AN ON-ORBIT CALIBRATION PROCEDURE FOR SPACEBORNE MICROWAVE RADIOMETERS USING SPECIAL SPACECRAFT ATTITUDE MANEUVERS

by

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ABSTRACT

This dissertation revisits, develops, and documents methods that can be used to calibrate spaceborne microwave radiometers once in orbit. The on-orbit calibration methods discussed within this dissertation can provide accurate and early results by utilizing Calibration Attitude Maneuvers (CAM), which encompasses Deep Space Calibration (DSC) and a new use of the Second Stokes (SS) analysis that can provide early and much needed insight on the performance of the instrument. This dissertation describes pre-existing and new methods of using DSC maneuvers as well as a simplified use of the SS procedure. Over TRMM’s 17 years of operation it has provided invaluable data and has performed multiple CAMs over its lifetime. These maneuvers are analyzed to implement on-orbit calibration procedures that will be applied for future missions. In addition, this research focuses on the radiometric calibration of TMI that will be incorporated in the final processing (Archive/Legacy of the NASA TMI 1B11 brightness temperature data product). This is of importance since TMI’s 17-year sensor data record must be vetted of all known calibration errors so to provide the final stable data for science users, specifically, climatological data records.
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<th>Full Form</th>
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<tbody>
<tr>
<td>ADM</td>
<td>Antenna Deployment Mechanism</td>
</tr>
<tr>
<td>AMSR-E</td>
<td>Advanced Microwave Scanning Radiometer – Earth Observing System</td>
</tr>
<tr>
<td>C</td>
<td>Radiometric counts of the scene / calibration target</td>
</tr>
<tr>
<td>CAM</td>
<td>Calibration Attitude Maneuver</td>
</tr>
<tr>
<td>CERES</td>
<td>Clouds and Earth’s Radiant Energy System</td>
</tr>
<tr>
<td>CFRSL</td>
<td>Central Florida Remote Sensing Lab</td>
</tr>
<tr>
<td>CSR</td>
<td>Cold Sky Reflector</td>
</tr>
<tr>
<td>DMSP</td>
<td>Defense Meteorological Satellite Program</td>
</tr>
<tr>
<td>DPR</td>
<td>Dual-Frequency Precipitation Radar</td>
</tr>
<tr>
<td>DSC</td>
<td>Deep Space Calibration</td>
</tr>
<tr>
<td>DSCM</td>
<td>DSC Maneuver</td>
</tr>
<tr>
<td>DSV</td>
<td>Deep Space View</td>
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<tr>
<td>EIA</td>
<td>Earth Incidence Angle</td>
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<td>G</td>
<td>Gain</td>
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<tr>
<td>GPM</td>
<td>Global Precipitation Measurement</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>GMI</td>
<td>GPM Microwave Imager</td>
</tr>
<tr>
<td>GNA</td>
<td>Geodetic Nadir Angle</td>
</tr>
<tr>
<td>JAXA</td>
<td>Japanese Aerospace Exploration Agency</td>
</tr>
<tr>
<td>LHCP</td>
<td>Left Hand Circular Polarization</td>
</tr>
<tr>
<td>MF</td>
<td>Multi-frequency</td>
</tr>
<tr>
<td>MR</td>
<td>Main Reflector</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NEDT</td>
<td>Noise Equivalent Differential Temperature</td>
</tr>
<tr>
<td>NSA</td>
<td>Nadir Spin Angle</td>
</tr>
<tr>
<td>O</td>
<td>Offset</td>
</tr>
<tr>
<td>PR</td>
<td>Polarization Rotation</td>
</tr>
<tr>
<td>PRC</td>
<td>Post-Reconstruction Correction</td>
</tr>
<tr>
<td>PRT</td>
<td>Platinum Resistance Thermistors (Check this)</td>
</tr>
<tr>
<td>RHCP</td>
<td>Right Hand Circular Polarization</td>
</tr>
<tr>
<td>RSS</td>
<td>Remote Sensing Systems</td>
</tr>
<tr>
<td>RTF</td>
<td>Radiometric Transfer Function</td>
</tr>
</tbody>
</table>
SR  Spillover Region
SFOV  Spillover Field of View
SS  Second Stokes
SSM/I  Special Sensor Microwave / Imager
SSMI/S  Special Sensor Microwave Imager / Sounder
TA  Antenna Temperature
TB  Brightness Temperature
TMI  TRMM Microwave Imager
TPR  Total Power Radiometer
TRMM  Tropical Rainfall Measuring Mission
TSE  Time Since Eclipse
UCF  University of Central Florida
WL  Warm Load
XCAL  GPM Intersatellite Calibration Working Group
CHAPTER 1: INTRODUCTION

Passive microwave, infrared and visible remote sensor observations from space have become an essential part of National Aeronautics and Space Administration’s (NASA) and the National Oceanic and Atmospheric Administration’s (NOAA) Earth science satellite missions for providing operational weather prediction and observational environmental data for scientific research to understand the role of ocean, atmosphere, land and ice in the evolution of the climate change of the Earth. For the microwave portion of the electromagnetic spectrum, today most space-faring nations operate dozens of collaborative satellite missions, with passive microwave sensors that cover frequencies from 1.4 GHz to several 100’s of GHz. These instruments are used to provide the international science community a multi-decadal time series of environmental measurements of atmosphere, ocean and land upon which scientists will develop climate models to predict future changes in the Earth’s climate. From a remote sensing technology perspective, the overriding issue is how to remove instrumental effects (time variable calibration biases and gain drifts) from the weak climate signals to allow scientists to reliably forecast the impact of climate change on human habitability into the future for hundreds to thousands of years.

Thus, the ability to perform periodic, on-orbit, absolute, end-to-end radiometric calibrations is crucial to providing reliable microwave radiometer climate data records. One approach, which was exploited on the Tropical Rainfall Measuring Mission (TRMM), and other recent microwave radiometers, involves the use of the known blackbody properties of “deep
space” as a distributed target for the radiometer system to view. In concept, this involves maneuvering the satellite to point the antenna system to “deep space”, whereby the brightness temperature is homogeneous, isotropic and well known by Planck’s law. Of course nothing is that simple on practice, but this technique and all of its practical issues are examined in this dissertation.

Therefore, this dissertation is an examination of the radiometric calibration issues associated with satellite-borne passive microwave instruments for the purpose of developing improved on-orbit calibration techniques that can be used under a variety of operating scenarios with many instrument configurations. While the dissertation objective is broad, the details are sharply focused into a single case study of one particular instrument, namely the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), a passive microwave radiometer instrument that was launched into a near circular, non-sun-synchronous orbit nearly 17-years ago.

The Tropical Rainfall Measurement Mission is a joint effort between the United States space agency (NASA) and the Japan Aerospace Exploration Agency (JAXA). Launched on November 27, 1997, this 3-year mission was intended to study the statistics of rainfall from the tropical and subtropical regions of Earth [1]. The primary instruments for measuring rainfall are both microwave, namely: the passive TRMM Microwave Imager (TMI), and the active Precipitation Radar (PR). Fortunately, the longevity of the satellite and instruments was
excellent surviving for nearly 17 years, thus providing a legacy of microwave radiometric data, the analysis of which is the basis of this dissertation.

The ability to analyze the TMI radiometric calibration characteristics over this extended period is a tremendous advantage, and fortunately the instrument stability has been excellent, which strengthens the dissertation conclusions. Further, since the Central Florida Remote Sensing Lab (CFRSL) has been a member of the TRMM inter-satellite radiometric calibration working group (also known as XCAL), it was provided the opportunity to conduct special radiometric experiments during the final days of the satellite mission. This unprecedented opportunity to conduct specific radiometric calibration tests with this valuable satellite instrument, has provided unique data that are analyzed in this dissertation research.

1.1 Dissertation Objectives

The objectives of this research are:

- To develop an on-orbit radiometric calibration technique that utilizes special satellite Calibration Attitude Maneuvers, Deep Space Calibration and Nadir-Looking “Second Stokes” Maneuvers, to provide an end-to-end absolute calibration for microwave radiometers
  - To use the TRMM Microwave Imager past and recent satellite Calibration Attitude Maneuvers for a radiometric calibration case study
To consolidate previous TMI results and develop new interpretations that utilize DSC maneuvers

Validate and document methods for future applications

1.2 Dissertation Overview

This dissertation is organized in the following manner. Chapter two, provides an overview of the motivation of this work in addition to the TRMM & GPM missions. Chapter three describes the TMI instrument in great detail. Chapter four touches upon microwave radiometry and calibration of microwave radiometers. Chapter five discusses the past and proposed benefits of calibration attitude maneuvers for microwave radiometers. Chapter six discusses the reconstruction of the radiometric antenna temperature for TMI during the inertial-hold which is used for the analyses in Chapters 8 and 10. Chapter seven discusses how the Earth’s horizon can assist in estimating TMI’s beamwidth and boresight. Chapter eight discusses the along-scan bias of TMI during the deep space view. Chapter nine describes a new technique by whereby the instrument’s boresight aligns along the geodetic nadir referred to as Second Stokes analysis using a Nadir-Look. Chapter ten contains a detailed overview of the procedure for estimating the emissivity of TMI. Chapter eleven briefly describes how to consolidate the results. Chapter twelve concludes the research, provides an overview of the future work, influences that have risen from this research, and recommendations for other missions.
CHAPTER 2: MOTIVATION AND MISSIONS

While experimental microwave radiometers flew on satellites during the 1960’s, the first operational passive microwave radiometer was the Special Sensor, Microwave Imager (SSM/I) [2] developed under the US Air Forces’ military weather satellite “Defense Meteorological Support Program” (DMSP) Block 5D-2 satellites starting in 1978, which is successfully operating to present. The SSM/I is a seven-channel, four-frequency, linearly polarized passive microwave radiometer that measures surface/atmospheric microwave brightness temperatures (Tb) at 19.35, 22.235, 37.0 and 85.5 GHz. These four frequencies measure both horizontal and vertical polarizations, except the 22 GHz, which obtains the vertical polarization only. The SSM/I has been a very successful instrument, superseding the across-track and Dicke radiometer designs of previous systems. Its combination of constant-angle rotary-conical scanning and total power radiometer design, with external radiometric calibration, has become standard for passive microwave imagers, e.g. TRMM Microwave Imager and others that have followed.

2.1 Tropical Rainfall Measuring Mission

The Tropical Rainfall Measurement Mission was a joint effort between the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA). Launched on November 27, 1997, by JAXA on their H-IIA rocket from their Tanegashima Space Center in Japan, the primary instruments for measuring rainfall are the TRMM Microwave Imager, the Precipitation Radar, and the Visible and Infrared Radiometer System.
Other instruments include the Clouds and Earth’s Radiant Energy System and the Lightning Imaging System.

TRMM was first conceived in the 1980’s to capture the diurnal variability of rainfall [3] and to satisfy the statistical sampling requirements for a monthly average rain rate in 5°x5° in longitude and latitude box. In order to achieve this goal TRMM was placed at an altitude of 350 km with an inclination angle of 35°, allowing these boxes in the tropics to be sampled about twice daily at different hours of the day. The advantage of this orbit is that it has a rapid revisit time, providing [4] extensive coverage in the tropics, thus allowing each location to be covered at a different local time each day, cycling through a 24-hour period in approximately 46 days. Because of its low altitude, the satellite experienced significant atmospheric drag, which required frequent orbit “delta-velocity" burns of an on-board propulsion system to maintain this orbital altitude.

Since the TRMM spacecraft flies in a non-sun-synchronous orbit, it has a sun-lighted portion (~60 min) and a night portion (eclipse~ 33 min). The time of eclipse (start-time and duration) changes daily on approximately a 46-day cycle, which is the TRMM orbit precession cycle. TRMM was thermally designed with heat-dissipating radiators on the +Y side of the spacecraft requiring them to be pointing away from the sun at all times. Thus, because of the non-sun-synchronous orbit, every 23 days the sun lies directly overhead in the orbit plane, and as a result, the spacecraft is required to perform a change in its direction of flight orientation.
(yaw flip = 180°), which keeps the sun on the –Y side of the spacecraft. Thus TRMM flies either with the +X-axis forward in the flight direction (0° yaw) or with the –X-axis forward (180° yaw).

During this orbit precession cycle, the angle of the sun with respect to the TRMM orbital plane, known as the solar beta angle, changes daily, and after 46.7 days, it repeats as depicted in Figure 2.1. Note that a negative solar beta angle corresponds to the “yaw flip” maneuvers where the TRMM flies backwards at a yaw of 180°. Also the angle of the “line-of-sight" between the Earth and sun relative to the equatorial plane of the Earth varies seasonally (period 365.25 days). Note that the TRMM orbit precession period and the yearly sun cycle are not in an integer ratio; therefore there is not an exact beta angle repeat cycle even after many years.

Originally planned as a 3-year mission, the success of the TRMM has exceeded expectations and as a result in 2001, NASA extended the mission by raising the satellite altitude to 402 km to significantly reduce atmospheric drag and thereby significantly prolong the TRMM life. Again in 2004, the mission was at risk of early termination by NASA because of concerns of safe reentry to minimize the hazard of orbital debris following reentry. Fortunately, TRMM was saved because of a very strong endorsement of the science community [5, 6], including the report from the National Academy of Sciences Assessment of the Benefits of Extending the Tropical Rainfall Measuring Mission: A Perspective from the Research and Operations Communities, Interim Report (NRC, 2004) [7]. As a result, NASA agreed with this
recommendation, and TRMM was extended” until it ran out of fuel and was turned off on April 15, 2015 just before reentering the atmosphere in June 2015.

Figure 2.1: TRMM solar beta angle for four years (in 2005-2007) (Source: [4]).
2.2 *Global Precipitation Measurement Mission*

The Global Precipitation Measuring (GPM) mission is the follow-on mission to TRMM, and as such is included in this dissertation as relevant material. GPM was initiated between NASA and the Japanese Aerospace Exploration Agency (JAXA) to measure precipitation globally using microwave radiometers and radar. The GPM mission is an international network of satellites, known as the GPM constellation, that provides the next-generation global observations of rain and snow with science objectives stated as 1) Advancing precipitation measurements in space 2) Improving knowledge of precipitation systems, water-cycle variability and freshwater availability 3) Improving climate modeling and prediction 4) Improving Weather Forecasting and 4-D climate reanalysis and 5) Improving hydrological modeling and prediction [8].

Launched on February 27, 2014, the GPM Microwave Imager (GMI) main role within the mission is to act as a brightness temperature calibration standard for the other constellation members. Through inter-satellite radiometric calibration (XCAL) with the GMI transfer standard, GPM will improve global spaceborne Earth scene brightness radiance observations by making them consistent with one another. The first step in gaining that consistency is to adjust the radiometric calibrations of the radiometers. The next step is to generate algorithms for all the radiometers using physical insights derived from the radar [9].

Unlike a polar orbiting satellite, GPM is in a non-sun-synchronous orbit (orbit inclination of 65°), allowing for GMI to view the same scenes, with rapid revisit time, over the Earth and the constellation members; hence, allowing for uniformly calibrated precipitation
measurements around the globe every 2-4 hours for scientific research and societal applications. An illustration of the GPM Constellation is shown in Figure 2.2.

Figure 2.2: A cartoon of the GPM Core observatory Microwave Imager's swath intersecting the other GPM constellation members (Source: http://pmm.nasa.gov/GPM/constellation-partners)

The GPM core observatory contains two instruments, the GMI and the Dual-Frequency Precipitation Radar (DPR), both in similar fashion to TRMM, whereby each offers different information of the illuminated scene. DPR provides three-dimensional distributions of precipitation and GMI retrieves multiple geophysical retrievals including light to heavy rain at
greater swath, an example of the swath geometry is shown in Figure 2.3. For a detailed discussion on the GMI instrument refer to Appendix B.1.

Figure 2.3: The swath characteristics of the GPM Core observatory. GMI (blue beam) and DPR (Yellow & Pink) beams show their respective swath.
CHAPTER 3: TMI INSTRUMENT DESCRIPTION

The TRMM Microwave Imager (TMI) is a nine-channel total power microwave radiometer which builds on the heritage of the Special Sensor Microwave Imager (SSM/I). Refer to Figure 3.1 for comparison of engineering models of the two instruments, which have slightly different designs. The most significant change between the two designs is the addition of the 10.65 GHz radiometer channel (dual-polarized receiver and feed horn). Also to accommodate the TMI two-horn feed cluster, there is a larger cold sky mirror. Finally, there is a shift of the center frequency for the water vapor line channel, from 22.235 GHz to 21.3 GHz in order to improve the measurement sensitivity in the tropical orbit of TRMM. Table 3.1 describes TMI parameters (post-boost to the 402 km altitude).

Table 3.1 TMI Instrument Parameters

<table>
<thead>
<tr>
<th>Center Frequency (GHz)</th>
<th>10.65</th>
<th>19.35</th>
<th>21.30</th>
<th>37.00</th>
<th>85.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polarization</td>
<td>V / H</td>
<td>V / H</td>
<td>V</td>
<td>V / H</td>
<td>V / H</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
<td>100</td>
<td>500</td>
<td>200</td>
<td>2000</td>
<td>3000</td>
</tr>
<tr>
<td>Sensitivity (K0)</td>
<td>0.63/0.54</td>
<td>0.50/0.47</td>
<td>0.71</td>
<td>0.36/0.31</td>
<td>0.52/0.93</td>
</tr>
<tr>
<td>IFOV (km x km)</td>
<td>73x43</td>
<td>35x21</td>
<td>274x21</td>
<td>19x10</td>
<td>8x6</td>
</tr>
<tr>
<td>Earth Incidence Angle (deg)</td>
<td>53.4</td>
<td>53.4</td>
<td>53.4</td>
<td>53.4</td>
<td>53.4</td>
</tr>
</tbody>
</table>

1 Original specifications [1] adjusted for TRMM mean altitude adjustment from 350 km to 402.5 km in August of 2001
As TMI scans at 31.6 rpm, data is collected from an azimuth arc of 130° (±65° about TRMM’s ground track), resulting in a 759-km swath (pre-boost) as shown in Figure 3.2. The 10.65 GHz and multi-frequency (MF) (19.35 – 85.5GHz) feed horn illuminates TMI’s main reflector (MR), an offset parabolic antenna, as it scans with a nadir angle of 49°, as shown Figure 3.3. As the entire radiometer rotates, two stationary external calibration targets obscure
the feed horns illumination of the MR, i.e., the warm load (WL) and cold sky reflector (CSR). The WL and CSR are illuminated by the feed horns once per scan providing TMI’s radiometric counts-to-TB transfer function. A 2D CAD illustration of TMI is shown in Figure 3.4 with the CSR and WL in plain view. The low frequency channels, 10.65 – 37.00 GHz, and the 85.5 GHz channels are sampled 104 and 208 times per scan, respectively. Figure 3.5 depicts when the feed is turned on for the MF and X-Band feed along with the scan position of when the cold sky mirror and warm load are illuminated.

TRMM was thermally designed with heat-dissipating radiators on the +Y side of the spacecraft requiring them to be pointing away from the sun so not to damage the spacecraft. Due to this requirement and being in a precessing orbit, every 23 days the spacecraft is required to perform a “yaw flip” change in its orientation, Yaw of 180°, to keep the sun on the -Y side of the spacecraft. Thus TRMM flies either with the +X-axis forward in the flight direction (0° yaw) or with the -X-axis forward (180° yaw) depending upon the polarity of the solar beta angle. Further, since TRMM was designed to never have the sun the +Y side, the TMI CSR points to this direction and can be better visualized referring to Figure 3.4 and Figure 3.5. This is of importance for calibration purposes since one does not want the sun vector to be parallel to the CSR LOS, and thereby to contaminate the cold sky view of the cosmic microwave background (CMB).
Figure 3.2: Schematic view of the scan geometries of the three TRMM primary rainfall sensors: TMI, PR, and VIRS
(Source: [1]).
Figure 3.3: TMI main reflector projecting the 10.65 GHz feed horn (Source: [10])
Figure 3.4: Isometric view of the TMI instrument with feed horns, calibration targets, receivers, and main reflector (Source: [10])
TMI and JAXA’s Precipitation Radar (PR) complement each other since each offers different information of the illuminated scene, providing three-dimensional distributions of precipitation and heating in the Tropics. TMI’s swath is larger than PR’s swath by over 500 km; hence, TMI retrieves a larger scene than PR and by training against TMI’s instantaneously
collocated PR data TMI can retrieve outside of PR’s swath. Refer back to Figure 3.2 of an illustration of the instruments swaths.

### 3.1 TMI On-orbit Anomaly

Shortly after the TRMM satellite was launched in November 1997, during the initial on-orbit instrument checkout, members of the TRMM science team discovered an anomaly in TMI brightness temperature measurements. It was first thought that the cause was radio frequency interference from TRMM’s Precipitation Radar; but this was dismissed during the September 1998 deep space calibration maneuver where by PR was turned on/off while TMI’s main beam was viewing space. No change in the counts was recorded during this radar transmit toggling; hence, this theory was dismissed. It was later determined [11] that TMI’s main reflector was emissive. Remote Sensing Systems (RSS) used the 1998 DSC maneuvers as well as inter-satellite calibration between SSMI and TMI to show a significantly higher than expected TMI brightness temperature and proposed emissivity values of the reflector.

Later Gopalan [4] and [12], discovered an orbit dependent, time-varying radiometric calibration error for TMI that was caused by the slightly emissive main reflector antenna. He demonstrated that correlating the inter-satellite calibration between WindSat and TMI to the local time of TMI observations reflected a systematic temporal dependence as a function of the thermal environment of TMI.

Following the dissertation of Gopalan, Biswas et al. [13], developed an empirical correction for this time-varying bias, which was implemented by NASA’s Precipitation
Processing System (PPS) in the TMI 1B11 Version 7 data set. The correction is applied using a biased $T_B$ term look-up table as a function of the TRMM’s time since eclipse (TSE) and elevation angle of the sun vector with respect to the TRMM’s orbital plane (solar beta angle). Even though reasons for the emissive reflector are still speculative in nature, the fact is that a bias in TMI’s $T_B$’s cannot be ignored. Thus, one focus of this dissertation research is to provide an independent estimate of the emissivity values previously determined by RSS by utilizing the full deep space view of the TMI DSC maneuvers.
CHAPTER 4: MICROWAVE RADIOMETRY AND
INSTRUMENT CALIBRATION

Microwave radiometric applications were first developed in the 1930s and 1940s for ground based measurements of the electromagnetic energy of extraterrestrial origin [14] (page 13) and the late 1960s for satellite-based Earth observing microwave radiometers. Essentially, the main applications for microwave radiometry are 1) astronomical studies, 2) military applications and 3) environmental monitoring. For all these applications, the radiometer is measuring the blackbody emitted electromagnetic radiation of an object whether it is Earth’s surface, atmosphere, or a galaxy. Hence, a radiometer is simply a highly sensitive receiver capable of measuring low levels of microwave radiation. This being said, relating the receiver output to a useful metric, the absolute antenna brightness temperature, at the radiometer input is a process referred to as radiometric calibration and is necessary for such a crucial instrument.

4.1 Microwave Radiometry

All matter at a finite absolute temperature radiates/emits electromagnetic energy which can be quantified using instruments known as radiometers. According to Planck’s Blackbody Radiation Law, the spectral brightness intensity, $I_f$, is related its physical temperature as,

$$I_f = \frac{2hf^3}{e^{hf/ckT} - 1}$$  \hspace{1cm} (4.1)
where $I_f$ is in Wm$^2$/sr·Hz, $h$ is Planck’s constant (joules·s), $f$ is frequency (Hz), $k$ is Boltzmann’s constant (joule/K), $c$ is the velocity of light in a vacuum. According to Rayleigh-Jeans Law approximation to Planck’s Law, which holds true within the microwave region, i.e., $f / T < 3.9 \times 10^8$ Hz·K$^{-1}$, expression (4.1) simplifies to

$$I_f \approx \frac{2kT}{\lambda^2} \quad (4.2)$$

where $\lambda$ is wavelength. If a blackbody is being measured by an antenna that is characterized by a radiation pattern then the brightness intensity is related to the total amount of power received by the antenna as

$$P = A_r \int_{f_1}^{f_2} \int_\Omega I_f F(\theta, \phi) d\Omega df \quad (4.3)$$

where $A_r$ is the effective aperture, $F(\theta, \phi)$ is the antenna radiation pattern, $d\Omega$ is the differential solid angle, and $f_1$ & $f_2$ are the bandwidth limits of the receiver. Using Eqs. (4.2) and (4.3) the relationship between power measured by the antenna and the brightness intensity of a blackbody becomes directly linear,

$$P = kTB \quad (4.4)$$

where $T$ is the physical temperature of the blackbody and $B$ is the receiver noise bandwidth.

Since most materials are not perfect blackbodies, the physical temperature $T$ becomes brightness temperature $T_B$, which is defined as the product of the physical temperature of the object and the greybody emissivity, $e$, where $T_B = T \cdot e$. 

22
\[ P = kT_B B \]  

(4.5)

The lossless antenna performs a weighted sum of the incident greybody radiation, \( T_B(\theta, \phi) \), according to its radiation (power) pattern, \( F(\theta, \phi) \), and the total noise at the antenna output is defined as the antenna temperature, \( T'_A \):

\[
T'_A = \frac{\iint_{4\pi sr} T_B(\theta, \phi) F(\theta, \phi) d\Omega}{\iint_{4\pi sr} F(\theta, \phi) d\Omega}
\]  

(4.6)

Refer to Figure 4.1 for an illustration of Eq. (4.6).

**Figure 4.1:** Example of the \( T_B \) constituents that are collected by an antenna pattern (Source [14]).
4.2 Total Power Radiometers

A total power radiometer (TPR), upon which all other radiometer types are based, is considered the reference standard because of its simple design. Essentially it is a receiver that measures the antenna collected blackbody emission from an object or scene, where its digitized output is directly proportional to the radiation that the instrument observes, i.e., radiometric antenna temperature \( T_A \) that is incident on the feed horn. Figure 4.2 depicts a noise model block diagram of a TPR where the receiver noise temperature, \( T_N \), which is the total noise represents the cascaded thermal noise for the entire receiver chain, which is moved to the receiver front-end. For purposes of this dissertation Figure 4.2 properly represents the TMI receiver and it should be noted that \( T_N \) is a function of the physical temperature of the radiometer components; hence, as the receiver physical temperature increases, in a similar manner the receiver noise temperature increases. Refer to Figure 7-15 of [14] for a more comprehensive figure of a TPR.

Figure 4.2: Block Diagram of a Total Power Radiometer obtained from [15]
The output noise power of the system (input to the square-law power detector) in Figure 4.2, using Eq. (4.5), can be rewritten as

\[ P = G k (T_A + T_N) B \]

where \( G \) is the gain of the system. Unfortunately, one of the limitations of this TPR radiometer design is that both \( G \) and \( B \) must be known before a radiometric transfer function can be established to relate the received power to the input noise temperature of the system. Moreover, if the characteristics of the TPR change after calibration then the determined relationship is invalid. This is why there are many other radiometer designs that build upon this incorporating radiometric calibration techniques during instrument operation.

### 4.3 Two-Point Calibration

The simple design of the TPR does not capture the physical temperature dependent gain changes of the instrument; hence, on-orbit calibration of the instrument is necessary. Most contemporary satellite radiometers are two-point total power radiometers that are externally calibrated. In this technique, the radiometer feed horns sequentially view a blackbody target (warm load microwave absorber) and a Cold Sky Reflector (CSR) that views space on a per scan basis.

As the name implies, this two-point process calibrates the linear instrument using two known brightness temperature points that covers the operational range of instrument (typically, 100-300 Kelvin). Figure 4.3 illustrates this process, whereby the CSR (cold point) views deep space, a known non-polarized \( T_B \) scene of \(~2.73\) K and the warm load (hot point) is a microwave
absorber that acts as a blackbody target with associated temperature sensors, which allows one to obtain the linear transfer function of the radiometric system, i.e., gain and offset. This externally calibrated TPR design is very practical since it the entire radiometric path from the feed horn through the detected output voltage; however, it does not provide an end-to-end calibration of the Earth scene through the main reflector. Normally if the reflector is highly reflective, this is not an issue; however with graphite epoxy reflectors with vacuum deposited aluminum (VDA) coatings, this has been an issue as will be discussed later.

Figure 4.3: Two-point calibration (transfer function) of an externally calibrated radiometer using a CSR (space view) and a heated blackbody absorber load.
Thus the radiometric transfer function is defined as:

\[ I_{\text{scene}} = T_{A,\text{scene}} \cdot G + O \] (4.8)

where \( I_{\text{scene}} \) is the radiometer output (digital counts), \( G \) and \( O \) are gain and offset (mathematical slope and y-intercept) between the two calibration points with units counts/Kelvin and counts, respectively. Using Eq. (4.8) and solving for \( T_{A,\text{scene}} \):

\[ T_{A,\text{scene}} = \frac{I_{\text{scene}} - O}{G} \] (4.9)

Equation (4.9) is what is used when reconstruction the full DSV.
CHAPTER 5: UTILIZATION OF DEEP SPACE CALIBRATION

To the knowledge of the author, the first use of the known cosmic microwave background for a mobile microwave radiometer was performed for the Electrically Scanned Microwave Radiometer (ESMR) and Airborne Multifrequency Microwave Radiometer on a NASA CV-990 in 1976 [16]. This maneuver was recommended by Dr. Thomas Wilheit during his investigation of the effect of EIA on these instruments and realized that a cold calibration point could be obtained during operation of the instrument. This maneuver known as a wing-over oriented the aircraft just over 60° in yaw so that the instrument could view the Earth’s horizon. Refer to Appendix D.1 for excerpts and a more colorful description of how the maneuver came about. In addition, Appendix A contains short discussions on deep space calibration of other spaceborne microwave radiometers.

5.1 Past benefits of TMI DSC

In 1998, the TRMM project performed a series of satellite maneuvers, which was referred to as the TRMM Calibration Attitude Maneuvers (CAM) [17], for calibration purposes of the Clouds and the Earth’s Radiant Energy System (CERES). While these maneuvers were not originally intended for TMI on-orbit calibration, they subsequently became quite useful for this purpose [15]. Seven non-consecutive maneuvers were conducted over several days, with each consisting of one orbit of nominal Earth pointing separated by a single (orbit) CAM. The first were performed on January 7-8, 1998 (maneuvers 1-6) and September 2, 1998 (maneuver 7). In addition, near the end of TRMM life, an additional set of CAMs were performed to duplicate
those conducted at the beginning of the TRMM mission, specifically: on July 22, 2014, 3 more CAMs (8-10), on February 26-27, 2015, 6 more CAMs (11-16), and on March 25-26, 2015, 4 more CAMs (17-20). These deep space calibration maneuvers are summarized in Table 5.1, but it should be noted that this dissertation only discusses results from maneuvers 1-10.

Table 5.1 TMI DSC Maneuver Summarization.

<table>
<thead>
<tr>
<th>DSCM Set</th>
<th>DSCM #</th>
<th>Date</th>
<th>Orbit #</th>
<th>Yaw (°)</th>
<th>Altitude (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 – 6</td>
<td>Jan 7, 1998</td>
<td>641-646, 657-662</td>
<td>180</td>
<td>349</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>Sept 2, 1998</td>
<td>4393-4394</td>
<td>0</td>
<td>350</td>
</tr>
<tr>
<td>3</td>
<td>8-10</td>
<td>July 22, 2014</td>
<td>95023-95028</td>
<td>0</td>
<td>400</td>
</tr>
<tr>
<td>4</td>
<td>11-16</td>
<td>Feb 26, 2015</td>
<td>98452-98457, 98468-98473</td>
<td>0</td>
<td>350</td>
</tr>
<tr>
<td>5</td>
<td>17-20</td>
<td>Mar 25-26, 2015</td>
<td>98879-98883, 98893-98898</td>
<td>90</td>
<td>341</td>
</tr>
</tbody>
</table>

Essentially, these deep space calibration maneuvers (DSCM) put the TRMM observatory into inertial hold, which allowed the spacecraft to perform a 360° pitch rotation over one orbit period relative to the normal geodetic Earth pointing mode, refer to Figure 5.1, which shows the spacecraft at yaw= 180°. From the starting point of the inertial hold at point-(a), the conical scanning main beam slowly decreased in Earth incidence angle and passed through nadir and then continued until at point-(b) it transitioned from the surface of the Earth and viewed a non-polarized homogenous scene (deep space) of ~ 2.7 K. However, while the main beam
progressively scanned off the Earth, the cold sky reflector (CSR), which viewed ~ 140° clockwise aft of the forward direction (see Figure 3.5), moved closer to the Earth. Eventually by point-(c) there was a strong interception of the Earth radiance in the cold sky beam, which invalidated the two-point radiometric calibration. Thus there was only a limited period of time (between point-(b) and –(c)) whereby both the MR and the CSR had usable radiances of deep space views (16% [18]) to convert from digital counts to calibrated antenna temperature, \( T_A \), which was required for analysis. Therefore, under this dissertation, an alternative procedure was developed (as described in Chapter 6) to reconstruct the TMI \( T_A \) during the entire CAM orbit.

Figure 5.1: Orientation of the TRMM observatory, Yaw 180°, for the CAM. The spacecraft enters inertial hold at (a) and performs a 360° rotation about geodetic nadir and exits inertial hold at (d).
During a conical scan for TMI, the mid-scan position for the low-resolution channel is azimuth scan position 52 (looking aft for yaw=180° opposite the flight direction); and the $T_A$ for this azimuth is used for the figures that follow. Figure 5.2 and Figure 5.3 presents results for orbit 641 and 642 of the reconstructed $T_A$ and EIA time series for DSCM 1 for the 10 V-Pol channel. For these figures, the x-axis is time expressed as relative scan#; and for scan 0 to ~2200, TMI is in the nominal Earth pointing mode (EIA = 53°); and after this point, the spacecraft enters the CAM inertial hold. While in the normal mode, the TMI views both ocean (radiometrically cold scene of 160-180 K) and land (radiometrically hot ~ 300 K). After scan 2200 TMI, the TRMM pitch decreases which causes the TMI boresight to sweep through an EIA of zero at scan ~2550 and then starts approaching the limb of the Earth, scan ~3120. Between scans 3120-4860, TMI MR views deep space (DSV), which at this frequency is homogeneous and isotropic brightness temperature equal to 2.7 K. Figure 5.4 is the expanded portion of Figure 5.2 but to emphasize on the DSV portion of the DSCM. This DSV is a result of the reconstruction Methods mentioned in Chapter 6 and what will be used in the rest of this dissertation. Also note that the DSV value is greater than the expected 2.7 K which is not an error on the reconstruction methods but Earth’s radiation entering the spillover regions; more detail on this is mentioned in Chapter 10.
Figure 5.2: $T_A$ time series for 10 V-Pol during DSCM 1 (scan position 52 corresponding to viewing along-track).

Reconstruction was performed by Method 1.

Figure 5.3: Time series of Earth Incidence Angles during DSCM 1 for scan position 52 corresponding to viewing along-track. Figure has similar x-axis as Figure 5.2.
5.2 Proposed Benefits of DSC

This dissertation documents the calibration of TMI using previous methods as mentioned in Appendix A, to determine along-scan bias, TMI main reflector emissivity, and antenna beamwidth. In addition to this, work and methods that are new and developed within this dissertation are:

1) Reconstruction of the $T_A$ for the full deep space view (DSV) during the DSCM, allowing use of the full time series of the TMI MR as it is viewing space. This is necessary since, as will be shown in Chapter 10, spillover affects the DSV and must be removed before calculating the MR emissivity.
2) It is shown that the boresight angles of the MR & CSR can be obtained using the sharp transition of the limb of the Earth.

3) Use the Second Stokes Parameter (Q), when the MR boresight points along the geodetic nadir as a relative calibration between orthogonal channels.

To go further in detail on the second stokes parameter the four Stokes, initially introduced by Sir George Stokes [19], are defined from [20] as:

\[
\begin{align*}
I &= \frac{\langle |E_v|^2 \rangle + \langle |E_H|^2 \rangle}{\eta} = S_v + S_H, \\
Q &= \frac{\langle |E_v|^2 \rangle - \langle |E_H|^2 \rangle}{\eta} = S_v - S_H, \\
U &= \frac{2 \text{Re}\langle E_x E_y^* \rangle}{\eta} = S_{+45} - S_{-45}, \\
V &= \frac{2 \text{Im}\langle E_x E_y^* \rangle}{\eta} = S_{lc} - S_{rc},
\end{align*}
\]

where the worth noting variables are the electric field E and the Second Stokes parameter, Q. Essentially Q, as defined in terms of brightness temperature is,

\[
Q = T_{B,V-Pol} - T_{B,H-Pol}
\]

If the instruments boresight is parallel to the geodetic vector then the Earth incidence angle (EIA) becomes 0°, refer to Figure 5.5 for an illustration for GPM of this maneuver. During this “Nadir Look” the orthogonal channels differences should theoretically be zero Kelvin for any surface whether it be land, a low polarized scene, or ocean, a highly reflective and polarized scene, assuming a specular surface is perfectly normal to the instruments LOS. For example of the dependence of the sea surface on the specular Fresnel reflectivity relationship refer to
Figure 5.6 on the $T_B$ curves as an example. Note that at an EIA of 0°, $T_{B,V}$ is equal to $T_{B,H}$ and any differences in this value can be attributed to a number of calibration issues.

Figure 5.5: Illustration of GPM pitching down allowing GMI boresight to align with the geodetic vector.
Figure 5.6: Theoretical brightness temperature of a specular sea surface at four microwave frequencies (Source: Figure 18-2 from [14]).
Finally, to give the reader a better understanding of the portions of the TRMM inertial hold that are used for this dissertation, these are illustrated using DSCM1 (TMI orbits 641 and 642) in Figure 5.7, where by the geolocation of the Earth intersection of the main refector line of sight (LOS) and the sub-satellite point (SSP) are represented by the colored locations (Radiometric Counts of 10.65 V-pol) and the black line, respectively. This figure subdivides the inertial hold into 3 parts:

1. Deep Space View:

   Portion of the orbit, where the orbit track (trajectory of subsatellite point) does not have the MR LOS intersecting the Earth, is the time period that the TMI MR is viewing space. This region will be used to calculate the along-scan bias of the instrument and to estimate the emissivity of the TMI main reflector.

2. SS Analysis:

   Scans within the green box are the duration that the mid-scan position is sweeping through nadir.

3. Beamwidth and Nadir Pointing

   The portion of the orbit identified by the purple arrows is where the MR LOS veers off-of and on-to the limb of the Earth. This portion is used to calculate the antenna beamwidth and relative boresight pointing of the various TMI channels.
It should be reiterated that this is just one example of a single maneuver and this research uses multiple maneuvers whereby many instances can be utilized. These methods that have just been discussed are covered in more detail in Chapters 6 through 10 and recommendations on how these analyzes are better suited for other instruments/missions are discussed in Section 12.3.

Figure 5.7: Using Orbits 641 and 642 (CAM 1) as an example to describe portions that will be used within this research.
Finally, for nomenclature purposes, the author wishes to clarify that a CAM is the general term used for a maneuver for any calibration purpose. With that said, the TMI inertial hold maneuver (CAM) encompasses both the Deep Space Calibration and Nadir-Look and within this dissertation the author may interchange the DSCM and Nadir-Look for CAM, for example, DSCM 1 and Nadir-Look 1 occurs during CAM 1.
CHAPTER 6: RECONSTRUCTION OF THE RADIOMETRIC ANTENNA TEMPERATURE

Unlike the DSC maneuvers of WindSat whereby the cold calibration point, obtained by the CSR, continues to view space the TMI CSR for the majority of the MR DSV illuminates the Earth. With the CSR observing Earth, the radiometric transfer function (RTF), Eq. (4.9), is invalidated. Using Analytical Graphics Inc’s (AGI) Systems Tool Kit (STK) software package [21], Figure 6.1 was constructed. This figure is an illustration of TMI’s MR (red) & CSR (green) beam for nominal operation and during DSV, panel (a) & (b), respectively. Notice in (a) that the red beam points down towards Earth and the green beam is illuminating cold space while in (b) the opposite can be said. Figure 6.2 complements this figure by showing the time series of the MR & CSR EIA during DSCM 1 where by a majority of the DSV, black line not present, the CSR (blue curve) is corrupted by intersecting the Earth. It is during this time the CSR counts are unknown and the RTF is not obtainable so to convert the MR counts to $T_A$. Hence, in order to obtain a longer DSV time series, to better evaluate the MR emissivity and along-scan biases, reconstruction of the $T_A$ is necessary.

Since the normal two-point radiometric calibration is not possible during most of the DSV, two alternate approaches have been developed [18] that permit TMI counts to estimate $T_A$ from only a single warm calibration point and a few ancillary physical temperature measurements. One approach establishes a complex correlation coefficient between the radiometer gain, offset and receiver physical temperature. This robust relationship is
established during the normal (geodetic) pointing mode as a function of the receiver physical temperature, which is cyclical over a single orbit and has a seasonal mean temperature pattern. During the DSC maneuver, the warm load count, physical temperature measurements, and other available instrument temperatures are used to estimate the receiver linear transfer function and thereby reconstruct the $T_A$. The second approach reconstructs the cold sky counts based on multiple linear regression based on a combination of ancillary measurements that are valid during the DSV. It should be noted that when referencing any form of $T_A$ within this dissertation it is the same as $T_{A,\text{out}}$ as is defined in [20].

Figure 6.1: Illustration of TMI during Earth Pointing Mode (a) and DSC Mode (b). The MR & CSR beams are the red & green contours. Images are created using AGI’s STK software package.
Figure 6.2: This associates the EIA of the MR (scan position 52) and estimated guess CSR LOS for DSCM 1, black & blue curves, respectively.

6.1 Reconstruction of the RTF

6.1.1 Method 1: Reconstruction of Gain and Offset

As mentioned, during most of the DSV the CSR beam is partially illuminating Earth and the normal radiometer calibration process is corrupted. However, assuming that the relationships between the RTF Gain and Offset \(G\) & \(O\) from Eq. (4.8) are linear, it is possible to reconstruct \(T_A\) from antenna counts.
Figure 6.3 illustrates the approach for obtaining the linear relationship between $G$ & $O$ for 10 GHz V-Pol. The upper left panel shows a normalized gain and offset time series for 3 nominal (Earth pointing) TMI orbits. The oscillation of the gain and offset are the result of cyclical orbital physical temperature variations of the TMI receiver. Note that the two curves exhibit an offset (phase difference) of 315 scans (~600 seconds). The upper right panel shows a scatter diagram of $G$ & $O$ for multiple TMI orbits with the hysteresis present due to their phase difference. The lower left shows corresponding results after applying a 315 scan phase adjustment to align the two time series. Also, note the scatter plot (lower right panel) with the hysteresis collapsed, which allows a simple linear fit to be obtained.
After applying the phase shift of 315 scans, the linear relationship between the Offset and Gain is:

\[ O = m \cdot G + b \]  \hspace{1cm} (6.1) 

where \( m \) & \( b \) are the slope and y-intercept, respectively. These two parameters along with the phase shift applied are referred to as the reconstruction coefficients. An analysis of a large
number of orbits reveals that these coefficients change with the spacecraft thermal environment over time.

Unfortunately, during a DSC maneuver the thermal changes are magnified (compared to the nominal attitude of TRMM); therefore, the phase shift between the $O$ & $G$ signals is determined empirically through cross-correlation. The length of the signal window to use for the cross-correlation is based on the metric of orbits; hence, six different lengths were chosen: 1, 3, 5, 7, 11, and 15 orbits, referred to as a window size. Refer to Figure 6.4 for an example of a time series of the reconstruction coefficients for TMI orbits 639 to 663 at 10 V-Pol with a Window Size of 7 orbits. It should be noted that the coefficients are determined only while the calibration process is valid, i.e., CSR views cold space which includes TRMM’s normal orientation. For completeness of the coefficients for 10V, refer to Figure 6.5 which is similar to Figure 6.4 but depicting all window sizes. Note that the two lower panels of Figure 6.4 and Figure 6.5 represent the instantaneous (per scan) reconstruction coefficients (slope & Y-Intercept) that there were depicted in the Offset vs Gain plot in Figure 6.3.
Figure 6.4: Reconstruction characteristics and coefficients for 10 V-Pol with a window size of 7 orbits. The blue curve is the assigned value for the full range of scans within a defined orbit and the red curve is the blue curve with a moving average of size 5001 scans.
When the feed horn passes beneath the warm load and the CSR this is referred to as hot load counts \((C_h)\) and cold sky counts \((C_c)\), respectively. Hence, the \(C_h\) can be written as:

\[
C_h = G \cdot T_H + O
\]  

(6.2)

where \(T_H\) is the physical temperature that the PRTs measure at the base of the WL, and \(G\) & \(O\) is the gain and offset (mathematical slope & y-intercept) between the two calibration points with units counts/Kelvin and counts, respectively. The linear radiometric transfer function is valid provided that nothing obscures the feed horn’s view of the two targets.
Once the linear relationship between $G$ & $O$ is obtained using Eqs. (6.1) & (6.2), the reconstructed (estimated) gain ($G_{\text{Recon}}$) & offset ($O_{\text{Recon}}$) are:

$$G_{\text{Recon}} = \frac{C_H - b}{T_H + m} \quad (6.3)$$

$$O_{\text{Recon}} = \frac{m \cdot C_H + b \cdot T_H}{T_H + m} \quad (6.4)$$

Once the $G_{\text{Recon}}$ & $O_{\text{Recon}}$ are determined, the phase difference is reapplied to put them to their initial phase and $T_A$ is calculated using the MR counts ($C_{\text{MR}}$).

The $T_A$ reconstruction using Method-1 will have residuals due to 1) imperfections in the simple linear relationship between $G$ & $O$ given by the reconstruction coefficients and 2) failure of the applied phase difference to align the $G$ & $O$ signals. Due to these shortcomings, a Post-Reconstruction Correction (PRC) was applied to mitigate the effects of these residuals. Recognizing that residuals are a function of the thermal environment and satellite orientation relative to the sun vector, it was decided that the proper PRC should be a function of solar angles, i.e., solar azimuth and elevation within the ECI coordinates. The PRC is essentially a lookup table of the residuals between the true and reconstructed gain and offset as a function of azimuth and elevation. The table is created using residuals during valid calibrated scans, i.e., non-DSV portions of the orbit. An example of the correction is shown in Figure 6.6 and a flow chart of this method is depicted in Figure 6.7. Section 6.2 discusses the validation of this technique.
Figure 6.6: Post-Reconstruction Correction that is applied to the reconstructed Gain and Offset for 10 V-Pol.

Channel: 10 V-Pol
TMI Orbits used for creating Table: 639-665
Window Size: 11 scans

[Earth centered inertial vehicle velocity local horizontal frame. This frame has the Z axis aligned with the anti-radial direction and the X axis constrained toward the inertial velocity direction. This frame is not restricted to Earth oriented vehicles despite its name.]
Method 2: Simulating Cold Sky Counts

Method-2 is a more recent, simpler and independent method of obtaining $T_A$ during the DSC calibration. Essentially, it is a multiple linear regression using a combination of TMI temperature sensors that are valid during the DSV but are trained using nominal and non-DSV scans. It reconstructs the cold sky reflector counts as a function of the $T_H$, $C_H$, Antenna Deployment Mechanism Physical Temperature Sensor (ADM), and Top of Radiator Physical
Temperature Sensor and can be expressed as:

\[ CSC = c_1 + c_2 \cdot C_H + c_3 \cdot T_H + c_4 \cdot T_{ADM} + c_5 \cdot T_{Rad} \]  

(6.5)

where \( c_{1-5} \) are the regression coefficients, and \( T_{ADM} \) & \( T_{Rad} \) are the physical temperatures of the ADM and Top of Radiator, respectively. The above equation is for 10 V-Pol but other channels may be different.

It should be noted that not all channels can be reconstructed for instance Method 1 limitation is when the \( O \) & \( G \) are in phase, not having a simple linear relationship and being too noisy. For Method 2 the \( C_C \) is weakly correlated to the thermal temperature sensors. Issues for both methods are rooted in the fact of how the \( C_H \) & \( C_C \) are not correlated well which is requirement. Figure 6.8 is an example showing Gain & Offset of orbit 601, for all 9 TMI channels; channels 10H, 21V and 86 V (within red box) will not be reconstructed within this dissertation. The 21.3 GHz channel is extremely difficult to reconstruct and an excerpt of a justification for this is within Appendix D.3. The following section, Section 6.2 discusses the validation of this technique.
Figure 6.8: TMI’s calculated Gain and Offset for a non-DSC maneuver (Orbit #: 601) for all nine channels. Within the red box there are 3 channels that this dissertation does not attempt to reconstruct the $T_A$.

### 6.2 Validation of the Reconstruction

The two methods for reconstructing TMI’s $T_A$ during the DSV are independent of each other; whereby Method 1 reconstructs the Gain & Offset of the radiometer transfer function with a correction based on Solar Angles that is applied after reconstruction, and Method 2 reconstructs a $C_C$ which is function of onboard temperature sensors. Figure 6.9 shows a time series of the residual for DSCMs 1 & 2 at 10V with scan positions 51 to 54 (mid-scan) averaged together; the areas between the black lines where the residual is significantly large is due to the fact that the calibrated $T_A$ (truth) is corrupted by the CSC intersecting Earth. The emphasis
of this figure is the performance of the $T_A$ reconstruction of the different methods while the calibration is valid. The lower panel is the same as the upper panel but with a moving average (low pass filter) of size 51 scans to smooth the data so to easily see the mean of the signal. The residual without the PCR is ±1 Kelvin (blue) and after (red) is less than 0.25 Kelvin. The different window sizes can differ up to 0.6 Kelvin during DSVs for 10V. As can be seen in Fig. 6.8, Method 2 (green curve) during non-DSV scans performs better than the previous method, i.e., the variation is significantly less (less uncertainty). For comparisons, Figure 6.10 presents the same results as Figure 6.9 but for 19 V.

The common factors between all reconstruction methods are 1) the algorithms are trained using nominal (non-DSV) scans and 2) the HLC and other ancillary data that is obtainable during non-DSV & DSV scans is used to reconstruct $T_A$. For Figure 6.11, in both panels the solid black curve is the calibrated $T_A$, which is not valid between the dashed black lines. Between the green dashed lines the TMI is in eclipse thus the physical temperatures are cooling down. Note that the first black line occurs simultaneously as TRMM goes into eclipse (1st green line) in the left panel. The curves with different colors are the average of all window sizes and scan positions 1-4 (left edge-of-swath) for a simplistic comparison between the three methods: Method 1 (blue), Method 1 + PCR (red), and Method 2 (green). Note for the 10V case that the disagreements between the methods are up to 0.6 Kelvin and for the 19V case less than 0.25 Kelvin. This is because the signal of the $C_H$ & $C_c$ is noisier for the 10V than 19V.
Figure 6.9: Time series of the 10V residuals of the reconstruction methods, Method 1 before PCR (blue curve), Method 1 with PCR (red curve), and linear regression (green) for DSCMs 1 & 2. Lower panel is the same as the upper panel but smoothed with a moving average of a window size of 51 scans.
Figure 6.10: Time series of the 19V residuals of the reconstruction methods, Method 1 before PCR (blue curve), Method 1 with PCR (red curve), and linear regression (green) for DSCMs 1 & 2. Lower panel is the same as the upper panel but smoothed with a moving average of a window size of 51 scans.
During the rest of this dissertation, for each channel that can be reconstructed we will use both the Method 1 & 2. Table 6.1 summarizes the best options for reconstruction of TA.

Table 6.1 Method 1 Window Sizes that are used for this dissertation.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Window Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>10V</td>
<td>5 orbits</td>
</tr>
<tr>
<td>19V</td>
<td>Any Window Size</td>
</tr>
<tr>
<td>19H</td>
<td>11 or 15</td>
</tr>
<tr>
<td>37V</td>
<td>1 or 3</td>
</tr>
<tr>
<td>37H</td>
<td>1</td>
</tr>
</tbody>
</table>
It should be noted that all reconstruction methods are trained using calibrated $T_A$ at much warmer radiometric temperatures, i.e., all the algorithms use ocean and land observations (100-300 K) which are then used to reconstruct a very cold $T_A$ value $\sim 3$ K. This “extrapolation” essentially is a difficult task for possible reasons 1) sun intrusion into the warm load where by the PRT and radiometric readings are biased between each other (not addressed in this dissertation) 2) imperfections in the reconstruction method whereby unjustifiable jumps in the gain and offset within Method 1 are not captured since a linear relationship is assumed or for Method 2 temperatures sensors not properly capturing the radiometer transfer function 3) time varying non-linearity of the system which was/is not characterized.

6.3 Acknowledgement of Spillover

Shortly after the $T_A$ reconstruction for the January 1998 maneuvers were finished it was obvious that the DSV $T_A$ for all maneuvers had an unexpected variation. These variations were not Gaussian in nature and lasted for many scans during the DSV. Figure 6.12 shows a time series for the $T_A$ reconstruction Method 2, 19 V-pol, for the first 6 DSVs. The solid black line is the CSR dependent calibrated $T_A$. Notice for all panels that the reconstructed $T_A$ (scan position 1-4 averaged) has sharp jumps early in the DSV. It was recognized once associating these temperatures with TRMM’s sub-satellite point that there was a high correlation between the $T_A$ signal and location of TRMM over the Earth. Figure 6.13 shows the geolocation for 19 V mid-scan for the 6 DSVs, where the saturated color bar represents a limited $T_A$, 10 to 20 Kelvin, blue and red, respectively. Notice, when the spacecraft is over the radiometrically warm land the $T_A$ signal jumps and then decreases over the cold ocean. It is believed this research that this is due
to the spillover region (in the angular region the feed horn does not illuminate the MR) illuminating the Earth whereby the Earth’s radiation affects the averaged MR view of deep space. It should be pointed out that during the DSV the spacecraft is pitched at an angle, whereby the MR views space but the spillover region (SR) that nominally illuminates deep space is now illuminating the Earth, and this region sweeps across the Earth as TRMM is pitching 360° relative to its geodetic nadir. Take DSV 6 (lower right panel) in Figure 6.12 where the first two jumps in $T_A$, between $3.2 \times 10^4$ & $3.25 \times 10^4$ scans, is when the spillover illuminates first Southern Africa then Madagascar (second jump). The third jump, between $3.25 \times 10^4$ & $3.3 \times 10^4$ scans, is when the SR illuminates Thailand/China. Refer back to Figure 6.13 for the visual reference.
Figure 6.12: 19V $T_A$ Reconstructions, Method 2, for DSV 1-6, for Scan Positions 1-4 averaged.
This unexpected radiation entering the spillover region adds to the complexity of calibrating TMI during its series of inertial holds. Hence, methods of calibrating TMI while addressing this issue are covered in detail in the next chapter.
CHAPTER 7: ESTIMATION OF BEAMWIDTH AND BORESIGHT

During any DSC maneuver, TMI’s conically scanning main beam will sweep from Earth to space and back again as the beam crosses the Earth’s limb. This results in a sharp transition in brightness temperature (100-300 K to ~ 3 K) and was utilized by JAXA [22] during the Aqua Roll Maneuver to obtain a post-launch estimated beamwidth (BW) of AMSR-E. For TMI, to date, there are 10 DSC maneuvers, each with two transitions; hence, 20 occurrences allowing for determination of antenna BW as shown in Figure 7.1. Within the figure there are 10 transitions whereby the MR boresight beam leaves the Earth, known as Transition 1; and as the spacecraft continues rotating the beam approaches the Earth from space, known as Transition 2. The location of where the transitions occur are of importance because during a transition it is imperative that the scene be as close to homogeneity as possible, since land/water crossings or heavy precipitation events would effect this analysis because it is a function of the difference between sequential scan samples. It should be noted that within this section two methods of analysis were used to determine the BW & pointing angle. The first analysis used only the mid-scan positions and the second used a larger range of scan positions so to improve the statistics. It should be noted for the mid-scan analysis that due to the NEDT affecting the results and in order to mitigate this effect it was decided to average over a small range of scan positions, 50 to 55 & 99 to 109 for the low & hi resolution channels, respectively. The BW described in this section is the estimation of the MR boresight pattern in the along-track dimension.
Figure 7.1: Geolocation of TMI mid-scan position before and after viewing space, Transition 1 & 2, respectively.

7.1 Beamwidth: Mid-Scan Analysis

To determine the BW the mid-scan position was chosen since polarization rotation effects are minimal compared to other positions, i.e., the plane of incidence stays aligned with the principal cut of the IFOV. For the mid-scan analysis only a small amount of scan position about the mid-scan, 50-55 for 10.65-37.00 GHz channels and 99-109 for 86GHz channels, were used to decrease the NEDT and to provide better statistics. The BW is calculated using the differentiated radiometer $T_A$ with respect to the difference in nadir angle, and is defined as:

$$
\Delta T_{A,j} = \frac{|T_{A,i} - T_{A,i+1}|}{\Delta \theta}
$$

(7.1)
where \( j \) is the differentiated \( T_A \) sample, \( i \) represents sequenced samples and \( \Delta \theta \) is difference in nadir angle at these two samples which so happens to be constant over the entire inertial hold, i.e. the pitch rate \( \sim 0.066^\circ/s \). Hence, for the TRMM maneuvers there is no advantage in normalizing with respect to \( \Delta \theta \). Thus, Eqn (7.1) is redefined without the \( \Delta \theta \). As the IFOV sweeps from or onto Earth, it will partially fill the beam as is presented in Figure 7.2. This figure illustrates as the half of the 3dB illuminates space and the other half Earth. It is at this time that \( \Delta T_A \) is maximum, i.e., the boresight is perfectly tangential to the Earth’s Limb. Another illustration of this is shown in Figure 7.3 where by the view of the instrument, the projection of the IFOV is illuminating space/Earth by half. Results from DSCM-4 for Transition 1 are shown in Figure 7.4 for four channels. The Y-axis is the normalized \( \Delta T_A \) where a 0.5 value reflects the -3dB beamwidth (BW) and the three curves in each plot are for the Raw data, i.e., normalized \( \Delta T_A \) (green), smoothed Raw data (blue), and a Gaussian fit applied to the smoothed Raw data that has been smoothed by a triangular filter of length 3 (red). The vertical dashed lines are to show where the signal crosses the -3dB mark. Also, the Gaussian is applied to the smoothed Raw data that is above the -3dB line. This is done since data below this point is noisy and of no interest in this analysis yet it can significantly influence the fit. This is how the estimation of BW is obtained within this section.
Figure 7.2: A side view as TMI's main beam -3dB BW illuminates half of space and Earth.
Figure 7.3: What the instrument views as the IFOV sweeps over Earth’s Horizon. That is, imagine as if the viewer is sitting on TMI with the -3dB IFOV projecting onto Earth/space.
During this analysis it became obvious that 1) horizontally polarized channels were noisier due to the larger dynamic range than the V-pol 2) due to 10 GHz being more sensitive to the surface than other channels, that subtle $T_B$ changes affected the results more than the higher frequency channels as well as the fact that the actual difference between sequential TAs is lower in amplitude because of the wider BW, and 3) transitions with discrete jumps due to high contrasting scenes needed to be removed. Figure 7.5 consists of the averaging of all valid Gaussian fits for all channels. The upper and lower panel are for Transition 1 & 2, respectively. For clarification of what DSCMs were used for each channel refer to Appendix C.1 for figures.
that reflect this. The average of all valid BWs, calculated from the individual maneuvers and transitions, are shown in Figure 7.6. The figure depicts prelaunch BW values from [1] and [10], green and black dots, respectively. The two transitions are grouped together and the error bar associated reflects one standard deviation. Table 7.1 contains the values that Figure 7.6 presents.

Figure 7.5: Average off all valid fitted Gaussians for all channels.
Figure 7.6: Averaged BW from the individual estimated BWs for valid DSCMs.

Table 7.1: Estimated of beamwidth for two transitions. Convention: <BW> / σ / # of points for Transitions 1 & 2
The mean BW values are based on the averaging of the Gaussian fit to the smoothed data for 10.65 to 37 GHz but for 85.5 V- & H-pol are based on the Gaussian fit on the raw data. The 85.5 GHz channels are so under sampled because the BW is small and using the smoothed data would lower the amplitude of the ΔTA. The standard deviation is calculated using the sample σ definition.

This analysis shows that there is good agreement between the prelaunch and post launch values, except for the 10.65 GHz H-pol channel which can differ up to 0.4 degrees when separating the data into transitions 1 & 2. The difference in BW between the transitions is also largest in the 10.65 H-pol case. If these values are not real, then justification for these large differences in the X-band H-pol results are most likely due to two reasons 1) 10.65 is significantly sensitive to subtle changes over the oceans and is compounded by the fact that H-pol has a larger dynamic TB, range and 2) the ΔTA is a lower signal than it is for higher frequencies. An example of the absolute magnitude of the ΔTA for Orbit 644 Transition 1 for all channels is depicted in Figure 7.7.
Figure 7.7: Magnitude of $\Delta T_A$ for Orbit 644 Transition 1 for all TMI channels with respect to the angle off the boresight of the beam.

### 7.2 Beamwidth: Large Range of Scan Positions

This section is similar to 7.1 with the objective to reduce the variance of the BW estimate, i.e., improve the BW estimate using a large range of scan positions. An example of a clean transitional scene, Transition 1 DSCM 2, for 19 V-pol is shown in Figure 7.8. The $y$-axis for panels (a) to (c) is scans minus 1, since $\Delta T_A$ is a function of the differences between scans. Panel (a) depicts the absolute magnitude of $\Delta T_A$, 0 to 20 Kelvin, with respect to all scan positions. The two white lines that define the smile (convex) like contours are the boundaries used to calculate the BW for a given scan position. The black line is the estimated maximum of the $|\Delta T_A|$ for a given scan position. Panels (b) & (c) are similar to (a) except the colors represent
Polarization Rotation of the main beam and the nadir angle, respectively. The Nadir angle is simply defined as the angle between the instruments LOS and the spacecraft geodetic vector. Panel (d) is essentially (a) whereby the Off-boresight Angle is the angle in degrees off of the black line in (a). Also, the color has been normalized to be 0 to 1 Kelvin. Essentially, for scan position 52 the colored slice is the Y value that was represented in Figure 7.4 (b). Panel (d) depicts the range of scan positions that are used for analysis within this section (between scan position 10 & 100). It should be noted that not all maneuvers, transitions, and channels are as clean as this. An example of a less clean scene is shown in Figure 7.9 using 10H Transition DSCM 1 whereby this is due to the inhomogeneity of land (Australia).

Figure 7.8: DSCM 2, Transition 1 for 19 V-pol where by panel (a) is the magnitude of ΔTA, (b) Polarization Rotation Angle, (c) Nadir Angle, (d) is the Off-boresight of the normalized ΔTA.
Figure 7.9: DSCM 1, Transition 1 for 10 V-pol where by panel (a) is the magnitude of ΔTA, (b) Polarization Rotation Angle, (c) Nadir Angle, (d) is the Off-boresight of the normalized ΔTA.

The method in calculating the BW is similar to what was done in the previous section. That is, for each scan position a Gaussian is fitted to the data above 0.5 K of the |ΔTA|. This is what is shown in the appendices of what was used for the estimation of the BW within this section. As was the case in Section 7.1, the more sensitive the channel is to the surface emission, the noisier it is leading to a large array of scan positions that must be removed for this analysis, which is compounded by the fact that the H-pol channels are always noisier. Hence, data that went into this analysis is listed in Table 7.2, whereby for Frequencies below
21.3 GHz the maneuvers, transitions, and scan positions were determined based on the 10.65 GHz channels “cleanliness”. For the 37.0 & 85.5 GHz channels scan positions 40-60 & 79-119 are chosen for all maneuvers and transitions. The reason for the range is the broadening of the BW as scan positions leaves the mid-scan. An example of this is shown within Appendix C.1. The biggest change between within this analysis, compared to the mid-scan, is how 10H moved towards agreement with the pre-launch values. Figure 7.10 is similar to Figure 7.6 except data from Table 7.2 is used to estimate the beamwidth. Hence, it is the results using the range of scans that is considered the final estimate of the TMI BW.

Table 7.2: Scan Positions for a given maneuver and transition that was used for the Range of Scan Positions analysis.

<table>
<thead>
<tr>
<th>DSCM</th>
<th>Transition 1</th>
<th>Transition 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50-80</td>
<td>20-90</td>
</tr>
<tr>
<td>2</td>
<td>10-93</td>
<td>NA</td>
</tr>
<tr>
<td>4</td>
<td>40-60</td>
<td>NA</td>
</tr>
<tr>
<td>5</td>
<td>10-93</td>
<td>NA</td>
</tr>
<tr>
<td>6</td>
<td>NA</td>
<td>10-93</td>
</tr>
<tr>
<td>7</td>
<td>NA</td>
<td>10-93</td>
</tr>
<tr>
<td>8</td>
<td>10-40</td>
<td>10-30</td>
</tr>
<tr>
<td>10</td>
<td>10-80</td>
<td>NA</td>
</tr>
</tbody>
</table>
7.3 TMI Main Beam Boresight

Recall that the TMI instrument consists of two feed horns, 10.65 GHz and the multi-frequency (MF) feeds, whereby the 10.65 GHz is squinted by 12.58° relative to the MF feed. There are two documents [23, 24] that contain the radio frequency boresight direction relative to the antenna’s optical boresight. The first document is from Hughes Space and Communications Company which contains measurements from the outdoor test range of TMI from September 9-29, 1994. The second document is a memo (12-11-1997) addressed to Dr. James Shiue, which contains boresight values based on antenna patterns from [23], whereby discrepancies in the boresight were discussed.
One objective of this research is to document on how to characterize a beam’s boresight using the Earth’s limb while at the same time understanding the TMI boresight discrepancy. The method of determining the boresight is in similar fashion as described in Section 7.2 except instead of performing the analysis with respect to the off-boresight angle, the focus is on the angle between the geodetic vector and the instruments estimated LOS which is defined as the Geodetic Nadir Angle (GNA) the is not to be confused with the nadir angle which is the angle between the LOS and spin-axis of the instrument. An example of normalized $|\Delta T_A|$ vs GNA for mid-scan position is shown in Figure 7.11. Since this analysis uses GNA to characterize the boresight this research is limited to discussing the relative difference between the X-band feed to the MF feed since this angle is not unique with respect to the instrument’s coordinate system.
Table 7.3: Offset (degrees) between the TMI Documents that contains the Main Beams Boresight

<table>
<thead>
<tr>
<th>Channel</th>
<th>Offsets From Shiue Memo [24] (deg)</th>
<th>Offset from TMI Subsystem Test Doc [23] (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Along-Track</td>
<td>X-Track</td>
</tr>
<tr>
<td>10.65 V</td>
<td>0.555</td>
<td>-0.185</td>
</tr>
<tr>
<td>10.65 H</td>
<td>0.185</td>
<td>0.555</td>
</tr>
<tr>
<td>19.35 V</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>19.35 H</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>21.30 V</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>37.00 V</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>37.00 H</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>85.50 V</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>85.50 H</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Figure 7.11: Representing the normalized $|\Delta T_A|$ with respect the boresight for all TMI channels for DSCM 2 Transition 1 at mid-scan position.

Before proceeding any further it is important to introduce the orientation that the TMI’s scan makes relative to the Earth’s horizon during these transitions, i.e., this section groups the analysis with respect to a convex or concave transition. An illustration of this is depicted in Figure 7.12 whereby for the Yaw 180° case, Transitions 1 & 2 is convex and concave, respectively, and opposite for the Yaw 0° case. An example of this grouping is shown for 19 V-pol for all maneuvers in Figure 7.13 (concave) and Figure 7.14 (convex). These figures are similar to Figure 7.11 in that the normalized $|\Delta T_A|$ and geodetic nadir angle are now the color (0-1 kelvin) and y-axis, respectively. Note that Figure 7.11 represented this relationship at the mid-scan position where as Figure 7.13 & Figure 7.14 represents a range of scan positions (on
the x-axis). The black dots are the estimated boresight of the main beam at a given scan position. It is these black dots that will be discussed next in more detail.

Figure 7.12: TMI scan (red curve) relative to the horizon for different Yaw and Transition for a given inertial hold.
Figure 7.13: Concave Transitions for DSCM 1 for all TMI channels. The x- & y-axis is scan position and geodetic nadir angle while the color is normalized $|\Delta T_A|$ (0 to 1 Kelvin). The black lines and dots indicate the half power BW and boresight, respectively.
Figure 7.14: Convex Transitions for DSCM 1 for all TMI channels. The x- & y-axis is scan position and geodetic nadir angle while the color is normalized $|\Delta T_A|$ (0 to 1 Kelvin). The black lines and dots indicate the half power BW and boresight, respectively.

The grouping of the transitions into Convex/Concave is necessary because any offset between feeds’ boresight would be visually repeated. Essentially, the 11 GHz channels relative to the MF feed are significantly different in the offsets with respect to whether it was concave or convex. This statement is supported by Figure 7.15 (concave) & Figure 7.16 (convex) which demonstrate the relationship between GNA and scan position whereby each panel is a DSCM and all TMI channels are the colored curves. Notice in Figure 7.15 that the 10 V- & H-pol, solid blue and red curve, have an offset relative to the MF feed channels. This is indicative that a boresight offset exists between the two feeds. In fact, based on Table 7.3 the offset in the
along-track (nadir) dimension is positive, i.e., the 10 V-pol nadir angle is larger than the nominal 49°. And since the geolocation code uses the nominal 49° nadir angle, the plots illustrate a lower GNA, that is, it transitions over the Earth’s horizon occurs earlier than the MF horn. For the convex transition, Figure 7.16, offset is less noticeable because the boresight offset exists in 2D, in the nadir and azimuth dimension; hence, there should be a relative difference for concave and convex transitions. It should be emphasized that the MF horn channels are in very close agreement with each other, which is indicative that they share the same boresight.

Figure 7.15: Geodetic Nadir Angle Dependence on Scan Position for all DSCMs for the Concave Transitions. Each panel contains this relationship for all TMI channels.
Figure 7.16: Geodetic Nadir Angle Dependence on Scan Position for all DSCMs for the Convex Transitions. Each panel contains this relationship for all TMI channels.

It should be re-iterated that this analysis is a comparison of the 10GHz channel relative to the MF feed, i.e., the mean of the 19.35-85.5 GHz boresights are used as the reference. Hence, there can still be an offset in the MF feed that was not corrected. The absolute bias for all channels is for future work. With this said, for DSCM 8, Figure 7.17 demonstrates the difference between the MF horn boresight, mean of all MF channels boresight, and 10 V-pol with respect to scan position whereby the blue and red curve are for convex and concave, respectively, for six different cases of the boresight. Panel (a) is the difference when there is no offset applied to the boresight of any of the TMI channels. However, (b) & (c), have just 0.5° in nadir and 0.5° in
azimuth, respectively, for 10 V-pol. Since Panel (b) only applies an offset in the nadir angle there will a significant offset of the curves when compared to Panel (a), no offset applied. At same time, Panel (c) only applies an offset in azimuth, whereby the curves flatten out with respect to the curves in Panel (a). Hence, a change in nadir angle causes a DC offset between the feeds, while a change in azimuth causes a change in the slope of the signal. Finally, Panels (d) to (f) are for three cases [24-26] where offsets are applied to both 10V & the MF horn boresights which is Figure 7.17 in Table 7.4. It should be noted that work by CSU [25] is preliminary and can change with more analysis. Notice within the figure that the Shiue angles causes even further disagreement between the feeds boresights, whereas RSS & CSU significantly improve the agreement. In fact, note the differences of the offsets in nadir and azimuth angle within the table for RSS & CSU and similarities of the curves within panel (e) & (f). That is, they are essentially the same or that the applied offsets force the feeds to agree with each other.
Figure 7.17: Differences in GNA between the mean of the MF feed and 10 V-pol boresight. The six panels represent different offsets applied to the channels’ boresights. Panel (a) no offsets are applied, (b) nadir angle of 0.5°, (c) azimuth angle of 0.5°, (d) offsets from [24] applied only to 10 V-pol, (e) from [25], (f) from [26].
Table 7.4: Offsets in the boresight applied from 3 sources. Convention for angles are nadir / azimuth in degrees.

<table>
<thead>
<tr>
<th>V</th>
<th>Shiue (°)</th>
<th>RSS (°)</th>
<th>CSU (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.65</td>
<td>0.555/-0.185</td>
<td>0.43 / 0.30</td>
<td>0.3 / 0.6</td>
</tr>
<tr>
<td>10.65 H*</td>
<td>0.185 / 0.555</td>
<td>0.43 / 0.30</td>
<td>0.18 / 0.15</td>
</tr>
<tr>
<td>19.35</td>
<td>0</td>
<td>0.3 / 0.3</td>
<td>0.18 / 0.15</td>
</tr>
<tr>
<td>19.35 H</td>
<td>0</td>
<td>0.3 / 0.3</td>
<td>0.18 / 0.15</td>
</tr>
<tr>
<td>21.30</td>
<td>0</td>
<td>0.3 / 0.3</td>
<td>0.18 / 0.15</td>
</tr>
<tr>
<td>37.00</td>
<td>0</td>
<td>0.3 / 0.3</td>
<td>0.18 / 0.25</td>
</tr>
<tr>
<td>37.00 H</td>
<td>0</td>
<td>0.3 / 0.3</td>
<td>0.18 / 0.25</td>
</tr>
<tr>
<td>85.50</td>
<td>0</td>
<td>0.3 / 0.3</td>
<td>0.18 / 0.12</td>
</tr>
<tr>
<td>85.50 H</td>
<td>0</td>
<td>0.3 / 0.3</td>
<td>0.18 / 0.12</td>
</tr>
</tbody>
</table>

*Not used for the relative analysis

In summary, this analysis shows that offsets in TMI’s boresight can be detected using the Earth’s Limb. Offsets in nadir and azimuth angle influences the GNA vs scan position differently which helps provide insights differences in boresight. Future work will utilize the Earth’s horizon to determine an absolute boresight error whereby geolocation relative to the spacecraft coordinate system which was not covered within this research.
CHAPTER 8: ALONG-SCAN BIAS

In order for a spaceborne instrument to provide meaningful and adequate information of the Earth, a broad area with appropriate resolution is desired. This broad area, known as the instruments swath, is necessary, for example, to capture the evolving/moving scenes of weather systems, such as clouds, wind vector and rain. This can be done by a series of stationary elements (series of horns or synthetic aperture) in a pushbroom fashion or in a scanning manner (TMI or GMI), and any bias as a function of the swath needs to be removed so not to introduce any errors. For example, if a large along-scan bias is present for a conically scanning radiometer on a polar orbiting satellite that has a swath that covers two hours of local time (edge-to-edge swath) it will introduce a repeatable error at the same local time for the ascending and descending pass, which must be removed so not to have erroneous scientific retrievals/conclusions.

It was first shown in [11] that TMI’s along-scan bias, at worst (37 H-pol), is over 0.75 K, peak-to-peak. In RSS’ analysis, there was good along-scan agreement between the DSC data and the TMI & SSM/I collocated methods, except for at the edge-of-scan which is reintroduced here in Figure 8.1. This disagreement, as will be shown within this section, is due to the limited amount of the DSV that was used.
Figure 8.1: Wentz’ Along-scan bias analysis for TMI’s 9 channels. Comparison of the average along-scan error derived from ocean observations and from deep-space observations. The observed $T_A$ anomaly is plotted versus scan position. The solid black and gray curves come from ocean observations for yaw orientations of 0 and 180, respectively, during 1998. The dashed curves come from deep-space observations during January 1998 (Source: Figure 2 from [11]).
Recall that Sections 6.2 & 6.3 discussed reconstruction of $T_A$, either edge-of-scan or mid-scan position during the DSV, so to show the correlation between the $T_A$ signal and Earth’s radiometric $T_B$ viewed by the spillover lobes. It should be noted that these jumps in $T_A$ affects all scan positions, as is depicted in Figure 8.2 (scan positions: 1 – 104) for 19 V-pol are for DSVs 1 – 6. The SR $T_A$ and the emissive reflector effects, which introduces a time-varying bias, complicates the along-scan analysis whereby the reconstructed $T_A$ is not just the known deep space (2.7 K) value but a more convoluted positive bias. Hence, it is not meaningful to just simply average all scans with respect to scan position but a more appropriate way of analyzing the along-scan bias is to remove the time-varying signal by normalizing each scan independently. To remove these effects from the signal it was chosen to subtract out the minimum value of each scan as is represented by:

$$T_{A,i,j}' = T_{A,i,j} - \min(T_{A,i,k}, \forall k \in \{1,..,t\}),$$

$$\forall i \in \{1,..,s\}, \forall j \in \{1,..,t\}$$

where $T_A$ is antenna temperature, and $T_A'$ is the normalized antenna temperature, $s$ is the instantaneous scan, and $t$ is scan position. By subtracting the minimum value of the instantaneous scan, the NEDT acts as a DC offset when averaging all scans. The results of Eqn. (8.1) is shown in Figure 8.3. It should be noted that this manner of performing along-scan bias mitigates any residuals from the $T_A$ reconstruction, refer to Appendix C.2 for proof of this. The benefit of normalizing the $T_A$ is that the time-varying bias is removed and only features of the instantaneous scan is highlighted; note all DSVs now contain repeatable bias features as is shown in Figure 8.4. For this same analysis for all channels of all frequencies & DSVs refer to
Appendix C.2.2. Notice in the lower two panels in Figure 8.3 around scan 3900 & 9700, left & right panel, respectively, that a jump of about 2 Kelvin occurs which was not noticeable in the upper two panels. This jump is a repeatable feature for all maneuvers and is explained in more detail later in this section.

![Reconstructed T_A DSV 1, 2, 3, 4, 5, 6 images](image)

Figure 8.2: DSV 1-6 for 19 V-pol; color bar represents the MR DSV, 10 to 20 Kelvin, blue and red, respectively.

Since TMI is a conical scanner, scan positions leave the Earth at different times relative to each other during the DSCM. In Figure 8.4 all edge of scan positions veer off the Earth first, with the mid-scan position being last. This is because the spacecraft is at a Yaw of 180°, i.e.,
spacecraft is flying backwards. Therefore, beams whereby all scan positions that are viewing space are used within this analysis, and are defined by the solid black lines within each panel of Figure 8.4. Figure 8.5 shows the averaged along-scan bias for DSCM Set 1 averaged for all channels. Except for the Mean Offset (Y-Axis) of the channels, these results agree (peak-to-peak) with [11] for all scan positions, except for edge-of-scan which has already been addressed. It should be noted, that there is a noticeable “saw-tooth” like feature in the 11, 37, and 86 GHz channels which is of the order of 0.1 K. This similar feature was first discovered for GMI, during the On-Orbit Check out period, and is referred to as “wiggles”. Hence, this feature is not exclusive to the GMI instrument and is fundamental in the hardware of the instrument. Refer to Appendix B.2 on the GMI wiggles.
Figure 8.3: For 19 V-pol, DSV 1 & 2 (left and right column, respectively) reconstructed $T_A$ (upper two panels) and normalized, $T_A'$, (lower two panels).
Figure 8.4: Same as Figure 8.2 but with Eqn. (8.1) applied.
Figure 8.5: A 2-dimensional along-scan bias for DSCM Set 1, all channels.

Figure 8.5 represents the along-scan biases for a given set of DSCMs, DSCM set 1, i.e., all were relatively close to each other in time while at the same yaw orientation. However, repeatability is of importance because if this bias is unique to this time period, then applying a correction for different time periods will introduce unwanted errors. The along-scan bias for DSCM set 2 & 3 are shown in Figure 8.6 by performing the same steps that were done for Set 1. Note that the largest deviation between sets occur for 37 H-pol which is approximately 0.25 K. This may imply that the difference is due to the bias changing as a function of time; however, set 2 & 3 are years apart in time and in excellent agreement. The only other characteristic that is different is that for DSCM Set 2 & 3 the spacecraft is at a yaw of 0 degrees unlike Set 1 which was performed at 180°; even with this said, at worst, the change is 0.25 K. Figure 8.7 shows the
DSC set 1 to 3 averaged along-scan with the error bars (entire length represents 1σ). It should be noted that this analysis was done to see if the region where there was a jump in TA’ was removed and how it would affect the results. Results where NSA range of 115° to 145°, were removed and the difference from this limited range to the full range were on average less than 0.05 K, peak-to-peak, but were largest for 10H & 19V at a 0.1 K difference, refer to Appendix C.2 for plot.

Figure 8.6: Averaged TA’ for DSCM Set 1 to 3 for all channels.
Figure 8.7: Along-Scan Bias DSC Sets 1-3 averaged together with error bars of 1σ length.

Finally, for comparison of the inter-satellite along-scan biases RSS’ delivered to NASA GSFC these biases so to be applied to TMI 1B11 V7, as shown in Figure 8.8. For clarity these values are applied on the $T_A$s for the data product. RSS’ biases for Low and Hi Resolution channels have offsets respectively applied at scan position 52 & 103 to agree with CFRSL’s values for ease of comparison. The biggest differences between the two are the edge of scan values which is similar to what was shown in Figure 8.1.
As was stated earlier in this section, after normalizing TA, a recurring jump in TA' became noticeable in all channels during the middle of the DSV, as was shown in Figure 8.4. This jump in the time series of TA' is independent of yaw orientation and occurs for all DSVs for the same orientation of the spacecraft. The Nadir Spin Angle (NSA) is defined as the angle between the spacecraft’s +X axis and geodetic vector. Figure 8.9 represents the average of DSC Set 1 (DSCMs 1-6) for all channels; this figure is similar to Figure 8.4 except that the Y-axis is the NSA. The recurring jump occurs around an NSA of ~133° and it is believed that this is due to the back lobe of the TMI secondary pattern sweeping through the Earth and/or simply how the SR
illuminates the Earth as TRMM rotates; an illustration of the orientation of TRMM with TMI is shown in Figure 8.10 at an angle of 133.8. Finally, it should be noted realized that the antenna back lobe produces spillover emissions was as high as 1-2 Kelvin depending on the channel.

Figure 8.9: A 3-dimensional representation of the along-scan bias for DSCM Set 1, all channels. The Y-Axis represents the angle between spacecraft’s +Z axis and geodetic nadir vector (Nadir Spin-axis Angle).
Figure 8.10: Orientation of TRMM for a NSA of 133.79° (Image created using AGI’s Systems Tool Kit).
CHAPTER 9: SECOND STOKES USING A NADIR-LOOK

As first mentioned in Section 5.2, the Nadir-Look Second Stokes (SS) analysis is a simplified case of investigating the SS parameter. Essentially, for a given frequency, it compares the vertical and horizontal polarization channels while the instrument’s boresight is parallel to the geodetic vector (Nadir-Look). At this orientation the EIA is 0° degrees, therefore the second stokes parameter (Q) theoretically is zero Kelvin and any deviation from this can be due to a number of calibration issues. For this maneuver it is ideal to have a good statistical amount of data points so to draw appropriate conclusions, such as having the spacecraft locked at this orientation (pitch angle) as it scans land and ocean scenes. Unfortunately, for the TMI case the spacecraft and software was not developed for this type of maneuver and so this analysis is left with observations as the boresight sweeps through nadir. Refer to Figure 9.1 for an image of the geolocation of the MR intersecting the Earth with the color representing EIA for TMI during DSCM 1. In addition to this limitation, since the azimuth/scan angle is symmetrical about the +X axis of the spacecraft which sweeps through nadir, however there is never an observation that is exactly parallel to nadir. In fact, the lowest EIA is ~0.4 & ~0.1 degrees for low & high resolution channels, respectively. This limits the analysis to only 14-15 samples per maneuver. See Figure 9.2 for short time series of EIA during the inertial hold for two scan positions that contain the minimum EIA. Within this dissertation SS will be reserved for the analysis and Q for the parameter.
Figure 9.1: Panel (a) is the geolocation of EIA for TMI orbit 641 during inertial hold (Colorbar: 0-90). Panel (b) is a zoomed in version of (a) (Colorbar: 0-50 degrees).
In order to address the limitation of number of samples used it was decided to not limit the analysis to such low EIAs. Hence, for ocean, a highly polarized scene, the EIA should be limited to 10° while using the RTM and land, a low polarized scene, at 20° (not using the RTM). This upper bound in EIA not only increases data by incorporating more scans but also the number of scan positions. With the EIA upper bound set, the analysis can be performed each time an inertial hold occurs. Figure 9.3 shows locations of where the mid-scan position intersect the Earth as it sweeps through the nadir for DSCMs 1-10; the colorbar represents EIA.

Figure 9.2: Depicting two scan positions that contain the minimum EIA as it sweeps through nadir.
Figure 9.3: Geolocation, mid-scan position, of the point closest to an EIA value of zero, DSCMs 1 – 10, with the color representing the Earth incidence angle.

9.1 Ocean Analysis

Since the ocean is a specular reflective surface, when increasing the samples, by not limiting the analysis to EIA of 0°, there are compounded effects that must be corrected. These effects are:

1) There is an expected separation of the V- & H-pol temperatures, due to Fresnel Reflection. Refer back to Figure 5.6 for an illustration of V- & H-pol $T_B$ as a function of EIA. Essentially, Fresnel Reflection states that as EIA increases the V- & H-pol
temperatures diverge causing \( T_B \) V-pol to become warmer than \( T_B \) H-pol. This effect can be mitigated by using the RTM to correct for this well-known relationship.

2) Using radiative transfer theory to correct for the EIA effect is only applicable when the MR electromagnetic antenna plane is aligned with the plane of incidence, which only occurs at the mid-scan during the inertial hold. Essentially, the RTM can only simulate purely polarized temperatures, i.e., it assumes that the designed antenna system electromagnetic field plane is aligned with the plane of incidence. As the main reflector boresight increments off mid-scan the vertically and horizontally polarized components of the electric fields received by the satellite instrument starts to misalign with the plane of incidence. Hence, the EIA correction, which uses the RTM, must take into account this misalignment which is known as polarization rotation (PR). The PR angle (PRA) can be calculated based on the orientation of the spacecraft and the geolocation of the instruments LOS. This is discussed in more detail in Appendix C.3.

3) The PR correction depends on the RTM, which considers the simulated \( T_B \) as truth; however, there are always imperfections in any RTM and the ancillary data that goes into it. Normally the ancillary data, which are numerical weather models, are spatially and temporally course and does not capture intense weather systems. It is for this reason that the PR correction is not a simple difference of the effect of the PR, but must be normalized relative to the temperature that simulated it.
It is for these reasons that the correction requires multiple steps whereby these effects are listed in order:

1) Simulate vertically and horizontally polarized brightness temperatures

2) Convert observed TBs as if they are aligned to the plane of incidence

3) Correct for difference in $Q$ that are a function of EIA

These steps are assembled and defines the corrected Second Stokes Parameter, $Q_C$, as:

$$Q_C = Q_{\text{Obs}} - Q_{\text{Sim,PR}},$$  \hspace{1cm} (9.1)$$

where the uncorrected observed $Q$ is $Q_{\text{Obs}}$ and the simulated $Q$ with PR applied is $Q_{\text{Sim,PR}}$. For proof of this equation and how PR is applied to the signal refer to in Appendix C.3. It should be emphasized that during normal operating conditions, since by design, a conical scanner’s V- & H-pol antenna planes stays aligned with the plane of incidence as it changes in scan angle that the PR effects are negligible for small PRAs.

The Radiative Transfer Model (RTM) used to accomplish this goal uses a combination of what the XCAL Science Team & RSS uses for their analysis. The RTM used for this research was provided by Dr. Wesley Berg of Colorado State University whereby the atmospheric absorption coefficients are calculated using Rosenkranz models for water vapor [27], cloud liquid water [28], $O_2$ [29], and nitrogen absorption [30] in the atmosphere; and all models are used among the entire XCAL team. This RTM incorporates the RSS ocean surface emissivity model [31] that is a function of a wide range of ocean surface parameters, including azimuthal wind direction,
which is important for this analysis, since wind direction component is not negligible because the use of instantaneous V- & H-pol observations of the instrument; hence, differences of a couple of Kelvin can significantly impact the results.

The environmental inputs for the RTM comes are from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis Interim (ERA-I) [32], which is the latest ECMWF global atmospheric reanalysis of the period 1979 to present. The data used for this study are available at 1.5° resolution. There are 29 pressure levels for ERA-I between 1000 and 50 mbar, from which 21 levels are used in our analysis. This data is provided by Dr. Wesley Berg of Colorado State University.

After applying the EIA & PRA corrections using radiative transfer theory as defined in Eqn. (9.1) all dependences on EIA and should be mitigated if not fully removed. An example of this correction for 10.65 GHz, DSCMs 2 & 5, is shown Figure 9.4 for the geolocation of the Q value before and after correction, Panel (a) & (b), respectively. This figure is similar to Figure 9.3 except that the observations are bounded by 10° EIA. The correction for the X-band channel was chosen because this is the most dependent on ocean surface emissions, EIA & PR effects compared to the other channels. Notice in (a) that the red Q values are 3 Kelvin, that is V-pol is greater than H-pol by this amount, which is dominated by EIA effect that which is depicted in Panel (c). Also, notice on the edges that Q is a negative number, whereby these are influenced by the high EIA and PR, as is shown in panel (c) & (d), respectively. To address the EIA & PR dependence, Figure 9.5 shows the level of corrections with respect to EIAs (panels in left
column) & PRAs (right column). For all panels the blue points are the scattered data set (all ocean scenes for DSCMs 1-10 that are no greater than 10° EIA) and the red error bars represent 1σ about the mean where they are binned averaged in bin sizes of 0.2 & 2 degrees for EIA & PRA, respectively. Notice in the upper left panel that the Q variation increases as EIA increases, but is then significantly mitigated in the lowest left panel. Also, the upper right panel shows a high correlation of Q to PRA which is then decorrelated in the lowest right panel. This figure is another representation that the correction is removing any dependence on EIA & PRA. For the rest of the channels of this same representation refer to in Appendix C.3; where it should be emphasized that for all channels the dependence on EIA & PRA are mitigated.
Figure 9.4: Panels (a) & (b) are the geolocation of Q before and after correction, respectively. Panels (c) & (d) show, respectively, the corresponding EIAs & PRAs.
Figure 9.5: Dependence on EIA (left columns) & PRA (right columns) for different stages of the corrections for 11GHz. The blue points are the scattered data set and the red error bars represent 1σ about the mean where they are binned averaged in bin sizes are 0.2 and 2 degrees for EIA & PRA, respectively. The “Diff” value in the title is the difference between first and last red point of each series.

It should now be noted since the rest of this analysis will depict results as a function of scan angle and to help relate back to the results within Chapter 8 that a scan angle of zero is approximately scan position 104 for the 85.5 GHz channels and positions 52 & 53 are symmetrical about zero for the rest of the channels. With that said, the 11GHz results for all DSCMs is depicted in Figure 9.6, where panel (a) represents the uncorrected Q parameter which has a concave feature because of the EIA & PR effects. Panel (b) shows the corrected Q
whereby the curves are flattened and collapsed on top of each other. Figures similar to this for the other frequencies are in Appendix C.3. Figure 9.7 is similar to Figure 9.6 but depicts the results with all data for all maneuvers averaged together. This figure is of significance these are the final results of the relative calibration between orthogonal channels (V- & H-pol) over ocean. Also, since this entails information on the relative calibration this information can be used to aid the properly offsetting of the biases between channels for the scan angle analysis that was covered in Chapter 8. For example, take the green curve that represents 37 GHz, from scan angle -11.9 to +11.9 degrees, a scan position of 43 & 62, Q differs by 1 Kelvin, and from the along-scan analysis (Chapter 8) that there was relative along-scan bias between the two channels. Finally, the corresponding mean Q & 1σ variation for each of these relative calibration is given in Table 9.1 and is stable over the limited scan angles as is depicted in Figure 9.8.
Figure 9.6: $Q$ at 10.65 GHz for DSCMs 1-10 before and after correcting for EIA & PR effects, panel (a) & (b), respectively.
Figure 9.7: Similar figure to Figure 9.6 but averaging all maneuvers with respect to each channel.

Table 9.1 Relative Calibration Values for Ocean Analysis. $<Q>$ and $\sigma$ are in Kelvin.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>$&lt;Q&gt;$ / $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.65 GHz</td>
<td>0.75 / 0.66</td>
</tr>
<tr>
<td>19.35 GHz</td>
<td>0.24 / 0.78</td>
</tr>
<tr>
<td>37.00 GHz</td>
<td>0.40 / 0.89</td>
</tr>
<tr>
<td>85.50 GHz</td>
<td>1.03 / 1.18</td>
</tr>
</tbody>
</table>
Figure 9.8: This is a similar Figure as Panel (b) of Figure 9.7 but with error bars representing 1σ about the mean for a given scan position.

9.2 Land Analysis

Initially, the Second Stokes analysis over land was to have an EIA cutoff of 20°; however, after analyzing the data it became obvious that the EIA affected the results which could not be corrected for since land radiative transfer theory for these cases is difficult and out of the scope of this research. It should also be stated that the lower the frequency the more sensitive it is to polarized scenes such as rivers, lakes, wetlands, and high soil moisture areas. Unfortunately, there were only 4 nadir-looks, Nadir-Look 1, 3, 4, 6, that observed enough land to encompass
the desired swath so to properly perform this analysis. Figure 9.9 shows the geolocation of the Q values over South America and Africa for all channels with these contaminated areas over land represented by red and blue Q values. For example near the west coast of South America, within the Andes Mountain Range notice the distinct orange to red areas (\(T_{A,V} > T_{A,H}\)). This bright spot is Salar de Uyuni, the world’s largest salt flat. Another but less intense area is over Africa where the Sua (Sowa) Pan, located in Botswana, is another salt flat. These areas are largely polarized scenes, whereby both salt flats can be filled with water depending on the season. Also, the areas that are highly negative are polarized areas due to wet lands or lakes that are present. Since these areas cannot be characterize over land, because in general radiative transfer theory for these cases is difficult and out of the scope of this research, it is required to remove them from this analysis. An example of the removal of these contaminated regions is given in Figure 9.10, where panels (a) & (b) depict Q at 37 GHz before removal, (c) & (d) depict Q at 37 GHz after removal, and (e) & (f) depict the associated EIA which will be of importance for the land analysis.
Figure 9.9: Q for all 4 TMI frequencies for Nadir-Look 1, 3, 4, 6 over South America and Africa.
Figure 9.10: Nadir-Look 1, 3, 4, 6 over South America and Africa where panel (a) to (b) & (c) to (d) are Q for 37 GHz before and after removal of contamination. Panels (e) & (f) are the associated EIA values.

After the removal of the contaminated areas the dependence on the Q on EIA broken down into 5 different EIA cutoffs, 3°, 5°, 10°, 15°, 20° to see the effect of EIA on the statistics. Figure 9.11 represents the average Q for the Nadir-Looks with respect to scan angle, whereby each panel is a frequency and each curve is an EIA cutoff; for plots of individual Nadir-Look refer Appendix C.3. Also, it should be emphasized that the Nadir-Looks are very stable with respect to the ocean analysis. Notice in Figure 9.11 that the surface effects becomes less dominate as frequency increases, which is indicated by the “rolling off” of the Q as the scan angle moves.
away from the mid-scan position, except for the 37 GHz case which is dominated by an Along-scan bias that has yet to be corrected and as was noticeable in for the SS analysis over ocean. In addition to this effect notice the difference in offset Q for a given EIA cutoff, i.e. the offsets between cutoffs are more significant for the 11 GHz than the 86 GHz case. This is indicative of the effects of EIA & PRA on the Q signal that was not corrected, and as frequency decreases that SS analysis over land is not as conclusive as for the ocean case. The importance of the EIA cutoff is further made in Figure 9.12, whereby the correlation between Q & PR is largest for 20 degrees (blue curve) and smallest for 3 degrees (cyan curve).
Figure 9.11: Q for 4 TMI frequencies where each panel contains the average of Nadir-Looks for a given EIA cutoff. The colors are respectively blue, red, green, black, and cyan for 20°, 15°, 10°, 5°, & 3°.
Figure 9.12: The dependence on PRA for 5 different EIA cutoffs: 20, 15, 10, 5, & 3 degrees for 4 frequencies.

In order to compare the ocean SS to land, a cutoff in EIA of 3° is used, since according to the preceding figures the improvement in the decorrelation between EIA & PR was not significant past 3°. In addition for Q over land the mean did not differ much from the 5° case, which means the statistics were converging; i.e., the EIA & PRA effect was becoming negligible over land. Table 9.2 compares the Q values over land and ocean. Recall that theoretically, the results over ocean and land should be same as long as Q is corrected for EIA & PR effects over ocean and the land scene is completely depolarized. With that said, the differences between ocean and land, listed in descending order, are: 10.65, 37.00, 19.35, 85.50 GHz. The 10.65 GHz
frequency is largest because, as was discussed in Section 7.3, the V- & H-pol are misaligned with each other as well as with respect to the multi-frequency feed boresight which the RTM characterizes all RTM inputs relative to the multi-frequency channels. Hence, the results over oceans are significantly higher because of the incorrect EIA & PR that is inputted into the RTM. Hence, the Q value over land is more realistic since these dependences on EIA & PR are insignificant, given the EIA cutoff of 3°. The reason for the 37.00 GHz difference is because the along-scan bias is not removed and the range of scan positions are different between land and ocean. Both are the governing reason for this disagreement. Finally, it should be mentioned that based on recent work from CSU [25] & RSS [26] on the alignment of TMI’s channels it was shown that the reported LOS is different for all channels. Hence, if the corrected LOS is applied it is highly likely that the ocean and land will have better agreement. Finally, it is always possible that TMI receivers can be non-linear; however, it is the author’s opinion that this cannot be determined until the LOS & along-scan bias effects are removed.

Table 9.2: Compares the mean and deviation for Ocean and Land Q for an EIA cutoff of 3°.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>&lt;Q&gt; / σ</th>
<th>&lt;Q_{Ocean} &gt; - &lt;Q_{Land}&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ocean</td>
<td>Land</td>
</tr>
<tr>
<td>10.65 GHz</td>
<td>0.78 / 0.67</td>
<td>0.06 / 0.83</td>
</tr>
<tr>
<td>19.35 GHz</td>
<td>0.27 / 0.82</td>
<td>-0.00 / 0.74</td>
</tr>
<tr>
<td>37.00 GHz</td>
<td>0.57 / 0.93</td>
<td>0.15 / 0.52</td>
</tr>
<tr>
<td>85.50 GHz</td>
<td>1.08 / 1.20</td>
<td>0.96 / 1.21</td>
</tr>
</tbody>
</table>
CHAPTER 10: MAIN REFLECTOR EMISSIVITY

Recall that TMI was a modification of the SSMI design with the addition of a second feed (and receivers) for the dual polarized 10 GHz channel. Thus, two feeds illuminate a main reflector whereby the Earth’s brightness scene is reflected and captured by the horns. By design TMI’s reflector, a multi-layer graphite shell with a thin layer of vapor deposited aluminum (VDA), is to be highly reflective at microwave frequencies and therefore non-emissive. However, at on-orbit checkout, it was first acknowledged by Wentz et al. [11] that TMI brightness temperatures were un-expectantly warm, and it was hypothesized that that the MR is emissive. Later it was conclusively determined that the reflector was emissive during inter-satellite comparison with the WindSat radiometer by Gopalan [4]. Recall in Section 4.1 that radiation that is incident upon the surface of a solid (or liquid) substance will result in a certain fraction being absorbed (emitted) and the remainder reflected, i.e., an emissive reflector will partially reflect and emit a portion of energy at its physical temperature. Hence, TMI’s emissive reflector can be defined by two terms, the reflective and emitting part of the signal:

\[ T_{A,Erroneous} = T_A \cdot (1 - \varepsilon) + T_{Phy} \cdot \varepsilon \]  \hspace{1cm} (10.1)

where \( \varepsilon \) is the emissivity of the reflector, \( T_{Phy} \) is the physical temperature of the reflector’s surface that the feed horn illuminates and \( T_A \) is the brightness scene reflective component, i.e., the desired signal. \( T_{A,Erroneous} \) has a time varying element because the \( T_{Phy} \) varies with an orbital cycle over the thermal environment of the instrument. For more recent radiometers, WindSat
and GMI, temperature sensors on the back of the reflector can accurately represent $T_{phy}$; however, for TMI there is no such sensor. It is for this reason that a more convoluted means is required to solve for the emissivity of the reflector using DSVs. This chapter concentrates on determining the TMI MR emissivity using the full DSV along with physically based methods that depend on feed radiation patterns as they sweep over the Earth and is discussed in this and succeeding sections.

Before proceeding further, it is prudent to define spillover, which is specific to a reflector antenna system. Spillover results because the feed radiation pattern extends beyond the subtended solid angle of the reflector. In other words spillover is the portion of energy collected by the feed pattern outside of the reflector solid angle, and this angular region (that a feed horn pattern does not illuminate the reflector) is defined as the spillover region. Figure 10.1 and Figure 10.2 illustrate the spillover region (SR) for TMI from a side and front view, respectively that extends to ±90° from the horn boresight. Beyond this region (i.e., the back hemisphere) the collected radiation is negligible.
Figure 10.1: Representation of the spillover region for TMI (side view).
Figure 10.2: Representation of the spillover region for TMI (front view). The blue circle is the the face of TMI’s main reflector.
To obtain Eq. (10.1), which neglects spillover, one must model the spillover term; therefore, a set of equations must first be defined. Modifying Eq. (4.6) for a hemispherical feed horn illuminating a reflector and ignoring back lobe contributions and diffraction effects at the reflector rim is defined as:

\[
T'_A = \frac{\iint T_{\text{B,MR}}(\Omega) F(\Omega) d\Omega}{\iiint F(\Omega) d\Omega} + \frac{\iint T_{\text{B,SR}}(\Omega) F(\Omega) d\Omega}{\iiint F(\Omega) d\Omega}
\]  

(10.2)

where on the right side of the equation, the first term is the antenna temperature contribution from the main reflector and the second term is the contribution from the spillover region. Eq. (10.2) can be redefined as:

\[
T'_A = T'_{A,MR} + T'_{A,SR}
\]  

(10.3)

where the two terms on the right side are the same as defined in Eq. (10.2). It should be noted that \(T'_{A,MR}\) is equal to \(T_{A,\text{erroneous}}\) for an emissive reflector (the objective of this section), and \(T'_A\) is obtained from the reconstruction method as discussed in Chapter 6. Obtaining \(T'_{A,SR}\) and \(T'_{A,MR}\) is discussed in Sections 10.1 to 10.2 and in Section 10.3, respectively.

### 10.1 Brightness Temperature Map and Simulation

As was acknowledged in Section 6.3, during the portion of the inertial-hold maneuver, the spillover region of the feed pattern illuminates Earth. Thus, the Earth’s brightness temperature affects the reconstructed antenna temperature, which must be removed from Eq.
(10.3) to solve for $T'_{A,MR}$. There were two methods investigated for removing the spillover effect, and both involve simulating the Earth’s brightness temperature. Method-1 involves radiative transfer modeling with known environmental parameters from numerical weather prediction models (NWP) that is used within XCAL [33], and method-2 is an empirical relationship of polarized brightness as a function of frequency and EIA. From a practical matter, the method used must be: consistent for all DSCMs; performed over land and ocean, and performed in a timely manner. Unfortunately, for Method 1 only ERA-I & MERRA environmental data exists to the TRMM launch (1998) and the data quality could be significantly different compared present NWP in 2014. Further, based upon the effort required to implement the ancillary data, Method 1 was abandoned and Method 2 was used for obtaining the $T'_{A,MR}$ using the following:

1) Create a background $T_A$ map of Earth.

2) Project the primary pattern on the Earth $T_B$ Map, space, spacecraft and instrument with the proper assignment of $T_B$ for a given radiation pattern angle for Eq. (10.2).

3) Vary $T'_{A,MR}$ until $T'_A$ matches the reconstructed $T_A$ that was obtained in Section 6.1.

In Step 1 determining the $T'_{A,MR}$ requires creating a brightness temperature map of the Earth for each given TMI channel. The $T_A$ map uses ±2 days about the DSCM set and are gridded globally and spatially in 1 x 1° degree resolution. Each map is broken up into temporal windows as a function of solar hours since local time plays an important role in the intensity of the Earth’s radiation. Each map is restrained or broken up into 6 hour durations with a three hour
overlap for each window, i.e., the solar mean time (SMT) windows are defined as: 0-6, 3-9, 6-12, 9-15, 12-18, 15-21, 18-0, and 21-3 hours. Refer to Figure 10.3 for an example of a 10 GHz V-pol $T_B$ map for all SMT windows.

These maps are used to assign Earth brightness ($T_B$) in the spillover region and to derive the empirical $T_B$ relationship between $T_B$ and EIA. The assumption for the empirical method is that since the spillover region field of view (SFOV) that illuminates the Earth is so large in area that the highly temporal variations of $T_B$ due to moving weather systems are averaged out. Hence, the averaging of ±2 days properly represents the SFOV being simulated. An example of 3 SFOV contours that intersects the Earth are shown in Figure 10.4 whereby the red lines represent the SFOV at the limb of the Earth and feed pattern cut-off. Note at scan 751 the SFOV is projected as a full circle; this is because the spacecraft is oriented in such a way that the feed horn is aligned along the geodetic vector (think of it as a flash light that is pointed directly at the ground). For the other scans the SFOV is not a full circle because the feed pattern is limited to 90° of the feed boresight, i.e., an angular cut-off of the pattern.

Since the SFOV sweeps over the Earth during the DSCMS, the radiation pattern will have numerous EIA values ranging from 0 to 90° as it intersects the Earth as shown in Figure 10.5 where dark blue represents EIA angles of 0° and red approaches 90°. The first step to simulating these TAs is to assign a given point of the pattern that intersects the Earth from the $T_A$ Maps. Once assigned a temperature it is translated based on the EIA of the pattern as it intersects the Earth. This translation is obtained by taking the difference between the $T_A$ map and the gridded
TMI observations as the LOS veers off and onto the Earth. Refer to Figure 10.6 & Figure 10.7 for an illustration of the collocated points over ocean and land, respectively. DSCM Set 1 and 2 with a polarization rotation angle less than 10° was used to derive this relationship. Figure 10.8 shows the derived relationship or the offset in $T_A$, the difference between $T_{A,Map}$ and the MR observations ($\Delta T_A$ refer to Eqn. (10.4)), for all channels over land and ocean, upper and lower panels, respectively. Figure 10.9 depicts the flowchart of the empirical method just described. To assign/simulated a specific $T_A$ value for a given angle within the SFOV is defined in Eqns. (10.4) to (10.5):

$$\Delta T_A = T_{A,Map,LOS} - T_{A,EIA,LOS}$$ \hspace{1cm} (10.4)$$

$$T_{A,Spillover} = T_{A,Map} - \Delta T_A$$ \hspace{1cm} (10.5)$$

where $\Delta T_A$ is the offset with respect to the nominal (EIA of 53°) $T_A$ that is due to the change in EIA. $T_{A,Spillover}$ is the translated temperature which is a function of EIA that was referred in the previous paragraphs.
Figure 10.3: Earth brightness at 10 GHz V-pol for DSCM Set 1 in eight solar mean time (SMT) windows.
Figure 10.4: Spillover IFOV’s on surface for DSCM 3 at different antenna scans.

Figure 10.5: Geolocation of the feed, without obscuration of the TMI reflectors for DSCM 6. The colorbar represents the EIA (0 to 90°).
Figure 10.6: TMI MR LOS during DSCM 1 over ocean that are gridded in 1°x1° boxes. The lower panel is the actual calibrated $T_A$ during the maneuver and the upper panel is the collocated Nominal $T_A$ map.

Figure 10.7: TMI MR LOS during DSCM 1 over land that are gridded in 1°x1° boxes. The lower panel is the actual calibrated $T_A$ during the maneuver and the upper panel is the collocated Nominal $T_A$ map.
Figure 10.8: Derived relationship or the offset in $T_A$, the difference between $T_{A,Map}$ and the MR observations for all channels over land and ocean, upper and lower panels, respectively.

Figure 10.9: Empirical method flowchart for deriving $T_B$ to EIA was derived.
The result of the simulation of TBs is shown in Figure 10.10 for 4 scan positions at 10GHz V-pol for DSCM 6, which is similar to Figure 10.5. The simulated antenna pattern was created using 72 x 42 angular elements (elevation and azimuth dimension). Notice, for over ocean, low EIA values are radiometrically cold relative to the outer rings. This is because of the specular Fresnel reflection that was previously represented in Figure 5.6. Also note the T_B points over land decrease as EIA increases because the atmospheric path length becomes longer resulting in greater absorption and also a secondary effect that the EIA’s have passed the Brewster angle.

![Figure 10.10: Simulated feed illumination pattern (no obstruction from the TMI reflectors) geolocated onto the Earth during DSCM 6. This figure contains the same points as was shown in Figure 10.5.](image)

Previous examples of the horn pattern where shown whereby the 72 x 42 points of the radiation pattern that intersect the Earth did not contain obscuration of TMI’s reflectors or
TRMM spacecraft. Accounting for these is absolutely necessary in order to simulate the overall TA. Appendix E provides details on how the obscuration of the feed was determined. A projection of the obscured pattern is shown in Figure 10.11 whereby the obscured objects (dark blue that is low TB) are the TMI MR and CSR and TRMM’s aft structure “Dog house” and high gain antenna (HGA). A zoomed-in image of this is within the Appendix E.

Figure 10.11: Similar figure as Figure 10.10 but with the points but with the binary mask of feed horn obscuration from the TMI instrument and TRMM spacecraft applied.
10.2 Simulating TMI Spillover

After developing a method on simulating brightness temperatures for the spillover region the next step is to apply the feed horn pattern (primary pattern) weights to all TMI channels where the reconstruction of $T_A$ is possible. Fortunately, in [10] an image of 10.65 GHz pattern is present and was used within this analysis which is shown in Figure 10.12. Unfortunately, this was the only pattern present since the TMI CDR was for updated or new features added to the pre-existing SSM/I instrument specifically the 10.65 GHz feed horn. After a comprehensive search of existing documentation, the multi-frequency primary patterns were not obtainable. The second option used was to estimate the radiation pattern based on spillover coefficients that were obtained from TMI’s outdoor antenna test range report [23] which is listed in Table 10.1.

<table>
<thead>
<tr>
<th>Channel</th>
<th>19.35 V</th>
<th>19.35 H</th>
<th>21.3 V</th>
<th>37.00 V</th>
<th>37.00 H</th>
<th>85.5 V</th>
<th>85.5 H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spillover Coefficient</td>
<td>2.18</td>
<td>2.25</td>
<td>2.43</td>
<td>1.25</td>
<td>1.23</td>
<td>1.21</td>
<td>1.08</td>
</tr>
</tbody>
</table>

Table 10.1: Spillover Coefficients for the multi-frequency feed horn.
Figure 10.12: Radiation Pattern for the 10.65 GHz V-Pol

The problem with obtaining a pattern in this manner is that more information about the feed dimensions and features is required to simulate it in any microwave software package, which is not available. In addition the method used to calculate the spillover coefficient is not documented. Hence, the simulation of the feed pattern for this research was restricted to making numerous assumptions.

1. The feed horn gain is constant for a given elevation angle of the feed’s boresight (pattern symmetry).
2. The method used to obtain the spillover coefficient, from [29], was the same as was calculated for the X-band feed as is shown on page 3-57 of [10].

3. The pattern in power ratio form is Gaussian.

According to [10], the X-band spillover coefficient is calculated using the feed pattern and at the feed’s off boresight angle of 30°; even though based on figures within [10], Appendix E reflects that the boresight does not exactly intersect the center of the reflector. It should also be noted that the spillover coefficient is different between [10] & [23] which adds uncertainty on how spillover coefficients are determined. Finally, the red curve (10.65 GHz V-pol) within Figure 10.13 which is was obtained from [10] & is the pattern that is used within this analysis.
Figure 10.13: Depicting the radiation patterns for a range of TMI channels and that is used within this analysis.
10.3 Calculating TMI’s Main Reflector Brightness Temperature

Once the spillover effect in Eqn (10.3) has been simulated the brightness temperature from the main reflector then $T'_{A,MR}$ can be calculated, which allows for the solving of $T'_{B,MR}$. To reiterate that $T'_{A,MR}$ is the signal of the reflector that is weighted by the feed radiation pattern. Hence, we wish to obtain the $T_B$ value in MR component in Eqn (10.2), i.e., the un-weighted component. Using Eqns (10.2) and (10.3) and specifying the $T_B$ as the Main Reflector signal $T_{B,MR}$ is rewritten as

\[
\frac{\iint\limits_{\text{MR Angles}} T_{B,MR}(\Omega) F(\Omega) d\Omega}{\iint\limits_{2\pi sr} F(\Omega) d\Omega} = T'_A - T'_{SR} \tag{10.6}
\]

The way that this is implemented is that the $T_{B,MR}$ is varied until it equals the right side of the equation. It should be mentioned that this analysis assumes the face of the reflector is of uniform brightness temperature since there is no other way to confirm it is not. Figure 10.14 shows for 10.65 GHz V-pol for DSV 3 the result of this variation of this component to match $T'_A$. Within the figure the blue curve is forced to match the mid-scan position green curve. The red curve is simply shown for comparison of the mid-scan to the edge-of-scan $T_A$. 
Figure 10.14: A time series of the antenna temperature for Edge-of-scan and mid-scan positions, red and blue curve respectively, for 10.65 GHz V-pol during the DSV 3. The blue curve is the simulated $T'_A$, which is forced to match the green curve.

Using the simulated $T'_A$, the associated $T'_{B,MR}$ that was used to equate Eqn. (10.6) is shown in the upper panel of Figure 10.15. The blue curve is the raw data, i.e., the step-like increments that forces Eqn. (10.6) to equate are in 0.2 Kelvin steps. However, this is not a realistic signal so a triangular weighted moving average of size 251 & 501 scans is applied to the raw data, green and red curves, respectively. Notice a 2 Kelvin swing in $T'_{B,MR}$ during this time strongly suggests that this is the result of the reduced surface emission from a “cooling main reflector” during the DSV. Also this hypothesis is supported by measured physical temperatures from the near by located antenna deployment mechanism (ADM, red curve) and Top of the Radiator (blue curve) temperature sensors on the TMI instrument. Thus as expected, while in
eclipse - within the dashed-green lines (scan ~200 to ~1300), both the physical temperatures and the calculated $T'_{B,MR}$ decrease. Hence, the ADM and Top of radiator physical temperatures can be used to predict the physical temperature of TMI’s main reflector. It should be noted that the jump in $T'_{B,MR}$ between scan 900 – 1100 corresponds to the location of the back lobe of the secondary pattern (that is not characterized within this research) passing over land. Therefore, due to the uncertainty of back lobe contributions over these range of scans for all maneuvers, these data are used only subjectively for this analysis. For an explanation of the back lobe during this time refer back to Chapter 8. Finally, a comparison between the $T'_A$ & $T'_{B,MR}$ is presented in Figure 10.16.
Figure 10.15: Upper panel is the time series of main reflector brightness temperature for 10.65 GHz V-pol during the DSV 3. The blue curve are the raw data, i.e., the step like increments that forces Eqn. (10.6) to equate. The red and green curves are simply moving averages of window sizes 501 & 251 scans, respectively. The lower panel curves are corresponding physical temperature sensors on the TMI instrument for the ADM (red) and Top of the Radiator (blue).
Figure 10.16: 10.65 GHz V-pol radiometric temperatures for DSV 3 whereby the blue curve is $T'_A$ for mid-scan and $T'_{B,MR}$ is the red curve.

### 10.4 Understanding Emissivity and Effective Conductivity of a Reflector

As described in equation 10.1, the desired signal to analyze for the effects of reflector emissivity is the time series of the reflector brightness temperature $T_{A,Erroneous}$ during DSV. While the main beam is viewing the cosmic microwave background and after removing the time variable spillover brightness contribution, the change in $T_{A,Erroneous}$ is simply due to the heating and cooling of the physical temperature of the reflector. This analysis depends heavily on previous work by Jet Propulsion Laboratory and University of Southern California on the SSMIS reflector, which will now be discussed in detail.
The Special Sensor Microwave Imager/ Sounder (SSMIS) is a DOD microwave radiometer on the Defense Meteorological Satellite Program (DMSP)'s spacecraft and is of similar design to the SSMI with the addition of sounder channels [34]. It has been determined that SSMIS (F-16 & F17) has multiple calibration errors [35]; specifically, an emissive reflector. In order to understand the emissivity of the SSMIS reflector, a research effort by Swadley et al. [36] measured the effective electrical conductivity of SSMIS reflectors and reflector test coupons using a resonant cavity technique at 7 & 32 GHz. During this study coupons of variable roughness were measured to determine whether or not the effective conductivity varies with surface roughness and results were reported by Brown [37]. The reflection coefficients for horizontally and vertically polarized plane waves, $\Gamma_H$ & $\Gamma_V$, from [38] where by a reflector that exists in free space is defined as:

$$\Gamma_H \approx \frac{\cos \theta_i - \eta_1/\eta_2}{\cos \theta_i + \eta_1/\eta_2}$$ \hspace{1cm} (10.7)$$

$$\Gamma_V \approx \frac{-\cos \theta_i + \eta_1/\eta_2}{\cos \theta_i + \eta_1/\eta_2}$$ \hspace{1cm} (10.8)$$

where

$$\eta_1/\eta_2 \approx \sqrt{\frac{\sigma_{\text{eff}}}{j2\pi\varepsilon_0}}$$ \hspace{1cm} (10.9)$$

where $\theta_i$ is the incidence angle of the wave at the conductor surface (measured with respect to the surface normal), $\eta_1$ & $\eta_2$ is the intrinsic impedance of medium 1 & 2, $\sigma_{\text{eff}}$ is the effective
conductivity of the conductor [S/m], $\varepsilon_0$ is the free-space permittivity [F/m], and $v$ is the frequency in Hz. Using these sets of equation the emissivity for a reflector is defined as:

$$\varepsilon_v \approx \sqrt{\frac{16\pi v \varepsilon_0}{\sigma_{\text{eff}} \sec \theta}} \quad (10.10)$$

$$\varepsilon_h \approx \varepsilon_v \cos^2 \theta \quad (10.11)$$

where $\varepsilon_v$ & $\varepsilon_h$ are the emissivity of a reflector for V- & H-pol. These equations are simplified because the main reflector is viewing a non-polarized scene, i.e., signal incident on the reflector face is a non-polarized so the angle of incidence has no effect on the emissivity; hence, there is no difference between $\varepsilon_v$ & $\varepsilon_h$. Using Eqns (10.10) & (10.11) the emissivity of TMI’s reflector during the DSV simplifies to:

$$\varepsilon \approx \sqrt{\frac{16\pi v \varepsilon_0}{\sigma_{\text{eff}}}} \quad (10.12)$$

Using Eqns (10.12) & (10.1), whereby $T_A$ will be changed to $T_B$, with conjunction that $T_B$ during DSV is a known scene with constraints of other knowns will allow the estimation of the TMI reflector emissivity. It should be re-iterated that this analysis assumes the effective conductivity is homogenous about the reflector. Finally, using Eqn. (10.12) for illustration purposes and for TMI channels the emissivity as a function of effective conductivity is represented in Figure 10.17 whereby the black dash lines are two examples of conductivity and there corresponding emissivity values as they intersect the curve. The line to far right, an $\sigma_{\text{eff}}$
value of 36.59 MS/m, is for a surface of pure aluminum and the line to the far left is the measured $\sigma_{\text{eff}}$ from [36] of a SSMIS model bare graphite reflector.

Figure 10.17: Depicting the emissivity response to effective conductivity for TMI frequencies whereby the two black dashed-lines is the effective conductivity of a SSMIS bare graphite reflector and pure aluminum surface, respectively.

10.5 Estimating TMI Reflector Emissivity

Now that the physically-based relationships for a reflector viewing deep space was discussed in the previous section the estimation of TMI’s reflector emissivity can be analyzed. Essentially, from Eqns (10.12) & (10.1) there are two unknowns, the emissivity of the reflector and the physical temperature of the reflector conductive coating. Concerning the former, this change of surface emissivity is a function of frequency, but the relationship is
known if the effective conductivity is known. On the other hand, the physical temperature of
the reflector’s face that is independent of frequency. Using these details it is necessary to
constrain some of the parameters based on a priori knowledge.

Since GPM satellite is in a similar Low Earth Orbit as TRMM and since the GMI antenna
system is of a similar design as TMI, we assume that the physical temperature of the main
reflectors would be similar. Since GMI has physical temperature sensors on the main reflector,
we use these on-orbit reflector temperature data as a constraint for our simulations. The
reason we don’t simply use these temperatures as a direct proxy is because the designs of the
main reflectors are not identical and because the spacecrafts are not in the exact same orbit.
The temperature constraints are discussed in Appendix G; with this said, the temperature range
used within this analysis is 235 – 305 Kelvin in 1 Kelvin steps and the effective conductivity
between 1000 to 36 MS/m in 100 S/m steps.

Before proceeding, we redefine Eqn (10.1) for an emissive reflector whereby the feed’s
aperture radiometric antenna temperature is equivalent to the brightness temperature of the
source it is measuring (an emissive reflector):

\[ T_{B,MR} = T_B \cdot (1 - \varepsilon) + T_{Phy} \cdot \varepsilon \]  

(10.13)

where \( T_{B,MR} \) is obtained from Section 10.3 & \( T_B \) is the cosmic microwave background that ranges
from 2.7 to 3.2 Kelvin for TMI channels. It is this equation that is used to compare a simulated
\( T_{B,MR} (T_{B,Sim}) \) based on the constraints that were just defined in conjunction with Section 10.4
and using all possible combinations of \( T_{Phy} \) & \( \sigma_{eff} \). This comparison between \( T_{B,MR} \) & \( T_{B,Sim} \) is
performed for 10.65 V, 19.35 H, & 37 V channels on a per scan basis. Whereby the minimum residual ($\Delta T_{B,MR}$) is kept and the corresponding $T_{Phy}$ & $\sigma_{eff}$ is used for this analysis. That is the method used is

1. For each scan of a given channel:

   a) Calculate $T_{B,Sim}$ for all combinations of $T_{Phy}$ & $\sigma_{eff}$

   b) Calculate for all combinations $|T_{B,MR} - T_{B,Sim}| = \Delta T_{B,MR}$

2. Average of $\Delta T_{B,MR}$ for 11V, 19H, & 37V channels, $< \Delta T_{B,MR} >$

3. Obtain the minimum Residual $< \Delta T_{B,MR} >$ with respect to scan and record the corresponding $T_{Phy}$ & $\sigma_{eff}$

A mathematically representation of obtaining the minimum residual for a given scan is:

$$Resid_{min} = \min(<\Delta T_{Bset}>_{i,j}, \forall \, i \in \{1, \ldots, 71\}, \forall \, j \in \{1, \ldots, 35991\}, \forall \, s \in \{1, \ldots, t\}) \quad (10.14)$$

where $\Delta T_{Bset}$ is the absolute difference between the referenced $T_{B,MR}$ and the simulated $T_{B,Sim}$ for the 3 $T_{B,MR}$ frequencies, $s$ is scan number, $i$ are the possible $T_{Phy}$ values, and $j$ are the possible $\sigma_{eff}$ values. Figure 10.18 represents the $T_{B,MR}$ (Section 10.3) for 11 V, 19H, & 37 V during DSV 3. Notice the difference between 10 & 19 GHz is less than the difference between 19 & 37 GHz. This is an expected feature between sequential frequencies since 10 to 19 GHz is ~9 GHz
separated whereas 19 & 37 GHz is 18 GHz separated, i.e., a larger step in emissivity which was discussed in Section 10.4.

Figure 10.18: For DSV 3 the brightness temperature (Section 10.3) of the main reflector for 10V, 19H, & 37 V in blue, green, and red, respectively.

Once, the estimated $T_{phy}$ & $\sigma_{eff}$ are determined on a per scan bases analysis, the next step is settling on the mean $\sigma_{eff}$ value. Figure 10.19, for DSV 3, shows the variation between $\sigma_{eff}$ as a function of scan whereby the color is the associated $T_{phy}$ and the minimum residual value for Panel (a) and (b), respectively. Since we must assume that the effective conductivity is constant, as stated in Section 10.4, and Panel (a) show a variation that can range from 7000 S/m the analysis must consider the fact that the constraints in the $T_{phy}$ can bound the data. That
is, Panel (c) depicts temperature sensors which for sake of discussion concentrate on the Top of the Radiator (blue), ADM (red), hot load temperature (HLT, black solid) lines. For the ADM case note that at scan 400 the temperature is warmest compared to the rest of the time series and is at a minimum at the end. Taking this relationship in account for the Panel (a) an upper & lower bound can be created based on the warmest values (beginning of time series) and coldest values (end of time series) which are represented by the two bolded dashed black lines. All \( \sigma_{\text{eff}} \) values within these bounds are averaged together which is represented by the lighter black dashed line. For DSV 3, the mean \( \sigma_{\text{eff}} \) is 6.26 KS/m. Using this value and applying a moving average on \( T_{\text{phy}} \) within the bounded data in Panel (a) provides the estimated \( T_{\text{phy}} \) in Panel (c), black dots. Notice how the envelope of the signal agrees with the rest of the temperatures within the plot, i.e., heating and cooling of the instrument is in strong agreement. It is this time series with the recent estimated 6.26 KS/m value that is used to recalculate \( T_{B,\text{MR}} \) which is shown in Figure 10.20 dashed lines. The solid curves within this figure are the same as in Figure 10.18 for comparison. Notice that there is not exact agreement between all the channels, specifically 10.65 & 37 GHz. It is believed that the disagreement for the 37 GHz channel is because there is an along-scan bias that is not corrected for this analysis. 10.65 GHz difference is possibly due to the fact that the simulated spillover and obscuration are based on the assumption that this feed is located in the same position as the multi-frequency (MF) feed during the scan. The fact that the 10.65 GHz is squinted off the reflector focus in the azimuth plane, this causes the 10.65 GHz beam boresight to be mis-aligned with the other co-
boresighted beams. If this were properly simulated then this residual could change, which will be investigated in future work.
Figure 10.19: Estimated $\sigma_{\text{eff}}$ for each scan where colors are the $T_{\text{phy}}$ and residual, respectively. For both panels the two bold dashed black lines are the upper and lower bounds for estimating the mean $\sigma_{\text{eff}}$ (thinner dashed line). Panel (c) are physical temperatures for Top of Radiator (blue), ADM (red), and HLT (black) solid line, respectively. The black dotted line is the mean $T_{\text{phy}}$ within the upper and lower bounded conductivity in Panel (a).
Figure 10.20: Same as Figure 10.18 except the estimated TB,MR based on mean $\sigma_{eff}$ and $T_{phy}$ time series.
Performing the same analysis using DSV 1 to 6, provides the mean $\sigma_{\text{eff}}$ as 6.3 KS/m with a standard deviation of 0.154 KS/m. Figure 10.21 reintroduces Figure 10.17 but with the addition of the recently estimated effective conductivity of TMI’s main reflector. Essentially, this indicates that TMI’s conductivity is one order of magnitude worse than a SSMIS bare graphite reflector. It is the authors opinion that without more information about the two reflectors, specifically, the differences in the reflector composite graphite materials that this is an acceptable conductivity value.

In support of the above estimation of TMI conductivity from this dissertation, note the reasonably good comparison in Figure 10.22 between the emissivity for TMI’s channels using our $\sigma_{\text{eff}}$ value of 6.3 KS/m (red curve) and the independent estimates (blue curve) from Wentz et al. [11]. Since the Wentz analysis is totally independent (being derived based on intersatellite $T_8$ comparisons with SSMI), only estimates between 19 and 86 GHz can be directly compared. Note that Wentz predicts nearly constant emissivity with frequency that causes the relative agreement to deteriorate.
Figure 10.21: Same as Figure 10.17 but with the addition of the recently estimated effective conductivity of TMI's main reflector.
Figure 10.22: Emissivity for TMI channels based on the mean $\sigma_{\text{eff}}$ of 6.3 KS/m (red) and RSS' (blue) values from [11].
CHAPTER 11: CONSOLIDATING THE RESULTS

Chapters 7 through 10 went into detail on methods of calibrating TMI using portions of TRMM’s inertial hold DSV’s. Even though there is additional work that remains to be done to finalize the calibration of TMI, consolidation of the results will be discussed next for clarification.

Chapter 7 discussed on how to estimate TMI’s beamwidth and boresight by utilizing the sharp $T_B$ contrast of Earth and space. The estimation of the beamwidth was broken up into using just the mid-scan and using a range of scan positions. Both results provided similar beamwidths but the analysis that used the range of scan positions is considered the final estimated BW which is summarized in Table 11.1. Whereby, the largest disagreement between estimated BWs from this research and pre-launch numbers are up to 0.27° for CDR at 10.65 H and 0.12 for numbers from TRMM’s sensor package [1] (also tagged as CSU). This analysis does not depend on errors from results from the existing chapters.

The estimation of TMI’s MB boresight utilizes the same sharp transition in $T_B$ as for the BW analysis. Even though this research is ongoing, it was shown that the relative differences in the MF & X-band feeds do exist and that boresight offsets from CSU & RSS mitigate these relative differences; however, an absolute offset using this analysis can only be obtained if the offset are in the instrument’s coordinate system which is discussed further in Section 12.1.
Table 11.1: Estimated beamwidth using a range of scan positions.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10.65 V</td>
<td>3.75 / 0.21</td>
<td>3.68 / 3.95</td>
<td>0.07 / -0.20</td>
</tr>
<tr>
<td>10.65 H</td>
<td>3.68 / 0.46</td>
<td>3.75 / 3.95</td>
<td>-0.07 / -0.27</td>
</tr>
<tr>
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<td>1.87 / 0.06</td>
<td>1.90 / 1.90</td>
<td>-0.03 / -0.03</td>
</tr>
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<td>1.88 / 1.90</td>
<td>-0.08 / -0.10</td>
</tr>
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<td>-0.01 / -0.01</td>
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<td>1.08 / 0.03</td>
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<td>-0.08 / -0.08</td>
</tr>
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<td>1.00 / 1.00</td>
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</tr>
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<td>0.12 / 0.09</td>
</tr>
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<td>0.18 / 0.16</td>
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</table>

Chapter 8 discusses the along-scan bias during the DSV for maneuvers 1-10. Due to the unwanted noise from Earth into the feed spillover regions, the emissive reflector changing MR signal and residuals within the reconstruction of $T_A$ only a relative along-scan bias was obtained. That is, for a given scan the minimum value is subtracted from all scan positions within that scan. With this said, it was found that there is very good agreement between this research and the post-launch results of Wentz et al. [11] except for at the edge-of-scan, which can vary as much as 0.5 Kelvin. In addition to these findings, it was realized that the antenna back lobe
produces spillover emissions was as high as 1-2 Kelvin depending on the channel. This is a source of error for the analysis for determining TMI’s MR emissivity.

The Second Stokes using a nadir-look (Chapter 9) introduced a new way of providing a relative calibration of an on-orbit microwave radiometer. The analysis was broadened to increase a range of EIAs, less than 10° & 3° for ocean and land, respectively, so to increase the amount of data for statistical purposes. It was shown that this analysis reflected differences in the ocean and land for the 10.65 & 37.00 GHz channels because of the boresight misalignment and along-scan bias that exists, respectively. Hence, the agreement between ocean and land should improve if these errors are taken into account. Overall, the highest Q, disagreement between V & H, is 1.0 K for 85.5 GHz which so happens to have the best agreement between land and ocean Q values.

The determination of the emissivity of TMI’s main reflector (Chapter 10) required an extensive amount of work so to remove spillover effect from Earth and obscuration of the feed’s radiation pattern including the simulation of the feed’s radiation pattern. With this said, the emissivity of TMI is determined to be worse than the emissivity of a SSMIS model bare graphite coupon whereby the effective conductivity of TMI is estimated to be 6.3 KS/m. Even though this was an expectantly low value, the emissivity values estimated within this research was in relatively good agreement with values from Wentz et al. [15] but this agreement progressively degraded for the higher frequencies.
Each of these methods when combined with the future work on boresight pointing and modifications in the estimation of the MR emissivity will be a physically based method of calibrating TMI using calibration attitude maneuvers.
CHAPTER 12: CONCLUSIONS

Spaceborne microwave radiometers provide invaluable global environmental observations for numerical weather predictions and geoscientific research into the understanding the climate of our Earth. For the climate applications, scientists require multi-decadal time series of observations, to infer weak climatic changes in the environment. Unfortunately, most weather satellites and microwave instruments have lifetimes much less than 10 years. This necessitates that two identical microwave instruments (original and replacement) have a significant overlap for inter-comparisons to remove biases that could be misinterpreted as climate change signals. Also, once in-orbit the instrument can have calibration errors that were not realized prior to launch or that may have developed as the “aging process” once in-orbit. Moreover, frequently replacement microwave instruments are not identical (e.g., incorporate newer technology or different suppliers) and this makes the inter-comparison even more difficult to remove biases based upon some consistent standard.

Thus, common methods for post-launch calibration of these instruments frequently depends on theoretical radiative transfer models (RTM), which require temporally and spatially collocated ancillary environmental data to simulate a reference brightness temperature. Another method, which uses the RTM procedure, is inter-satellite calibration whereby the target instrument is calibrated to the reference instrument. The disadvantage of this method is that the source instrument (calibration transfer standard) should be stable and vetted of all calibration errors. In both methods mentioned, it is common practice to have at least one year of data so to properly remove residual effects in the ancillary data and instrument being
calibrated. Alternatively, a set of satellite maneuvers (referred to as Calibration Attitude Maneuver) can provide early and much needed insight into the performance of the instrument since it does not depend on RTM as heavily as previously mentioned methods.

This dissertation revisited, developed and documented procedures for post-launch calibration of spaceborne microwave radiometers utilizing preexisting and new calibration attitude maneuvers. Analyses of the TRMM’s deep space calibration maneuvers (inertial-hold) were performed to develop these alternate on-orbit radiometric calibration procedures. Afterwards, these were used to perform an absolute radiometric calibration of the TRMM Microwave Imager so to be incorporated for the upcoming and final processing of TMI’s 1B11 (Version 8). Ten DSCMs from 1998 & 2014 were used and shown to have consistent results within these analyses. There are five sets of analyses that were documented for calibrating a microwave radiometer:

1. Antenna Beamwidth
2. Antenna Beam Boresight Pointing
3. Along-scan Radiometric Bias
4. Main reflector emissivity
5. Second Stokes Radiometric Bias (using a Nadir-Look comparison)

The antenna beamwidth and boresight pointing utilizes $T_B$ observations during transition of the antenna pattern across the well-defined Earth’s limb. In this series of measurements, the sharp contrast in $T_B$ between Earth and space allows the estimation (deconvolution) of the
antenna pattern to characterize the beamwidth and location of the pattern maximum (boresight of the beam). Results presented in this dissertation for BW are considered conclusive; but the boresight is a work in progress, since it is the author’s overall goal to provide an absolute offset in boresight instead of relative offset between beams.

Both the TMI along-scan radiometric biases and main reflector emissivity investigations were performed, while both the main beam and the cold sky mirror was viewing the cosmic microwave background (deep space) and the radiometric antenna temperature was known from the two-point radiometer transfer function. Later during the inertial-hold maneuver, the cold sky mirror intercepted Earth; and it was during this portion of the maneuver that two methods were developed (under this dissertation) for reconstructing the antenna temperature that are in good agreement with each other.

Due to many sources of unavoidable noise and residuals in the reconstruction of $T_A$, the along-scan bias analysis was forced to provide a relative along-scan bias, i.e., not an absolute bias, which is compared to the homogenous non-polarized CMB. This was done on a per scan bases from which the minimum value within the scan is subtracted for all scan positions within that scan.

The determination of TMI’s main reflector emissivity became a convolved procedure due to same sources of unavoidable noise as for the along-scan bias. Essentially, the feed spillover region (beyond the main reflector) that illuminated the Earth had to be removed before the emissive antenna signal could be analyzed. The desired emissive main reflector
signal is a time-varying brightness bias that is the product of the unknown (but constant) reflector emissivity and the unknown reflector physical temperature (not measured).

The spillover illumination of Earth was simulated using an empirical based method, developed within this research, which was derived from TMI observations during nominal operation and during DSCMs. During this analysis, we used an available software package provided as an educational resource, namely; Systems Tool Kit (STK) orbital analysis and 3D geometry visualization by AGI [21]. Obscuration of the feed (which was used to determine what portion of the feed horn radiation pattern illuminated the parts of TMI, the TRMM spacecraft, and Earth) required the conversion of the TRMM thermal model into a format that STK could use. Once the model was converted and using STK, a binary mask was created in the spherical coordinate system whereby regions (that were not obscured by TMI and TRMM) illuminated either space or Earth radiances. Finally, the feed radiation pattern was assigned its corresponding spillover brightness temperature collection (and this effect was subtracted) to obtain the total brightness temperature of the emissive reflector. This procedure was performed for a range of TMI channels; and in conjunction with emissivity studies from JPL and USC [36, 37], an effective conductivity value for the TMI main reflector was obtained that allowed the emissivity for a given channel to be calculated.

The second stokes analysis (using a nadir-look) is a new method developed during this research that provides a relative calibration between V- and H-pol channels of the same frequency. Essentially, using Fresnel Reflection relationship for a linearly polarized signal, for an EIA of 0° the Second Stokes Parameter (Q) should theoretically be zero Kelvin. Any bias present
is due to calibration errors or misalignment of main beams’ boresight. Results (for channels where Q did not equate to zero) were due to errors that were evident in the other procedures discussed within this research.

Finally, all goals were met within this dissertation, i.e., documenting preexisting and new methods that can be used for future microwave radiometric missions. Moreover, the TRMM Microwave Imager calibration was revisited by using all procedures that have been put forth.

12.1 Future Work

Future work will focus on using all TRMM DSCMs, i.e., methods developed within this research will be applied to the 2014/2015 maneuvers whereby providing both a beginning-of-life and end-of-life radiometric calibration of the instrument that can be used to assess aging effects over the ~17 years of on-orbit operation. In addition to this, an absolute offset in boresight angles for TMI will be obtained whereby the analysis will concentrate on the LOS with respect to the instrument’s coordinate system. Once the absolute boresight is determined, a reanalysis of the second stokes will be performed to determine how it affects this dissertation’s results for land and ocean scenes.

Moreover, the estimation of the emissivity of TMI’s main reflector will be further analyzed:

- If obtained, use the true feed radiation patterns for the multi-frequency feed
• Confirming the spillover coefficient by using STK and the true feed radiation patterns

• Apply the squint angle of the 10.65 GHz for the projection of the spillover and obscuration of the feed pattern

• Investigate if polarization rotation effects for sections of the spillover region that illuminate the Earth are not negligible

• Use an RTM with conjunction with environmental parameters from a numerical weather model (ERA-I) instead of the empirical based Earth T_B map over ocean

Finally, once all procedures are finalized the calibration corrections will be applied to the TMI whereby validation using XCAL procedures will be performed.

12.2 Influences

Realizations and influences have come about due to work performed within this research. Take for example the calibration of TMI, essentially, all DSCMs were performed at either 0° or 180° yaw. In order to provide a different time series of the DSCM, i.e., provide different insight into the errors of TMI, it was proposed that a DSCM be performed at a Yaw 90°. This proposal was supported by the TRMM XCAL group and TRMM project management and was implemented by the TRMM operations team project whereby 4 maneuvers were performed on March 25-26, 2015. Analysis and reporting of results using these maneuvers will be encompassed in future work.
Since work on the second stokes using a nadir-look started before the launch of GMI this provided enough time to develop and prove the importance of this maneuver. This CAM was put forth and supported by the XCAL group and then forwarded onto the project. Since the GPM spacecraft design allowed more freedom in the control of its attitude compared to TRMM, the spacecraft aligned GMI’s LOS to nadir, locked in a constant pitch angle, for two orbits each for the different nadir-angles of GMI. This maneuver proved useful beyond what was initially planned.

Finally, due to the reconstruction of the $T_A$ for TMI and the July 2014 TRMM DSCMs, it was recognized that the cold sky mirror deep space radiance scene was also being corrupted by RFI from geostationary satellites. Further investigation revealed that this corruption, albeit less severe, was present since the beginning of the mission [39] which is explained more in Appendix F. Moreover, the methods developed within this dissertation can be applied to most TMI channels since the main beam views a warmer radiometric scene whereby the residuals in the reconstruction methods are negligible; allowing a corrected $T_B$ to be used for retrievals.

12.3 Recommendations

Even though this research concentrated on calibration of a spaceborne conically scanning radiometer, instruments of different design can benefit from the methods that have been documented not excluding airborne instruments, as long as its altitude is high enough so that no atmospheric attenuation is present. A short and selected discussion of which CAMs can significantly benefit a specific instrument is discussed next.
Synthetic aperture radiometers [40] utilize interferometric technology whereby the beam is synthesized based on a specific arrangement of feeds or stick/patches to increase the beam’s resolution. The Hurricane Imaging Radiometer [41, 42] (HIRAD) & SMOS’ MIRAS [43] are two such technologies that can benefit from CAMs. Both instruments are internally calibrated; hence, the DSV for HIRAD channels is homogenous and MIRAS even though is not homogenous is a well-known scene. Moreover, since both technologies synthesize their beams, the utilization of Earth’s horizon for determining their respective beamwidth and boresight would prove an invaluable on-orbit/in-flight confirmation of the instruments specifications.

The Soil Moisture Active/ Passive (SMAP) instrument was recently launched on January 31, 2015. SMAP is an L-Band radiometer/radar that is internally calibrated whereby the sole feed horn illuminates a 6 meter parabolic mesh reflector as it scans 360 degrees [44]. Refer to Figure 12.1 for an illustration. Due to its large size the reflector is made up of metallic-like material that must be folded up during launch, which is then deployed once in orbit. It is for this reason that confirmation of the instrument’s boresight and beamwidth be validated since mesh surface can potentially change its RF characteristics. Also, self-emission of the reflector, back lobe, and spillover confirmation/determination can be done as the main beam views deep space while the spillover and back lobe sweeps over the Earth.
The Compact Ocean Vector Wind Radiometer (COVWR) is an Air Force proof-of-concept technology demonstration that is being designed and built by JPL [45]. It is a low-cost,-mass,-power fully-polarimetric imaging radiometer. What sets it apart from other conventional conically scanning radiometers is that the feed does not rotate as the reflector spins, Figure 12.2. Due to the feed being stationary the signal received is fully-polarimetric as COVWR spins 360°. Since there are no external calibration targets the full-end-to-end calibration is recognized, i.e., the radiometric signal from the reflector to the feed is not captured. Hence, DSV would benefit this instrument as well as utilizing the second stokes analysis.
Finally, it is the author’s recommendation that all future imager/sounder based missions/flights utilize the procedure put forth within this dissertation. By performing these maneuvers during the missions on-orbit check out period can provide early and accurate knowledge of the instruments performance.

Figure 12.2: COVWR Instrument design (Image Source: [45]).
APPENDIX A: A SHORT DISCUSSION ON PREVIOUS DSC MANEUVERS
According to the literature the first proposal for a spaceborne instrument to view space for calibration purposes was the Naval Remote Ocean Sensing System (N-ROSS) Low Frequency Microwave Radiometer (LFMR) instrument, initially set to launch in the early 1990s. J. P. Hollinger recommended to Harris Corp that a deep space calibration would achieve an end-to-end absolute radiometric calibration which is documented in the 1987 Harris Corp. Technical Report [46]; refer to Appendix D.2 for LFMR excerpts from Harris Corp. Technical Report. These proposed maneuvers, for a 10-20 minute duration, would slowly roll the spacecraft 360° relative to its nominally oriented position; allowing the LFRM Main reflector view the CMB. Refer to Figure 12.3 for a cartoon on the maneuver from the report. Unfortunately, due to significant cost overrun the program was cancelled in 1988 and this post-launch procedure was never utilized and not until 1998 did TRMM perform a spaceborne deep space calibration (DSC) maneuver that was eventually used to calibrate a microwave radiometer.

![Figure 12.3: Proposed LFMR DSC maneuver whereby a 360° roll was proposed (Source: [46]).](image-url)
The WindSat instrument on the Coriolis satellite was launched into a polar orbit on January 6th, 2003 with the mission objective being a “proof of concept” to demonstrate that the ocean wind vector be passively measured. WindSat is the first spaceborne fully polarimetric instrument that operates at 6.8, 10.7, 18.7, 23.8, and 37.0 GHz. The 10.7-, 18.7-, and 37.0-GHz channels are fully polarimetric [vertical/horizontal (V/H), ±45° and left-hand (LHCP) and right-hand circularly polarized (RHCP)], and the 6.8- and 23.8-GHz channels are dual polarized only (vertical and horizontal).

Over a 15 month period, to assess the calibration repeatability, an extensive radiometric calibration campaign was put into action where Coriolis performed 8 maneuvers at ±45 degrees pitch, 4 maneuvers at each pitch angle. The ±45 degrees pitch was necessary due to WindSat having a forward- & aft-look and so to address any possible along-scan biases required the spacecraft to pitch in opposite directions relative to geodetic nadir.

In [47] WindSat, during the ~600 seconds of view of cold space for each maneuver, the along-scan bias, biases between orthogonal channels, and cold sky mirror (CSR) / main reflector (MR) emissivity ratios were addressed. It was found the along-scan and and orthogonal channel biases (ΔTB_{orth}) were less than 0.1 K and stable over the 8 maneuvers except for the 18 GHz ± 45° which exhibited a larger ΔTB_{orth} of 0.5 K. The T_B differences between the MR & CSR were on average less than 0.1 K with a max bias of 0.16 K. The overall conclusion of the WindSat campaign was that WindSat met spec.
On October 16, 2002, during the Moderate Resolution Imaging Spectroradiometer (MODIS) lunar calibration maneuver, the Aqua spacecraft performed approximately a 20° roll which allowed the angle between the Advanced Microwave Scanning Radiometer-EOS (AMSR-E) [48] MR boresight and tangent to the Earth to be ~3°. The analysis in [22] allowed JAXA to determine the beamwidth (BW) in the azimuth direction allowing the comparison between pre- and post-launch BW values. The method of determining BW was done by differentiating the MR count with respect to azimuth angle. It was found that the disagreement between pre- & post-launch BW were less than 0.31° where disagreement increased with frequency. In addition to the BW comparisons, the MR & CSR $T_A$ differences were analyzed and exhibited very stable biases, 0 Kelvin mean, with only the NEDT of a given channel causing a larger variation.

Finally, it should be mentioned that more recent missions have performed DSCMs. The Aquarius has performed multiple maneuvers since its launch and currently performs these maneuvers monthly. The Global Precipitation Mission performed multiple types of CAMs during the course of this research.
APPENDIX B: GPM MICROWAVE IMAGER
B.1 GMI Instrument Characteristics

The GPM Microwave Imager (GMI) is a thirteen-channel counter-clockwise conically scanning externally calibrated total power radiometer with a diode that injects noise into channels 1-7 (10.65-36.64 GHz) during the warm and cold sky calibration [49, 50]. GMI’s imager channels are: 10.65, 18.70, 23.8, 36.64, and 89 GHz where all frequencies are dual-linearly polarized, with the exception of the 23.8 GHz, which is V-Pol. The sounding channels are at frequencies: 166 (V- & H-Pol) and 183.31±3.0 & 183.31±7.0 GHz where both operate at V-Pol. GMI is a 4-point calibrated total power radiometer whereby two of the points are external targets such that the feed horns sequentially view a blackbody target (warm load microwave absorber) and a Cold Sky Reflector (CSR) that views space as depicted in Figure 12.4. The two additional calibration points take place every other scan whereby a diode injects noise into the receiver while the feeds view the WL & CSR. This multi-point calibration captures the receiver non-linearity which is the first for a spaceborne total power radiometer.

Due to GMI being the calibration transfer standard to the GPM constellation, there was extra consideration and time taken in the design of the instrument in order to guarantee calibration stability, in other words, the GMI design includes some unique features to eliminate problems that have plagued past conical scanners. Previous radiometers such as WindSat [51] and the Special Sensor Microwave Imager/ Sounder (SSMI/S) [34] are known to have direct and reflected solar illumination of the warm load emissive surface [52] & [35] creating a
temperature gradient between the microwave absorber pyramid-like tips and the base which is where the physical temperature sensors are placed. This difference between the temperature sensors, which are to represent the physical temperature of microwave absorbing material and what the feed horn measure radiometrically causes an erroneous reading when obtaining the two point calibration radiometric transfer function. In order to mitigate any possible solar or lunar effects into the warm load, the WL is covered by an aluminum shroud that looks like and is known as the “top hat.” The top hat is lowered into and rotates over a reflective tray known as the “hot load tray.” Refer to Figure 12.5 (left panel) for a depiction of the WL incased in the top hat. Note that if any solar or lunar intrusion were to reflect into the warm load it would require multiple bounces between the top hat rim and the tray thus significantly attenuating the signal before reaching the microwave absorber as shown within the hot load tray in Figure 12.5 (right panel).

GMI is an externally calibrated total power radiometer whereby channels 1-7 & 8-13 are four- & two-point calibrated channels, respectively. All channels are calibrated using the WL & CSR with the addition of noise injected for 10.65 – 36.64 channels for every other GMI scan, i.e., these channels measure cold, cold + noise, hot, hot + noise. An example of a GMI noise source assembly including the noise diode and waveguide coupler is shown in Figure 12.6. An example of a 4-point calibration curve is shown in Figure 12.7 which relates the radiometric counts to the physical temperatures of the calibrated targets. Note how the non-linearity curve differs with respect to the less accurate two-point calibrated curve. In addition to capturing the non-
linearity of the system, the noise diodes allows for a backup calibration should the radiometric transfer function not be obtainable using both the CSR & WL.

GMI’s feed horns are arranged on the feed bench as shown in Figure 12.8, with the 37-GHz conical feed at the focal point of the reflector. This feed configuration results in each feed illuminating a different spot of the Earth but with only two sets of nadir angles, i.e., channels 1-9 & 10-13 are at a nominal nadir angle of 48.5 & 45.36 degrees, respectively. An example of the projected beams is shown in Figure 12.9. Table 12.1 contains important GMI instrument and orbital parameters.

![GMI instrument with the proper calibration targets visible. (Source: [53])](image)

Figure 12.4: GMI instrument with the proper calibration targets visible. (Source: [53])
Figure 12.5: The GMI warm load encompassed within the Top Hat (Left Panel) and a cross section of the hotload (Right Panel) (Left from PPS ATBD, Right from [53]).

Figure 12.6: Noise Coupler for GMI channels 1-7 (Source: [53])
Figure 12.7: Example of the 4-Point Calibration for GMI (Channels: 1-7) (Source: [53]).

Figure 12.8: View from above the GMI Instrument (a) and a photo of the feed bench (b) (Figure provided by David Draper of Ball Aerospace and Technologies)
Figure 12.9: An example of GMI’s IFOV projected on the Earth. (Source: From Calibration book)
Table 12.1 Reference for Important GMI Instrument and Orbital Parameters (Source: PPS GPM GMI L1B ATBD).

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B.2 GMI Along-scan Wiggles

This section contains content from the GMI TIM Meeting June 2014 [54] that was presented by Ball Aerospace.

Figure 12.10: Along-scan bias for radiometric counts vs sample index for all GMI channel.
Figure 12.11: Along-scan Bias for 10 GHz H-pol whereby the high frequency oscillations are the GMI wiggles. The Ball and GSFC curves are pre-launch measurements and the cyan and red are post launch confirmation of the wiggles.
C.1 Beamwidth and Boresight

Figure 12.12: Beamwidth for all TMI channels for Transition 1.
Figure 12.13: Beamwidth for all TMI channels for Transition 2.
Figure 12.14: Beamwidth for all TMI channels during DSCM 2 for Transition 1.
Figure 12.15: Beamwidth for all TMI channels during DSCM 2 for Transition 2.
C.2 Along-Scan Bias
C.2.1 Insignificance of $T_A$ Reconstruction

Since the $T_A$ signal has an unwanted and non-negligible emissive and spillover component during the deep space view the chosen method to analyze the along-scan bias was to subtract out the minimum $T_A$ value with respect to each scan, as described in Chapter 8. The benefit of this normalization essentially nullifies the importance of the absolute value of the reconstructed $T_A$ and so the errors in the reconstruction methods are considered negligible. Refer to Figures in E.1 & E.2 which supports this fact using DSCMs 1-6 for 10GHz V-pol. The upper two panels of Figure E.1 show the reconstructed Gain and Offset (red curve) while the blue curve is the linear interpolation during the DSV by using the valid calibration points just before and after the maneuver. The last panel represents the radiometric antenna temperature using the both methods that were just described whereby the color coding is the same. Note that the difference during the DSV is over 5 Kelvin between the red and blue curve. This would be significant if the along-scan analysis wasn’t normalizing each scan. Figure E.2 compares multiple window sizes from Method 1 and the linear interpolated gain and offset (Simple Recon) for DSV 1 & 4. The Y-axis averages all scan positions and the with respect to the relative scan number during the DSV. Note that the time series shown are DSV only (a subset of the previous figure) and, that differences are less than 0.01 K. This supports that the along-scan bias analysis is independent of any reconstruction residuals that may be present.
Figure 12.16: Upper two panels, respectively, represent Gain and Offset of the RTF using two methods. The lower panel is the reconstructed $T_A$ at mid-scan using the two methods in the upper two panels. Color scheme are same for all three panels.
Figure 12.17: For two DSVs, DSV 1 & 4, the two left panels are the averaged along-scan biases for multiple reconstruction methods. The right panel is an expanded view of DSV emphasizing the negligible differences.
C.2.2 Normalized Along-Scan Bias

This Section contains normalized along-scan biases figures for DSCMs 1-10 for all channels.
Figure 12.18: Normalized $T_A$ for 10.65 GHz Vertical Polarization
Figure 12.19: Normalized $T_A$ for 10.65 GHz Horizontal Polarization
Figure 12.20: Normalized $T_a$ for 19.35 GHz Vertical Polarization
Figure 12.21: Normalized $T_A$ for 19.35 GHz Horizontal Polarization
Figure 12.22: Normalized $T_\alpha$ for 21.3 GHz Vertical Polarization
Figure 12.23: Normalized $T_A$ for 37 GHz Vertical Polarization
Figure 12.24: Normalized $T_A$ for 37 GHz Horizontal Polarization
Figure 12.25: Normalized $T_a$ for 85.5 GHz Vertical Polarization
Figure 12.26: Normalized $T_A$ for 85.5 GHz Horizontal Polarization
Figure 12.27: A 3-dimensional representation of the along-scan bias for DSCM Set 2, all channels. The Y-Axis represents the angle between spacecraft’s +Z axis and geodetic nadir vector (Nadir Spin-axis Angle).
Figure 12.28: A 3-dimensional representation of the along-scan bias for DSCM Set 3, all channels. The Y-Axis represents the angle between spacecraft’s +Z axis and geodetic nadir vector (Nadir Spin-axis Angle).

Figure E.16 depicts the difference in scan angle between the full range of scans to a subset with NSA range of 115° to 145° removed. It should be noted that this analysis was done to see if the region where there was a jump in TA’ was removed and how it would affect the results. On average the differences are less than 0.05 K, peak-to-peak, but are largest for 10H & 19V at a 0.1 K difference.
Figure 12.29: Difference in along-scan bias between using the full range and subset.
C.3 Second Stokes

C.3.1 Figures so to Understand PR

Within this research the Polarization Rotation of a signal which is due to the misalignment between the plane of incidence of the scene and the antenna’s polarized components of the electric fields is generally negligible for spaceborne conically scanning microwave radiometers where the attitude of the space is in very good control. However, due to the orientation of the spacecraft during the Nadir-Look, this misalignment is no longer negligible and must be addressed. Essentially, this misalignment is calculated as the dihedral angle between the plane of incidence (POI) and, for example, the vertically polarized electric field of the antenna. The POI can be defined by the 3 points in 3 dimensional space as 1) the spacecraft position, 2) the intersection of the instruments line of sight as it pierces the Earth and 3) the spacecraft’s geodetic point on the Earth. The antenna electric field is, by design, restricted by points 1 & 2 as previously mentioned and the intersection of instruments spin axis into the Earth; which, for TMI’s case is the spacecrafts +Z vector. Essentially, this misalignment is due to the spin axis and the spacecraft-to-geodetic vector misaligning during the maneuver which is depicted, using AGI’s STK software package, in Figure 12.30. The blue vector labeled Body Z and green vector are, respectively, the spin axis and spacecraft-to-geodetic vector. An example of this using the planes is depicted in Figure 12.31. This is a screenshot above TMI as it views Earth. The yellow bucket, blue circle, and gray structure are the TMI radiator bucket (spin
mechanism assembly), TMI main reflector, and the TRMM spacecraft, respectively. The yellows circle illuminating the Earth is the IFOV at a certain scan position. Now, there are two planes within this figure, the red plane and yellow plane where the yellow plane looks like a yellow line that is slicing through the IFOV. These two planes are the POI and antenna V-pol E-field, respectively. Figure 12.32 is another representation of this but zoomed out so one can see the Earth. Upper three panels are just above TRMM and the lower three as if the viewer is below the Earth’s surface. Finally, an illustration this misalignment is depicted in Figure 12.33 where the reader is viewing from above the instrument projecting 5 IFOVs, black circles, onto the Earth. The solid and dashed lines within the IFOV represents the antenna electric field and what the RTM simulates which is discussed in Chapter 9.
Figure 12.30: A view above TMI whereby the blue reflector is projecting the IFOV on the Earth (yellow). The two planes are pure V-pol plane of the antenna system and the plane of incidence, red and yellow, respectively (using AGI STK software).
Figure 12.31: Similar to the previous figure but with emphasis on TMI’s coordinate system (blue) while the green and white are the geodetic nadir and the scan position projected in the XY plane of TMI’s coordinate system, respectively (using AGI STK software).
Figure 12.32: Similar figure as the previous two whereby the scan position and planes are the same but viewing the spacecraft from different angles (using AGI STK software).
C.3.2 Correcting For EIA and Polarization Rotation

The two effects that must be corrected for, normalized, so to increase the number of observations for the SS analysis are 1) the expected separation in V & H-pol as EIA increases which is due to Fresnel Reflection coefficient and 2) the Polarization Rotation of the signal which is due to the misalignment between the plane of incidence of the scene and the antenna’s polarized components of the electric fields are discussed in this section.
Normalizing $Q$ so to eliminate the EIA dependence is defined as,

$$
Q_{\text{Norm}} = Q_{\text{Obs}} - \Delta TB_{\text{EIA}},
$$

(12.1)

$$
\Delta TB_{\text{EIA}} = TB_{V,\text{Sim}} - TB_{H,\text{Sim}}
$$

where $Q_{\text{Obs}}$ is based on the observed brightness temperatures and $TB_{V,\text{Sim}}$ & $TB_{H,\text{Sim}}$ are simulated TBs using radiative transfer theory.

Normalizing $Q$ using Eqn (12.1) is only valid if the signal being simulated perfectly aligns with the antenna’s electric field and since, for this particular instrument during this maneuver, polarization rotation increases as the scan position deviates from mid-scan. Hence, an additional normalization step must be applied so to remove this effect. Before addressing this additional step a polarized transverse wave with respect to the antenna’s electric field is defined as,

$$
TB_{V,\text{Mix}} = TB_{V,\text{Pure}} \cdot \cos^2(\phi) + TB_{H,\text{Pure}} \cdot \sin^2(\phi)
$$

(12.2)

$$
TB_{H,\text{Mix}} = TB_{V,\text{Pure}} \cdot \sin^2(\phi) + TB_{H,\text{Pure}} \cdot \cos^2(\phi)
$$

(12.3)

where $\phi$ is the polarization rotation angle and $TB_{V,\text{Pure}}$ & $TB_{H,\text{Pure}}$ is the TB that is properly aligned within the plane of incidence. The correction for the PR effect is defined as,

$$
TB_{V,\text{Corr}} = TB_{V,\text{Obs}} + \Delta TB_{V}
$$

(12.4)

$$
TB_{H,\text{Corr}} = TB_{H,\text{Obs}} + \Delta TB_{H}
$$

(12.5)

where, for example, $\Delta TB_{V}$ is defined as,

$$
\Delta TB_{V} = TB_{V,\text{Mix}} - TB_{V,\text{Pure}}
$$

(12.6)

Then setting Eqn (12.6) to be equal to the same parameters using the RTM is,
\[ TB_{V,\text{Corr}} = TB_{V,\text{Mix}} - TB_{V,\text{Pure,Simulated}} - TB_{V,\text{Mix,Simulated}} \]  
(12.7)

and Solving (12.7) for the corrected TB,

\[ TB_{V,\text{Corr}} = TB_{V,\text{Mix}} + TB_{V,\text{Pure,Simulated}} - TB_{V,\text{Mix,Simulated}} \]  
(12.8)

Now that the two normalization or corrections have been defined,

\[ Q_C = TB_{\text{Obs},V} + (TB_{\text{Sim},V} - TB_{\text{Sim},V,PR}) - (TB_{\text{Obs},H} + (TB_{\text{Sim},H} - TB_{\text{Sim},H,PR})) - EIA_{TB} \]  
(12.9)

Which simplifies down to,

\[ Q_C = Q_{\text{Obs}} - Q_{\text{Sim,PR}} \]  
(12.10)

To address the EIA & PR dependence Figure 12.34 to Figure 12.37 shows the level of corrections with respect to EIAs (panels in left column) & PRAs (right column). For all panels the blue points are the scattered data set (all ocean scenes for DSCMs 1-10 that are no greater than 10° EIA) and the red error bars represent 1σ about the mean where they are binned averaged in bin sizes of 0.2 & 2 degrees for EIA & PRA, respectively. Notice the upper left panel that the Q variation increases as EIA increases but is then significantly mitigated in the lowest left panel. Also, the upper right panel shows a high correlation of Q to PRA which is then decorrelated in the lowest right panel. These figures are another representation that the correction is removing any dependence on EIA & PRA. The “Diff” value in the title is the difference between first and last red point of each series.
Figure 12.34: Showing the dependence on EIA (left columns) & PRA (right columns) for different stages of the corrections for 11GHz.
Figure 12.35: Showing the dependence on EIA (left columns) & PRA (right columns) for different stages of the corrections for 19.35 GHz
Figure 12.36: Showing the dependence on EIA (left columns) & PRA (right columns) for different stages of the corrections for 37.00 GHz.
Figure 12.37: Showing the dependence on EIA (left columns) & PRA (right columns) for different stages of the corrections for 85.50 GHz.
Figure 12.38: 10.65 GHz $Q$ as a function of scan position, over ocean, DSCMs 1-10 before and after removing PR & EIA dependences, Panels (a) & (b), respectively.
Figure 12.39: 19.35 GHz Q as a function of scan position, over ocean, DSCMs 1-10 before & after removing PR & EIA dependences, Panels (a) & (b), respectively.
Figure 12.40: 37.00 GHz Q as a function of scan position, over ocean, DSCMs 1-10 before & after removing PR & EIA dependences, Panels (a) & (b), respectively.
Figure 12.41: 85.50 GHz Q as a function of scan position, over ocean, DSCMs 1-10 before & after removing PR & EIA dependences, Panels (a) & (b), respectively.
Figure 12.42: 10.65 GHz Q as a function of scan position for 4 maneuvers and its respective locations over land, Panels (a) & (b), respectively.
Figure 12.43: 19.35 GHz Q as a function of scan position for 4 maneuvers & its respective locations over land, Panels (a) & (b), respectively.
Figure 12.44: 37.00 GHz Q as a function of scan position for 4 maneuvers & its respective locations over land, Panels (a) & (b), respectively.
Figure 12.45: 85.50 GHz Q as a function of scan position for 4 maneuvers & its respective locations over land, Panels (a) & (b), respectively.
APPENDIX D: EXCERPTS
D.1 Wing-Over Description

From Dec 4, 2014: Dr. Thomas Wilheit to Spencer Farrar

Spencer,

No publications on the wing-overs. I was too busy in those days to write up how we calibrated our instruments. I think that Charlie Calhoon wrote some kind of GSFC internal document on it.

I had a set of airborne radiometers that flew on the NASA CV-990 aircraft. The A/C Electrically scanned microwave radiometer (ESMR) scanned +/- 50 degrees cross track. The Airborne Multifrequency Microwave Radiometer was a set of non scanning radiometers that looked 45 degrees to the right of the aircraft track. To investigate the effect of eia we rolled the aircraft +/- 45 degrees sometimes 60 degrees. I realized that at 60 degrees we could see over the horizon but wanted a cleaner look. I wanted the pilots to bank the aircraft more but they said that was not permitted. In a coordinated turn at 60 degrees roll angle the aircraft and everything, (everybody) in it are pulling 2 g's.

I had a long talk with the chief pilot, Fred Drinkwater, . . . in (I think) San Juan . . . [h]e suggested the wingover. It is a very gentle maneuver. The pilot would pull the nose up maybe 15 degrees, lose a little airspeed, and then roll 90 degrees (not in a coordinated turn) The lift vector of the wings is now horizontal. Inside the aircraft you feel like you are still in 1 g (more or less) even though the aircraft is in free fall. As we accelerated downwards the nose would fall below the horizon and the airspeed would build up. Before the airspeed got too high, the pilot would roll the wings level. Due to the excess speed, now the wings are developing more than enough lift to counteract gravity and the rate of fall would decrease and we would stabilize about 5000' lower than when we started. We would get 12 to 15 seconds of a very clean sky view this way. Typically we would start at about 25000 feet and end up at 20000 feet--above most of the water vapor and we would do it clear of clouds.

The cattle in the back of the plane were 50/50 on this. Half loved it/ half threatened to get out of the plane right then and there. The JPL radar crowd was a real pain in the butt about it. Naturally the pilots were absolutely crazy about it. It was a lot more fun than punching waypoints into the navigation system.

On the first one I was standing in the cockpit door. I braced myself lightly against the top of the door jamb and could actually sight the windshield braces against the horizon.
Timing: This was in the run up to the launch of the SMMR instruments mid to late 70s.

Since learning to fly (and taking some advanced maneuvering training in a T34), I understand the maneuver better than I did then.

Tom

From Dec 4, 2014: Spencer Farrar to Dr. Thomas Wilheit

These are some very good details on the subject. I assume, the flight is from March 2, 1973 (refer to attachment). Can you described how you used it? I assume you used it an additional calibration point.

From Dec 4, 2014: Dr. Thomas Wilheit to Spencer Farrar

It was later than this. This was an early attempt at getting windspeed etc. from microwave measurements. Actually I wasn't on this flight. I prepped the airplane with the help of a crew that couldn't use a soldering iron or even a screwdriver, but Bill Nordberg (my boss then) had other uses for me during the flight period. The flights were under the . . . direction of Per Gloersen.

It was a cold end calibration point. Warm end was easy (just not in flight) [:] [j]ust hold some eccosorb in front of the horn.

I see from a plaque on the wall that my first hurricane penetration was in 1976. I think that expedition was the first time we did wing overs.

Tom
D.2 LFMR

Deep Space Calibration

Once steady state operation has been achieved (after one or more orbits), the spacecraft will perform a slow 360° roll (duration of 10-20 minutes). As illustrated in Figure 6.4-2, this maneuver will enable the LFMR to be pointed toward deep space and thereby achieve an end-to-end absolute radiometric calibration. Since deep space presents a nearly constant 2.7K unpolarized brightness temperature, it provides an excellent means for removing relative radiometric biases between channels, as well as for removing systematic brightness temperature biases versus azimuth position introduced by antenna backlobes and feed spillover striking the spacecraft. Further, this procedure will provide simultaneous mesh temperature and radiometer brightness temperature data to "tune"

empirical coefficients in the radiometer math model to correct for biases introduced by the finite mesh emissivity.

External Targets

During the following 30 days, Harris will perform engineering evaluations to assess the LFMR performance. Tests will include the use of ground targets such as the York Peninsula of Australia and the Amazon rain forest, which are near black body radiators with excellent homogeneity and large area spatial characteristics, and the southern Greenland ice sheet which is an extremely low-emissivity target. While the brightness temperature of these targets is not well known on an absolute scale, their brightness temperature stability is excellent thereby allowing the assessment of time-variable radiometric biases. Further antenna pointing (beam boresights) and pattern shape (beam efficiencies) will be verified using land/water boundaries and cooperative earth-based transmitters. Data products obtained from Fleet Naval Oceanographic Center (FNOC) will be used to perform the above LFMR performance verification.

6.4.2 Operational Data Collection Phase

Following the performance verification phase, a minimal LOE support will be provided during the first six months of LFMR operations. General consultation, "fine-tuning" of performance algorithms, and reviewing of engineering housekeeping data are the principal tasks to be performed.

During the first eclipse period (Winter solstice), the deep space calibration test will be repeated. This procedure will permit evaluation of the mesh temperature calculations and associated mesh temperature measurements along with simultaneous radiometric brightness temperature measurements. Coefficients for the mesh emissivity/brightness temperature correction algorithm will be "tuned" and overall algorithm effectiveness validated. Additional deep space calibrations are recommended yearly to develop a data base to validate the LFMR long-term absolute calibration accuracy.
Figure 6.4-2. LFMR Absolute Radiometric Calibration Test
D.3 Analysis of Cold Load Anomaly on TMI 21.3 V-Pol Channel

The TMI was placed into orbit on November 27, 1999. An anomaly was noticed in the ensuing months. The cold load counts on the 21 V channel on the Instrument Analysis Records [138] showed that the 21 V cold load counts deviation was larger than the hot load deviations most of the time when it should have been lower. All the other channels were lower. This was tracked and seemed to be loosely a function of temperature. Plots of the cold load counts for one orbit were obtained and this showed the spikes on the cold load counts moving only slightly in orbital position from orbit to orbit. The magnitude was from 10 to 250 counts lasting about 5 minutes each time. The spikes did not appear on the hot load, but a small effect of depressurizing the hot load counts was coincident with the cold load spikes. The root was ruled out, as the anomaly occurred during eclipse. A satellite operating at 21.2 GHz was ruled out, as it was 40 dB from the level which would cause interference. Various other scenarios were investigated but did not match the anomaly. Tom Keating of the TMI program office at GSFC came up with the explanation.

When an attenuation is placed between the feed and the LNA of the receiver, the noise figure goes up. If the temperature of the attenuation is close to the hot load temperature, then the receiver output will not go up since the attenuation is at the same temperature. The cold load will go up in response to the increased signal level. The scale factor of the 21 V channel is 205 K/count or 5 counts per degree. Thus if the cold load counts went up 190 counts that would be equivalent to 20 K. Although only a few were have been plotted of the cold load counts, the general behavior of the anomaly has not changed since launch. At the beta equals 0 crossings, which is when the TMI is the coldest, the anomaly disappeared. This occurred for revs 761, 387, and 533. The exact cause has not been pinpointed, but is likely a mechanical joint in the isolators, waveguide to coax transition or semi-rigid coax. There is no evidence to suggest that the anomaly will get worse with time.

Cold load counts were plotted for revs 1056 and 1057 and supplied today. The maximum rate of increase for these revs was on rev 1057 from scan 1558 to 1603 where the cold load counts increased from 715 to 942. This is 9.7 counts per scan. This rounds up to 10 K per scan. This will be used as a worst case cold load increase per scan. Other revs might have higher numbers.

Six scenarios will be described to cover the full range of TMI operating conditions. The jump is assumed to occur instantaneously, which is a worst case. The TMI is calibrated each scan. The jump can occur:

1.---Before the earth scan: this will be calibrated out and have no effect on the data.
2.---During the earth scan: the pixels before the jump will be calibrated different from the following pixels. The earlier pixels
will be in error.

3-----Between the earth scan and the cold load : all the earth scan pixels will be calibrated incorrectly. Similar to number 2 but all the pixels will be misaligned.

4-----During cold load scan: will reduce calibration error but is not the worst case.

5-----Between the cold load and the hot load: no effect, cal ok. Hot load will not be changed by the attenuation change.

6-----During the hot load scan: no effect, same as 5 above.

Thus cases 2 and 3 are the same and are the worst case. These will be analyzed.

From the start of the earth scan to the end of the cold load is 210 degrees. If the attenuation changed on the other part of the scan, the change in attenuation would have no effect on the calibration. Thus the probability of a jump affecting the scan data during a high cold change is 28%. If the worst case of 5 spikes per orbit and 15 scans per rise and fall is used as a model, then the percentage of time the error would be at the values computed below is .58 * 150/2900 = .3%.

The error from the above source is the cold load change times the percentage of distance from the cold load to where the earth temperature is located. If the earth scene is at the cold load temperature then the error would be 100% and if at the hot load the error would be 0%.

Error = (hl-(et-3))*coldloaderror/h

hl= hot load, et= earth temperature,
coldloaderror as shown above is 2 K

The hot load varies from 6 beta angle to 27 degrees from 270 to 288. Using 288 as the worst case, the error in the scene temperature is shown below.

<table>
<thead>
<tr>
<th>Earth scene temp</th>
<th>error, K</th>
</tr>
</thead>
<tbody>
<tr>
<td>185K</td>
<td>.58</td>
</tr>
<tr>
<td>201K</td>
<td>.63</td>
</tr>
<tr>
<td>251K</td>
<td>.28</td>
</tr>
</tbody>
</table>

using rev 1016 as a model the lowest earth scene temperature was 290K and the .63K error is well within the 2k specification.

CONCLUSION

The TM1 is operating within specification and the small error would only be present in the data 3% of the time.


**D.4 TRMM RFI Test During Sept 1998 DSCM**

From: TRMM 3-Year Report

TMI scientists have reported interference seen in the data (refer to the TMI section). On 98-245, a Deep Space Calibration was scheduled to help troubleshoot the cause. Normally, PR is placed in Standby mode for the duration of the calibration, but one theory for the TMI problem was that PR radiation was affecting the science data. To test the theory, PR would have to radiate out into space. After working with FDF to avoid radiating towards other spacecraft, a suitable time was selected. At 11:23:41, PR was placed in Standby mode and then set to radiate (Observation mode) at 12:18:00 for a duration of one minute. It was then returned to normal science collection mode 30 seconds after the maneuver completion at 13:06:38.
APPENDIX E: OBSCURING TMI'S FEED RADIATION PATTERNS
In order to project the TMI feed horn radiation pattern on its surroundings a very accurate CAD model needed to be obtain so to determine what angular regions are obscured by either the TMI instrument or TRMM spacecraft. The model was obtained from Walter Ancarrow, of WCA Engineering, Inc, whereby the model was a geometric model in TSS format. Unfortunately, this format was not useful since it was decided to use AGI’s Systems Tool Kit (STK) software to determine the obscuration angles. The TSS file is not one of the accepted formats by STK so the model was converted to FBX by using AutoCAD which was then sent to PSR Outdoors whereby through many telecons was modified and converted to lightwave object (lwo) format. This format was then converted by AGI LWO-to-MDL executable where it was then utilized in STK. Figure 12.46 is a snapshot of the TRMM CAD model using STK. The white structure is the TRMM spacecraft and other instruments. The two solar panels are in green and red. The High Gain Antenna (HGA) is used for communicating with TDRSS. On the front of the spacecraft is TMI in yellow, red, and blue.

It was confirmed using this model that the dimensions of TMI’s main reflector and warm load matched what was given in the documentation. This lends itself to the notion that the model is a suitable representation of TRMM to be used for this research. TRMM/TMI parts of interest for identifying what obstructs the horns field of view are the main reflector, cold sky reflector, warm load, TRMM dog house, and HGA. Figure 12.46 is a snapshot of TMI instrument where the warm load was removed since it was represented as a flat plate which was not an accurate representation.
Figure 12.46: A snapshot of the TRMM spacecraft during nominal operation mode. Image was created using AGI’s STK software.

With the TRMM model inputted into STK, the next step was to determine what objects obscure the horns field of view. This was done by obtaining the body mask (bmsk) which is a file that contains angles which define the blockage, i.e., a binary mask as a function of Azimuth and Elevation angle from the reference of a sensor whereby, for our case, the feed horn is 360° & 90° in azimuth and elevation, respectively. However, they did not report past 90 degrees and the format was not useful. The next step was a work around whereby AGI provided a scenario that inputted the mask which allowed a usable format for this research.
Figure 12.47: A snapshot of the TMI instrument. Image was created using AGI's STK software.
Figure 12.48: The STK scenario that allowed the determination the obscuration of the horn due to the main reflector.
Figure 12.49: The STK scenario that allowed the determination the obscuration of the horn due to the HGA, CSR, and "Dog House" of the spacecraft.
Figure 12.50: The projection of the spillover with obscuration applied for 10 GHz, DSCM 03.

Figure 12.51: The projection of the spillover with obscuration applied for 10 GHz with emphasis on scan 1050, DSCM 03.
APPENDIX F: RFI OBSERVED BY THE COLD SKY MIRROR
On July 22, 2014 TRMM performed 3 DSCMs at a Yaw of 0°. These maneuvers were for the sole purpose of calibrating TMI years after the 1998 maneuvers, i.e., to provide insight on whether there was any degradation of the instrument over the years. Within a week of the maneuvers the reconstruction methods, as discussed in Chapter 6, were used so to analyze the data. During validation of the reconstruction method which compared the reconstructed \( T_A \) to the TMI calibrated \( T_A \) during TRMM nominal mode certain portions of the orbit whereby the residuals between the reconstructed and calibrated \( T_A \) were curiously higher than expected. After investigation on why the residuals were occurring, it was determined that the disagreement was due to the sudden jumps and variation in the cold sky counts [39]. An example, for 20 orbits for 19 V-pol, of this cold sky count time series is shown in Figure 12.52. The three large jumps (100’s of counts) in the middle of the time series is due to the cold sky mirror illuminating Earth. Figure 12.53 is a zoomed-in image where the unexpected spikes occur. An either further zoomed-in image of these spikes is depicted in Figure 12.54 where the time series clearly shows disagreement between the 8 samples of the cold sky mirror.

The effects of these jumps on the calibration transfer function is depicted in Figure 12.55 whereby an additive bias in the cold sky counts, assuming the CSR is viewing the CMB, decreases the calibrated \( T_A \). This is further illustrated in Figure 12.56 whereby all panels pertain to an intense event of RFI for 19 V-pol, orbit 92235 over the Philippine Sea. Panel (a) shows a time series for the 8 cold sky samples which vary up to 600 counts relative to each other. Panel (b) is the geolocated \( T_A \) where the depression is very noticeable for the entire swath. Using the reconstruction method developed in Chapter 6 and comparing it to the erroneous \( T_A \) is
Figure 12.52: Time series of the cold sky counts of 20 orbits (Orbits 95015-95034) for 19 V-pol.

Figure 12.53: A zoomed in image of Figure 12.52 where the anomalies become apparent.
Figure 12.54: A zoomed in image of Figure 12.53 8 cold sky samples show a large variation between each one.

Figure 12.55: Two-point calibration curve showing the effects due to a positive bias in the cold sky counts.
Figure 12.56: An RFI event for 19 V-pol, orbit 92235, whereby Panel (a) is are the 8 cold sky samples, (b) is the depression in $T_A$ due to this event, (c) the difference in erroneous and corrected TA, (d) the corresponding TMI 2A12 surface rain rate product.

represented panel (c) where the difference is up to 30 Kelvin. Panel (d) depicts the corresponding TMI 2A12 surface rain rate product in mm/hr.

In order to flag these occurrences of RFI it was decided that since each cold sky sample is affected differently, that applying a simple threshold on the CSC standard deviation on a per channel bases would flag these events. The threshold is listed in Table 12.2. An example of
using this threshold for 19 V and isolating this intense event over the Philippine Sea for the 2013
Table 12.2: Thresholds (counts) used in detecting RFI for 10.65 to 37.00 GHz channels of TMI.

<table>
<thead>
<tr>
<th></th>
<th>11V</th>
<th>11H</th>
<th>19V</th>
<th>19H</th>
<th>21V</th>
<th>37V</th>
<th>37H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold</td>
<td>1.7</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.5</td>
<td>1.2</td>
<td>1.1</td>
</tr>
</tbody>
</table>

The year is depicted in Figure 12.57. This figure is the geolocation of the satellite once the σ is above the threshold which, for this particular event, so happens to occur only for descending passes of TMI. The color is the σ in counts whereby it is apparent that RFI occurs only over a specific location of the Earth and that the intensity of the σ trails off the maximum. This is indicative of a geostationary satellite illuminating the Earth in conjunction of the fact that the cold sky beam illuminates the geostationary belt at for this pass and yaw maneuver (0°). Further investigation into multiple RFI events over North America is shown for 19 H-pol for the Years 2000 to 2014, Figure 12.58 to Figure 12.72, respectively. These figures depict the RFI increasing in number and σ as time increases. It should be stated that these features are very similar for the 19 V-pol channel which is depicted in Figure 12.73 for the 2013 year. Figure 12.74 selects one orbit from the extreme events that was just discussed, orbit 86351, supports the case that the effects for 19 H-pol in are not negligible. Panel (a) is the geolocation of the main beam’s $T_A$ where the colorbar, 180-300 K, is saturated so to highlight land which shows nothing of interest but for Panel (b) where the colorbar, 60-160 K, has been saturated to highlight ocean is evident that a value of 80 K for this channel is unrealistic. Panels (c) & (d) depict the difference in the
erroneous $T_A$ and the corrected $T_A$ using the reconstruction method. Panel (c), colorbar 0-10 K, shows at worse a 10 Kelvin decrease in brightness temperature due to RFI and Panel (d) whereby the colorbar is 0 to 80 Kelvin shows that the ocean should be 80 Kelvin warmer. This difference between ocean and land makes sense since land is closer to the warm calibration so it will be less affected than the radiometrically colder ocean.

There are many other events over the Earth for other channels and for more about those refer to [39].

Figure 12.57: The geolocation of an RFI, 19V, for the 2013 year over the Philippine Sea where the color is the $\sigma$ in counts.
Figure 12.58: Geolocation of SSP (color of counts) for 19 H-pol during the 2000 year.

Figure 12.59: Geolocation of SSP (color of counts) for 19 H-pol during the 2001 year.
Figure 12.60: Geolocation of SSP (color $\sigma$ of counts) for 19 H-pol during the 2002 year.

Figure 12.61: Geolocation of SSP (color $\sigma$ of counts) for 19 H-pol during the 2003 year.
Figure 12.62: Geolocation of SSP (color $\sigma$ of counts) for 19 H-pol during the 2004 year.

Figure 12.63: Geolocation of SSP (color $\sigma$ of counts) for 19 H-pol during the 2005 year.
Figure 12.64: Geolocation of SSP (color σ of counts) for 19 H-pol during the 2006 year.

Figure 12.65: Geolocation of SSP (color σ of counts) for 19 H-pol during the 2007 year.
Figure 12.66: Geolocation of SSP (color $\sigma$ of counts) for 19 H-pol during the 2008 year.

Figure 12.67: Geolocation of SSP (color $\sigma$ of counts) for 19 H-pol during the 2009 year.
Figure 12.68: Geolocation of SSP (color $\sigma$ of counts) for 19 H-pol during the 2010 year.

Figure 12.69: Geolocation of SSP (color $\sigma$ of counts) for 19 H-pol during the 2011 year.
Figure 12.70: Geolocation of SSP (color σ of counts) for 19 H-pol during the 2012 year.

Figure 12.71: Geolocation of SSP (color σ of counts) for 19 H-pol during the 2013 year.
Figure 12.72: Geolocation of SSP (color σ of counts) for 19 H-pol during January to July, 2014.

Figure 12.73: Locations of RFI during the 2013 year for 19 V- & H-pol.
Figure 12.74: Geolocation the 19 H-pol temperatures whereby Panel (a) & (b) emphasize the $T_a$ over land & ocean radiometrically, respectively. Panel (c) & (d) emphasize the difference between the corrected & erroneous $T_a$ for land & ocean, respectively.
APPENDIX G:  GMI MAIN REFLECTOR PHYSICAL TEMPERATURE
Figure 12.75: GMI pitch angles during the inertial holds on May 20th & December 9th, panel (a) & (b), respectively. GMI main reflector physical temperature during the inertial holds on May 20th & December 9th, panel (c) & (d), respectively.
Figure 12.76: GMI main reflector physical temperature for solar beta angles close to +/- 45 degrees, panel (a) & (b), respectively.
LIST OF REFERENCES


