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Thermal Testing and Model Correlation of the Magnetospheric Multiscale (MMS) Observatories

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The Magnetospheric Multiscale (MMS) mission is a Solar Terrestrial Probes mission comprising four identically instrumented spacecraft that will use Earth's magnetosphere as a laboratory to study the microphysics of three fundamental plasma processes: magnetic reconnection, energetic particle acceleration, and turbulence. This paper presents the complete thermal balance (TB) test performed on the first of four observatories to go through thermal vacuum (TV) and the mini-balance testing that was performed on the subsequent observatories to provide a comparison of all four. The TV and TB tests were conducted in a thermal vacuum chamber at the Naval Research Laboratory (NRL) in Washington, D.C. with the vacuum level higher than 1.3 x 10-^{4} Pa (10^{-6} torr) and the surrounding temperature achieving -180 °C. Three TB test cases were performed that included hot operational science, cold operational science and a cold survival case. In addition to the three balance cases a two hour eclipse and a four hour eclipse simulation was performed during the TV test to provide additional transient data points that represent the orbit in eclipse (or Earth's shadow) The goal was to perform testing such that the flight orbital environments could be simulated as closely as possible. A thermal model correlation between the thermal analysis and the test results was completed. Over 400 1-Wire temperature sensors, 200 thermocouples and 125 flight thermistor temperature sensors recorded data during TV and TB testing. These temperature versus time profiles and their agreements with the analytical results obtained using Thermal Desktop and SINDA/FLUINT are discussed. The model correlation for the thermal mathematical model (TMM) is conducted based on the numerical analysis results and the test data. The philosophy of model correlation was to correlate the model to within 3 °C of the test data using the standard deviation and mean deviation error calculation. Individual temperature error goal is to be within 5 °C and the heater power goal is to be within 5% of test data. The results of the model correlation are discussed and the effect of some material and interface parameters on the temperature profiles are presented.

Nomenclature

ADP = Axial Double Probe
ASPOC = Active Spacecraft Potential Control
BOL = Beginning Of Life
CIDP = Central Instrument Data Processor
CPT = Comprehensive Performance Test
DES = Dual Electron Spectrum
DIS = Dual Ion Spectrum
DPU = Digital Processing Unit
EOL = End Of Life
ETU = Engineering Test Unit
EVD = Engin Valve Drive
FEEPS = Fly's Eye Energetic Particle Sensors
GBK = Germanium Black Kapton
GDU = Gun Detector Unit
GEVS = General Environmental Verification Standard (GSFC-STD-7000)
GMM = Geometric Math Model
GSE = Ground Support Equipment

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GSFC = Goddard Space Flight Center
HPCA = Hot Plasma Composition Analizer
IS = Instrument
PSEES = Power System and Engine valve drive Electronic Systems
SDP = Spin-plane Double Probe
MLI = Multi-Layer Insulation
MMS = Magnetospheric MultiScale
NRL = Naval Research Laboratory
STP = Solar Terrestrial Probe
TB = Thermal Balance
TCS = Thermal Control System
TCU = Thermal Conditioning Unit
TICD = Thermal Interface Control Drawing
TMM = Thermal Math Model
TQCM = Thermoelectric Quartz Crystal Microbalance
TV = Thermal Vacuum

I. Introduction

The Magnetospheric Multiscale (MMS) mission is the fourth mission of the Solar Terrestrial Probe (STP) program of the National Aeronautics and Space Administration (NASA). The MMS mission uses four identically instrumented observatories to perform the first definitive study of magnetic reconnection in space and will test critical hypotheses about reconnection. Magnetic reconnection is the primary process by which energy is transferred from the solar wind to the Earth's magnetosphere and is also fundamental to the explosive release of energy during sub storms and solar flares.

The MMS mission will study magnetic reconnection in the Earth's magnetosphere. The four MMS observatories will be required to fly in a tetrahedral formation in order to unambiguously determine the orientation of the magnetic reconnection layer. MMS orbit is highly elliptical consists of two phases: first phase day side of magnetic filed is 1.2 times of Earth radius (R_E), Perigee, by 12 times of R_E, Apogee. Second phase night side of magnetic field is 1.2 times of Earth radius (R_E), Perigee, by 25 times of R_E, Apogee (see Figure 1). The MMS mission successfully launched all four observatories on March 12, 2015 at 10:44 P.M. Eastern from Cape Canaveral, Florida with a primary mission duration of twenty-nine months.

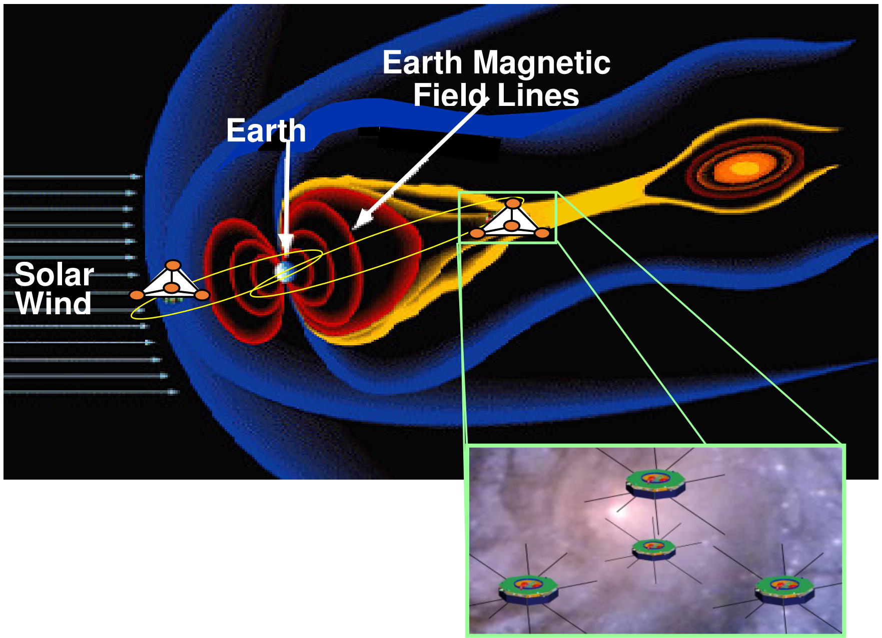
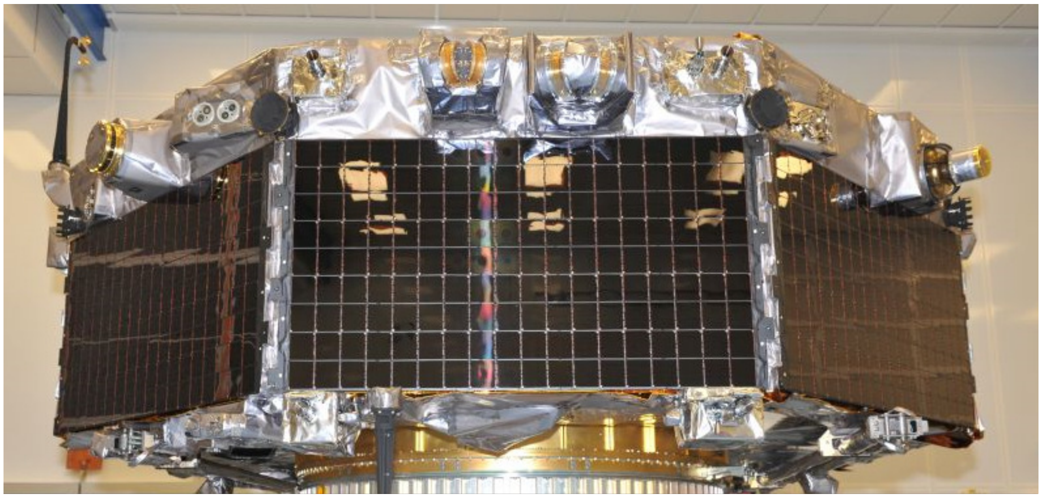
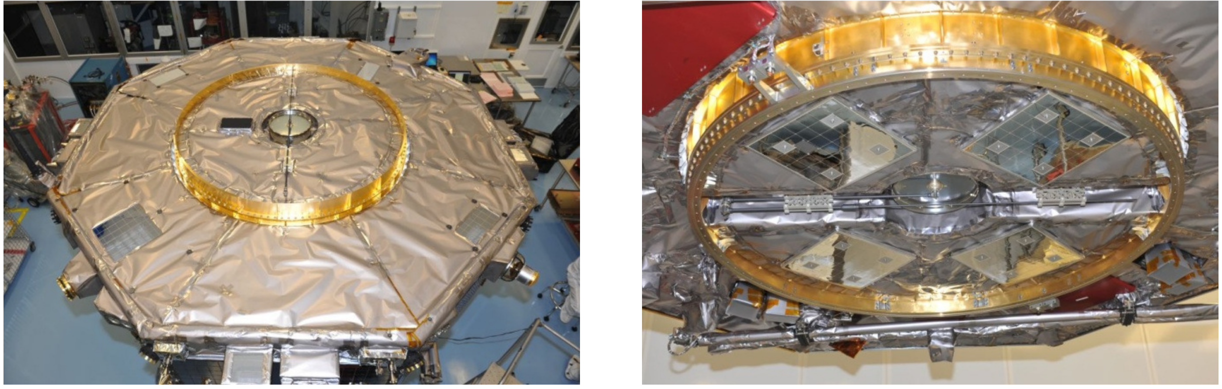


Figure 1. MMS Mission Orbit and Formation



View of Solar Arrays and Instrument Suite



Instrument Deck

Spacecraft Deck and Shunt Panels

Figure 2. MMS Observatory Integration Photos

The MMS observatories consist of a passive thermal design that include Optical Solar Reflector (OSR) radiators on the instrument and spacecraft decks to reject heat from avionics and instrument electronics during hot environments, thermal gaskets (Choseal) to conductively couple electronics to their respective radiators, multi-layered insulation (MLI) blankets covering all exterior surfaces except for instrument apertures, solar arrays, and radiators. To minimize heat loss during the eclipse portion of the orbit, the MMS thermal design incoporates titanium isolators separating the Solar Arrays from the spacecraft, high-efficiency blankets on hydrazine propulsion tanks and ultem isolators on propulsion lines and thruster valves. The gold plated thrust tube rings and separation system rings provide additional thermal energy into the system while in the sunlit portion of the orbit while reducing the heat loss during the cold and long duration eclipses.

The MMS instruments and electronic components performed subsystem level thermal vacuum (TV) and thermal balance (TB) testing prior to delivery to the observatory integration and test (I&T) team at NASA/GSFC. The testing consisted of eight (8) TV cycles in accordance GSFC-STD-7000 (GEVS) and three (3) TB points. In addition, the instruments and spacecraft electronic components verified performeance of the operational and survival thermostatically controlled heaters that were mounted to the instrument and electronic component chassis. Further thermal testing was performed on some of the spacecraft engineering test unit (ETU) hardware to reduce risk at the observatory level. Such testing included a calormetric test of a gold plated ring to verifiy the surface emissivity and thermal balance test of a propulsion zone to verify the thermal isolation of the custom made propulsion line standoffs and heater zone thermal control[3].

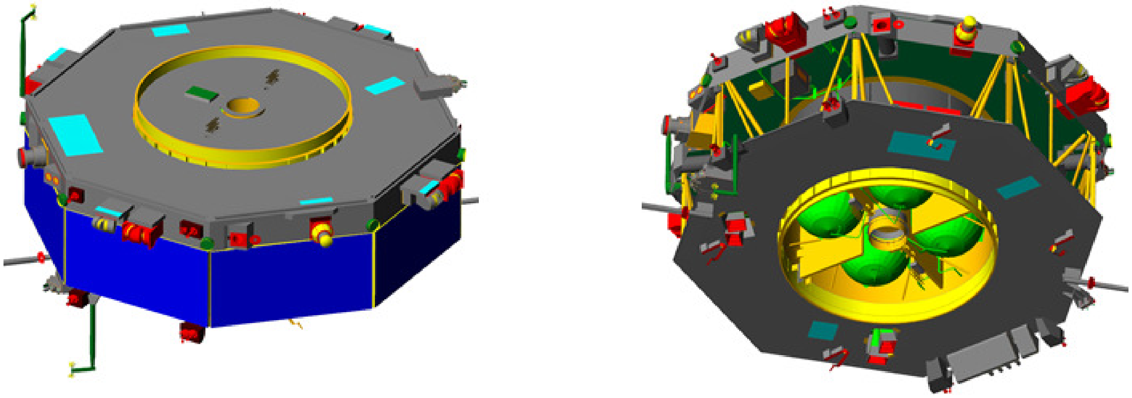


Figure 3. MMS Thermal Desktop$^{\text{TM}}$ Geometry Model

II. Thermal Vacuum and Thermal Balance Test Overview

The MMS Observatories, in as close as possible configuration to flight, was subjected to thermal vacuum (TV) testing at the Naval Research Lab (NRL) beginning November 2013 and continuing through July 2014. The primary goal was to demonstrate repeated system-level performance at the extremes of the flight predicted temperatures (with margin). The flight predicted temperatures are obtained using a thermal model of the Observatory that combines measured powers, thermal coatings, multi-layer insulation effectiveness, conductivities and other thermal parameters in worse case combinations to produce a maximum and minimum predicted range for each component. The testing included both thermal balance (TB) and thermal cycling (TC) phases. The TB phase included a hot bake-out, one hot operational balance plateau, one cold operational balance plateau and a cold survival balance plateau in order to obtain the performance data necessary to assess the effectiveness of the thermal design. The thermal performance data generated during the thermal balance plateaus was also used as the basis for correlation and modification of the MMS Observatory Thermal Desktop$^{\text{TM}}$ and SINDA/FLUINT thermal mathematical model (TMM). Mission mode operations were performed during the hot and cold thermal balance plateaus with additional functional testing representing one thermal cycle. With four observatories, the MMS program performed many of the I&T activities in parallel. For example, while MMS1 was preparing for vibration testing, MMS2 was performng TB and TV testing After a chamber break and reconfiguration of the EGSE, the first Observatory to go through TV/TB testing (MMS2) was subjected to three additional thermal cycles to verify system performance over the range of expected flight environments plus 10 °C (hot case) and -10 °C (cold case; -5 °C for heater controlled items). This range is nominally -25 °C to + 50 °C. The test duration was based on the time required to complete the thermal balances cases, comprehensive performance testing (CPT), transition and soak times, mission simulations, special tests and Functional Tests. There was a minimum time at each thermal vacuum phase temperature plateau of 24 hours to achieve a total of 100 hours of operation at the hot and 100 hours at the cold plateau.

The MMS Observatory was in flight thermal configuration (except for Star Camera stimulus and S-Band hat couplers) for thermal balance. During chamber pump down for both TB and TV, the observatory was powered in a “launch-mode” configuration. Additionally, two cold starts and two hot starts of the observatory’s power switchable loads were performed during the TV test (i.e., A side and B sides.).

A bake-out of the chamber and test GSE was performed prior to the start of thermal testing and a certification of an acceptable low out gassing rate was monitored using TQCM’s throughout the TB and TV testing. All first unit instruments and the instrument and spacecraft electronic components shall have successfully completed at least eight thermal vacuum cycles prior to this Observatory Thermal Vacuum test sequence. Exceptions are the subsequent instrument units that shall have successfully completed at least four thermal vacuum cycles, the passive spacecraft structure, the electrical harness internal to the spacecraft and the propulsion subsystem.

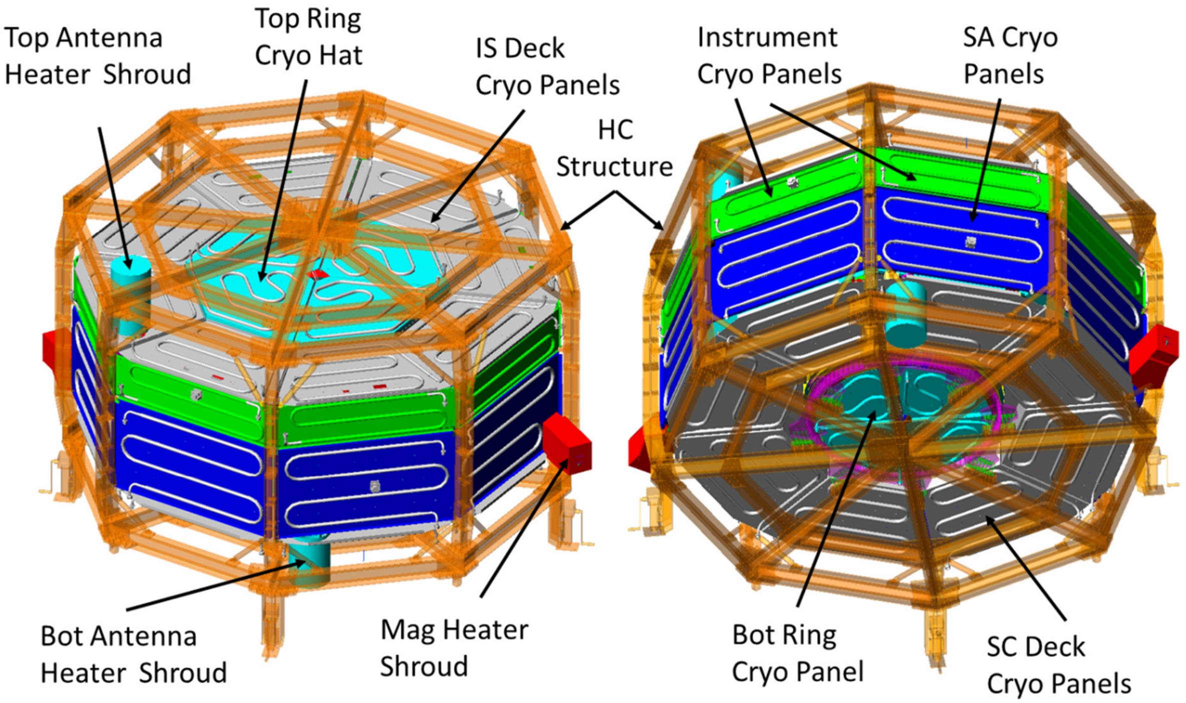


Figure 4. Thermal Balance/Thermal Vaccuum Test Set-up

The main program objective for the thermal vacuum cycling test phase was to flight qualify the MMS Observatory for on-orbit operation over the required temperature range with margin. This objective was realized by driving the Observatory temperatures through three (3) temperature cycles while exercising the Observatory components. Electrical tests, conducted at both hot and cold plateaus are compared to the baseline Comprehensive Performance Test (CPT). The thermal cycling was intended to stress the Observatory components, harnesses and connectors while accelerating developing failures in marginal designs and to make sure that performance margins exist when all the hardware is performing at hot or cold extremes. During this Observatory Thermal Vacuum (TV) testing, no component or subsystem was taken beyond its operational qualification or acceptance limits (as appropriate) or beyond its survival non-operating survival limits. The component temperature limits were established from data review of the component and subsystem test data and from those listed in the Thermal interface control drawings (TICDs).

The thermal vacuum test levels experienced for instruments and spacecraft electronic components were 10 °C above and below the operational limits for all units except for heater controlled items that were subjected to 5 °C below the operational limits. For the instruments, the total time accumulated during their individual thermal vacuum tests was a minimum of 48 hours at hot and 48 hours at cold in accordance with the GSFC-STD-7000 (GEVS) recommendation for instruments and for spacecraft components. Prior to observatory TB testing the instruments (except for instrument electronics housed within the spacecraft bus) performed an instrument level TB test in accordance with NASA/GSFC Gold Rule 4.29 to provide an empirical verification of the thermal design and correlate the thermal math models (TMMs). The first Observatory to enter observatory thermal vacuum testing was MMS2 and therefore, MMS2 completed a full TB test with three balance cases that included a transient eclipse simulation. The main objective of the TB test was to demonstrate proper operation of the thermal design and to obtain thermal performance data at specified hot and cold equilibrium conditions, which was used as the basis for correlation and modification of the Thermal Desktop^{TM} and SINDA/FLUINT thermal math models (TMM). The instruments had previously correlated their TMM's to their individual thermal balance tests (except for instrument electronics housed within the spacecraft bus). After completion of the MMS2 TB test a chamber break was performed to install instrument stimulus required for the TV cycle testing. During the thermal cycle phase of the qualification testing the MMS2 performed a "mini-TB" that was used as a baseline for comparison with the other three observatories that performed a similar "mini-TB"test. The "mini-TB" was an extended plateau at hot and cold to compare the thermal performance of each of the observatories. For the instruments, this observatory level "mini-

TB" concentrated on demonstrating the control of instrument interface temperatures, proper simulation of the environment for instrument radiators and correlation of the TMM's of the instrument electronics housed within the spacecraft bus.

III. Thermal Balance

For thermal balance testing, the Observatory TMM was to be correlated with the test data from three TB test points: Hot Op Balance, Cold Op Balance and a Cold Survival Balance to an accuracy of ± 5 °C, with a goal of ±3 °C for spacecraft components and ±3 °C for instrument interfaces. Thermal equilibrium was defined by the °C/hr stability values listed in Table 1. The stability is calculated using all temperature sensors for each TCS control zone for a period of four (4) consecutive hours with the temperatures showing neither an increasing nor decreasing trend. For conditions where heaters were cycling, equilibrium was determined when cycle extreme temperatures met the stabilization criteria from cycle-to-cycle, and duty cycles were consistent. For thermal cycling testing, soak temperatures were deemed reached when the control temperature sensors (i.e., thermistors, thermocouples, 1-Wire GSE sensors) were within 2 °C of a plateau goal and the TB stabilization criterion (dT/dt) was 2 to 5% of the total energy (per GEVS) of the thermal control subsystem (TCS). Total energy balance calculation is shown below:

$$\text{Total Energy Balance (\%)} = \frac{mCp\left(\frac{dT}{dt}\right)}{Q*3600}$$

Where Q = electronic power dissipation (J/s)
m = mass (kg)
Cp = Heat Capacitance (J/kg-°C)
dT/dt = temperature change per time (°C/hr)
3600 = time converstion from second to hour

TCS Control Zone	Electronic Power, Q Watts (J/s)	Mass, M kg	Specific Heat, Cp J/kg-°C	Test Stability Criteria dT/dt	Test Energy Balance Percentage %
Bay #1 (Navigator+USO)	38.41	21.37	879	0.25	3.40%
Bay #2 (Battery)	1	27.46	879	0.005	3.35%
Bay #3 (F/D)	1	1	879	0.15	3.66%
Bay #4 (Comm)	26.9	14.36	879	0.25	3.26%
Bay #5 (C&DH)	24.61	23.26	879	0.15	3.46%
Bay #6 (Star Sensor)	10.88	8.41	879	0.15	2.83%
Bay #7 (Misc)	1	1	879	0.15	3.66%
Bay #8 (PSEES)	35.94	36.96	879	0.15	3.77%
Bay #1 (+X DIS/DES)	11.6	11.88	879	0.125	3.13%
Bay #2 (CIDP)	19.7	17.01	879	0.125	2.64%
Bay #3 (+Y DIS/DES)	11.6	11.88	879	0.125	3.13%
Bay #4 (IDPU/EDI/EIS/SDP)	14.68	20.44	879	0.125	4.25%
Bay #5 (-X DIS/DES)	11.6	11.88	879	0.125	3.13%
Bay #6 (SDP/HPCA/ASPOC)	13.06	23.4	879	0.1	4.37%
Bay #7 (CEB,-Y DIS/DES)	22.94	22.85	879	0.125	3.04%
Bay #8 (SDP, EDI)	4.09	15.96	879	0.05	4.76%

Table 1 Total Energy Balance Calculation

The TB test data and the post-test correlated TMM are required to assess the effectiveness of the thermal design elements including coatings, multi-layer insulation (MLI), heater circuit capacities and duty cycles. Both A and B side heater and temperature sensor circuits verified that the correct control points (i.e., thermostat set points, flight software temperature sensor data) and heater duty cycles met the design requirements, as well as verification of proper thermal interfaces, radiator sizes, MLI effective emittance, current draw for specific components and temperature sensor calibration. An A side hot and cold turn on was performed during this test phase to demonstrate the ability of the instruments and spacecraft components to operate satisfactorily during cold operational conditions and after a cold restart. Additionally, the thermal vacuum test demonstrated that the instruments and spacecraft components can operate satisfactorily during and after temperature transition through a two hour (minimum) eclipse and a four hour (maximum) eclipse. The TV test data demonstrated that the workmanship of all four observatories (spacecraft and instruments) was thermally and functionally adequate and that the observatories met the contamination cleanliness requirements.

For TB testing the Observatory was in its flight configuration with the following exceptions:

- Star Camera Stimuli installed
- S-Band Antenna hat couplers installed
- Mag booms partially deployed to expose radiators
- SDP and ADP booms stowed
- Propulsion system pressurized to 30 psia with Helium

Thermoelectric quartz crystal microbalances (TQCM's), a coldfinger, and a scavenger plate were used during TB/TV. This was done to verify a clean spacecraft after bakeout at the end of TB/TV. The TQCM's were located near the observatory and the coldfinger and scavenger plate were used to determine the contaminant composition. To minimize contamination risks, it was desirable to keep the observatory warmer than its surroundings and testing began and ended with a hot soak.

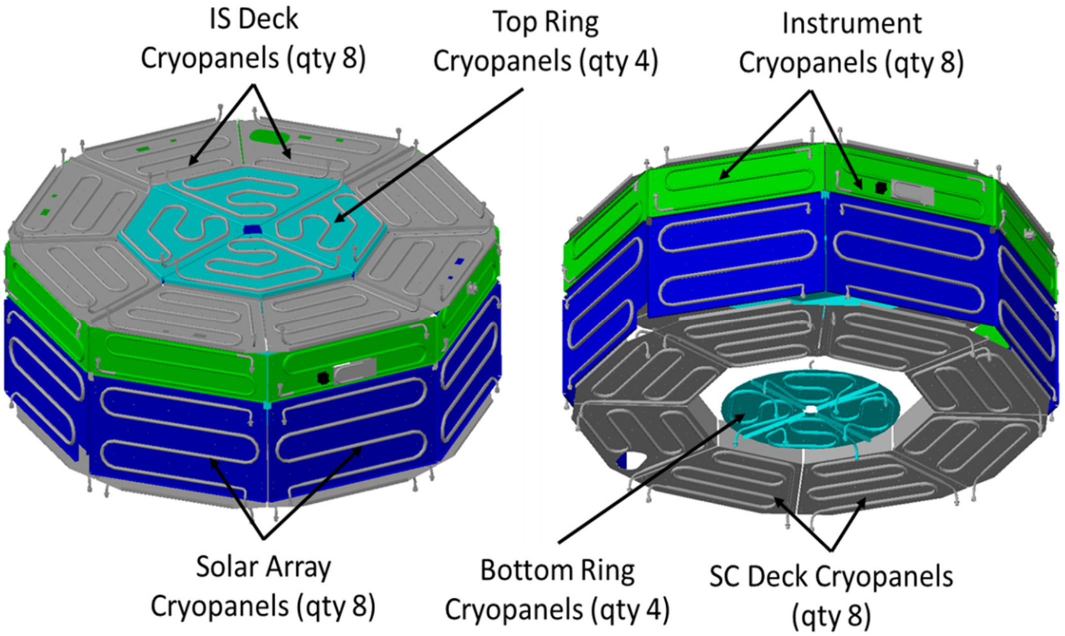


Figure 5: Thermal Vacuum Test Cryopanel Layout

The Top Cryo Panels (Figure 5) view the instrument deck (not instruments) that is mostly GBK blanket with some OSR radiators. The pre-test thermal analysis assumed the same temperature for all eight (8) top cryo panels per case. However, test limitations (# of TCUs, Omega Controllers, etc) did not permit panels to achieve uniform temperatures and test data showed temperature gradient from -140 °C to -126 °C (14 °C delta) for hot case and less than 5 °C delta for cold cases because of the similar temperature within the shroud. The impact to the model correlation was minimal since it is mainly radiative heat exchange to the external MLI blankets.

The Bottom Cryo Panels view Spacecraft Deck that is mostly GBK blanket with some OSR radiators. The pre-test thermal analysis assumed same temperature for all eight (8) bottom cryo panels per case, however, test data shows temperature gradient from -182 °C to -164 °C (18 °C delta) for hot case and less than 5 °C delta for cold cases because of the similar temperature within the shroud. The impact to the model correlation is minimal since it is mainly radiative heat exchange to the external MLI blankets.

The solar array panels view solar arrays and any external components that are located near the outer edge of the instrument or spacecraft decks (e.g., Digital Sun Sensors, FEEPS instruments and magboom). The instrument cryo panels view instruments only. Each bay (sometimes with multiple instruments) views each panel that is controlled with averaged sink temperature. Instrument cryo panels were able to control the temperature within 2 °C to their expected sink temperatures.

Solar flux (or total absorbed environment heat load) was simulated using eight (8) GSE heaters on the Thruster Tube (TT) Rings, top and bottom. Heat flow gains/losses were minimized between the test GSE and Observatory using Zero-Q heater control between the GSE ring and the Observatory ring (Figure 6). During the MMS4 TVAC test, additional verification of the Zero-Q interface was performed to confirm zero Q loss (or very small heat loss) at this interface. The values for the Zero-Q heaters are show in Table 2.

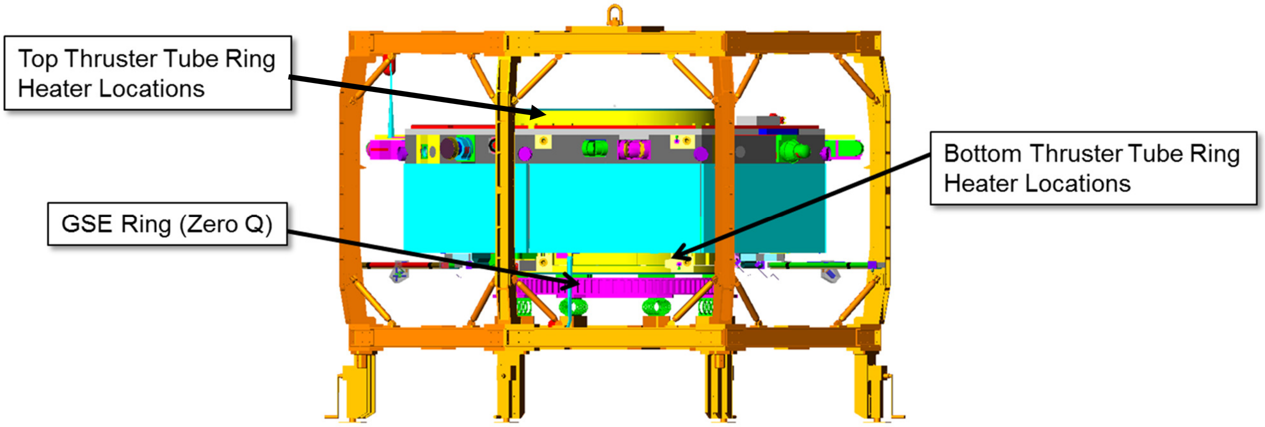


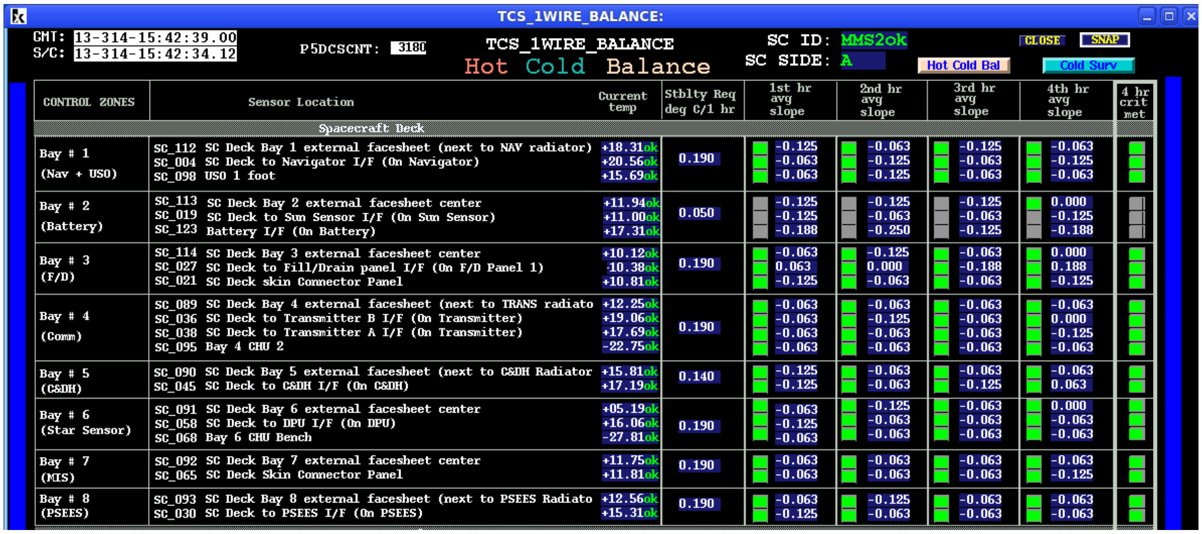
Figure 6. Cryopanel Attach Frame (cryopanels are removed to show Spacecraft)

	Hot Op Thermal Balance			Cold Op Thermal Balance			Survival Thermal Balance		
	Model, Pre-test	Achieved in Test	Delta (°C)	Model, Pre-test	Achieved in Test	Delta (°C)	Model, Pre-test	Achieved in Test	Delta (°C)
Heat Load to Ring									
Top Ring Heat Load	160 W	160 W	0 W	107 W	107 W	0 W	107 W	107 W	0 W
Bot Ring Heat Load	83 W	83 W	0 W	66 W	66 W	0 W	66 W	66 W	0 W

Table 2. Predicted Environmental Heat Load

A. Thermal Balance Data Acquistion

The TB test temperature telemetry consisted of flight sensors, thermocouples and 1-wire GSE sensors. The MMS thermal engineers worked with the MMS test engineers to develop a data acquisition page that would assist in determining when thermal equilibrium had been achieved based on the predefined criteria described earlier. Figure 7 shows a snapshot of a sample data acquisition screen. When four green lights in a row are illuminated the test engineers can easily acknowledge that thermal equilibrium for that specific control zone had been achieved. This telemetry page proved to be a significant aide for the TB testing and was used for both the full MMS2 TB test and the “mini-TB” test that was performed on all four observatories.



GMT: 13-314-15:42:39.00
S/C: 13-314-15:42:34.12
P5DCSCNT: 3180
TCS_1WIRE_BALANCE
Hot Cold Balance
SC ID: MMS2ok
SC SIDE: A

CONTROL ZONES	Sensor Location	Current temp	Stblty Req deg C/1 hr	1st hr avg slope	2nd hr avg slope	3rd hr avg slope	4th hr avg slope	4 hr crit met
Spacecraft Deck								
Bay # 1 (Nav + USO)	SC_112 SC Deck Bay 1 external facesheet (next to NAV radiator)	+18.31ok	0.190	🟩 -0.125	🟩 -0.063	🟩 -0.125	🟩 -0.063	🟩
	SC_004 SC Deck to Navigator I/F (On Navigator)	+20.56ok		🟩 -0.063	🟩 -0.125	🟩 -0.063	🟩 -0.125	🟩
	SC_098 USO 1 foot	+15.69ok		🟩 -0.063	🟩 -0.125	🟩 -0.063	🟩 -0.063	🟩
Bay # 2 (Battery)	SC_113 SC Deck Bay 2 external facesheet center	+11.94ok	0.050	⬜ -0.125	⬜ -0.125	⬜ -0.125	🟩 0.000	⬜
	SC_019 SC Deck to Sun Sensor I/F (On Sun Sensor)	+11.00ok		⬜ -0.125	⬜ -0.063	⬜ -0.063	⬜ -0.125	⬜
	SC_123 Battery I/F (On Battery)	+17.31ok		⬜ -0.188	⬜ -0.250	⬜ -0.125	⬜ -0.188	⬜
Bay # 3 (F/D)	SC_114 SC Deck Bay 3 external facesheet center	+10.12ok	0.190	🟩 -0.063	🟩 -0.125	🟩 -0.063	🟩 0.000	🟩
	SC_027 SC Deck to Fill/Drain panel I/F (On F/D Panel 1)	10.38ok		🟩 0.063	🟩 0.000	🟩 -0.188	🟩 0.188	🟩
	SC_021 SC Deck skin Connector Panel	+10.81ok		🟩 -0.125	🟩 -0.063	🟩 -0.063	🟩 -0.125	🟩
Bay # 4 (Comm)	SC_089 SC Deck Bay 4 external facesheet (next to TRANS radiato	+12.25ok	0.190	🟩 -0.063	🟩 -0.063	🟩 -0.063	🟩 -0.063	🟩
	SC_036 SC Deck to Transmitter B I/F (On Transmitter)	+19.06ok		🟩 -0.063	🟩 -0.125	🟩 -0.063	🟩 0.000	🟩
	SC_038 SC Deck to Transmitter A I/F (On Transmitter)	+17.69ok		🟩 -0.063	🟩 -0.063	🟩 -0.063	🟩 -0.125	🟩
	SC_095 Bay 4 CHU 2	-22.75ok		🟩 -0.063	🟩 -0.063	🟩 -0.063	🟩 -0.063	🟩
Bay # 5 (C&DH)	SC_090 SC Deck Bay 5 external facesheet (next to C&DH Radiator	+15.81ok	0.140	🟩 -0.125	🟩 -0.063	🟩 -0.063	🟩 -0.063	🟩
	SC_045 SC Deck to C&DH I/F (On C&DH)	+17.19ok		🟩 -0.125	🟩 -0.063	🟩 -0.125	🟩 0.063	🟩
Bay # 6 (Star Sensor)	SC_091 SC Deck Bay 6 external facesheet center	+05.19ok	0.190	🟩 -0.063	🟩 -0.125	🟩 -0.063	🟩 0.000	🟩
	SC_058 SC Deck to DPU I/F (On DPU)	+16.06ok		🟩 -0.125	🟩 -0.063	🟩 -0.063	🟩 -0.063	🟩
	SC_068 Bay 6 CHU Bench	-27.81ok		🟩 -0.063	🟩 -0.063	🟩 -0.063	🟩 -0.063	🟩
Bay # 7 (MIS)	SC_092 SC Deck Bay 7 external facesheet center	+11.75ok	0.190	🟩 -0.063	🟩 -0.063	🟩 -0.063	🟩 -0.063	🟩
	SC_065 SC Deck Skin Connector Panel	+11.81ok		🟩 -0.063	🟩 -0.063	🟩 -0.063	🟩 -0.125	🟩
Bay # 8 (PSEES)	SC_093 SC Deck Bay 8 external facesheet (next to PSEES Radiato	+12.56ok	0.190	🟩 -0.063	🟩 -0.125	🟩 -0.063	🟩 -0.063	🟩
	SC_030 SC Deck to PSEES I/F (On PSEES)	+15.31ok		🟩 -0.125	🟩 -0.063	🟩 -0.063	🟩 -0.063	🟩

Figure 7. Snap-shop of Screen Monitor that shows green lights when achived steady-state

The MMS2 TB testing was completed in approximately fifteen days. Figure 8 illustrates the 'as run' test profile. The initial bakeout was important to obtain a clean observatory and remove the water containted in the MLI blankets and thermal coatings. The chamber achieved better than 1 x 10^{-06} torr creating a 'flight like' vacuum environment that was essential for correlating the MLI effective emittance for the numerous blankets that covered the spacecraft and instrument components. After completing the first hot qualification CPT's the observatory was placed in the Hot Thermal Balance configuration and after approximately 24 hours the hot thermal balance criterion was achieved.

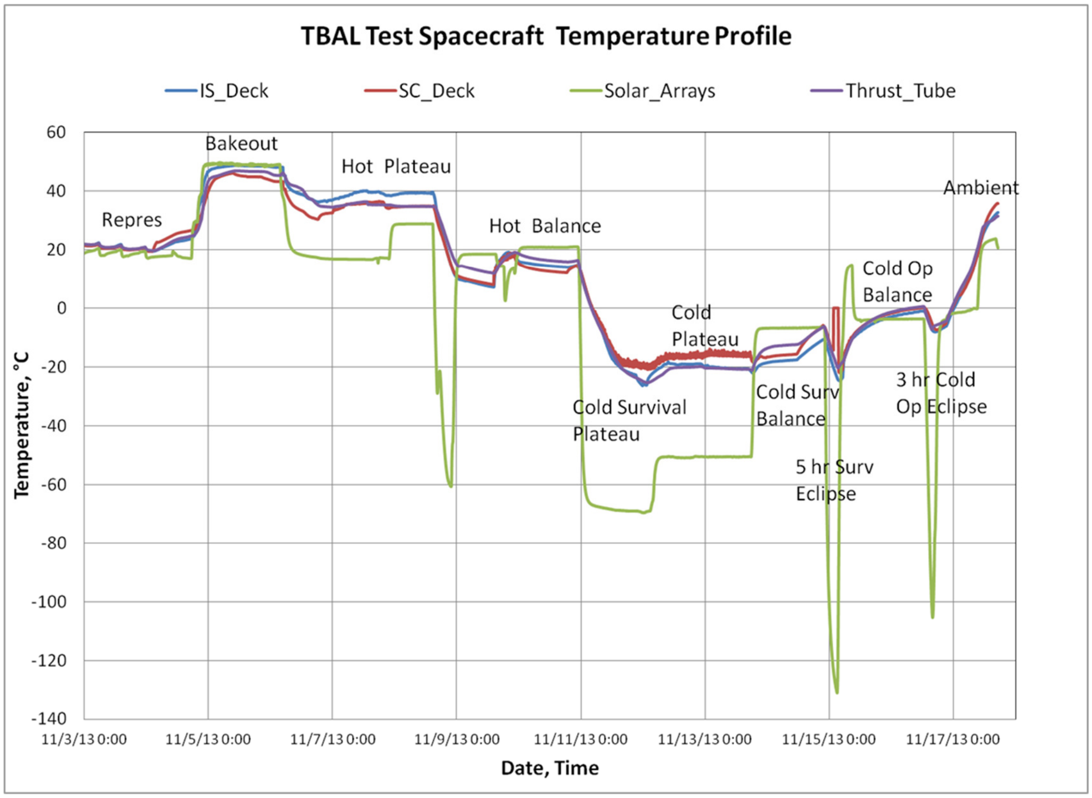


Figure 8. Thermal Balance Test Temperature Profile

B. Thermal Balance Instrument and Spacecraft Power Dissipation Comparison

A significant aspect for achieving thermal balance is to maintain constant power dissipations on all electronic components. The MMS thermal engineers worked closely with the MMS Systems engineers to develop the test scripts to achieve this goal. The power dissipations listed in Table 3 show the comparison of the pre-test flight model instrument power dissipatons to what was achieved during the thermal balance testing.

	Hot Op			Cold Op/3hr Eclipse			Cold Survival/5hr Eclipse		
Instruments	**FLIGHT MODEL Avg (W)**	**TEST DATA (W)**	**MODEL - TEST DELTA (W)**	**FLIGHT MODEL Avg (W)**	**TEST DATA (W)**	**MODEL - TEST DELTA (W)**	**FLIGHT MODEL Avg (W)**	**TEST DATA (W)**	**MODEL - TEST DELTA (W)**
CIDP	11.7	11.1	1	11.8	11.1	1	0.0	0.0	0
HPCA	11.7	10.7	1	10.1	7.0	3	0.0	0.0	0
EIS	2.5	1.8	1	2.0	1.7	0	0.0	0.0	0
FEEPS (X2)	3.8	3.6	0	3.5	3.7	0	0.0	0.0	0
ASPOC (X2)	4.2	2.6	2	4.2	2.8	1	0.0	0.0	0
IDPU	5.1	4.9	0	5.1	5.7	-1	0.0	0.0	0
DES (X4)	31.6	18.4	13	22.0	13.4	9	0.0	0.0	0
DIS (X4)	26.9	18.0	9	20.5	11.9	9	0.0	0.0	0
GDU/EDI (X2)	8.9	4.6	4	8.4	4.8	4	0.0	0.0	0
CEB	8.5	8.6	0	8.4	8.4	0	0.0	0.0	0
AEB	0.9	0.9	0	0.9	0.9	0	0.0	0.0	0
SDP (BEB + Preamp) (X4)	2.3	1.9	0	1.9	1.9	0	0.0	0.0	0
AFG/DFG	0.2	0.2	0	0.2	0.2	0	0.0	0.0	0
PreAmp	0.2	0.2	0	0.2	0.2	0	0.0	0.0	0
IS_XBOX	4.4	0.0	4	0.0	0.0	0	0.0	0.0	0
INSTRUMENT SUM =	**122.8**	**87.4**	**35.4**	**99.1**	**73.6**	**25.4**	**0.0**	**0.0**	**0.0**

Table 3. Instrument Power Dissipation Comparison

For predicting the worst case flight hot operational (fast survey mode) temperatures the flight power dissipations use End of Life (EOL) power (i.e., 15% power margin added to BOL power). For the hot operational thermal balance test Beginning of Life (BOL) power was used. The differences between the instrument pre-test (flight model) assumptions and what was observed during the TB testing is captured in Table 3 and was accounted for in the model correlation. In addition most of the instruments in flight assume high voltage power (e.g., DES and DIS, GDU, ASPOC and HPCA), however, high voltage power was not required for thermal balance and was also taken into account in the model correlation. For the cold operational thermal balance case (i.e., Slow Survey Mode), most of the instruments in flight assume high voltage power (e.g., DES and DIS, GDU, ASPOC and HPCA), but the same philosophy used in the hot thermal balance was applied to the cold thermal balance. For the Survival case (safe mode) all instruments were turned off.

	Hot Op			Cold Op/3hr Eclipse			Cold Survival/5hr Eclipse		
Instruments	**FLIGHT MODEL Avg (W)**	**TEST DATA (W)**	**MODEL - TEST DELTA (W)**	**FLIGHT MODEL Avg (W)**	**TEST DATA (W)**	**MODEL - TEST DELTA (W)**	**FLIGHT MODEL Avg (W)**	**TEST DATA (W)**	**MODEL - TEST DELTA (W)**
C&DH	17.0	17.7	-1	17.0	17.4	0	12.1	14.0	-2
PSEES	58.9	41.2	18	43.6	50.4	-7	37.9	40.0	-2
NAVIGATOR & USO	33.5	31.5	2	27.3	30.1	-3	3.9	5.1	-1
TRANSPONDER (X2)	27.4	23.8	4	25.8	54.5	-29	23.3	23.6	0
ACCELEROMETER	9.0	7.7	1	7.8	7.8	0	0.0	0.0	0
BATTERY	0.0	0.0	0	0.2	0.0	0	0.4	0.0	0
STAR SENSOR (CHU + DPU)	11.1	6.0	5	0.2	5.4	-5	0.0	0.0	0
SUN SENSOR (X2)	0.4	0.4	0	0.4	0.4	0	0.4	0.0	0
TRANSDUCER (X4)	3.2	0.9	2	0.0	0.0	0	0.0	0.0	0
SPACECRAFT BOX SUM =	**160.4**	**129.2**	**31.2**	**122.2**	**165.9**	**-43.7**	**77.9**	**82.7**	**-4.8**
TOTAL SPACECRAFT SUM	**283.2**	**216.6**	**66.6**	**221.2**	**239.5**	**-18.3**	**77.9**	**82.7**	**-4.8**
Shunt	136.0	75.0	61	0.0	63.0	-63	0.0	67.0	-67

Table 4. Avionics Power Dissipation Comparison

The spacecraft electronic components follow the same power philosophy that was used for the instruments. The differences between the spacecraft pre-test (flight model) assumptions and what was observed during the TB testing is captured in Table 4 and was accounted for in the model correlation. For the flight model the hot operational case assumes Engine Valve Drive (EVD) firing that corresponds to power dissipation within power supply electronics (PSEES) box. In addition the star sensor flight cases assumed EOL degraded properties and the battery shunt power used was averaged (e.g, test shunt power varies from 26 W to 109 W). These difference were accounted for in the model correlation. For the cold operational case the transmitter A was turned ON 100% during test, however, the flight model assumes only 9% duty cycle. The star sensor data processing unit (DPU) assumed 0W power for the worst cold flight case, however, it was on during test dissipating about 5 watts. The battery shunt power observed in test was averaged (i.e., test shunt power varies from 3 W to 121 W). For the cold survival case, the shunt power observed in test is averaged (i.e., test shunt power varies from 14 W to 106 W).

C. Understanding the Model Correlation Energy Balance

In the pre-test thermal analysis you assume you are going to achieve the environment sinks that you predict and have designed the test hardware to achieve. However, for MMS this was not the case. A newly refurbished thermal vacuum chamber with unstable thermal control units (TCUs) brought additional challenges to running the thermal balance test. For the environmental sink temperatures (i.e., temperature controlled cyro panels) there were what seemed to be significant differences between the pre-test sink temperature predictions and those achieved in test. However, during the thermal model correlation analysis it was determined that the variations in temperature that occurred during testing had minimal impact to the system energy balance and thermal model correlation. Additionally, the test environment values were used in thermal model correlation to provide one-to-one comparison between thermal balance model and thermal balance test. As for the difference in power dissipation, these values were understood, a rationale for the power difference was achieved and the test power dissipation is used to show one-to-one prediction comparison. There orbit average environmental heat load (i.e., solar flux) on the gold interface rings was simulated using kapton foil heaters mounted directly to the inside surface of the rings.

Additional pre-correlation modelling assumptions include using BOL optical property for all cases. This included gold ring optical properties assumed a = 0.19 and e=0.03, Germanium Black Kapton (GBk) MLI blanket and tape outer layer $\alpha = 0.49$ and $\varepsilon=0.81$, Optical Solar Reflectors (OSRs) $\alpha = 0.08$ and $\varepsilon=0.85$, spacecraft and instrument deck MLI blanket $\varepsilon^*=0.01$ for hot $\varepsilon^*=0.03$ for cold and instrument and electronic box $\varepsilon^* = 0.05$ for hot and $\varepsilon^* = 0.07$ for cold.

IV. Thermal Model Correlation

A. Test Model Adjustments and Iterations

The thermal model correlation started with reasonable adjustments of large system variables such as spacecraft and instrument deck MLI effective emittance and Gold Rings interfaces to get the spacecraft average temperature in line with the test data for the three steady state cases (Hot Op, Cold Op and Cold Surv). Then focus was placed on individual instruments and electronic box temperatures and adjustments to component MLI effective emittance and interface conductances. For the transient five hour survival and three hour operational eclipse correlation, comparison of the thermal model mass to the latest measured mass was performed. Adjustments were made taking into account the specific heat assumptions for various materials (majority of time, aluminum 6061 is assumed). Additionally, initial temperatures were adjusted to match the measured test data, transition rates and final temperatures were compared. The goal was to correlate the model to within 3 °C of the test data using the standard deviation and mean deviation error calculation. Individual temperature error goal was to be within 5 °C. The heater power goal is to be within 5% of test data. The standard deviation and mean deviation is tracked for every major model iteration. Flight temperature predictions were updated based on final correlation.

B. Thermal Model Steady-State Correlation Results

The MMS observatory thermal model spacecraft deck and the critical components correlated to within 2 °C of the hot thermal balance test data with a mean of -1.3 °C and standard deviation error of 1.9 °C.

TCS Control Zone	**Sensor Location**	**Post-Correlated Model (°C)**	**Test Data 11/10/2013 GMT: 16:58**	**Model - Test Delta (°C)**
Bay #1 (Navigator+USO)	Nav Foot	15.7	20.5	-5
	USO1 Foot	14.6	15.6	-1
Bay #2 (Battery)	DSS Foot	7.9	10.9	-3
	Battery Foot	12.6	17.1	-5
Bay #3 (F/D)	Prop Fill/Drain Panel	10.9	10.4	1
	Connector Panel	11.1	10.8	0
Bay #4 (Comm)	TRANS 'B' Foot	17.2	19.0	-2
	TRANS 'A' Foot	16.8	17.6	-1
	Star Sensor CHU	-21.7	-22.8	1
Bay #5 (C&DH)	C&DH Foot	15.7	17.1	-1
Bay #6 (Star Sensor)	DPU Foot	15.9	16.0	0
	Star Sensor CHU	-30.2	-27.9	-2
Bay #8 (PSEES)	PSEES Foot	14.4	15.2	-1
Bay #1 (+X DIS/DES)	DIS	14.2	20.1	-6
	DES	12.6	15.3	-3
Bay #2 (CIDP)	CIDP	15.4	18.5	-3
	SDP	11.7	14.6	-3
	ASPOC	11.7	15.7	-4
Bay #3 (+Y DIS/DES)	DIS	14.4	19.7	-5
	DES	11.6	14.3	-3
Bay #4 (IDPU/EDI/EIS/SDP)	IDPU	13.6	18.3	-5
	EDI	11.8	12.4	-1
	EIS	19.8	20.8	-1
	SDP	11.8	15.4	-4
Bay #6 (SDP/HPCA/ASPOC)	SDP	9.4	13.2	-4
	HPCA	13.1	12.7	0
	ASPOC	9.9	13.6	-4
Bay #7 (CEB,-Y DIS/DES)	CEB	17.1	19.5	-2
	DIS	16.0	18.9	-3
	DES	12.5	15.8	-3
Bay #8 (SDP, EDI)	SDP	12.7	15.8	-3
	EDI	12.6	14.8	-2

Table 5. Post Model Correlation Temperature Comparison (Hot Operational Case)

		hot_tb 11/10/13 (314) GMT:13:00-17:00			Model Predict Rev-N		Model-Test
		Avg I	**Htr Pwr (W)**	**Htr D.C. (%)**	**Htr Pwr (W)**	**Htr D.C. (%)**	**delta (W)**
Op Heater	PSE_PROP_TNK_OPHTR1_CUR	0.05	1.5	5%	2.0	7%	1
	PSE_PROP_TNK_OPHTR2_CUR	0.05	1.8	6%	2.0	7%	0
	PSE_PROP_TNK_OPHTR3_CUR	0.04	1.3	4%	2.0	7%	1
	PSE_PROP_TNK_OPHTR4_CUR	0.05	1.8	6%	2.0	7%	0
	PSE_PROP_THRVLV_OPHTR_CUR	0.09	3.0	6%	3.8	7%	1
	PSE_PROP_LN_OPHTR1_CUR	0.08	2.5	3%	5.9	6%	3
	PSE_PROP_LN_OPHTR2_CUR	0.19	6.3	6%	6.3	5%	0
	PSE_SC_OPHTR1_CUR	0.00	0.0	0%	0.0	0%	0
	PSE_SC_OPHTR2_CUR	0.00	0.0	0%	0.0	0%	0
	PSE_IS_OPHTR_CUR	-0.01	0.0	0%	0.0	0%	0
	PSE_AMS_OPHTR_CUR	0.31	10.3	46%	9.3	41%	-1
	PSE_HPCA_OPHTR_CUR	0.00	0.0	0%	0.0	0%	0
Surv Heater	PSE_PROP_TNK_SVHTR_CUR	0.00	0.0	0%	0.0	0%	0
	PSE_PROP_LN_SVHTR1_CUR	0.01	0.4	1%	0.0	0%	0
	PSE_PROP_LN_SVHTR2_CUR	0.01	0.2	0%	0.0	0%	0
	PSE_PROP_LN_SVHTR3_CUR	0.00	0.0	0%	0.0	0%	0
	PSE_PROP_THRVLV_SVHTR_CUR	0.00	0.0	0%	0.0	0%	0
	PSE_SC_IS_SVHTR_CUR	0.01	0.4	0%	0.0	0%	0
	PSE_EDI_GDU_SVHTR_CUR	0.00	0.0	0%	0.0	0%	0
	Total Heater Power		**29.5**		**33.4**		4

Table 6. Post Model Correlation Heater Power Comparison (Hot Operational Case)

The correlated thermal model shows that the average instrument deck and the critical components are within 3 °C of the hot balance thermal test data with a mean of -3.0 °C and standard deviation error of 1.5 °C. In addition, the heater power correlates within 13%, more than our goal (within 5%), however, there are no concerns with this difference since the hot operational case is so benign and the actual power difference is only four (4) watts. For the cold thermal balance test the MMS observatory thermal model spacecraft deck and the critical components correlated to within 1 °C average of the cold thermal balance test data with a mean of 0.8 °C and standard deviation error of 1.7 °C.

TCS Control Zone	Sensor Location	Post-Correlated Model (°C)	Test Data 11/16/2013 GMT: 11:52	Model - Test Delta (°C)
Bay #1 (Navigator+USO)	Nav Foot	4.3	6.4	-2
	USO1 Foot	3.4	0.6	3
Bay #2 (Battery)	DSS Foot	-2.7	-4.0	1
	Battery Foot	13.0	12.8	0
Bay #3 (F/D)	Prop Fill/Drain Panel	3.5	0.0	4
Bay #4 (Comm)	TRANS 'B' Foot	19.0	16.6	2
	TRANS 'A' Foot	24.5	23.3	1
	Star Sensor CHU	-29.4	-31.1	2
Bay #5 (C&DH)	C&DH Foot	6.8	4.6	2
Bay #6 (Star Sensor)	DPU Foot	3.3	1.9	1
	Star Sensor CHU	-41.2	-40.9	0
Bay #8 (PSEES)	PSEES Foot	5.8	1.0	5
Bay #1 (+X DIS/DES)	DIS	2.6	4.6	-2
	DES	1.0	0.3	1
Bay #2 (CIDP)	CIDP	3.7	3.1	1
	SDP	-0.4	-1.1	1
	ASPOC	0.2	0.5	0
Bay #3 (+Y DIS/DES)	DIS	-0.1	1.7	-2
	DES	-2.1	-2.7	1
Bay #4 (IDPU/EDI/EIS/SDP)	IDPU	3.5	4.5	-1
	EDI	1.4	2.4	-1
	EIS	7.3	7.6	0
	SDP	1.4	1.7	0
Bay #6 (SDP/HPCA/ASPOC)	SDP	-2.6	-1.8	-1
	HPCA	1.2	-1.0	2
	ASPOC	-1.2	-0.3	-1
Bay #7 (CEB,-Y DIS/DES)	CEB	4.6	3.9	1
	DIS	0.5	0.8	0
	DES	-1.6	-1.3	0
Bay #8 (SDP, EDI)	SDP	0.7	-0.1	1
	EDI	1.9	2.6	-1

Table 7. Post Model Correlation Temperature Comparison (Cold Operational Case)

		cold_tb 11/16/13 (320) GMT: 8:00-12:00			Predict		Test - Predict
		Avg I	**Htr Pwr (W)**	**Htr D.C. (%)**	**Htr Pwr (W)**	**Htr D.C. (%)**	**delta (W)**
Op Heater	PSE_PROP_TNK_OPHTR1_CUR	0.02	0.8	3%	1.0	3%	0
	PSE_PROP_TNK_OPHTR2_CUR	0.03	1.0	3%	1.0	3%	0
	PSE_PROP_TNK_OPHTR3_CUR	0.04	1.3	4%	1.0	3%	0
	PSE_PROP_TNK_OPHTR4_CUR	0.02	0.8	3%	1.0	3%	0
	PSE_PROP_THRVLV_OPHTR_CUR	0.23	7.9	15%	8.1	15%	0
	PSE_PROP_LN_OPHTR1_CUR	0.46	15.5	15%	15.7	15%	0
	PSE_PROP_LN_OPHTR2_CUR	0.59	19.9	18%	15.6	13%	-4
	PSE_SC_OPHTR1_CUR	0.00	0.0	0%	0.0	0%	0
	PSE_SC_OPHTR2_CUR	0.00	0.0	0%	0.0	0%	0
	PSE_IS_OPHTR_CUR	-0.01	0.0	0%	0.0	0%	0
	PSE_AMS_OPHTR_CUR	0.14	4.6	20%	2.8	12%	-2
	PSE_HPCA_OPHTR_CUR	0.16	5.3	24%	7.7	36%	2
Surv Heater	PSE_PROP_TNK_SVHTR_CUR	0.00	0.0	0%	0.0	0%	0
	PSE_PROP_LN_SVHTR1_CUR	0.00	0.0	0%	0.0	0%	0
	PSE_PROP_LN_SVHTR2_CUR	0.00	0.0	0%	0.0	0%	0
	PSE_PROP_LN_SVHTR3_CUR	0.00	0.0	0%	0.0	0%	0
	PSE_PROP_THRVLV_SVHTR_CUR	0.00	0.1	0%	0.0	0%	0
	PSE_SC_IS_SVHTR_CUR	0.01	0.4	0%	0.0	0%	0
	PSE_EDI_GDU_SVHTR_CUR	0.45	15.0	99%	14.9	100%	0
	Total Heater Power		**72.6**		**69.0**		-4

Table 8. Post Model Correlation Heater Power Comparison (Cold Operational Case)

Correlated model shows that the average Instrument Deck and the critical components are within 1°C of the test data with a mean of -0.3°C and standard deviation error of 1.2 °C. The heater power correlates within 5% which is important for the cold operational predictions.

For the cold survival balance case the correlated model shows that the average Spacecraft Deck and the critical components are within 2 °C of the test data with a mean of 0.2°C and standard deviation error of 1.4 °C. Correlated model shows that the average Instrument Deck and the critical components are within 3 °C of the test data with a mean of -0.7 °C and standard deviation error of 1.6°C. The heater power for the both the 3 hour and 5 hour eclipses was about 3%, which is within 5% goal.

TCS Control Zone	**Sensor Location**	**Post-Correlated Model (°C)**	**Test Data 11/14/13 GMT: 11:00**	**Model - Test Delta (°C)**
Bay #1 (Navigator+USO)	Nav Foot	-16.9	-18	1
	USO1 Foot	-14.4	-15	1
Bay #2 (Battery)	DSS Foot	-12.4	-16	3
	Battery Foot	14.1	12	2
Bay #3 (F/D)	Prop Fill/Drain Panel	-5.4	-6	1
	TRANS 'B' Foot	-6.5	-5.8	-1
Bay #4 (Comm)	TRANS 'A' Foot	-6.7	-6.9	0
	Star Sensor CHU	-48.7	-48	-1
Bay #5 (C&DH)	C&DH Foot	-10.8	-11	0
Bay #6 (Star Sensor)	DPU Foot	-20.5	-22	1
	Star Sensor CHU	-55.2	-53	-2
Bay #8 (PSEES)	PSEES Foot	-9.7	-11	2
Bay #1 (+X DIS/DES)	DIS	-20.6	-19	-2
	DES	-20.6	-21	1
Bay #2 (CIDP)	CIDP	-15.9	-18	2
	SDP	-16.4	-17	1
	ASPOC	-17.1	-17	0
Bay #3 (+Y DIS/DES)	DIS	-18.9	-17	-1
	DES	-19.9	-21	1
Bay #4 (IDPU/EDI/EIS/SDP)	IDPU	-14.9	-15	1
	EDI	-16.5	-18	1
	EIS	-15.7	-13	-3
	SDP	-15.4	-14	-2
Bay #6 (SDP/HPCA/ASPOC)	SDP	-21.7	-19	-3
	HPCA	-24.3	-27	2
	ASPOC	-22.0	-21	-1
Bay #7 (CEB,-Y DIS/DES)	CEB	-16.7	-16	-1
	DIS	-20.1	-17	-3
	DES	-21.8	-21	-1
Bay #8 (SDP, EDI)	SDP	-15.6	-14	-1
	EDI	-16.6	-17	0

Table 9. Post Model Correlation Temperature Comparison (Cold Survival Case)

		surv_tb 11/14/13 (318) GMT: 7:00 - 11:00			Predict		Test - Predict
		Avg I	**Htr Pwr (W)**	**Htr D.C. (%)**	**Htr Pwr (W)**	**Htr D.C. (%)**	**delta (W)**
Op Heater	PSE_PROP_TNK_OPHTR1_CUR	0.0	1.5	5%	1.5	5%	0
	PSE_PROP_TNK_OPHTR2_CUR	0.1	2.0	7%	2.5	7%	0
	PSE_PROP_TNK_OPHTR3_CUR	0.0	1.4	5%	2.0	5%	1
	PSE_PROP_TNK_OPHTR4_CUR	0.1	2.3	7%	2.3	7%	0
	PSE_PROP_THRVLV_OPHTR_CUR	0.0	0.0	0%	0.0	0%	0
	PSE_PROP_LN_OPHTR1_CUR	0.0	0.0	0%	0.0	0%	0
	PSE_PROP_LN_OPHTR2_CUR	0.0	0.0	0%	0.0	0%	0
	PSE_SC_OPHTR1_CUR	0.0	0.0	0%	0.0	0%	0
	PSE_SC_OPHTR2_CUR	0.0	0.0	0%	0.0	0%	0
	PSE_IS_OPHTR_CUR	0.0	0.0	0%	0.0	0%	0
	PSE_AMS_OPHTR_CUR	0.0	0.0	0%	0.0	0%	0
	PSE_HPCA_OPHTR_CUR	0.0	0.0	0%	0.0	0%	0
Surv Heater	PSE_PROP_TNK_SVHTR_CUR	0.0	0.0	0%	0.0	0%	0
	PSE_PROP_LN_SVHTR1_CUR	0.3	10.9	20%	10.0	20%	-1
	PSE_PROP_LN_SVHTR2_CUR	0.4	12.5	27%	14.3	27%	2
	PSE_PROP_LN_SVHTR3_CUR	0.9	28.6	25%	22.5	25%	-6
	PSE_PROP_THRVLV_SVHTR_CUR	0.3	9.5	18%	10.2	8%	1
	PSE_SC_IS_SVHTR_CUR	0.5	19.1	9%	20.9	0%	2
	PSE_EDI_GDU_SVHTR_CUR	0.0	0.1	0%	0.0	0%	0
	Total Heater Power		**88.1**		**86.3**		-2

Table 10. Post Model Correlation Heater Power Comparison (Cold Survival Case)

C. Thermal Model Transient Correlation Results

The steady-state results correlated so well, it was now time to look at transient profiles for some of the critical components. The figures below show comparison of pre-correlated and post-correlated transient profiles. Figure 9 shows that the Navigator box model need an adjustment but the Figure 10 shows that the Solar Array model is so accurate that did not need any adjustment.

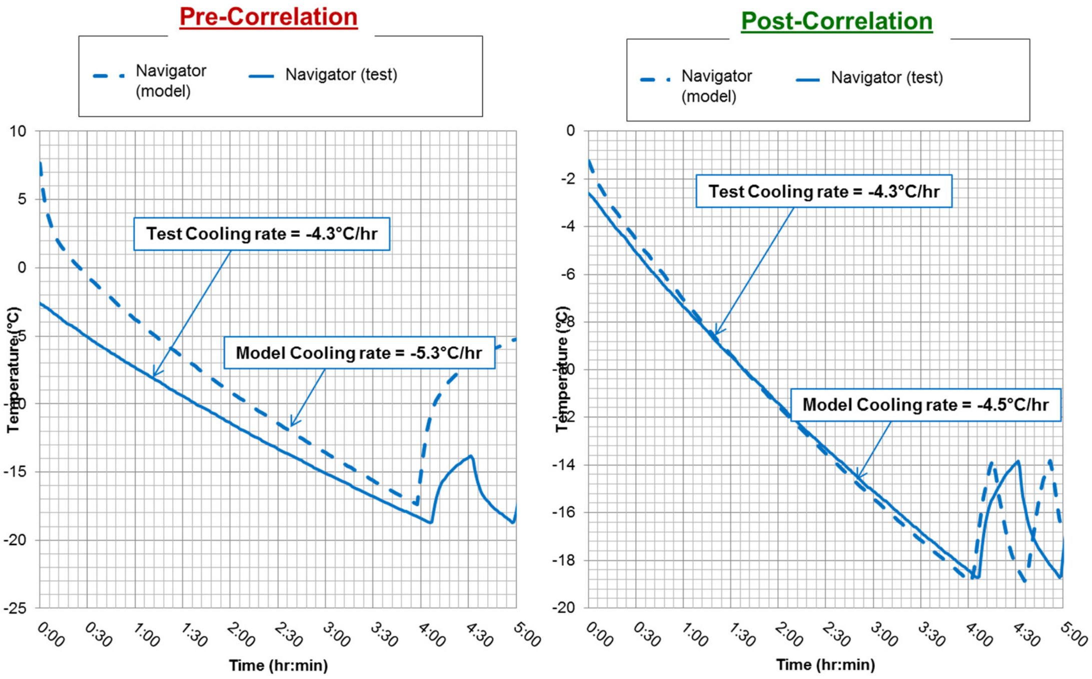


Figure 9. Transient Model Correlation Plot for Navigator Box

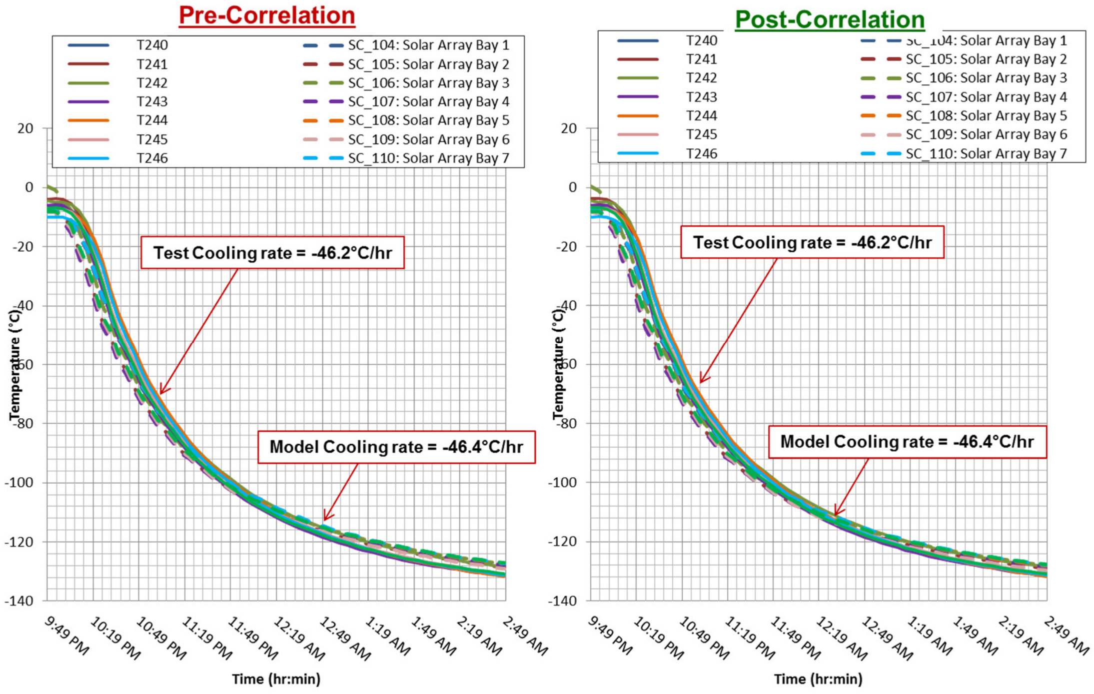
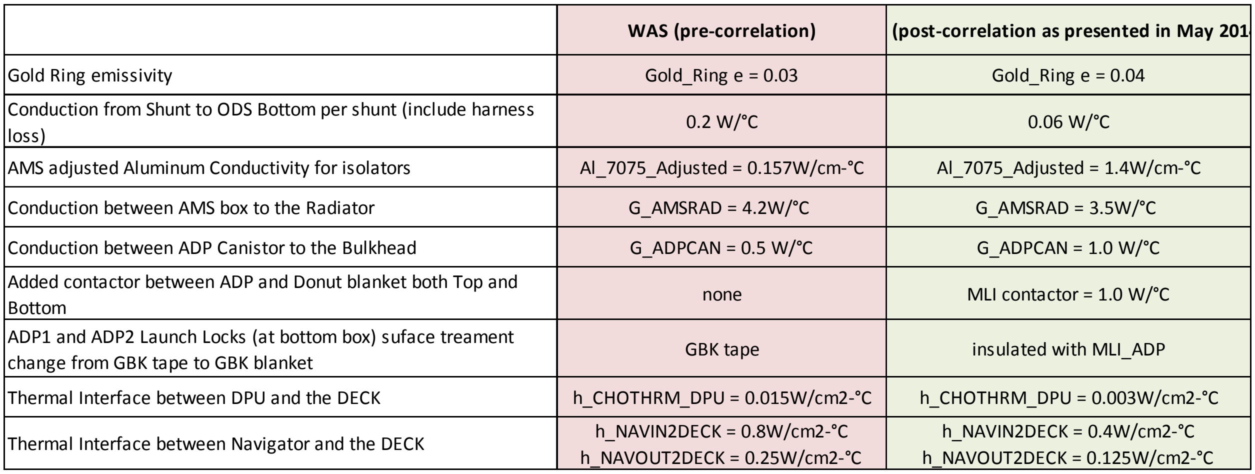


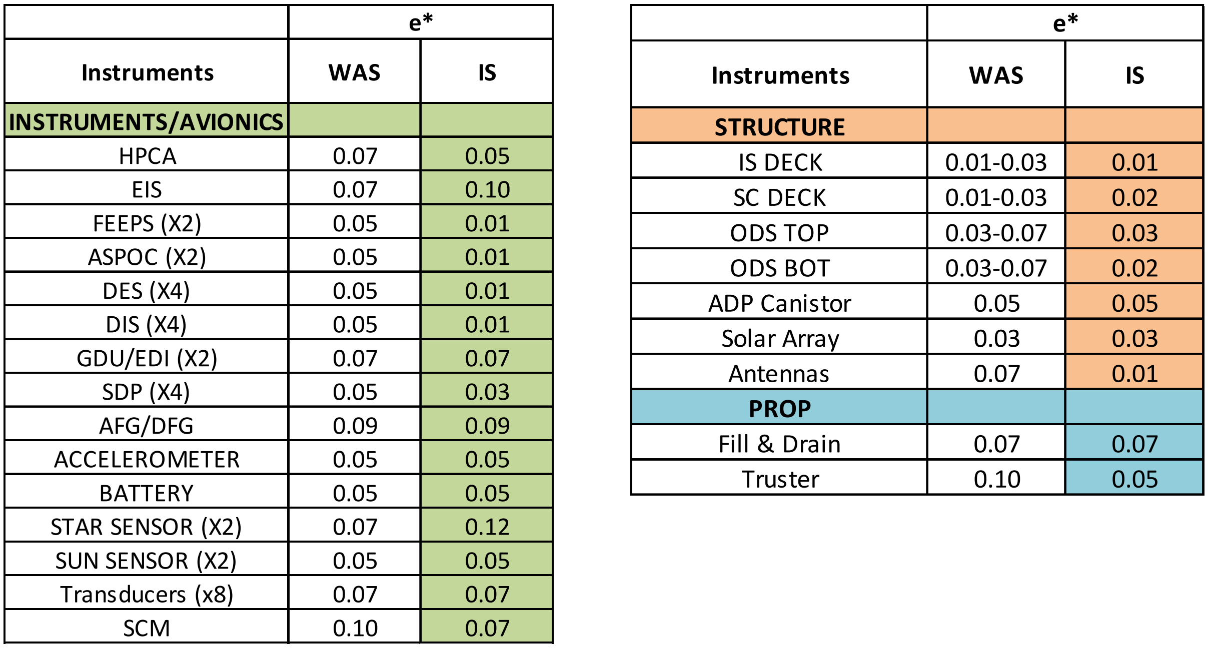
Figure 10. Transient Model Correlation Plot for Solar Array

The transient correlation is important for predicting accurate heater duty cycles since in flight the MMS observatories will be exposed to eclipse durations as long as four hours. The tables below provide additional insight into the parameters that were reviewed and modified for the thermal model correlation (e.g., interface conductors, thermal blanket effective emittance).



	WAS (pre-correlation)	(post-correlation as presented in May 201
Gold Ring emissivity	Gold_Ring e = 0.03	Gold_Ring e = 0.04
Conduction from Shunt to ODS Bottom per shunt (include harness loss)	0.2 W/°C	0.06 W/°C
AMS adjusted Aluminum Conductivity for isolators	Al_7075_Adjusted = 0.157W/cm-°C	Al_7075_Adjusted = 1.4W/cm-°C
Conduction between AMS box to the Radiator	G_AMSRAD = 4.2W/°C	G_AMSRAD = 3.5W/°C
Conduction between ADP Canistor to the Bulkhead	G_ADPCAN = 0.5 W/°C	G_ADPCAN = 1.0 W/°C
Added contactor between ADP and Donut blanket both Top and Bottom	none	MLI contactor = 1.0 W/°C
ADP1 and ADP2 Launch Locks (at bottom box) suface treament change from GBK tape to GBK blanket	GBK tape	insulated with MLI_ADP
Thermal Interface between DPU and the DECK	h_CHOTHRM_DPU = 0.015W/cm2-°C	h_CHOTHRM_DPU = 0.003W/cm2-°C
Thermal Interface between Navigator and the DECK	h_NAVIN2DECK = 0.8W/cm2-°C h_NAVOUT2DECK = 0.25W/cm2-°C	h_NAVIN2DECK = 0.4W/cm2-°C h_NAVOUT2DECK = 0.125W/cm2-°C

Table 11a. Adjusted Thermal Parameters



	e*	
Instruments	**WAS**	**IS**
INSTRUMENTS/AVIONICS		
HPCA	0.07	0.05
EIS	0.07	0.10
FEEPS (X2)	0.05	0.01
ASPOC (X2)	0.05	0.01
DES (X4)	0.05	0.01
DIS (X4)	0.05	0.01
GDU/EDI (X2)	0.07	0.07
SDP (X4)	0.05	0.03
AFG/DFG	0.09	0.09
ACCELEROMETER	0.05	0.05
BATTERY	0.05	0.05
STAR SENSOR (X2)	0.07	0.12
SUN SENSOR (X2)	0.05	0.05
Transducers (x8)	0.07	0.07
SCM	0.10	0.07

	e*	
Instruments	**WAS**	**IS**
STRUCTURE		
IS DECK	0.01-0.03	0.01
SC DECK	0.01-0.03	0.02
ODS TOP	0.03-0.07	0.03
ODS BOT	0.03-0.07	0.02
ADP Canistor	0.05	0.05
Solar Array	0.03	0.03
Antennas	0.07	0.01
PROP		
Fill & Drain	0.07	0.07
Truster	0.10	0.05

Table 11b. Adjusted Thermal Blanket Effective Emittance

V. Lessons Learned

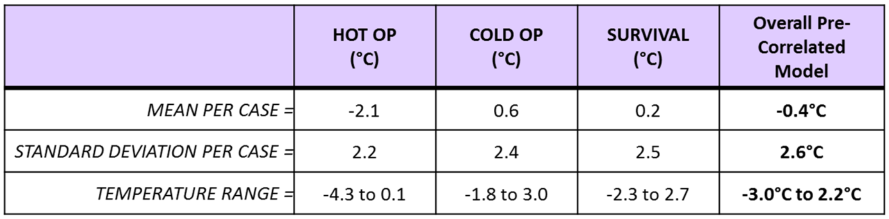
It is important to understand the mechanisms and capability of the thermal chamber prior to performaning the test especially when you have to use an outside facility thermal chamber. During the first six months of the MMS TV test program, thermal engineers had to deal with many issues such as vacuum chamber leaks, pressure spikes, and capability of GSE hardware to reach desired temperatures. For example, in an effort to prevent the occurrence of experiencing vacuum leaks helium leak tests were performed prior to closing the chamber door. The chamber technicians and test engineers faced issues with leaks at various chamber interfaces making it difficult to reach the required vacuum level for a good thermal balance. Finding chamber leaks once the chamber door is closed is a time-consuming and costly task so it is critical to check all the interfaces for leaks prior to closing chamber door.

Maintaining a database to track the parameter changes made to the Thermal Desktop^{TM} model and document how those changes impacted the model results for better or worse model correlation was advantageous to establishing an efficient model correlation process. Each analysis run was documented with a standard deviation error from one run to the next. The most difficult challenge was that the parameter change made to the thermal model had to be applied to all three thermal balance cases to check whether the change improved the correlation for all cases. Sometimes a parameter change may have improved one case, but did not improve any of the other cases.

It's important for engineers to be involved in both analysis/design and integration to get a full understanding of the thermal control system configuration. For example, one of the instrument thermal models delivered to the MMS observatory thermal lead did not model the MLI representative of the final flight configuration. By observing the flight configuration and updating the thermal model accordingly, more accurate temperature predictions would have been realized earlier in the integration phase. In addition, one could acquire photos of the MLI closeouts, radiators sizes, locations of thermal sensors, and all the GSE set-up. Having documented photos of these items provides the thermal analysts with valuable information that ultimately allows for a better correlate thermal math model.

VI. Conclusion

The thermal balance model correlation success criterion for MMS Observatory #2 (MMS2) was achieved. The steady-state cases are correlated within 3°C and the transient cases show well defined mass in the model so that the heater power is within 5%. The mean temperature of all the data (hot op, cold op and survival) is -1.1 °C and the standard deviation error is 2.7 °C. The overall post-correlated model MCp was determined to be 4% lighter.



	HOT OP (°C)	**COLD OP (°C)**	**SURVIVAL (°C)**	**Overall Pre-Correlated Model**
MEAN PER CASE =	-2.1	0.6	0.2	**-0.4°C**
STANDARD DEVIATION PER CASE =	2.2	2.4	2.5	**2.6°C**
TEMPERATURE RANGE =	-4.3 to 0.1	-1.8 to 3.0	-2.3 to 2.7	**-3.0°C to 2.2°C**

Table 12. Overall Model Correlation Standard Deviation Temperature

Additionally, the correlated thermal model was used to complete the verified by analysis of some requirements. The MMS spacecraft requirement for the battery heater power energy draw during umbra for orbits with umbra durations of less than 2 hours, not to exceed 250 Watt-hours was verified by using the correlated thermal model prediction of 214 Watt-hours during a 2 hour thermal balance eclipse. For orbits with umbra durations greater than 2 hours the battery heater power draw requirement was not exceed 490 Watt-hours with IS, CDIP, and Navigator OFF and this was verified using the cold survival thermal balance results and the correlated thermal model to be 386 Watt-hours during a 4 hour eclipse.

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References

[3] Solimani, J., and Zara, R., Vertex Aerospace, Greenbelt, MD, "Magnetospheric MultScale (MMS) Propulsion Line Thermal Control Design Validation and Model Correlation" ,42nd International Conference on Environmental Systems (ICES), San Diego, CA, 2012