_{A_{rtm}}$ (K) from WindSat, TMI, and AMSR-2.

<table>
<thead>
<tr>
<th></th>
<th>11V</th>
<th>11H</th>
<th>19V</th>
<th>19H</th>
<th>24V</th>
<th>37V</th>
<th>37H</th>
<th>89V</th>
<th>89H</th>
</tr>
</thead>
<tbody>
<tr>
<td>No offsets, MoM $\eta$</td>
<td>2.43</td>
<td>1.23</td>
<td>3.64</td>
<td>2.21</td>
<td>1.68</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>No offsets, PO $\eta$</td>
<td>0.29</td>
<td>0.07</td>
<td>0.33</td>
<td>0.09</td>
<td>-0.30</td>
<td>0.02</td>
<td>0.02</td>
<td>-0.08</td>
<td>-0.12</td>
</tr>
<tr>
<td>Offsets applied (k=0), GMI $\eta$</td>
<td>0.16</td>
<td>0.04</td>
<td>0.08</td>
<td>-0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>-0.04</td>
<td>0.03</td>
<td>-0.05</td>
</tr>
<tr>
<td>Offsets applied (k=1), GMI $\eta$</td>
<td>0.07</td>
<td>-0.01</td>
<td>-0.00</td>
<td>-0.08</td>
<td>-0.21</td>
<td>-0.02</td>
<td>-0.09</td>
<td>-0.02</td>
<td>-0.09</td>
</tr>
<tr>
<td>Optimum offsets, GMI $\eta$</td>
<td>0.07</td>
<td>-0.01</td>
<td>-0.00</td>
<td>-0.06</td>
<td>-0.09</td>
<td>0.01</td>
<td>-0.06</td>
<td>0.00</td>
<td>-0.07</td>
</tr>
<tr>
<td>TMI, Optimum offsets, GMI $\eta$</td>
<td>0.04</td>
<td>-0.09</td>
<td>-0.01</td>
<td>-0.13</td>
<td>-0.10</td>
<td>-0.04</td>
<td>-0.13</td>
<td>-0.15</td>
<td>-0.21</td>
</tr>
<tr>
<td>AMSR2, Optimum offsets, GMI $\eta$</td>
<td>0.01</td>
<td>-0.05</td>
<td>-0.07</td>
<td>-0.16</td>
<td>-0.22</td>
<td>-0.07</td>
<td>-0.15</td>
<td>-0.11</td>
<td>-0.26</td>
</tr>
</tbody>
</table>

WindSat retrievals are used for the RTM for the first 5 rows. GMI $\eta$ is spillover derived herein.
Figure Caption List

Fig. 1. The earth minus cold count difference $\Delta C_{ec}$ (K) as measured during the deep-space maneuver as a function of scan position and scan number. These results are before removing the magnetic susceptibility error.

Fig. 2. Same as figure 1 except the magnetic susceptibility error has been removed.

Fig. 3. Results of the GMI deep-space maneuver during which the primary reflector and cold mirror simultaneously view cold space. Each column is a different frequency. The plots show the Earth minus cold count difference $\Delta C_{ec}$ scaled to units of Kelvin. The red and green curves show the v-pol and h-pol $\Delta C_{ec}$, respectively. The top row show results before adjusting the counts. The bottom row shows results after applying offsets to $C_e$ and $C_c$ derived from the deep-space calibration. The black show $\Delta C_{ec}$ predicted by the MoM antenna pattern. The predicted values correspond to the average of v-pol and h-pol. For 24 GHz, the predicted $\Delta C_{ec}$ curve is the 11 GHz curve with a minus sign appended and slightly offset. We do this to show the dominate Earth contamination at 24 GHz seems to be in $C_c$, not $C_e$.

Fig. 4. Histograms of the GMI’s 2nd Stokes $T_A$ measurements for near-nadir observations.

Fig. 5. Results of the May 20, 2014, backlobe maneuver that occurred in the South Pacific. GMI $T_A$ measurement (red) compared to the simulated $T_A$ (blue). The time during which the pitch was between 177° and 183° is marked by the small black bar. During this time, the GMI backlobe is completely subtended by the Earth, and this is the time period used to find $\eta_{bl}$.

Fig. 6. Same as Figure 5 except these results are from the December 9, 2014, backlobe maneuver that occurred over the Gulf of Alaska.
Fig. 7. Rain rate from the SSMIS flying on the DMSP F17 satellite taken within one hour of the GMI backlobe observations during the May 20, 2014 maneuver. The 180° pitch point occurs at 23°S, 194°E.

Fig. 8 Geographic maps of the cold count anomaly. Counts have been converted to $T_A$ Kelvin units by multiplying by the typical gain for a given channel. The larger features are due to gain variation in the cold counts that persist even after averaging for 13 month and should not be interpreted as an error. The continents of South America and Australia are barely visible at 11 and 19 GHz.

Fig. 9. GMI $T_A$ minus RTM $T_A$ anomaly plotted versus the sun azimuth angle $\phi_{sun}$ and zenith angle $\theta_{sun}$. The larger features at 89 GHz are attributed to the RTM mismodeling clouds. The dark blue area is the region of $\phi_{sun}, \theta_{sun}$ not sampled by GMI. There is no evidence of hot-load problems.

Fig. 10. GMI $T_A$ minus RTM $T_A$ anomaly plotted versus the orbit number and intra-orbit position. The results go up to orbit 6182. WindSat, TMI, and AMSR-2 are the reference sensors. The larger features at 89 GHz are attributed to the RTM mismodeling clouds. There is no evidence of residual MSE or other calibration problems.

Fig. 11. GMI $T_A$ minus RTM $T_A$ anomaly plotted versus the orbit number and intra-orbit position. Same as Figure 10 except the GMI retrievals are used to compute the RTM $T_A$ rather than WindSat, TMI, and AMSR-2. Since there are GMI retrievals for all observations, there is complete coverage. There is no evidence of residual MSE or other calibration problems.
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Fig. 2. Same as figure 1 except the magnetic susceptibility error has been removed.
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\[ \\]
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