45th International Conference on Environmental Systems

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

Jong S. Kim and Nicholas M. Teti.

Vertex Aerospace, LLC

Hilton Bellevue, Bellevue, WA

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AGENDA

- Introduction
- MMS Thermal Design
- Thermal Balance (TB) Test Objectives
- TB Test Overview
- Thermal Balance
- Correlation Results
- Lessons Learned
- Summary

Introduction

- The MMS mission uses four identically instrumented observatories to perform the first definitive study of magnetic reconnection in space
- Magnetic reconnection is the primary process by which energy is transferred from the solar wind to the Earth's magnetosphere
- Magnetic reconnection is also fundamental to the explosive release of energy during sub storms and solar flares
- MMS will test critical hypotheses about reconnection.

Introduction

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- 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
  - Phase 1: Day side of magnetic field is 1.2 times of Earth radius (R_E), Perigee, by 12 times of R_E, Apogee.
  - Phase 2: Night side of magnetic field is 1.2 times of Earth radius (R_E), Perigee, by 25 times of R_E, Apogee.
- The MMS mission successfully launched all four observatories on March 12, 2015 at 10:44 P.M. Eastern from Cape Canaveral, Florida
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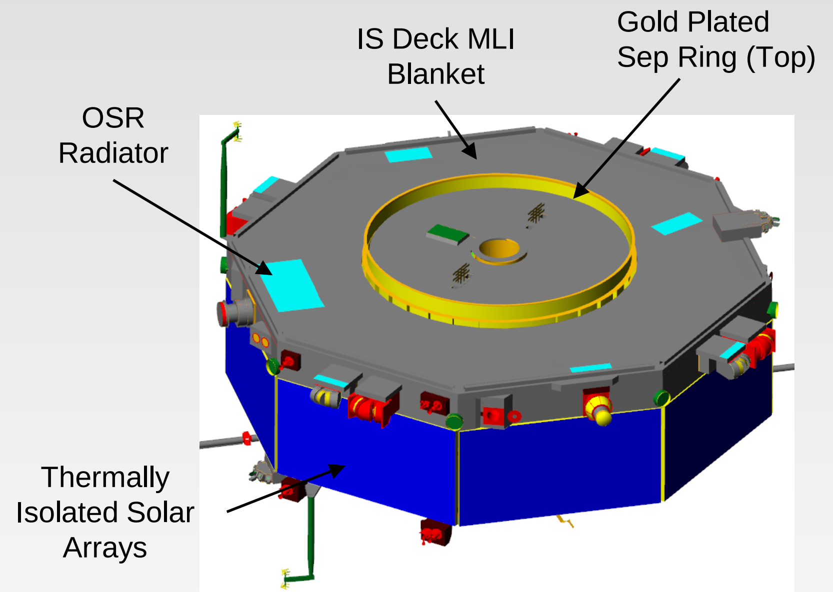
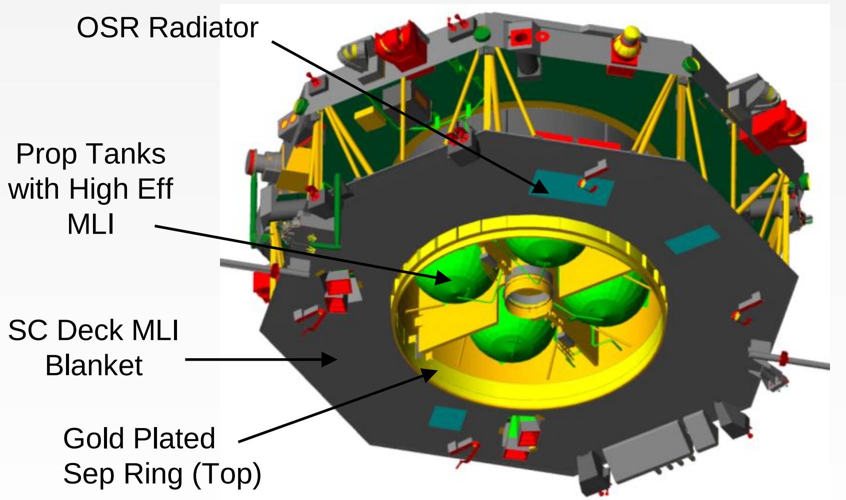
Thermal Design

MMS has 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 to conductively couple electronics to their respective radiators.
- Multi-layered Insulation blankets cover all exterior surfaces except for instrument apertures, solar arrays, and radiators.
- Titanium isolators separate the Solar Arrays from the spacecraft to minimize heat loss in eclipse.
- High-efficiency blankets on hydrazine propulsion tanks minimize heat loss in eclipse.
- Ultem Isolators on propulsion lines and thruster valves minimize conductive losses in eclipse.
- Gold plated thrust tube rings and separation system rings.





TB Test Objectives

1. To provide an empirical verification of the system's thermal design margin.
   - Successful – Hot Balance Case showed Temperature margin relative to test predicts which means radiators are sized adequately.
   - The four-hour Survival Eclipse and the two-hour Operational eclipse baseline extended to 5 hours and 3 hours respectively showing margin on the cold side.
   - Most heaters verified (except for some IS Survival Heaters due to HV801s)
2. To provide steady state temperature data to be used to validate/correlate subsystem/system thermal math models (TMMs).
   - Successful – Three balance cases achieved steady state criteria (m*Cp*dT/dt <5% of total Power). Over 400 onewire sensors, 200 thermocouples and 125 flight temperature sensors recorded data during Hot Balance, Cold Survival Balance, and Cold Operational Balance.
3. To measure power dissipations within 1% for input into thermal model (GEVS section 2.6.3.4)
   - Successful – TCS_POWER page in ASIST measured all dissipations including opposite side currents

TB Test Objectives

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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%

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

TV/TB Test Overview

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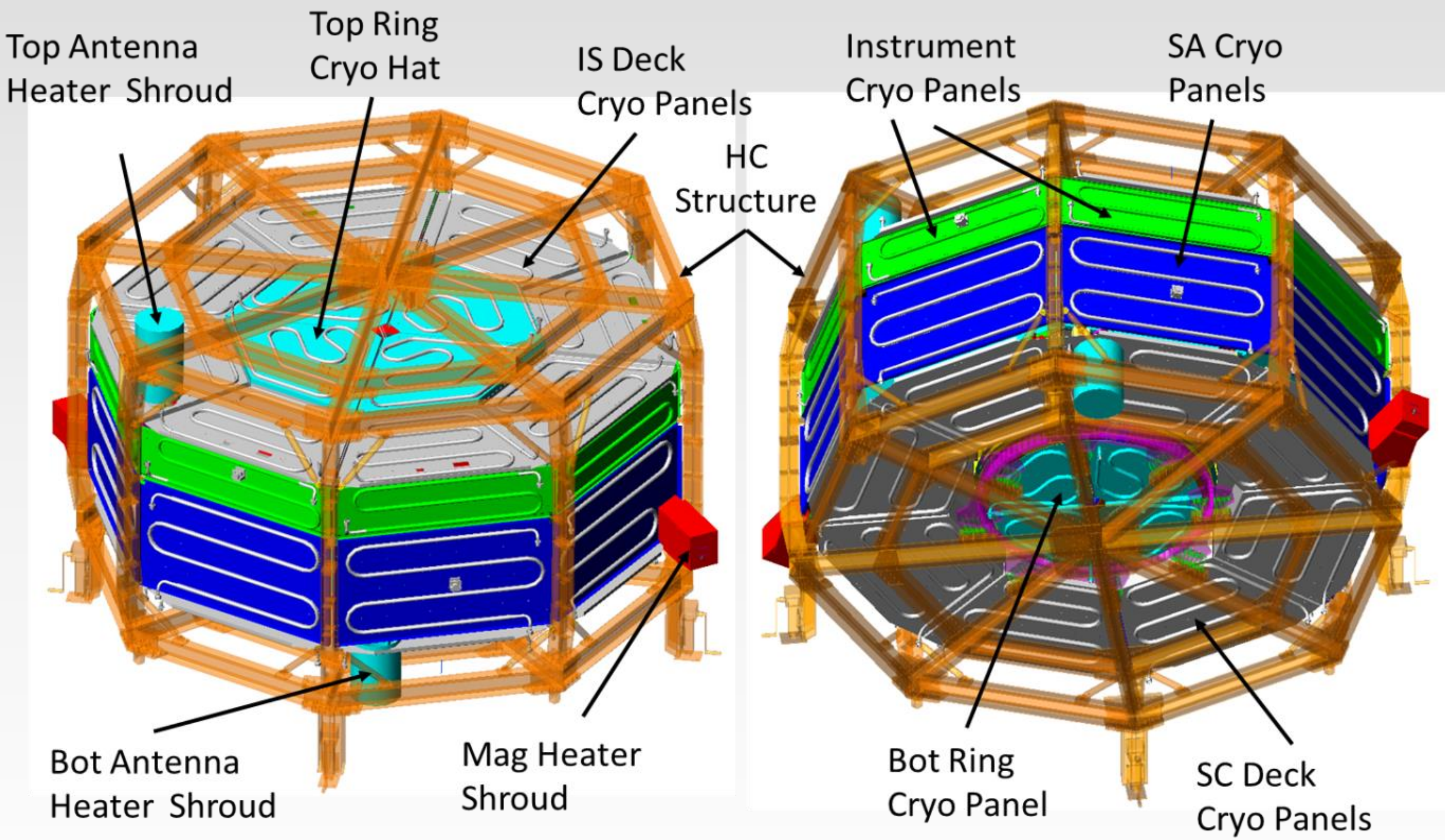

TV/TB Test Overview

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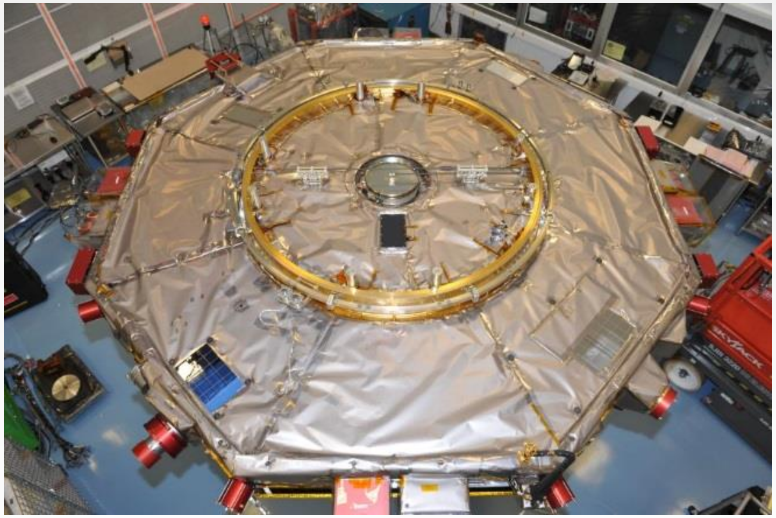
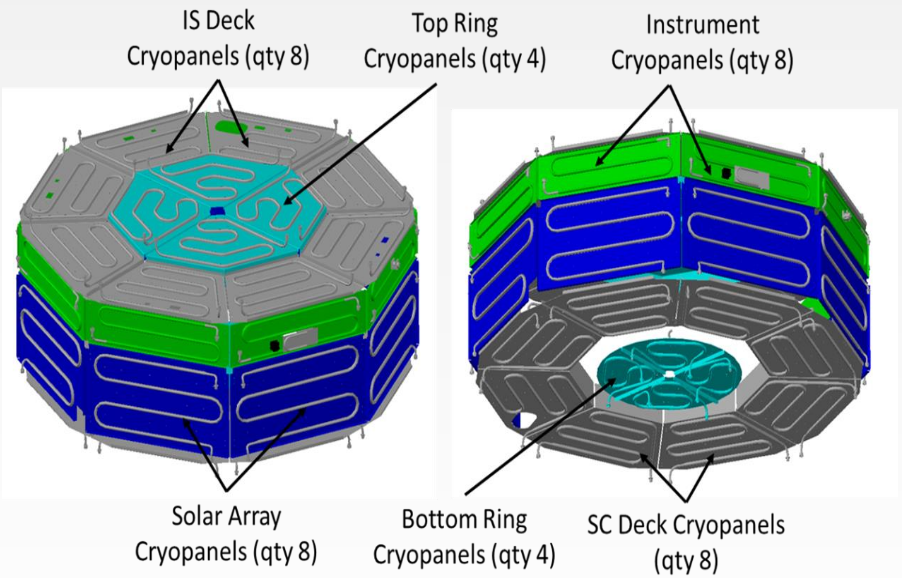
- The Top Cryo Panels view the instrument deck (not instruments) that is mostly GBK blanket with some OSR radiators.
- The pre-test thermal analysis assumed the same temperature for all eight (8) top cryo panels per case.
- However, test limitations (# of TCUs, Omega Controllers, etc) did not permit 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





TV/TB Test Overview

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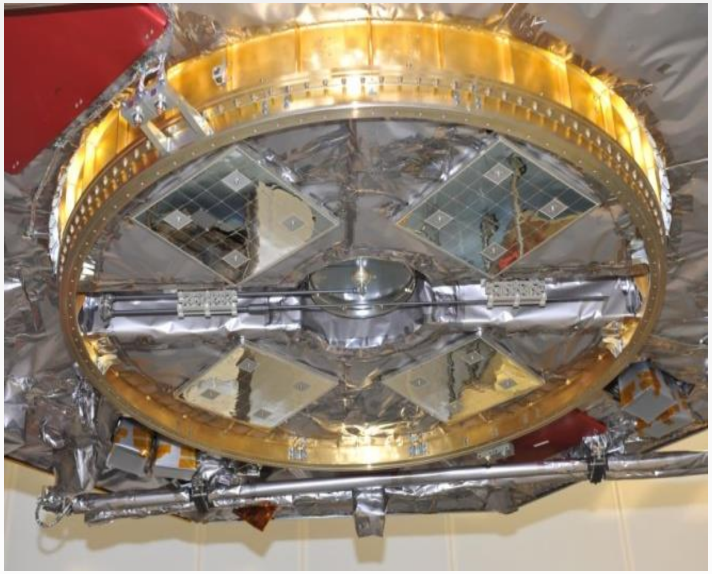
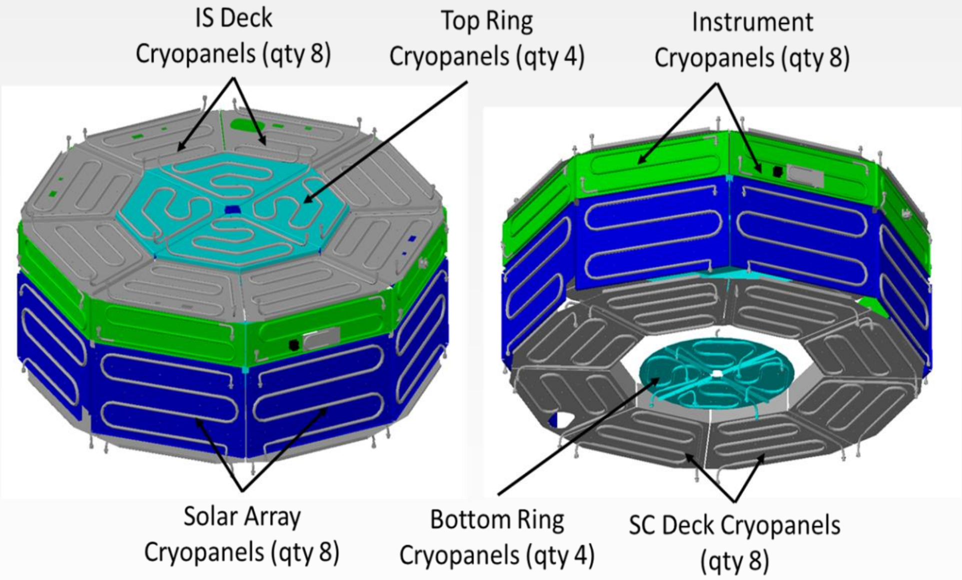
- The Bottom Cryo Panels view Spacecraft Deck that is mostly GBK blanket with some OSR radiators.
- The pre-test thermal analysis assumed same temperature for all eight (8) bottom cryo panels per case, however, test data shows temperature gradient from -182 °C to -164 °C (18 °C delta) for hot case and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





TV/TB Test Overview

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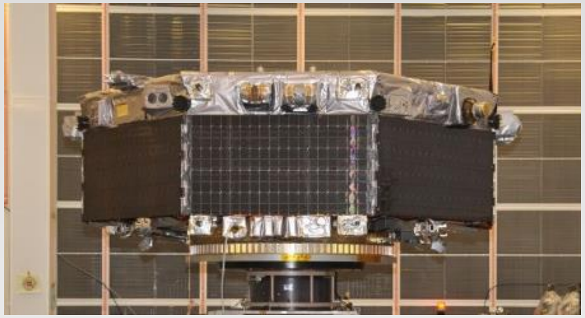
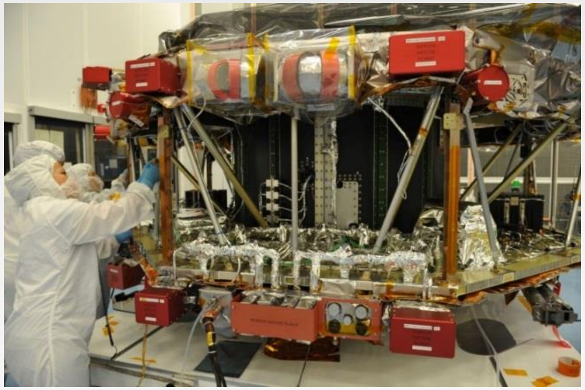
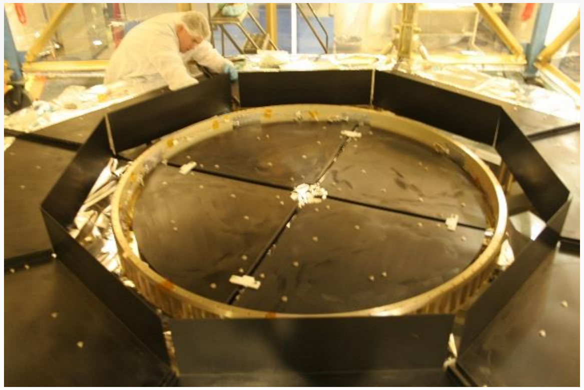
- The solar array panels view solar arrays and any external components that are located near the outer edge of the instrument or spacecraft decks (e.g., Digital Sun Sensors, FEEPS instruments and magboom).
- The instrument cryo panels view instruments only. Each bay (sometimes with multiple instruments) 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.



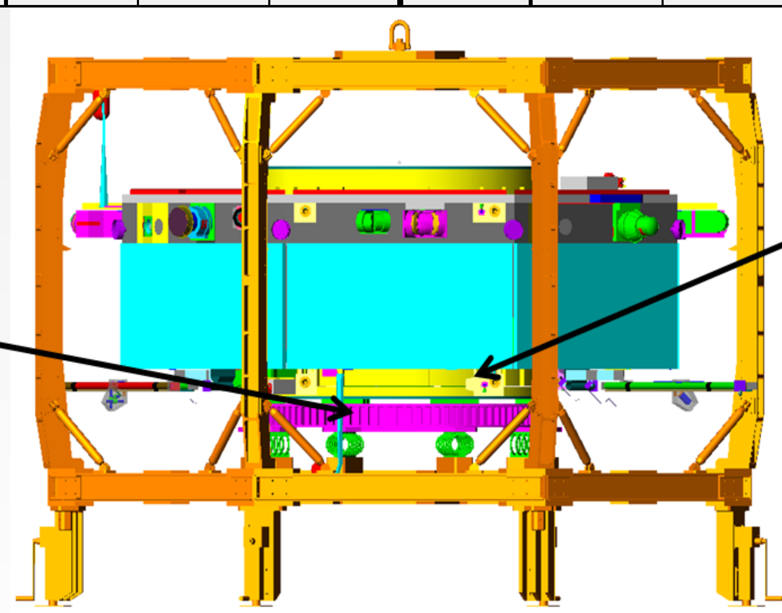




TV/TB Test Overview

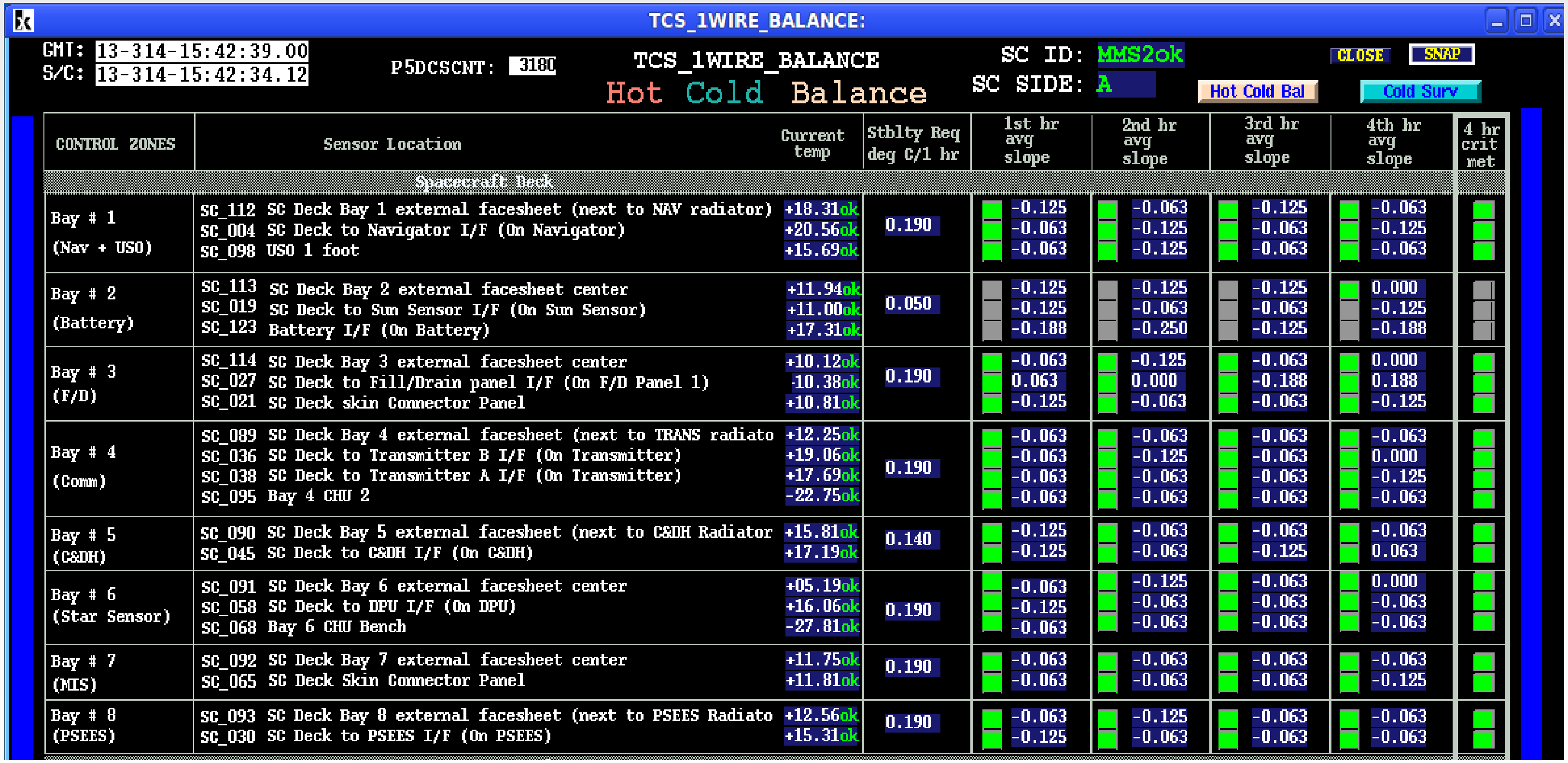
- During the MMS4 TVAC test, additional verification of the Zero-Q interface was performed to confirm zero Q loss (or very small heat loss) at this interface. The values for the Zero-Q heaters are shown in the table below.

	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



TB Test Overview

- 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. 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.



TCS_1WIRE_BALANCE:

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
CLOSE SNAP
Hot Cold Bal Cold Surv

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

Thermal Balance

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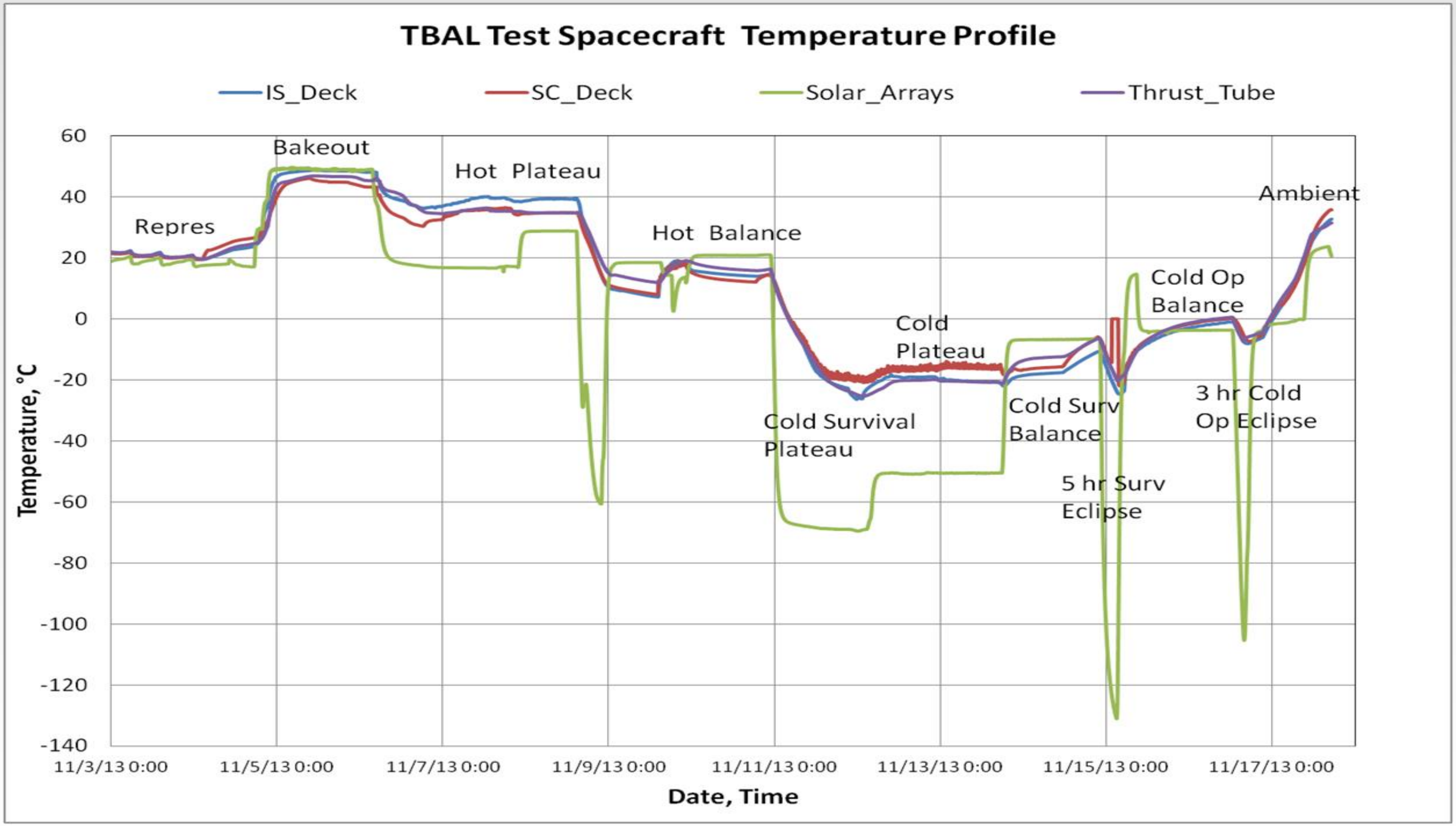
- The MMS2 thermal balance (TB) testing was completed in approximately fifteen days. Figure below illustrates the 'as run' test profile. After completing the first hot plateau qualification CPT's the observatory was placed in the Hot Thermal Balance configuration and after approximately 24 hours the hot thermal balance criterion was achieved



Thermal Balance

- The thermal model correlation started with reasonable adjustments of large system variables such as spacecraft and instrument deck MLI effective emittance and Gold Rings conductive 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).
- Individual instruments and electronic box temperatures followed with 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 (aluminum 6061 is typically 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.
- Finally, flight temperature predictions were updated based on final TB model correlation.

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. 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.

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

Correlation Results

- 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. 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.

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

Correlation Results

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- For the **<u>cold survival balance</u>** 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
Bay #4 (Comm)	TRANS 'B' Foot	-6.5	-5.8	-1
	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

Correlation Results

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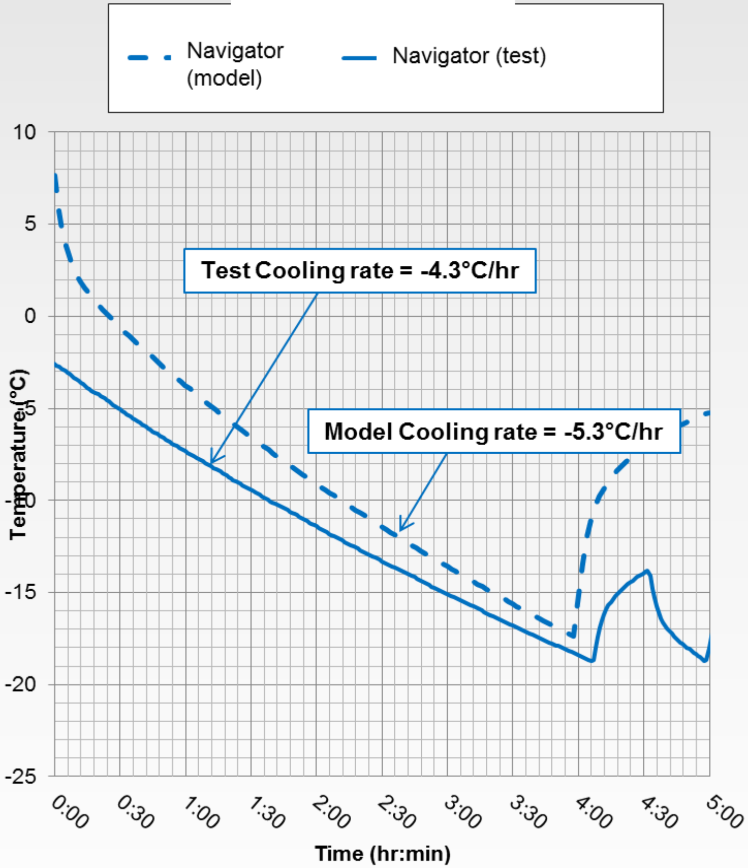
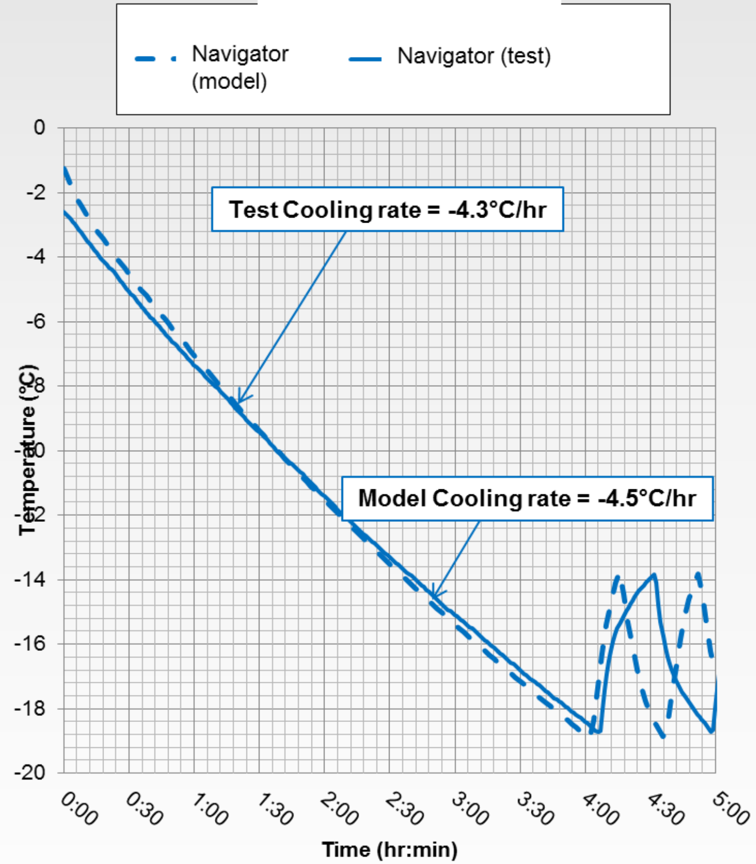
- The steady-state results correlated so well, it was now time to look at transient profiles for some of the critical components. The figures below show comparison of pre-correlated and post-correlated transient profiles.

Pre-Correlation



Post-Correlation



Correlation Results

- 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

	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*	
DESCRIPTION	**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

Lessons Learned

- 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
- 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.

Lessons Learned

- 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.
- 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. Having documented photos of these items provides the thermal analysts with valuable information that ultimately allows for a better correlate thermal math model

Summary

- 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**

- 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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