Calibration Anomalies and Radiance Assimilation Correction Strategies for the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager Sounder (SSMIS)

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1. Introduction

The Defense Meteorological Satellite Program (DMSP) launched the first (F-16) in a series of five spacecraft carrying the Special Sensor Microwave Imager Sounder (SSMIS) on October 18, 2003. The SSMIS is a 24 channel conically scanning microwave radiometer, with center frequencies ranging from 19.35 to 183.31 GHz. The SSMIS instrument is the first conical scanning instrument with temperature and moisture sounding channels, and also adds the first operational mesospheric sounding capability. The F-16 orbit is near 850 km in an inclined 98.8º sun-synchronous polar orbit with a local time of ascending node (LTAN) of 20:03. The main reflector ha a diameter of 0.61 m, and rotates at 31.6 rpm. The F-16 travels at 6.5 km sec^{-1} that translates to 12.5 km separation between adjacent scans. The SSMIS scanning geometry and channel characteristics are shown in Figure 1 and Table 1, respectively.

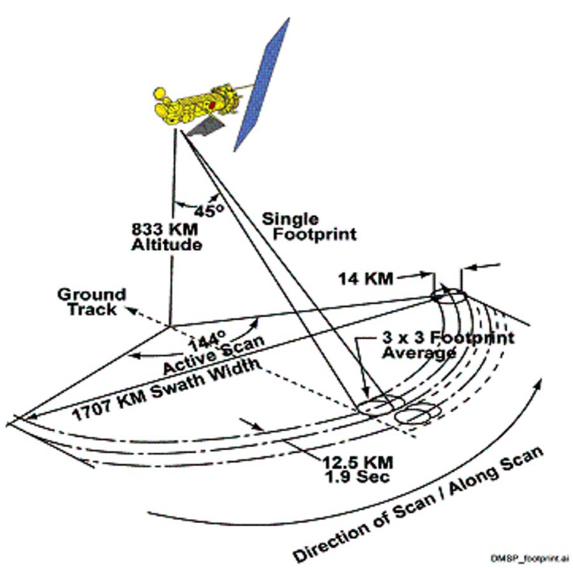

Figure 1. SSMIS Scan Geometry

A comprehensive SSMIS Calibration and Validation (Cal/Val) program was undertaken and discovered unexpected calibration anomalies in the radiometric data [1]. The two principal anomalies detected were, 1) an intermittent solar intrusion to the warm load calibration target; and 2) reflector emission due to solar heating of the reflector surface itself. Other intermittent calibration anomalies detected were random noise spikes mostly near the South Atlantic Anomaly (SAA), and lunar intrusions into the cold space reflector.

Table 1. F-16 SSMIS channel characteristics and comparison to current microwave sensors (AMSU-A, AMSU-B, SSM/I and New Mesospheric channels)

Ch. No.	Center Frequency [GHz]	1st IF [MHz]	2nd IF [MHz]	Band Width [MHz]	Pol	Peak [hPa]
1	50.3	0.	0.	400.	V	1000
2	52.8	0.	0.	400.	V	700
3	53.596	0.	0.	400.	V	400
4	54.40	0.	0.	400.	V	200
5	55.50	0.	0.	400.	V	100
6	57.29	0.	0.	350.	LCP	60
7	59.4	0.	0.	250.	LCP	30
8	150.0	1250.	0.	1500.	H	
9	183.31	6600.	0.	1500.	H	
10	183.31	3000.	0.	1000.	H	
11	183.31	1000.	0.	400.	H	
12	19.35	0.	0.	400.	H	
13	19.35	0.	0.	400.	V	
14	22.235	0.	0.	500.	V	
15	37.0	0.	0.	1500.	H	
16	37.0	0.	0.	1500.	V	
17	91.655	900.	0.	1500.	V	
18	91.655	900.	0.	1500.	H	
19	63.283248	±285.271	0.	1.5	LCP	0.02
20	60.792668	±357.892	0.	1.5	LCP	0.05
21	60.792668	±357.892	±2.	1.5	LCP	0.7
22	60.792668	±357.892	±5.5	3.0	LCP	2
23	60.792668	±357.892	±16.	8.0	LCP	7
24	60.792668	±357.892	±50.	30.0	LCP	15

Microwave radiances provided by polar orbiting satellite sensors have become an increasingly important component of observing systems for both global and regional data assimilation systems (DAS) for numerical weather prediction (NWP) systems. Assimilation of radiances from instruments such as the Advanced Microwave Sounding Unit (AMSU) have led to significant reduction in short term forecast errors in the southern hemisphere and improvements in the northern hemisphere in global NWP systems. Microwave radiance data typically undergo a series of bias removal steps prior to assimilation, and bias correction methods have become an integral part of the radiance assimilation process. The observed scene temperatures (OB) are compared with those computed using a fast radiative transfer model (RTM) with the NWP analysis or short–term forecast as the background (BK). The European Centre for Medium Range Weather Forecasts (ECMWF) provided global analyses from the surface to 0.1 hPa to the SSMIS Cal/Val team. The computed TBs (BK) referred to in this study were produced using ECMWF analyses and RTTOV-7. The sources of the OB-BK bias can be errors in the RTM, NWP background bias, calibration errors, scan angle bias and scan asymmetries, etc. DAS for global NWP typically demand less than 0.4 K uncertainties in the atmospheric temperature sensitive channels (50-60 GHz oxygen absorption channels) after bias corrections have been applied. The stringent DAS requirements mandate that the calibration anomalies and resulting scene temperature biases identified by the SSMIS Cal/Val efforts be mitigated prior to assimilation.

2. SSMIS Calibration

Radiometric calibration for the SSMIS is performed by a two-point method where the radiometer feedhorns are passed under a warm load target and a cold space reflector. The warm load target consists of an array of pyramidal tines coated with highly emissive paint. The key assumptions in this calibration method are 1) the relationship between antenna temperatures and raw radiometric counts is linear between the warm and cold calibration points, and 2) the warm load and cold space temperatures are representative of the respective calibration targets. The linear calibration used to convert SSMIS counts to antenna temperatures is:

$$T_{Ai} = T_C + \frac{\overline{T_W} - T_C}{\overline{C_W} - \overline{C_C}}\left(C_i - \overline{C_C}\right) = T_C + \frac{C_i - \overline{C_C}}{G}$$

T_{Ai} = Antenna Temperature

T_C = Cosmic Background Temperature

$\overline{C_C}$ = Mean Cold Space Reflector Count

$\overline{T_W}$ = Mean Warm Load Temperature

$\overline{C_W}$ = Mean Warm Load Count

C_i = Scene Count

$$G = \frac{\overline{C_W} - \overline{C_C}}{\overline{T_W} - T_C} = \text{Radiometer Gain}$$

The averaging is performed in a symmetric manner about the current scan, and uses 8, 16 and 32 scans for channels 8-18, 1-7,24, and 19-23, respectively.

3. SSMIS Warm Load Solar Intrusions

The orbit of the DMSP F-16 allows for solar elevation angles with respect to the SSMIS canister top to vary between ± 40º, with the range for a given day varying with time of year. The design of the SSMIS warm load and shroud combined with the reflective canister top resulted in four distinct geometric scenarios where solar radiation can impinge upon the surfaces of the warm load tines (Figures 2 and 3). Software developed by the Aerospace Corporation, DMSP Graphic Simulator (DGS) allows for precise visualizations of the F-16 spacecraft as viewed form the Sun.

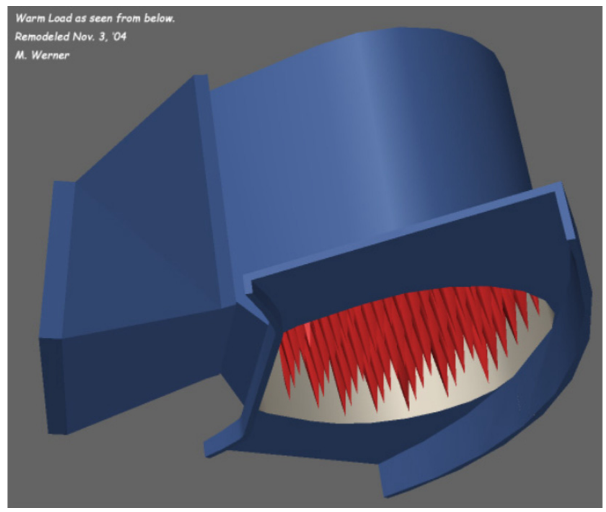

Figure 2. The SSMIS Warm Load and Shroud

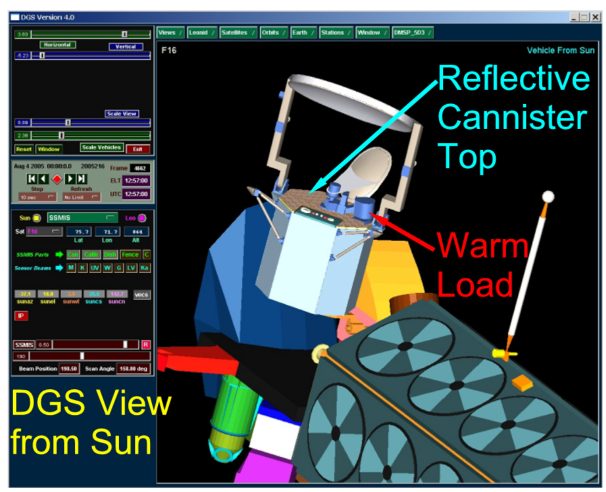

Figure 3. DGS image of the F-16 SSMIS as viewed from the Sun

Two direct solar impingements (negative elevation angles) and two reflections off of the canister top can occur per orbit. The impingements can last up to 400 scans during which rapid heating of the warm load tines is not sensed by the three platinum resistance thermistors embedded deep inside the substrate of the warm load. This results in anomalous positive radiometer gains, subsequent calibration errors, and lower effective scene temperatures. The solar intrusion caused anomaly is readily evident in the time series of the individual channel radiometer gains and match the cool anomalies in the scan-averaged OB-BK time series seen in Figure 4.

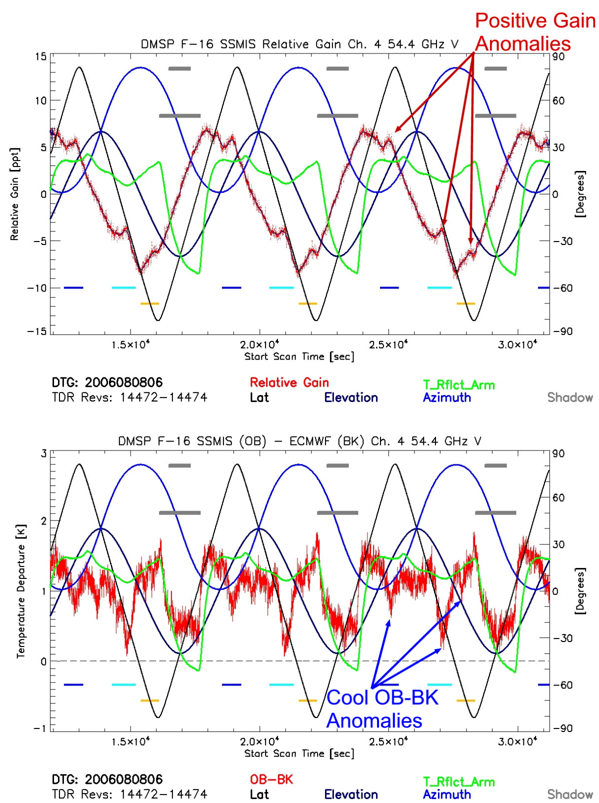

Figure 4. SSMIS Channel 4 Relative Gain Time Series depicting the positive gain anomalies induced by solar intrusions to the warm load, and the coincident SSMIS Scan-averaged OB-BK Time Series depicting the negative anomalies induced by solar intrusions to the warm load. Solar elevation and azimuth angles, spacecraft latitude, reflector rim temperature, earth and spacecraft shadows are also shown.

4. Warm Load Intrusion Mitigation Strategy

The solar intrusion anomaly can impart up to a 1.5 K peak depression in the observed scene temperatures near the center of the intrusion period. The duration and shape of the intrusion is channel dependent as the feedhorns view different warm load tines. A Fourier based filtering mitigation strategy has been implemented to perform the gain filtering in the SSMIS processing software for the sensor data records (SDRs). NRL has applied a Gain Ratio correction to the temperature data record (TDR) files used for radiance assimilation as follows: The ratio formed by the Original Gain, G_o, to the Fourier filtered Gain, G_f, should be equal to 1.0 and have values greater than unity only where the intrusions occur. So the corrected TB_c is

$$TB_c = T_{Cosmic} + \left(TB_o - T_{Cosmic}\right)\left(G_o / G_f\right)$$

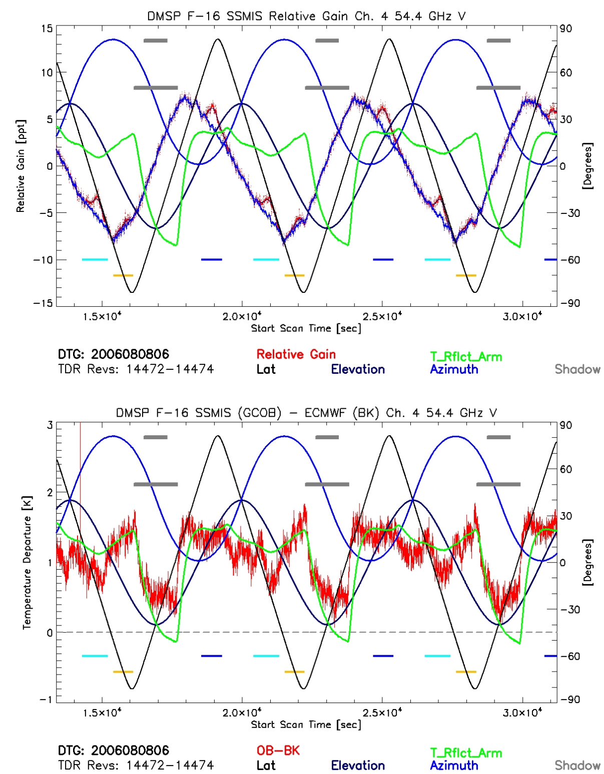

Figure 5. Same as Figure 4, but showing the effect of the Fourier Filtering algorithm upon the SSMIS Channel 4 Relative Gain Time Series, and the Coincident SSMIS Channel 4 Gain Corrected OB-BK Scan-averaged Time Series.

5. SSMIS Reflector Emission

The SSMIS main reflector is a comprised of a graphite-epoxy laminate parabolic shell with layers of vapor deposited aluminum (VDA), Silicon Oxide (SiO_x) and a single base layer of chromium as shown in Figure 6. The SSMIS reflector was designed to be non-emissive at microwave frequencies, and was specifically coated with SiO_x to minimize thermal emission effects. Pre-launch tests of the SSMIS main reflector showed a reflectivity > 0.9999. The F-16 SSMIS is equipped with a thermistor placed upon the rim of the reflector and is the only telemetry data available to estimate the true reflector face temperature. On orbit, the reflector rim thermistor observes a solar induced thermal cycle ranging from 220 - 300 K. The green curve in figures 4 and 5 depict the thermal cycle of the reflector rim temperature. Once a gain correction is applied to the scene temperatures, the OB-BK time series closely follows the rim temperature.

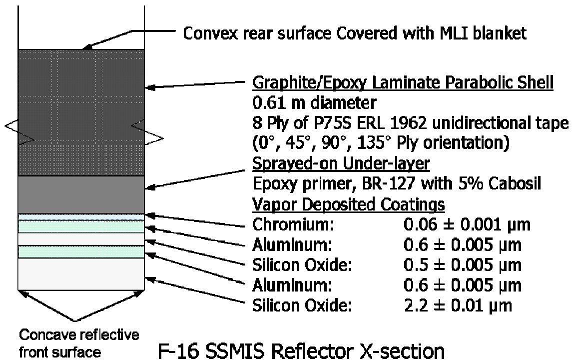

Figure 6. Cross-section of the SSMIS main reflector.

Analysis of the relative magnitudes of the OB-BK for the SSMIS channels show a frequency dependent emissive behavior. Warm OB-BK biases of 1-2.5 K in the 50-60 GHz channels and ~ 5 K in the high frequency channels are observed. The maximum reflector emission anomaly occurs just after the spacecraft emerges from earth and/or spacecraft shadow, and the reflector face is directly illuminated by the sun. A simple physical model governs the reflector emission and resulting scene temperature bias.

$$T_{OB} = \left[1 - \varepsilon_R(\nu)\right] T_{Scene} + \varepsilon_R(\nu) T_R$$

$$\Delta T_{R\_Emis} = T_{OB} - T_{Scene} = \varepsilon_R(\nu)\left[T_R - T_{Scene}\right]$$

The goal of applying the SSMIS Reflector Emission Correction, ΔT_{R_Emis}, is to remove the effect of the reflector emissions from the observed brightness temperature and produce an improved scene temperature.

$$T_{Scene} = T_{OB} - \Delta T_{R\_Emis} = T_{OB} - \varepsilon_R(\nu)\left[T_R - \hat{T}_{Scene}\right]$$

However, this requires accurate knowledge of three parameters:

T_R True Reflector Temperature

$\varepsilon_R(\nu)$ Frequency Dependent Reflector Emissivity, and

$\hat{T}_{Scene}$

an estimate of the True Scene temperature. The effect of reflector emission is shown in Figure 7. On this date, 8 August 2006, the SSMIS reflector emerges from earth shadow on the ascending nodes near 20 N and a solar intrusion to the warm load occurs at 30 S on the descending nodes.

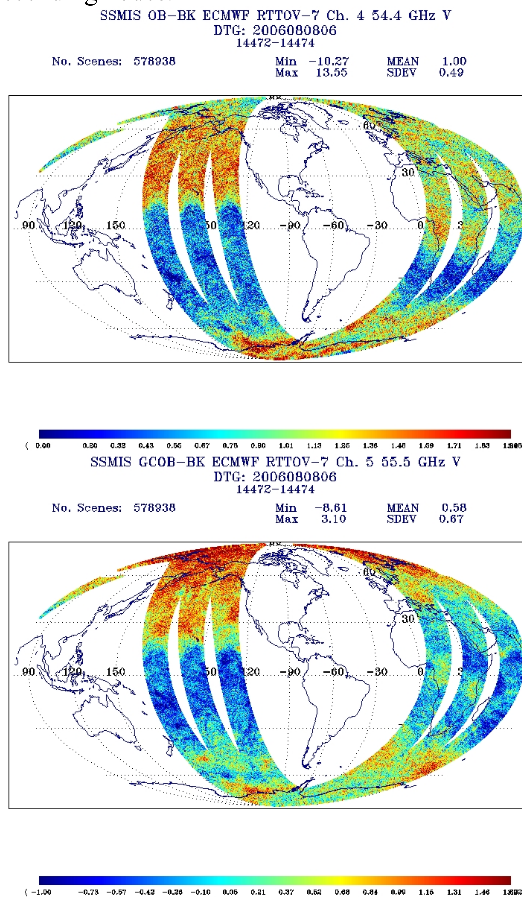

Figure 7. SSMIS Reflector Emission induced bias in the channel 4 OB-BK.

6. SSMIS Reflector Emission Mitigation Strategy

It is assumed that an accurate estimate of the true reflector temperature can be constructed empirically from a lag filtered time rate of change of the observed SSMIS reflector rim temperature [2], as follows:

$$T_{rflct} = T_{rim} + c_F \int_0^P e^{(-\tau/\sigma)} \frac{dT_{rim}}{dt}(t-\tau)\,d\tau$$

where,

σ is the lagged filter width

P is the lag period

c_F is correction factor constant

The NRL method employs the following values for the empirical model constants: $C_F = 250$, P =120 s, τ = 32 s, σ = 320 s. The results for the reflector temperature estimate, using these values is shown in figure 8. Initial analysis of the OB-BK and emission correction patterns indicated that the reflector rim may undergo greater cooling than that of the reflector face in earth shadow. The reflector face always “sees” the earth, whereas the rim does not. The earthshine contribution to the reflector face is driven by the outgoing longwave radiation (OLR). While in earth shadow an OLR correction is also applied. The OB-BK results indicate that the reflector face heats up much faster upon exiting shadow than the rim. Reflector emissivities were chosen to be 0.02 for the 50-60 GHz channels and 0.07 for the 150-183 GHz channels, based upon the NRL antenna model for a graphite epoxy shell.

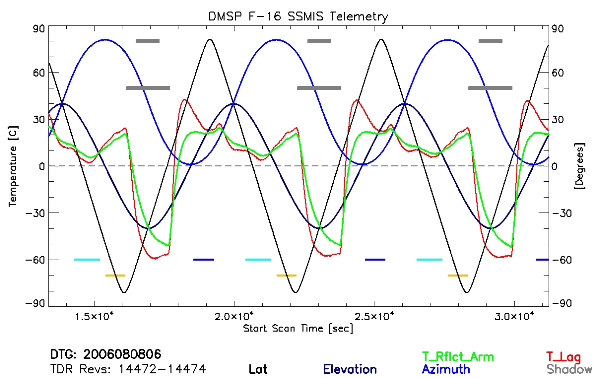

Figure 8. NRL Reflector face temperature estimate without OLR correction in earth shadow.

6. Results

The SSMIS Fourier filtered Gain corrections have been applied to the TDR files and an estimate of the reflector face temperature has been made available for NRL radiance assimilation. Results of using these files in radiance assimilation trials are being presented in a companion paper. The following observations have been made regarding the SSMIS reflector emission corrections:

1) Scene temperatures immediately upon emergence from shadow are still not adequately emission corrected, but can be QC’d using magnitude of dT_{rim}/dt

2) Channels 10 and 11 show that the mean monthly OLR values mimic the effect of the clouds as apparent in the scene temperatures, i.e. the double hump feature in near the minimum in the rim temperature

3) Channel 5 OB-BK characteristics and to a lesser degree Channel 6, seem to point to an O_2 absorption RTM error, i.e. the Gamma correction as the bias appears to be air-mass dependent with negative biases in the tropics.

The results with and without applying the OLR correction in the earth shadow region are shown in figures 9 and 10. The three-panel plot shows the telemetry data, observed and corrected brightness temperatures, and the original (OB-BK), gain corrected (GCOB-BK), and gain and emission corrected departures (ECGCOB-BK).

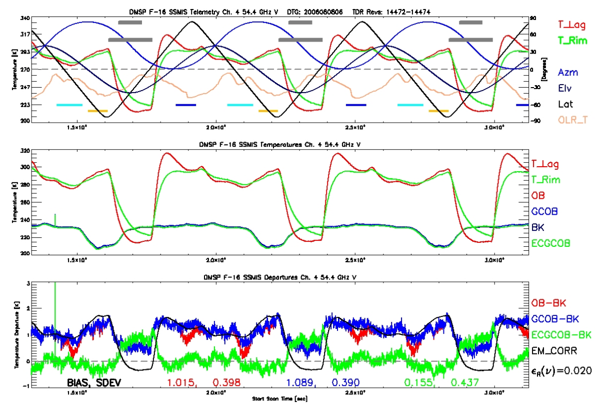

Figure 9. SSMIS Gain and Emission correction results without OLR correction

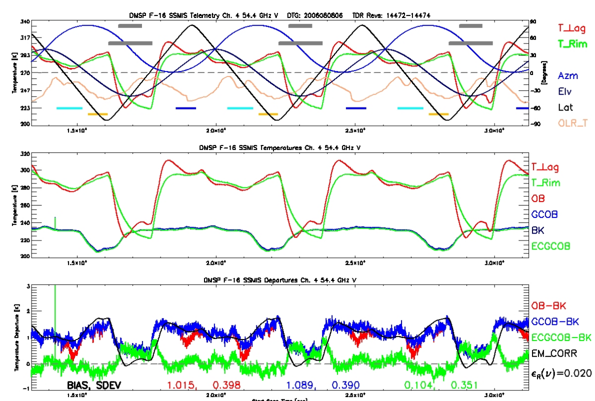

Figure 9. SSMIS Gain and Emission correction results with OLR correction

7. Conclusions

An NRL SSMIS preprocessor has been developed that creates a new TDR file that contains the Gain corrected antenna temperatures, and an estimate of the reflector face temperature, T_R. The estimated T_R can then be used in the application of the emission correction. Further refinements to the lagged reflector temperature estimator are planned. Hardware modifications are planned for DMSP F-17 and beyond to mitigate these calibration anomalies at the source [3]. F-17 Hardware modifications include building a fence to eliminate the direct warm load solar intrusions and converting channels 1-5 to horizontal polarizations as originally intended in the design of the SSMIS.

8. References

[1] Poe, G. and Coauthors, 2005: Defense Meteorological Satellite Program Special Sensor Microwave Imager Sounder (F-16) Calibration/Validation Final Report. November 2005.

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9. Acknowledgements

The efforts of the SSMIS Cal/Val team were performed under support from the DMSP and Navy PMW-180. The support of the Space and Naval Warfare Systems Command, through program element 063207N is gratefully acknowledged. SSMIS data were provided by the Fleet Numerical Meteorology and Oceanography Center (FNMOC). European Centre for Medium Range Weather Forecasts (ECMWF) provided high quality atmospheric analyses that proved invaluable to the Cal/Val efforts.

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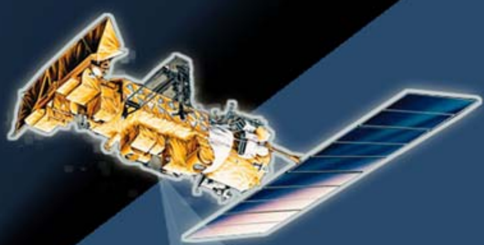

Proceedings of the Fifteenth International TOVS Study Conference

Maratea, Italy

4 October - 10 October 2006

cover design by Nicola Afflitto