Special Sensor Microwave Imager Sounder (SSMIS) Radiometric Calibration Anomalies—Part I: Identification and Characterization

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Abstract—Two calibration anomalies of the Defense Meteorological Satellite Program’s (DMSP) Special Sensor Microwave Imager Sounder (SSMIS) radiometer are examined by using several sources of data. Early orbit mode data from the SSMIS are used to create radiometric images of the warm calibration load that evolve over an entire orbit to elucidate the effects of direct and reflected solar illumination of the warm-load (WL) emissive surface. Analysis of the radiometric gain and apparent WL radiometric brightness temperature observed during the solar intrusion events show the impact of these events on the SSMIS calibration. A graphical simulation of the SSMIS and DMSP spacecraft is used to define the regions where solar intrusion occurs and to characterize the WL anomalous regions for the specific DMSP F-16 orbit. The graphical simulation is also used to determine the cause of additional calibration errors that were identified by using comparisons to numerical weather prediction (NWP) models, as emission from the SSMIS reflector antenna. Mitigation of these calibration anomalies is critical if the operational SSMIS radiometers achieve the full utility in NWP, climate monitoring, forecasting, and other emerging applications. A detailed characterization of the SSMIS calibration provides a basis for this process.

Index Terms—Calibration, microwave radiometry, Special Sensor Microwave Imager Sounder (SSMIS) calibration/validation.

I. INTRODUCTION

The Special Sensor Microwave Imager Sounder (SSMIS) was designed to be a precision-calibrated microwave radiometer that is capable of sub-Kelvin calibration accuracy with a conical scan configuration of SSM/I heritage [1]. The SSMIS calibration approach is also of SSM/I heritage utilizing a single warm calibration target and a cold-sky reflector (CSR) to calibrate the entire radiometer system except for the main reflector antenna. Conical-scanning microwave radiometers with similar heritage and calibration approach have experienced calibration anomalies associated with the main reflector [2] and warm calibration loads [3]. Analysis of the SSMIS sensor on the Defense Meteorological Satellite Program (DMSP)’s Flight 16 (F-16) satellite also indicates that calibration anomalies exist, albeit with unique attributes compared with those experienced with other Earth-observing radiometers.

The F-16 spacecraft carrying SSMIS was launched on October 18, 2003 from Vandenberg Air Force Base in California. The nominal orbit altitude is 833 km with an initial local ascending-node crossing time of 19:54 hours. The SSMIS sensor is described in other publications in this issue that address the instrument design and evaluation of on-orbit performance [4], geolocation and pointing [5], and field-of-view (FOV) analysis [6]. Precision calibration of the SSMIS is addressed in this paper and in the accompanying SSMIS Calibration Anomalies Part II [7]. In this paper, we identify the root cause of two SSMIS on-orbit calibration anomalies: 1) solar illumination of the SSMIS warm calibration load and 2) anomalously high reflector antenna emission. This was determined by the use of three diverse data sources: 1) SSMIS on-orbit radiometric and ambient sensor (thermistor) data; 2) graphical simulation of the on-orbit SSMIS sensor; and 3) globally simulated SSMIS observations using the RTTOV-7 forward radiative transfer model [8] with input numerical weather prediction (NWP) geophysical fields from the European Centre for Medium-range Weather Forecasts (ECMWF) model. The synergy provided by these data was significant, enabling the scope of this paper. Of the two calibration anomalies, the anomalously high antenna reflector emission has the most serious impact to SSMIS performance. However, most of the discussion in this paper will provide a background on the SSMIS calibration anomalies and characterization of the warm-load (WL) errors. A good understanding of errors attributable to the WL is necessary in order to develop corrections for the reflector emission. Part II of this paper [7] will provide additional analysis of the antenna emission and mitigation strategies to improve the calibration of SSMIS data for use in NWP.

II. DATA FOR ON-ORBIT ANALYSIS OF SSMIS CALIBRATION

This section provides a short discussion on the three primary types of data used for the evaluation of the SSMIS calibration and for the initial characterization of the calibration anomalies for SSMIS.

A. SSMIS Radiometric, Diagnostic, and State-of-Health Data

In addition to radiometric data for each of its 24 channels, the SSMIS sensor provides supporting scientific and
engineering data such as temperature measurements of its six receiver plates, the WL, and antenna arm. In normal mode, the SSMIS provides calibrated scene data over 180 of the 450 total beam positions (BPs) by reporting 180 scene values for Channels 8–11, 17, and 18; 90 values for Channels 12–16; 60 values for Channels 1–7; and 30 values for Channels 19–24. The sensor can also be placed in diagnostic modes called the early orbit (EO) modes. In three of the EO modes, the on-board along-scan averaging and calibration steps are disabled such that the sensor provides raw radiometric counts sampled at each BP over the full 360° rotation of the canister. A fourth diagnostic mode configures the sensor to provide sparse but calibrated uniform samples of the scene from each channel. The combination of engineering, operational, and diagnostic data provides the ability to gain substantial insight regarding the sensor on-orbit operation and state-of-health. The state-of-health (engineering) data and the EO mode operation are an important means for characterizing the on-orbit sensor operation.

B. DGS

The DMSP graphic simulator (DGS) tool developed at Aerospace utilizes OpenGL, an open-source graphics library, to create a graphic image of the DMSP spacecraft and its sensors. To build this capability, the simulator utilizes a commercial 3-D computer animation package to simplify and import computer-aided design files of the DMSP spacecraft and sensors. The graphic simulation of the SSMIS sensor and its subassemblies are provided as a detailed part of DGS. For on-orbit evaluation of the SSMIS during the Cal/Val, a key aspect of DGS was the development of the SSMIS calibration load assembly model. The SSMIS calibration load assembly is composed of a CSR and the warm calibration target or WL. The calibration load assembly is shown as simulated by using DGS in its position on the top of the SSMIS canister in Fig. 1.

For analyses involving the calibration load assembly, we define a reference basis consisting of the top plane of the SSMIS canister and its normal vector that is aligned with the SSMIS spin axis. Within this reference basis, the WL sun azimuth angle \( \phi_w \) in the plane of the canister top is defined with respect to the dark-gray vector in Figs. 1 and 2, which represents \( \phi_w = 0^\circ \), and the dashed dark-gray vector, which represents \( \phi_w = 90^\circ \). The WL sun elevation angle \( \theta \) is also defined with respect to the plane of the canister top with positive elevation angles when the sun is above the canister. Similarly, the CSR sun azimuth angle \( \phi_{cs} \) is defined by the light-gray vectors in Figs. 1 and 2. The sun elevation angle with respect to the CSR and WL is the same. The white vector appearing in Fig. 1 represents the normal vector of the CSR reflecting surface translated to the SSMIS spin axis at the canister top. Fig. 2 also shows the orbit vectors for reference. The DGS simulator calculates the orientation of the WL and CSR with respect to the sun using the position of the DMSP satellite computed from the current two-line orbital elements.

The DGS simulation does well in reproducing solar illumination of objects in 3-D; however, DGS is not able to model shadowing or reflections. Because many surfaces of the SSMIS canister, including the top of the canister and portions of the WL itself, are reflective, a ray-tracing graphical simulation was also developed in order to more completely understand solar illumination of the SSMIS sensor and calibration load assembly on orbit. The ray-trace simulation is performed separately in a fixed reference position and is not part of the overall DGS functionality. As designed for SSMIS calibration analyses, the ray-trace simulation allows up to four specular ray “bounces” and has the ability to “darken” or roughen selected surfaces in order to more accurately depict the amount of impact from multiple reflections of sunlight.

C. NWP Model Background Fields

A highly accurate simulation of expected SSMIS temperature sounding measurements on a global scale can be obtained by using NWP background fields (6-h forecasts) with a forward radiative transfer model. Short-range forecasts are estimated to be accurate to \( \sim 0.2 \) K–0.4 K (average residual error) for the
SSMIS lower atmospheric sounding (LAS) channels that are free from significant surface contributions (Channels 3–5). This capability provides an excellent basis to observe detailed sensor characteristics. Although local prediction errors can contribute sporadically to the difference between the SSMIS-observed and modeled brightness temperatures, the spatial structure of the error (difference) signal can play a major role in determining if the error is attributable to sensor calibration or the local background.

Direct assimilation of on-orbit radiances has come to be the preferred means of utilizing space-based microwave sounding and imaging measurements for weather forecasting. This shift toward radiance assimilation has also moved emphasis from the validation of environmental data records to the validation of measured brightness temperatures or sensor data records (SDRs) as strongly reflected by the SSMIS Cal/Val activities [4]. Accordingly, NWP data from ECMWF were found to be a valuable tool for identifying sensor calibration anomalies and for evaluating the proposed calibration improvements and sensor performance for improving forecasts.

III. SSMIS Radiometric Gain Anomalies

Early indicators of calibration anomalies in the F-16 SSMIS were observed by investigating the trends of the calibrated SSMIS gain functions over several orbits. The F-16 orbit is placed effectively midway between afternoon and terminator orbits; hence, the spacecraft enters solar eclipse once every orbit for a period between ∼0 and ∼15 min depending on the time of year. There is typically a short period, ≤1 week, that the satellite is in continuous sunlight. The ∼90-min orbital cycle causes the temperature of the SSMIS receivers to vary periodically as a function of position during the orbit. The radiometer gain is highly correlated with its ambient temperature, and the result is a periodic variation of the SSMIS radiometer gains as a function of the orbit. However, the W-band radiometers (Channels 17 and 18) were found to be highly stable compared to other SSMIS channels due to temperature stabilization from an internal heater located adjacent to the receivers.

The receiver-plate temperatures, radiometric gain, and WL and cold-target radiometric counts are shown in Fig. 3 as a function of the number of scans from the beginning of rev 6804 on February 13, 2004. The receiver-plate temperatures, which are shown by the cyan traces in Fig. 3(a)–(e), change by ∼2 °C over the orbit; however, Fig. 3(f) shows the receiver-plate temperature variation for Channel 17 to be very small, i.e., <0.5 °C. The scale in Fig. 3 for radiometric counts is different for every channel but is the same for warm and cold within any one channel and an offset applied in order to align the cold and warm count data. In this manner, the radiometric gain and the warm and cold calibration counts can be overlaid in order to compare trends in the data.

Of concern are the strong short-term variations in gain that are readily apparent in all parts of Fig. 3 near scans 170, 650, and 1500, with the most readily identifiable occurrences appearing in Channels 17 and 16. These areas are numbered 1–3 for identification purposes in the order they occur in Fig. 3(f). Another very small short-term gain variation, which is labeled as number 4, may be apparent in the Channel-17 data, as shown in Fig. 3(f) near scan 2200. The short-term gain variations, typically <500 scans in duration, are not correlated with changes in the receiver-plate temperature, or cold calibration radiometric counts, but do appear to be strongly correlated with similar short-term variations in the warm calibration radiometric counts, suggesting that an investigation of the WL effective $T_B$ is necessary.

IV. EO Mode Warm Load Imaging

The SSMIS EO modes are special diagnostic modes that can be commanded from the ground. The diagnostic modes do not provide much of the data preprocessing that is performed within the SSMIS flight software in SSMIS normal operating mode (normal mode). In this paper, a special subset of the EO modes, EO2A, EO2B, and EO2C, will be utilized. The EO2 modes enable the SSMIS to collect radiometric data at each individual BP over the full 360° rotation (450 BP). Each BP is separated by 0.8° of rotation and represents the fundamental sampling interval of ∼4.22 ms (see [4] for additional detail regarding the sensor design). By using data collected in any of the EO2 modes, an image of the entire scan, including the warm calibration load, can be created. Imaging of the SSMIS WL is not possible with the sensor in normal mode because the multiple WL samples are averaged on-board, and only a single value for each of the warm and cold calibration points from each channel is available within the ground data.

Initial EO2 mode data were acquired during revs 136–145 in October 2003, with a minimum of two revs devoted to each of the three modes: EO2A, EO2B, and EO2C. The EO2A mode measures all SSMIS channels over a period of eight sequential blocks of 60 contiguous BPs. Therefore, BPs 1–60 are measured and recorded for all 24 channels during the first scan (full canister rotation), BPs 61–120 are measured during the second scan, and so on. The entire sequence repeats after eight scans when the full range of 450 BPs has been covered. The eighth scan includes data from only 30 BPs, and the first BP of every scan contains no data due an initialization sequence from the on-board processor. For the EO2B and EO2C modes, data from all 450 BPs are collected continuously (each scan) for only three channels: Channels 1, 6, and 8 (EO2B) and Channels 12, 15, and 18 (EO2C). An additional and more extensive collection of EO data was carried out in January and February 2005, during revs 6432–6525, in order to improve the quality and scope of the EO data analysis for SSMIS calibration anomalies and FOV analysis [6].

Within the EO2 modes, the SSMIS reports radiometric counts for each BP. The raw counts may be calibrated to radiometric brightness temperatures ($T_B$) by utilizing data from the same warm and cold calibration BPs that would be used in normal mode from every scan. However, the calibration of EO2 data in this fashion would erase any variation of effective $T_B$ from images created of the WL. Therefore, in order to examine the SSMIS WL effective $T_B$, a constant calibration is applied to the EO2 data for multiple orbits (revs). The fixed calibration is derived from average values of the WL and CSR over the entire period used for the analysis or collection of the WL image. The single calibration values allow the short-term and
long-term variations of the WL counts to be seen in terms of an equivalent change in effective WL brightness temperature. The mathematical description of the EO2 calibration is shown as

\[
    \hat{T}(i,j)_P = \frac{4}{N} \sum_{n=1}^{N} \left\{ \sum_{m=H}^{H4} C(n,m)_P - \sum_{m=C}^{C4} C(n,m)_P \right\}^{-1} \times \left[ T(H) - T(C_P) \right] C(i,j)_P
\]

where \( \hat{T}(i,j)_P \) is the estimated brightness temperature for channel \( P \), scan number \( i \), and \( BP = j \), \( C(n,m)_P \) is the raw counts for scan number \( n \) and \( BP = m \), \( T(H) \) is the average measured hot calibration load temperature, and \( T(C_P) \) is the effective cold space temperature for channel \( P \) (e.g., 19.35 GHz = 2.752 K). The terms \( H1-H4 \) indicate the four BPs used for the WL observation, \( C1-C4 \) are the four BPs used for the cold-sky observation, and \( N \) is the number of scans.\(^1\) This

\(^1\)The number of scans depends on the length of the EO data collection. For the initial collection in 2003, there were six orbits of EO2B data (Channels 1, 6, and 8) and two orbits of EO2C data (Channels 12, 15, and 18). The approximate number of scans available can be found by assuming \( \sim2800 \) scans per orbit. For EO2A data, the number of scans is reduced by a factor of eight due to the data collection scheme.
same approach is used in the EO FOV analysis [6]. It should also be noted that for all of the EO2 modes, a few BPs are not available due to the limitations of the on-board SSMIS data processor. In the EO2B and EO2C modes, BPs 1, 149–151, and 299–301 are not reported; unfortunately, BPs 299, 300, and 301 occur when Channels 15 and 16 are viewing the WL. Finally, the odd and even BPs are typically offset by ~1–2 K due to residual A/B integrator offsets. The odd and even numbered BPs utilize separate analog integrator circuits that are not exactly matched and exhibit a residual voltage offset for identical scenes. The residual offsets need to be manually removed in the EO2 mode when data from odd and even BPs are displayed on the same plot or graph. The approach described by (1) does not remove the residual A/B integrator offset.

The apparent radiometric brightness temperature of odd-numbered BPs under the SSMIS WL after applying (1) is shown in Fig. 4(a) and (c). Note that the bottom trace in Fig. 4(a) is the data from BP 287 during the entire orbital rev, and the next trace above contains data from BP 289, etc. Supporting data showing the WL core temperature and spacecraft latitude (position) are shown in Fig. 4(b) and (d). Note that each of the traces in Fig. 4(a) and (c) is offset by 6 K to allow simultaneous viewing and comparison of the data from each BP as a function of time from the beginning of the orbit. In this manner, an image can be constructed of the WL effective radiometric temperature as a function of BP and time over the orbit. Note that BPs 299 and 301 are missing from Fig. 4(a), as described previously.

The purpose of Fig. 4 is as follows: 1) to illustrate characteristics of radiometric data calibrated by using (1) for providing an “image” of the WL and 2) to show that short-term variations in radiometric data collected from the WL are related to the derived variations in gain shown in Fig. 3 and are not correlated with changes in the temperature of the WL magnesium core. The short-term $T_B$ variations, which are identified by the numbered vertical lines, are shown to be imposed over the long-term variations (on the order of the orbital period) of the effective WL $T_B$ in four distinct areas or “regions” of the orbit. The long-term variations are caused by changes in the radio-frequency channel gain occurring in response to changes in the ambient temperature of the radiometer electronics; this
is a consequence of using a fixed calibration (1) for the entire sequence of orbits. Variations in the effective short-term WL $T_B$, which are highlighted and identified by numbers 1 through 4, occur at the same time and orbital position (latitude) as the short-term ($\sim$200–300 scans) gain increases shown in Fig. 3. However, the effective temperature of the SSMIS WL core measured by three platinum resistance thermometers, as shown in Fig. 4(b) and (d), is stable by comparison and not correlated with the change in effective radiometric $T_B$. For example, in Region 2, the WL core temperature increases by $<0.2$ K, whereas the effective radiometric temperature for Channel 1 increases by $\sim 2$ K and then drops back to the original value. Accordingly, the short-term variations appearing in Fig. 4(a) and (c) are hypothesized to be due to sunlight illuminating the WL tines, causing an effective increase in the WL radiometric temperature.

A set of SSMIS WL radiometric $T_B$ images is shown in Fig. 5. Within this set, each receiver feedhorn is represented by the set of Channels 4, 8, 14, 16, 17, and 22. These channels were selected to represent each receiver system, its associated antenna feed, and view of the WL. The channel selection was determined by two factors: 1) gain stability over the orbit in order to minimize the impact of a varying baseline on the ability of the image to highlight the WL solar illumination and 2) sensitivity (NEΔT). In order to improve the sensitivity of the images shown in Fig. 5, 23 revs of EO2A data, which were collected from a specially designed EO2 diagnostic mode collection in January 2005, were averaged together in order to reduce the single image noise by a factor of $\sim 5$. The orbital position (latitude) is overlaid in each image in order to locate the time and position of the solar interactions in the DGS and ray-trace simulations. The images in Fig. 5 clearly show short-term increases of radiometric temperature of the WL. The color schemes and ranges have been adjusted in order to highlight different areas of the WL and different parts of the orbit. Therefore, the overall set within Fig. 5 provides a more complete visualization of the WL solar illumination over the orbit.

For example, Fig. 5(a) and (b) shows data from Channels 16 and 4, which are the most stable with respect to orbital and ambient temperature variations at the receiver. The WL image of these channels is shown for nearly a complete orbit using a single color scheme in order to highlight the relative strength of short-term temperature variations of all WL anomaly regions. Second, Fig. 5(c) and (d) shows data from Channels 8 and 17 associated with the two highest frequency antenna feeds which have the smallest beam “footprints” on the WL. The higher spatial resolution images highlight the temperature variations in Region 3 showing a “double peak” behavior centered near scan 1400 on the graph. Fig. 5(f) shows data from Channel 14 characterized by low overall gain variation over the orbit that is similar to Channels 16 and 4. Channel 14 provides the best example from the lowest frequency band antenna feed, allowing a comparison with Fig. 5(a) for Regions 1 and 2; however, the gain drift in this channel does not allow Regions 3 and 4 to be shown well. Finally, Fig. 5(e), showing Channel-22 data, represents the relatively narrow band upper atmospheric sounding channel set and shows similar behavior, completing the set of images from each antenna feed.

V. ANALYSIS OF WARM LOAD SOLAR INTRUSIONS USING DGS AND RAY TRACING

In order to confirm the hypothesis of solar intrusions as responsible for the short-term apparent temperature increase shown in Figs. 4 and 5, the DGS and ray-tracing simulations were examined during the periods of the short-term WL radiometric temperature “anomalies.” For the F-16 orbit, there are four regions, which are identified in Figs. 3 and 4, in which the $T_B$ anomalies occur. These regions are also seen in the WL images in Fig. 5 from January 2005 and occur at generally the same latitude and phase in the orbit. The related SSMIS normal-mode gain, WL counts, cold-target counts, and receiver-plate temperatures collected during rev 6439$^2$ are shown in Fig. 6. The four WL solar intrusion regions are also identified in Fig. 6 for the selected channels that represent each antenna feed. Note that the position and characteristics of each of the labeled WL anomaly regions have changed slightly from Fig. 3. In particular, Region 4 is much stronger. For each region, Figs. 7–10 show the SSMIS (DGS and ray-tracing simulations) and the F-16 vehicle (DGS only) on orbit during the 2005 EO2 data collection period that began on January 18, 2005. These images show the sun’s view of the spacecraft and SSMIS in each of the four solar anomaly regions identified in Figs. 5 and 6.

Region 1 is shown in Fig. 7 and is characterized by occurrences in the Northern Hemisphere typically at or near the beginning of the descending orbital phase when the solar elevation angle is slightly below the canister top deck ($\theta < 0^\circ$) and the solar azimuth angle is low ($\phi_w \sim -10^\circ$ to $+15^\circ$). The DGS and ray-tracing simulations indicate that within this region, the sun can directly illuminate portions of the WL tines (colored red). Fig. 8 shows the DGS simulation of the F-16 vehicle and SSMIS in the center of the WL “Region 2” anomaly. The red tines of the WL cannot be seen in the DGS simulation because DGS does not have the ability to show reflected images. However, the ray-tracing simulation [Fig. 8(b)] indicates that the WL tines are in view of the sun through reflections involving the highly specular mirrored top of the canister and the inside of the WL shroud. This portion of the WL shroud is more diffuse than the mirrored SSMIS canister top, but still reflective. Region 2 typically causes the largest calibration bias of the four SSMIS WL anomaly regions in the F-16 orbit and is characterized by $0^\circ < \theta \leq 25^\circ$–$30^\circ$ with solar azimuth angles, $0^\circ < \phi_w \leq 45^\circ$.

Fig. 9 shows the DGS and ray-trace simulations with SSMIS in the center of the “Region 3” WL anomaly. Similar to Region 2, the red tines of the WL cannot be seen in this region with DGS but appear in the ray-tracing simulation. Region 3 typically causes the second largest calibration bias of the SSMIS WL anomaly regions and is characterized by solar illumination elevation angles of $0^\circ < \theta \leq 25^\circ$–$30^\circ$ with solar azimuth angles, $40^\circ < \phi_w < 90^\circ$. In Region 3, the magnetometer mast of the F-16 spacecraft routinely blocks

$^2$Rev 6439 occurred during January 16 with the SSMIS in normal-mode operation. The second EO2 mode collection began on January 18, 2005.
Fig. 5. EO2A data from January 2005, F-16 revs 6472–6494, using fixed radiometric calibration (1) for the entire multi-orbit period in order to highlight solar illumination of the WL. The color scheme has been adjusted to highlight different regions of the WL. The channels are presented in the order they pass under the WL: (a) Channel 16, (b) Channel 4, (c) Channel 8, (d) Channel 17, (e) Channel 22, and (f) Channel 14. Note the black triangles appearing toward the left-hand side of parts (c)–(f) are due to a short period of partial data loss occurring when the F-16 SSMIS initially enters the EO2A mode.

The sun from illuminating the WL for a very brief time near the peak of the anomaly. An example of this phenomenon for Region 3 is shown in Fig. 11. The typical result is a “double-peaked” characteristic gain anomaly which is commonly seen in channel gain data in a normal mode. For example, in Fig. 6, the characteristic double peak of the Region 3 anomaly...
Fig. 6. Computed SSMIS gain for rev 6439 on January 15, 2005 showing counts per kelvin (black), WL radiometric counts (red), cold calibration radiometric counts (blue), relative receiver-plate temperature (cyan), and latitude (green) for the following channels: (a) Channel 4, (b) Channel 6, (c) Channel 8, (d) Channel 12, (e) Channel 16, and (f) Channel 17. Temperature range shown includes the range of $9^\circ C$–$19^\circ C$ for all channels.

can be seen very clearly in the Channel-17 gain series plot [Fig. 6(f)].

Finally, Fig. 10(a) and (b) shows, respectively, the DGS and ray-tracing simulations of F-16 and SSMIS in the center of the “Region 4” WL anomaly. This region is characterized by a direct solar illumination of the warm tines. In this example, the ray-trace model [Fig. 10(b)] clearly shows the red tines of the WL core. The Region 4 WL anomaly does not always materialize due to the occasional blockage of the sun by the spacecraft or the solar array during certain times of the year. However, for the January 15 data shown in Figs. 6 and 10, the Region 4 anomaly is quite strong. Region 4 is characterized by solar illumination elevation angle $\theta < 0^\circ$ and solar azimuth angles limited to $0^\circ < \phi_{wl} < 40^\circ$.

When the F-16 spacecraft is in Region 4, the CSR reflecting surface may also be illuminated by the sun, as shown in Fig. 10(a).\textsuperscript{3} This condition may cause additional and sometimes

\textsuperscript{3}The view is provided from the direction of the sun; therefore, everything that appears in the figure is directly illuminated by the sun. The pink edge of the CSR surface indicates the front (reflecting) surface which appears between the canister and the main reflector.
offsetting calibration biases. Indications of channel-dependent biases associated with illumination of the CSR in this region can be seen in Fig. 6 and are perhaps most noticeable in the Channel-4 data near scan number \( \sim 2000 \). Occurrences of simultaneous biases in the WL and CSR calibration observations, coupled with the additional task of modeling the solar eclipse from the spacecraft and Earth, add complexity to any approach for correcting the SSMIS calibration in Region 4.

A summary of the key features and conditions for each of the four WL anomaly regions is provided in Fig. 12. Each anomaly region was examined over an entire year in order to derive the conditions on \( \phi_w \) and \( \theta \) listed. A graphic depiction of the solar intrusion is also provided for each region near the bottom of Fig. 12. Because of their different characteristics and modeling requirements of the direct illumination cases compared to cases of reflected illumination, Regions 1 and 4 will be called the Direct 1 and 2 regions or D1 and D2 (respectively), and Regions 2 and 3 will be called the Reflected 1 and 2 regions or R1 and R2 (respectively).

VI. WARM LOAD DISCUSSION

Characteristics of the WL-related gain anomalies found in Figs. 3 and 6 for SSMIS in the F-16 orbit suggest that the anomalies occur for periods of a few scans of up to \( \sim 300–400 \) scans (\( \sim 15 \) min) and always appear to increase the effective temperature of the WL compared to the previous or quiescent state. However, analyses of the WindSat WL solar illumination have shown that a relative decrease in effective WL \( T_B \) occurs immediately after solar illumination of the tines is removed [3]. Although occurrences of this “cooling effect” are not as apparent with the SSMIS WL, an example may exist in Fig. 6(f) near the scan numbers 1675 and 1950 showing data from Channel 17 (W-band). In these two examples the WL counts momentarily drop below the local mean (smoothed) value after the solar illumination is removed. Near scan 1675, the sun is blocked temporarily by the magnetometer boom, and scans near \( \sim 1950 \) represent a brief period between R2 and D2 (Regions 3 and 4). Indeed, the W-band channels may provide the best opportunity to view the cooling effect due to the strong dependence of the WL \( T_B \) on the viewing position that is relative to
the WL tine structure, as shown by the patterns in Fig. 5(d). This image shows that the tips provide a higher $T_B$ during illumination (black) near BP 342 and scan $\sim$1400, whereas the valleys are warmer during shadow (yellow) near BP 340 and scan $\sim$1300. Although Fig. 5(d) suggests that a cooling effect may exist with the SSMIS WL under these circumstances, the effect does not appear to be as significant as shown with the WindSat WL. This could be due to the relative size of the SSMIS WL or stabilization of the SSMIS WL core temperature by its backplane heaters. Regardless, potential cooling of the WL effective temperature should be considered in the design of any correction algorithm for the SSMIS WL $T_B$.

In general, the short duration of WL $T_B$ perturbations caused by solar illumination suggests that a flagging process could be used to remove regions of the orbit where the calibration is impacted by errors in the WL or CSR radiometric temperature caused by solar illumination. The flagging scheme could operate on an algorithm designed to identify periods where the anomaly exists by detecting rapid changes in the calibrated radiometric gain, or alternatively, the algorithm could use deterministic methods associated with the position of the sun with respect to the WL and CSR to identify regions that the effective WL $T_B$ is in error. The anomalous region would then be replaced by an empirical gain function that emulates the slowly varying true gain function driven by the ambient temperature variation as would normally occur throughout the orbit. Short well-defined durations and accurate flagging of the affected regions are critical for establishing a reliable WL correction in this fashion.

One characteristic of the F-16 WL anomalies that may add some difficulty in accurately flagging and removing the anomalous regions is the indistinct separation of R1 and R2 (Regions 2 and 3) during the months that the maximum WL solar angle $\theta$ within a single orbit is at a yearly minimum. The problem is shown in Fig. 13(a) on February 11, 2004 when $\theta_{(max)} = 26.2^\circ$. On this day, Fig. 13 shows the point of minimum solar illumination of the WL tines in the period between R1 and R2. However, it is clear that the WL anomaly may still exist at this point because the red tines remain visible in Fig. 13(a). Therefore, an extended period of up to $\sim$30 min where the WL calibration is impacted by solar illumination may exist.
For this same day, Fig. 13(b) shows the Channel-17 receiver gain. Channels 17 and 18 are colocated with an operational heater that stabilizes the ambient temperature of these receivers to a greater extent than the others. Accordingly, the gain (counts per kelvin) of these channels remains relatively stable over the entire orbit. Small WL errors caused by solar illumination are easily discernible as sharp changes in the nominally stable and slowly varying channel gain, as shown in Fig. 13(b) by the sharp changes in gain at Regions 1, 2, and 3 and a small change at Region 4. The dotted black line indicates a rough estimate of the true Channel-17 gain based on the slowly varying trend of the channel gain over the period shown in the graph. The gap depicted by the red arrows indicates the apparent remaining calibration error at the point between R1 and R2 (Regions 2 and 3) caused by solar illumination of the WL in this season.

In summary, the design and implementation of an algorithm to mitigate the impact of undesired solar heating of the WL tines that is based on orbital characteristics of the radiometer gain and the relative solar geometry and orbital illumination conditions may take advantage of the gain stability of Channels 17 and 18 to improve the detection of anomalous gain conditions. Due to seasonal variations and the characteristics of the WL anomalies for F-16, calibration errors may persist for extended periods of up to ∼30 min when R1 and R2 are not distinct. During this period, however, errors will be at a minimum near the midpoint between R1 and R2. Accordingly,
a small empirical gain correction at this point may be needed in order to maintain a division between the R1 and R2 regions over the entire year. A first-order correction of anomalous orbital radiometer gain behavior has been developed by the instrument manufacturer (Northrop-Grumman Electronic Systems, Azusa, CA) and implemented in the SSMIS ground data processing software. The algorithm performs a Fourier analysis to first identify and remove the time segments of the orbital gain variations associated with the anomalous “high-frequency” characteristics followed by interpolation of the “normal” low-frequency variation. The results of this and other mitigation algorithms will be presented in Part II, a companion paper [7].

VII. REFLECTOR EMISSION

Detailed comparisons of SSMIS-measured $T_B$ with background NWP model data have strongly suggested that antenna emission from the SSMIS main reflector is the cause of additional SSMIS residual calibration biases. These biases are very noticeable when comparing ECMWF-modeled background observations to SSMIS measured data as the SSMIS transitions from solar eclipse into sunlight during the F-16 ascending node. For example, Fig. 14 shows the DGS model of DMSP F-16 as it emerges from the solar eclipse in the ascending node in March 2004. The simulation is showing the spacecraft as viewed from the sun as it illuminates the F-16 vehicle and the SSMIS main reflector. The sequence shows the location of the SSMIS main reflector emerging from “behind” the spacecraft as it continues across the equator and into the Northern Hemisphere during the ascending phase of the orbit. Fig. 15 shows the difference between SSMIS observations (SDRs) and the ECMWF forecast applied to RTTOV-7 (fast radiative transfer model) [8] in order to simulate the SSMIS measured $T_B$. The conical scan geometry is imposed upon the “step” in residual bias near $\sim 10^\circ$ N latitude located in the figure by the green arrow in the ascending phase of the orbit. This location is precisely the SSMIS observing location at the time the main reflector is first illuminated by the sun as the SSMIS emerges from the shadow of the spacecraft. Note that the SSMIS is looking forward of the spacecraft and that the DGS model reports the location of the ground track rather than the SSMIS antenna beam footprint location.

The $\sim 2$-K change of bias between the ECMWF background simulations and SSMIS observations in the ascending phase, as shown in Fig. 15, is directly correlated with an $\sim 80\, ^\circ C$ increase in the reflector support arm temperature also due to solar illumination. Assuming that the antenna reflector surface temperature is similar to the reflector arm temperature and that the scene temperature is $\sim 270\, K$, the emissivity $\varepsilon$ of the main reflector would have to be $\varepsilon = 0.025$ near 50 GHz to explain the change in bias. Note that Channel 3 was chosen for Fig. 15 due to its limited $T_B$ dynamic range and slow $T_B$ variation over all portions of the orbit. Channel-3 data show almost no contribution from the surface emission that would introduce higher frequency spatial variations in the measured $T_B$. Sudden changes in measurement biases are therefore attributed to the sensor and are typically not confused with errors originating with the background brightness temperature model. The impact of solar intrusions into the WL on the SSMIS calibration residual biases can also be seen in Fig. 15 by the anomalous low values of SSMIS-RTTOV-7. These occur primarily in the descending phase of the orbit and near the North and South Poles as identified. The magnitude of each WL anomaly appears to be $\leq 2\, K$ when compared to the Channel-3 background. This conclusion is consistent with the earlier summary of characteristics from each WL region shown in Fig. 12.

The data and simulations shown in Figs. 14 and 15 have been performed for all seasons of the orbit annual cycle in order to confirm the hypothesis that antenna emissivity is responsible for the $\sim 2$-K step increase in residual bias of the SSMIS observations compared to the ECMWF background. High values of antenna emission have been observed from radiometers operating at microwave frequencies within the range used by the SSMIS such as the TRMM Microwave Imager (TMI) and the Microwave Limb Sounder (MLS) on the Earth Observing System Aura. An analysis of TMI data by Wentz et al. [2] concluded that the TMI antenna emissivity, after the coating was removed by exposure to atomic oxygen present at the low orbital altitude of TMI, was $\sim 4\%$ for all TMI channels ranging from 10.65 to 85.5 GHz. The MLS antenna baseline correction operates on data that suggest up to $\sim 10$-K offset between the space observation port and the limb viewing port. This offset is attributed to thermal emission, and scattering and diffraction at the MLS antenna reflectors [9]. The MLS primary antenna has similar multilayer construction of vapor-deposited aluminum

<table>
<thead>
<tr>
<th>Region</th>
<th>WL El, $\theta$ (°)</th>
<th>WL Az, $\phi_w$ (°)</th>
<th>$\Delta T_B(K)_{\text{MAX}}$</th>
<th>Latitude (°) *</th>
<th>Phase *</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (D1)</td>
<td>&lt; 0</td>
<td>-10 – 15</td>
<td>2</td>
<td>81 – 60 N</td>
<td>Descending</td>
</tr>
<tr>
<td>2 (R1)</td>
<td>∼ 5 – 25+</td>
<td>0 – 45</td>
<td>3</td>
<td>55 – 0 N</td>
<td>Descending</td>
</tr>
<tr>
<td>3 (R2)</td>
<td>∼ 5 – 25+</td>
<td>40 – 90</td>
<td>2</td>
<td>20 S – 75 S</td>
<td>Desc &amp; Asc</td>
</tr>
<tr>
<td>4 (D2)</td>
<td>&lt; 0</td>
<td>0 – 40</td>
<td>&lt;1</td>
<td>60 S – 15 S</td>
<td>Ascending</td>
</tr>
</tbody>
</table>

Fig. 12. Summary of the WL anomaly regions and the relative sun locations that cause direct and reflected illuminations of the WL tines. The (∗) indicates that data are for January only.

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Fig. 13. (a) Ray-trace model showing the point of the SSMIS orbital season where the highest sun elevation with respect to the SSMIS WL, $\theta = 26.2$ during the orbit, is at a yearly minimum on February 11, 2004 and (b) associated plot of Channel-17 gain. Both (a) and (b) suggest that there may be anomaly-free area between Regions 2 and 3 in this example. The black dotted line indicates a rough estimate of the true channel gain based on the slowly varying gain characteristic.

(VDA) roughened for thermal control [10] as the SSMIS antenna surface. From these collective experiences, we conclude that when compared to bare aluminum, high emissivity characteristics of antennas that are similar to the SSMIS reflector are not unique to SSMIS. However, due to alternating periods of sunlight and shadow and the inability to accurately estimate the $T_B$ offset either by precision thermal measurements of the antenna surface or by an alternate calibration path, thermal emission from the main reflector has a much greater impact to the sensor data quality.
VIII. REFLECTOR ANTENNA DISCUSSION

The SSMIS antenna is an offset parabola with an aperture of ~60 cm (24 in) and a focal length of ~51 cm (20 in). The offset is ~5.1 cm (2 in) from the bottom of the reflector. The antenna boresight off-nadir angle is 45° with respect to the vertical spin axis of the sensor. The impact of SSMIS main reflector thermal emission to the sensor calibration and NWP assimilations resulted in an investigation to identify root cause and potential improvements for later SSMIS flight units. The main reflector and CSR have the same manufacturing pedigree in general, suggesting that the smaller CSR, 0.2 m × 0.3 m, could be used in laboratory tests in order to confirm or exonerate the antenna reflector as a source of the calibration error. Accordingly, laboratory tests of the CSR were performed by using the Conical Scanning Microwave Imaging Radiometer (CoSMIR), an airborne microwave radiometer with a channel set consisting of the SSMIS Channels 1–5 (LAS) and Channels 8–11, 17, and 18 (high-frequency imaging channels) [11].

An absolute emissivity test was performed, as shown in Fig. 16. Measurements of a stabilized ambient temperature calibration load with the CSR reflector in alternating states of room temperature (~25 °C) and elevated temperature...
Residual biases in the ascending node show the contour of the SSMIS conical scan and precisely coincide with the location of the spacecraft as it emerges from eclipse. Biases primarily identified in the descending phase are the result of WL solar intrusion.

\[ T_a(T_{\text{ref}}) = \eta RT_i + \varepsilon T_{\text{ref}} + (1 - \eta)T_x \]  

\[ \frac{\partial T_a}{\partial T_{\text{ref}}} = \eta \varepsilon_{\text{ref}} \approx \varepsilon_{\text{ref}} \]

where \( \eta \) is the beam fill fraction on the reflector (> 0.9), \( R \) is the CSR reflectivity, \( \varepsilon \) is the CSR emissivity, \( T_{\text{ref}} \) is the CSR temperature, \( T_x \) is the room temperature, and \( T_i \) is the ambient target temperature. The test was repeated several times, allowing the radiometer to stabilize at room temperature for > 1 h. The emissivity measurement was dependent only on the difference of two measurements of the ambient load; absolute accuracy was not critical as long as the radiometer was demonstrated to be stable over the CSR hot and ambient temperature measurement periods.

The experiment consistently indicated < 0.5-K brightness temperature change in the apparent ambient target temperature at 183.31 GHz as a result of moving the CSR temperature from 25 °C to 80 °C. The estimated emissivity is therefore < 0.8% at 183.31 GHz. This value is nearly a factor of ten less than 7%, the estimated emissivity of the F-16 SSMIS main reflector based on residual biases observed from comparisons of measured data to background ECMWF fields and RTTOV model data at 183 GHz. The results of this experiment suggest that the characteristics of the reflecting-surface change from prelaunch to on-orbit, or that the reflecting surface of the CSR (under test), is, in some other manner, not representative of the main reflector emissivity characteristics. It is also noted that the operating temperature of the main reflector on-orbit is typically
scheduled for launch in mid-2008 has been replaced with a spare reflector.

One area of the current investigation is directed at the intensity of the thin VDA reflector coating as manufactured for SSMIS. Microcracking of the thin reflective coating due to rapid temperature changes (thermal shock) caused by a direct solar illumination is hypothesized to create areas where the graphite epoxy substrate becomes exposed [12]. For the F-16 SSMIS, rapid temperature variations occur during every orbit. Currently, this explanation is supported by a related experiment involving measurements from CoSMIR. Smooth uncoated graphite epoxy panels tested at 183 GHz were found to exhibit ≈77% emissivity. The highly emissive nature of the base graphite epoxy supports the suggestion that higher emissivity can result from exposure of a small fractional area of the underlying graphite epoxy structure. Indeed, scanning electron microscope images of the CSR reflecting surface show areas where the base graphite epoxy is not covered by the VDA at room temperature. In conclusion, several explanations exist for the apparent main reflector emission. Related investigations are in progress to demonstrate root cause.4

IX. Summary

This paper has described two anomalies of the SSMIS radiometric calibration, each having a significant impact on the calibration and quality of the measured SSMIS $T_B$’s. The SSMIS sensor is a precision radiometer combining the following: 1) conical-scan geometry enabling polarized measurements over the Earth’s surface and 2) coincident measurements of the atmospheric temperature and moisture profile at improved resolution (compared to cross-track sensors) and constant viewing geometry. The full range of data applications has not yet been fully explored in part because retrieval algorithms and models designed to take full advantage of the information content provided by the SSMIS measurements have not been developed. These potential new applications also rely on precision correction, $\ll 1$ K. In order to achieve this goal, precise corrections to the SSMIS calibration must be designed in order to mitigate the effects of WL solar intrusion and the reflector emission anomalies. Of the two anomalies discussed in this paper, the reflector emission appears to pose the most significant obstacle to new and emerging applications of SSMIS radiometric data. Biases originating with the main reflector are larger in magnitude, $\sim 5$–$7$ K at the highest SSMIS frequency (183 GHz) and $\sim 2$ K or less at 50 GHz, where precision calibration is needed ($\lesssim 0.2$–$0.4$ K) in order to provide significant positive impact on the quality of NWP analysis and forecasts. Calibration errors due to SSMIS antenna emission are more difficult to mitigate for several reasons: 1) The temperature of reflecting surface is needed to design a mitigation algorithm and is only known indirectly, and as a result, 2) the time response and absolute value of the antenna’s reflecting-surface temperature when exposed to the sun are very difficult to model. In contrast, the WL errors on the F-16 SSMIS are typically below $\sim 2$ K for all channels and of relatively short duration, typically $\sim 5$ min or less. As a result, it is likely that correction algorithms can be designed to effectively utilize all of the data and information available to the SSMIS ground processing software in order to mitigate WL-related calibration errors on the order of a small fraction of a Kelvin.

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REFERENCES


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