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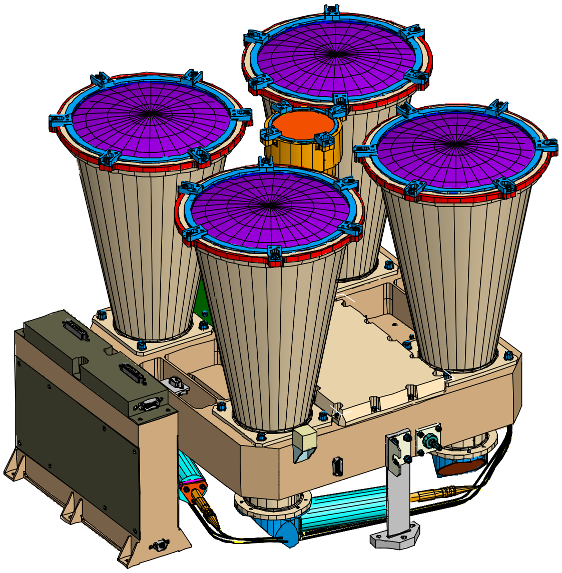
MLA Thermal Balance Test Results and Model Correlation



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3 INTRODUCTION

3.1 Purpose

This document presents the Mercury Laser Altimeter (MLA) thermal balance test results and thermal model correlation. The thermal balance test was performed in Facility #239 at Goddard Space Flight Center (GSFC) from 5/23/2003 to 5/31/2003.

3.1.1 Test Objectives

The MLA thermal balance test was performed to accomplish the following objectives:

1. Demonstrate satisfactory operation of the MLA thermal control system. This includes checking thermostat set points, thermistor data, heater operation, and heater duty cycles.
2. Provide steady state temperature data for correlation of interface conduction and blanket e-star values used in the thermal model.
3. Provide transient temperature data for correlation of specific heat values used in the thermal model.
4. Provide voltage and current data for correlation of power dissipation values used in the thermal model.

3.2 Background

The Mercury Laser Altimeter (MLA) is one of eight instruments on the MESSENGER spacecraft. The MESSENGER spacecraft, which stands for **ME**rcury **S**urface, **S**pace **EN**vironment, **GE**ochemistry, and **R**anging spacecraft, will investigate key scientific questions regarding Mercury's characteristics and environment. Data is provided by an optimized set of miniaturized space instruments and the spacecraft telecommunications system. MESSENGER will enter Mercury's orbit in April 2009 and carry out comprehensive measurements for one Earth year. Data collection concludes in April 2010.

MLA couples an infrared laser transmitter with a receiver that measures the round-trip time of a laser burst reflected off Mercury's surface, yielding a distance measurement. It produces highly accurate measurements of topography and measures Mercury's slight wobble due to the planet's libration.

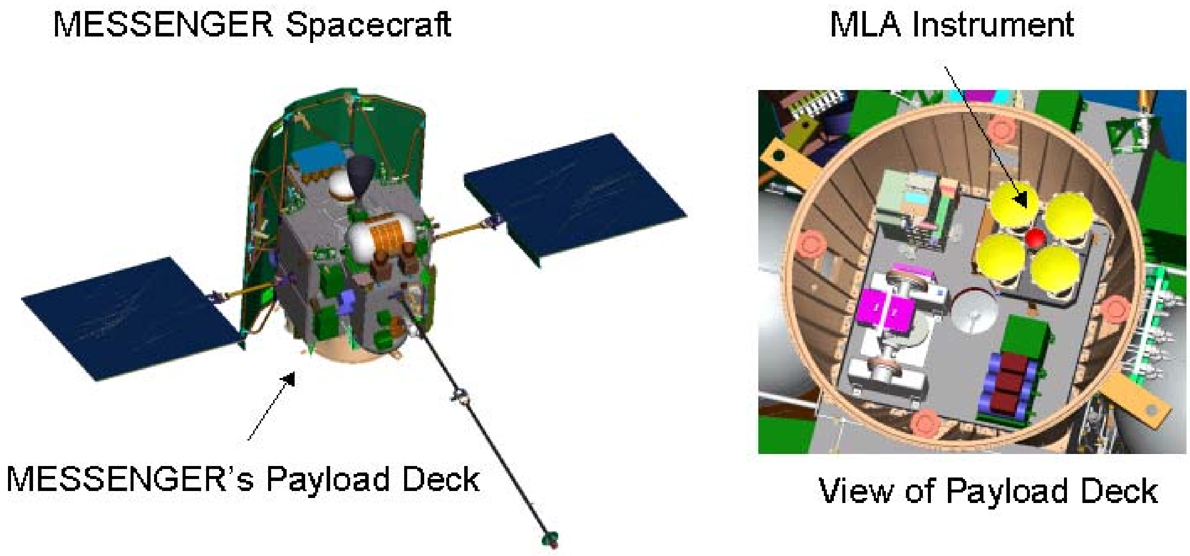


Figure 1. MLA on MESSENGER

3.3 MLA Instrument Description

The MLA instrument consists of several components. Four Receiver Telescopes and the Beam Expander are mounted to the Main Housing, the main structural component of MLA. The Laser Assembly and the Analog/Detector Assembly also mount to the top of the Main Housing. Underneath the Main Housing is the Electronics Assembly, which include the Capacitor Board, Laser Electronics Board, RMU Board, and CPU Board. The MLA assembly is mounted to the MESSENGER spacecraft deck via three titanium flexures. The MLA Power Converter Assembly is also mounted to the MESSENGER spacecraft deck adjacent to the Main Housing. Table 1 lists the MLA components and their temperature requirements.

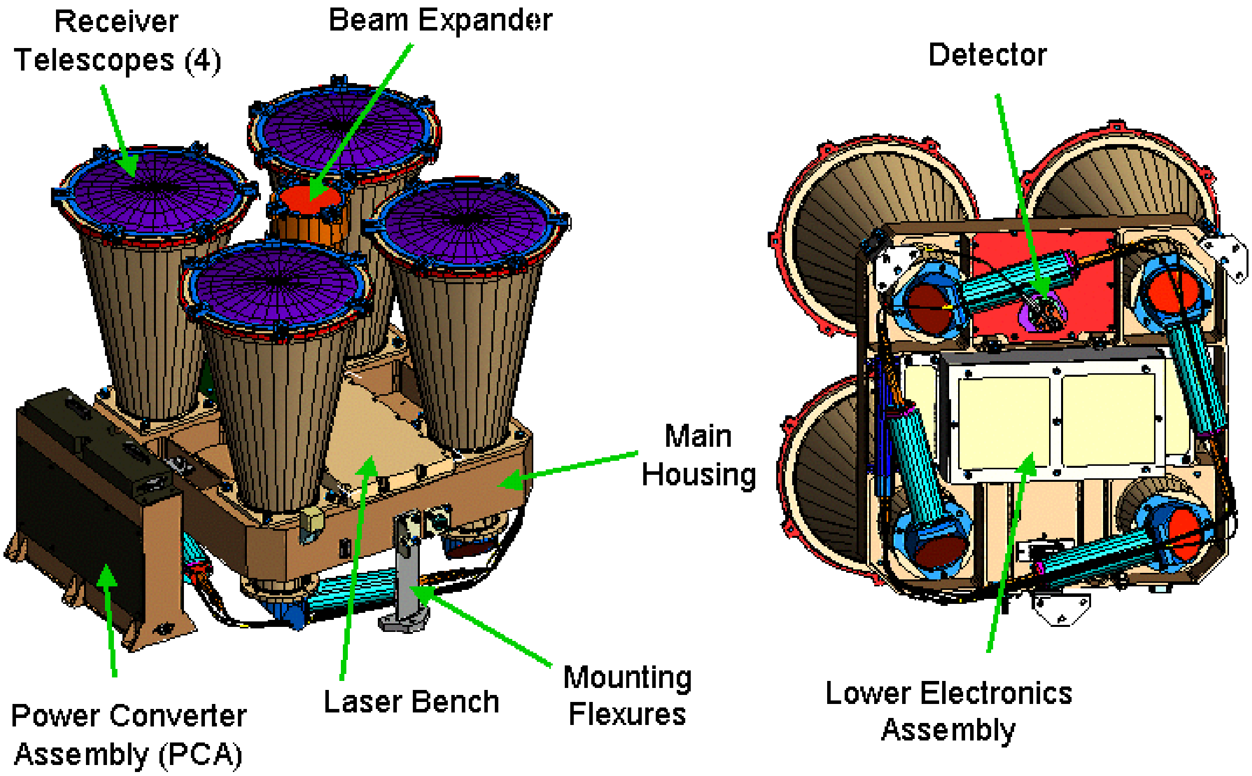


Figure 2. MLA Instrument

Component	Operational Limits, °C		Survival Limits, °C	
	Min	Max	Min	Max
Receivers	-10	40	-30	60
Beam Expander	-20	60	-30	70
Laser Bench	15	25	-20	40
Main Housing	-20	60	-35	60
Analog Board	-10	40	-35	80
Detector Board	0	40	-45	100
Capacitor Board	-10	50	-20	60
Laser Electronics Board	-10	50	-20	60
RMU Board	-10	50	-20	60
CPU Board	-10	50	-20	60
PCA	-20	60	-35	70

Table 1. MLA Component Temperature Requirements.

3.3.1 MLA Thermal Control System

The MLA Thermal Control System (TCS) is a passive system that relies on Beryllium's high heat capacitance to maintain temperatures within operating range (-10°C to 50°C). The Receiver Lenses serve as radiators to dissipate internal heat from the Laser and Electronics. Operational heaters located on the Laser Bench and the Detector supplement the passive TCS. In addition, survival heaters on the Main Housing and PCA provide heat to the instrument during safehold, cruise, and other cold environment scenarios. To monitor component temperatures, sixteen thermistors are placed in key locations listen in Table 2. MLI blankets consisting of a Vapor Deposited Gold (VDG) outer layer cover the entire instrument with exception of the lenses.

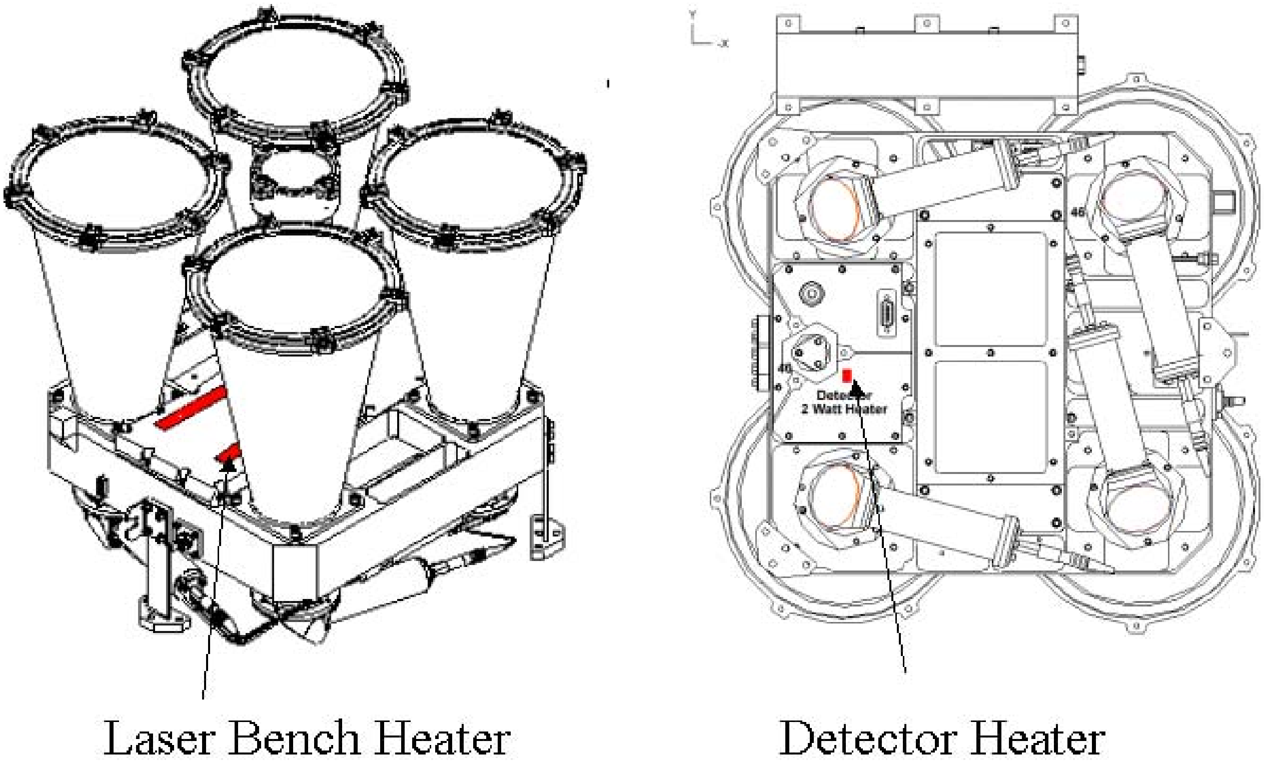


Figure 3. MLA Operational Heaters

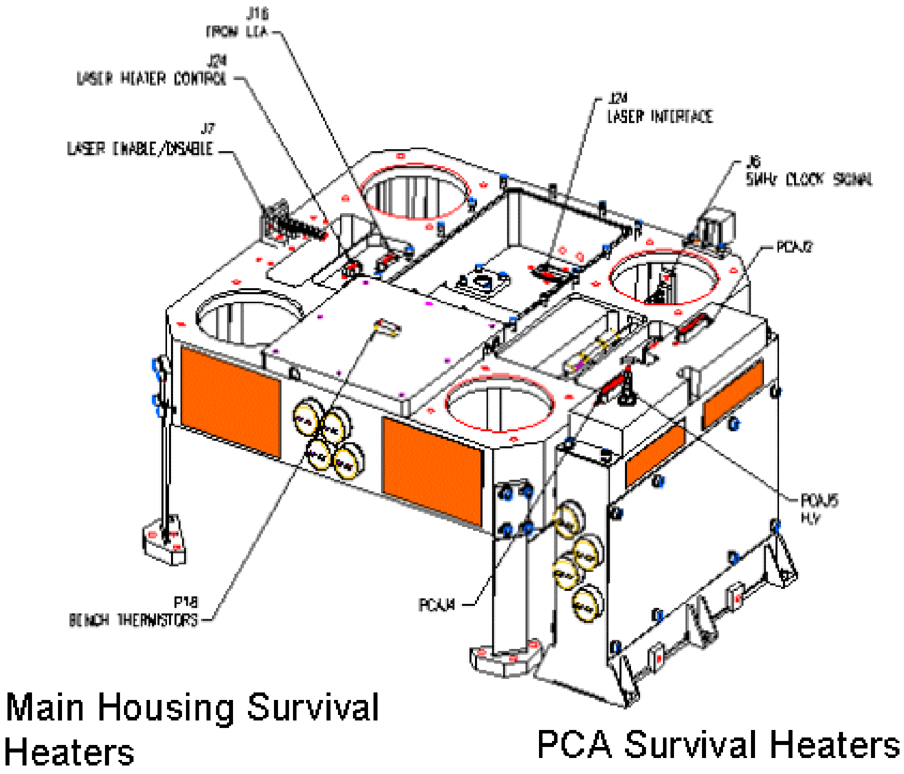


Figure 4. MLA Survival Heaters

Thermistor	Description
1	Detector Board
2	Altimeter Detector (for calibration)
3	Analog Electronics
4	RMU
5	RMU Oscillator
6	CPU
7	Laser Electronics
8	Laser 1
9	Laser 2
10	PCA
11	Beam Expander Top
12	Beam Expander Bot
13	Receiver Tube Top
14	Detector Plate
15	Calibration Low
16	Calibration High

Table 2. MLA Flight Thermistors.

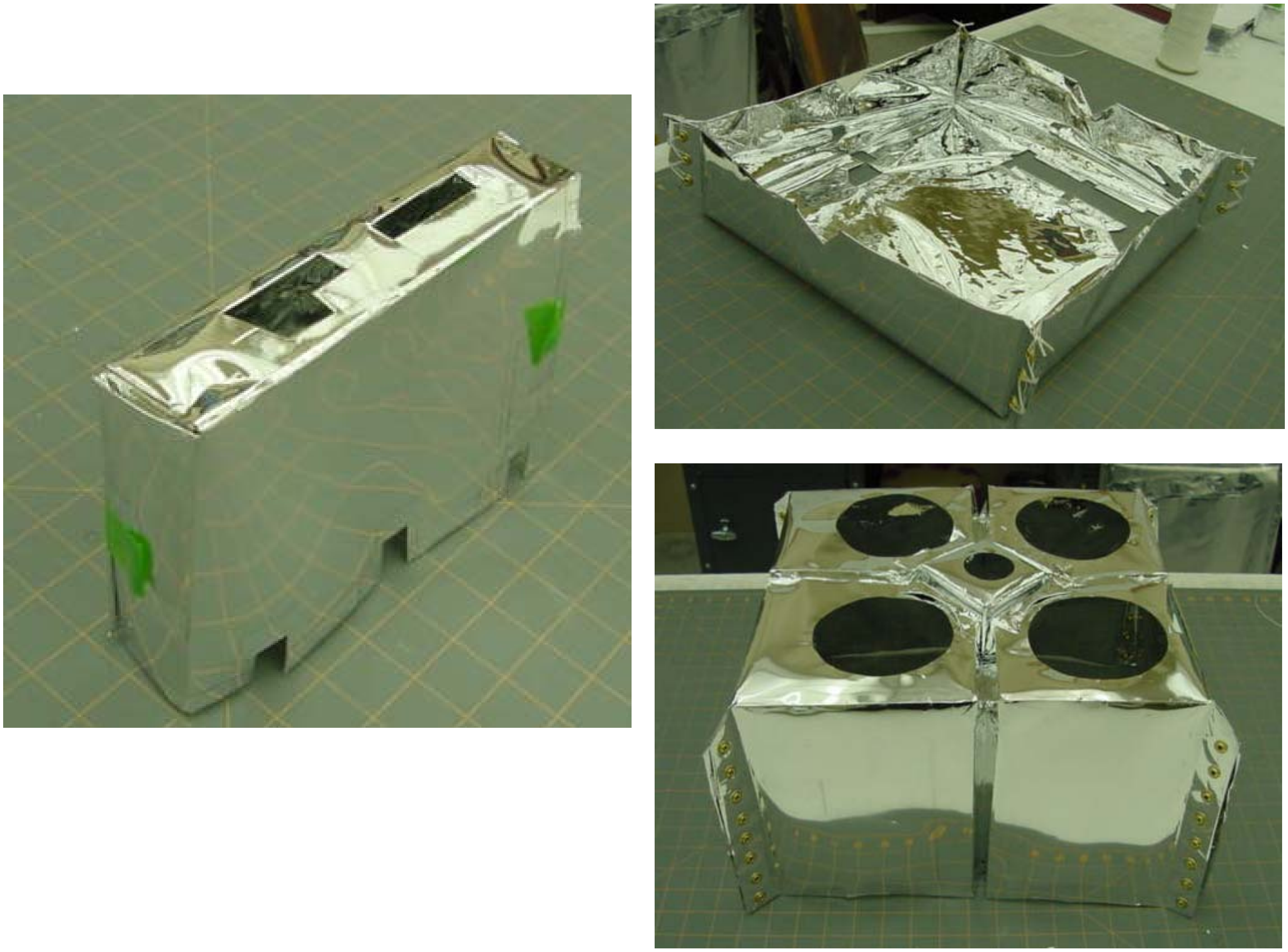


Figure 5. MLA Thermal Blankets

4 SUMMARY

The MLA thermal balance test was performed to verify the MLA thermal model and analysis. The test was comprised of a hot steady state case, a hot transient case, a cold steady state case, and a cold transient case. The hot and cold steady state cases were performed to get a system heat balance measurement and to measure delta T's across key interfaces for hot and cold environments. The hot and cold transient cases were performed to simulate orbital changes in instrument power and heat fluxes and to verify the thermal masses of key components of the MLA instrument. The thermal balance test started on 5/21/03 and ended on 5/31/03.

Prior to testing, thermal analysis was performed to determine sink temperatures and boundary conditions that MLA sees during flight. Assumptions were made regarding the MLI blanket effectiveness and some of the interface conduction couplings. The test configuration was modeled and temperature predictions were generated for each test case.

To simulate orbit conditions, the MLA instrument was in flight configuration with flight heaters and blankets. An aluminum plate that was controlled by a GN2 TCU simulated the MESSENGER spacecraft deck. A separate aluminum plate that was controlled by another GN2 TCU simulated the planet Mercury. Heaters that totaled 200 Watts were installed on the planet target plate to provide added heat. The chamber walls simulated the views to space and the MESSENGER thruster cone.

During hot steady state balance testing, the instrument temperatures were, on average, 10 degrees warmer than the temperature predictions generated for the Pre-Environmental Review (PER). Upon investigation, it was discovered that the instrument was dissipating about 30 percent more power than what was in the thermal model. The thermal model was then updated and a new set of temperature predictions was generated.

Comparison of the updated temperature predictions and test results show that the model (with exception of the PCA) was about 3 degrees warmer in the hot steady state case, and 4 degrees warmer in the cold steady state case.

Comparison of the transient predictions and test results show that the thermal masses calculated in the model were accurate to within 0.1 deg/hour.
Upon inspection of the operational heater on the Laser Bench, it was discovered that it operated with a thermostatic control instead of the proportional control that was assumed in the PER analyses. The model was then corrected to reflect this new heater controller. Adjustments were also made to the interface coupling between the Laser Bench and Main Housing to match the heater duty cycles seen in test.

The PCA temperatures were about 5°C warmer in test for the hot case and about 15°C warmer for the cold case. The PCA internal conduction was adjusted and the correlated model is now within 3°C of the test results for hot and cold cases.

In addition to updating the Laser Bench and PCA models, a few other changes were made to the model to correct some of the minor discrepancies between model predictions and test results. These changes include increasing the blanket effective emissivity from 0.03 to 0.05. The correlated results are shown in Table 15.

5 TEST HARDWARE AND SETUP

5.1 Thermal Balance Test Configuration

The thermal balance test configuration is shown in Figure 6. The entire test assembly was placed in facility #239 at GSFC (Figure 7).

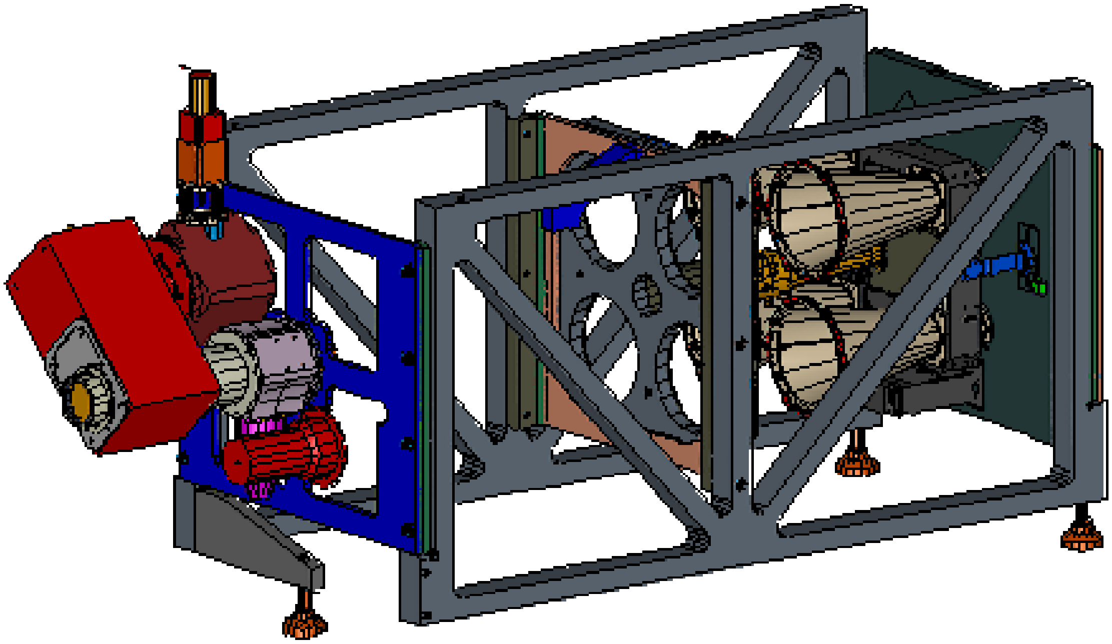


Figure 6. MLA Thermal Balance Test Configuration.

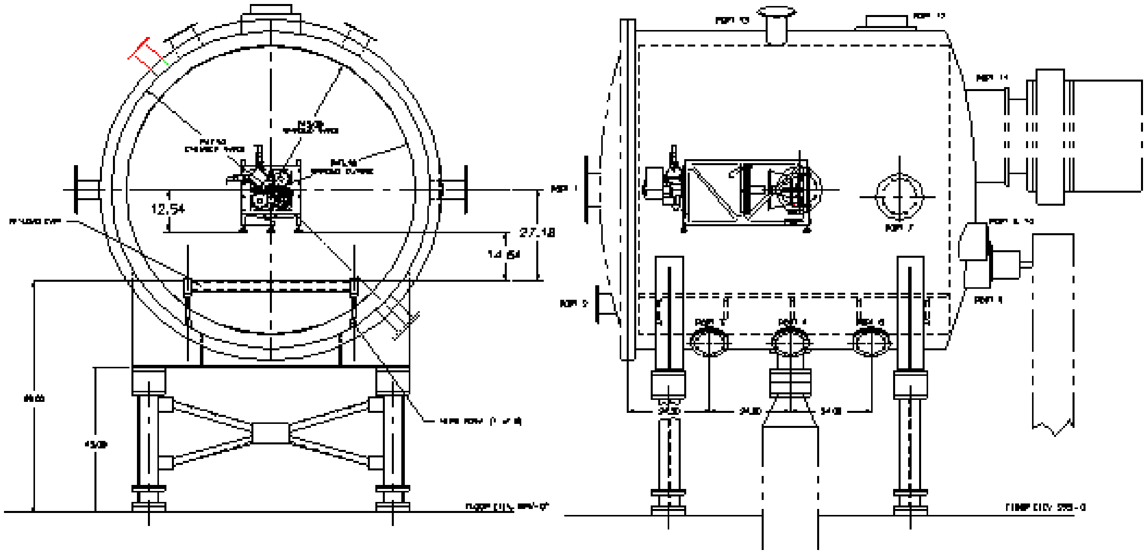


Figure 7. Thermal Vacuum Chamber # 239

5.2 Spacecraft Deck Simulator

The MLA instrument with its flight blankets was bolted to a temperature controlled aluminum plate that simulated the spacecraft (MESSENGER) deck. The spacecraft deck simulator used a Gaseous Nitrogen Thermal Control Unit (GN2 TCU) to maintain its temperature at 50°C for the hot cases and –20°C for the cold cases. Test blankets covered the front and back of the plate.

5.3 Planet Target Plate

The front of the instrument faced another temperature controlled aluminum plate that simulated the orbit environment of the planet Mercury (planet target plate). The planet target plate also used a GN2 TCU to achieve a temperature of –140°C for cold transient testing and 140°C for hot transient testing. In addition, 200 Watts of heater power was added to the planet target plate to increase the hot transition rates. Test blankets closed out the planet target plate to the instrument. The back of the planet target plate was also blanketed.

5.4 Test Stand

The planet target plate and spacecraft deck plate were mounted to a test fixture that was designed for optical performance testing. Heaters and blankets were installed on the test fixture to maintain the assembly at 20°C for optical alignment.

5.5 Instrumentation

The test setup was equipped with 108 thermocouples, 58 on the instrument, and 50 on the test hardware. Thermocouple locations are in Appendix A.

6 TEST PROFILE

6.1 Hot Steady State Balance

The MLA thermal balance test started with a hot steady state balance case where the instrument is in Stand-By mode (11.5 Watts of dissipation). The spacecraft deck was at 50°C, the planet target plate was at -30°C, and the chamber walls were at –90°C. After 32 hours, steady state criteria was achieved (0.5°C per hour) and hot transient testing started.

6.2 Hot Transient Cycling

During hot transient testing, MESSENGER's 12 hour orbit at 280° Mercury true anomaly was simulated by cycling the planet target plate from –120°C (MESSENGER's apogee) to 140°C (MESSENGER's perigee). The instrument power was also cycled starting with Stand-By power for 1 hour, Science Power (18 Watts of dissipation) for 35 minutes, and Keep-Alive power (8.2 Watts of dissipation) for 10 hours and 25 minutes. The spacecraft deck was maintained at 50°C and the chamber walls remained at –90°C. Four cycles were performed before transitioning to cold steady state balance.

6.3 Cold Steady State Balance

During cold steady state balance, the instrument was in Keep-Alive mode. The spacecraft deck was at –20°C, the planet target plate was at –90°C, and the chamber walls were at –170°C. After 24 hours and steady state criteria was achieved, cold transient testing began.

6.4 Cold Transient Cycling

During cold transient testing, which simulated the spacecraft orbit at 140° Mercury true anomaly, the planet target plate was cycled from –140°C (apogee) and 10°C (perigee). The instrument power was cycled starting with Stand-By power for 8 hours, Science power for 35 minutes, and Keep-Alive power for 3 hours and 25 minutes. Three cycles were performed until dynamic steady state was achieved. The thermal balance test lasted 7 days. Figure 8 shows the thermal balance test profile. Table 3 shows the sink temperatures for Hot and Cold Balance and Tables 4 and 5 shows the transient power and temperature timelines.

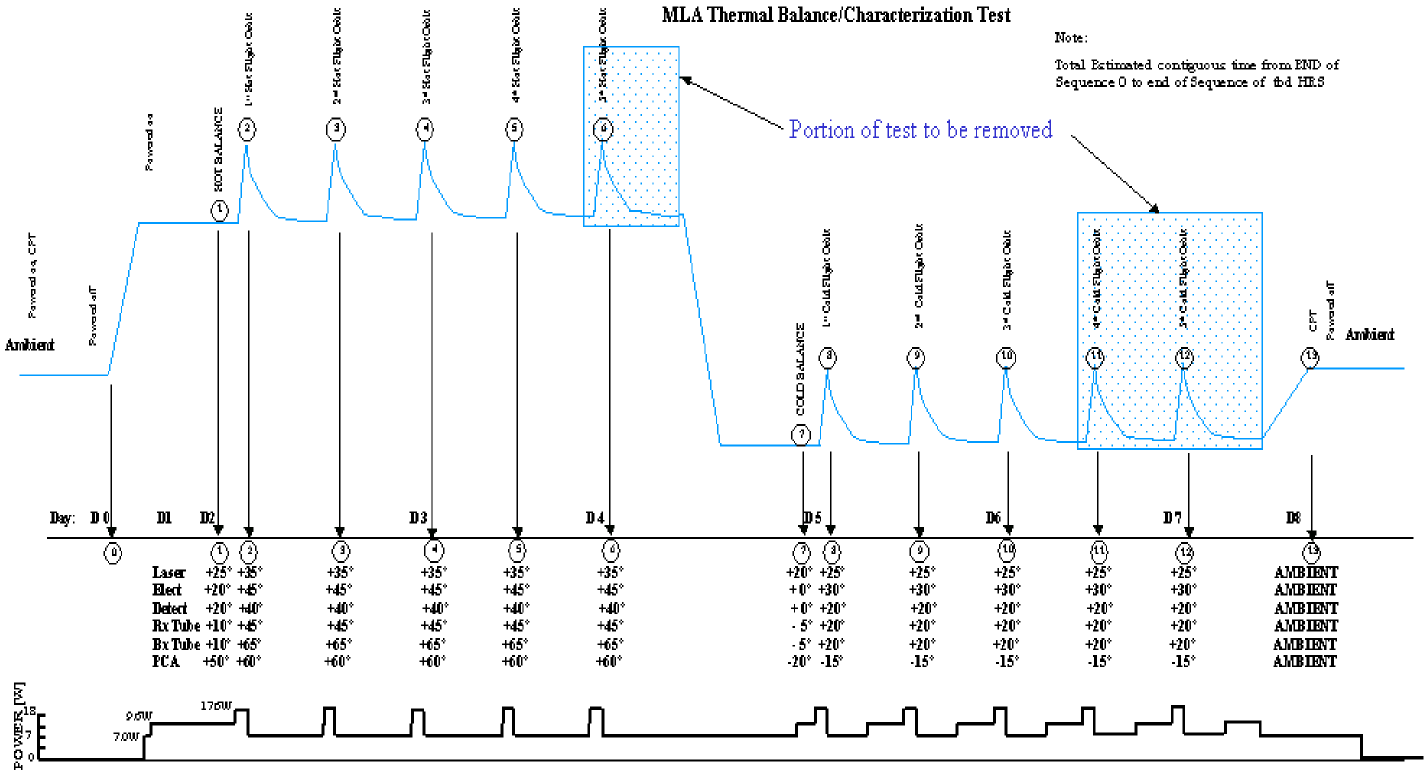


Figure 8. MLA Thermal Balance Test Profile

<table>
<tr><th rowspan="2">Test Case</th><th colspan="3">Temperature (°C)</th><th rowspan="2">Instrument Power (Watts)</th></tr>
<tr><th>Planet Target Plate</th><th>Spacecraft Deck</th><th>Chamber Wall</th></tr>
<tr><td>Hot Steady State</td><td>-30</td><td>50</td><td>-90</td><td>Stand-By (11.5)</td></tr>
<tr><td>Cold Steady State</td><td>-90</td><td>-20</td><td>-170</td><td>Keep-Alive (8.2)</td></tr>
</table>

Table 3. MLA Steady State Balance Sink Temperatures

Hot Transient Timeline		
Cycle Time (Minutes)	**Instrument Power**	**Target Plate Temperature Setting (°C)**
0	Standby	-120
30	Standby	140
60	Science	140
95	Keep Alive	140
135	Keep Alive	-120
720	Keep Alive	-120

Table 4. MLA Hot Transient Cycling Timeline.

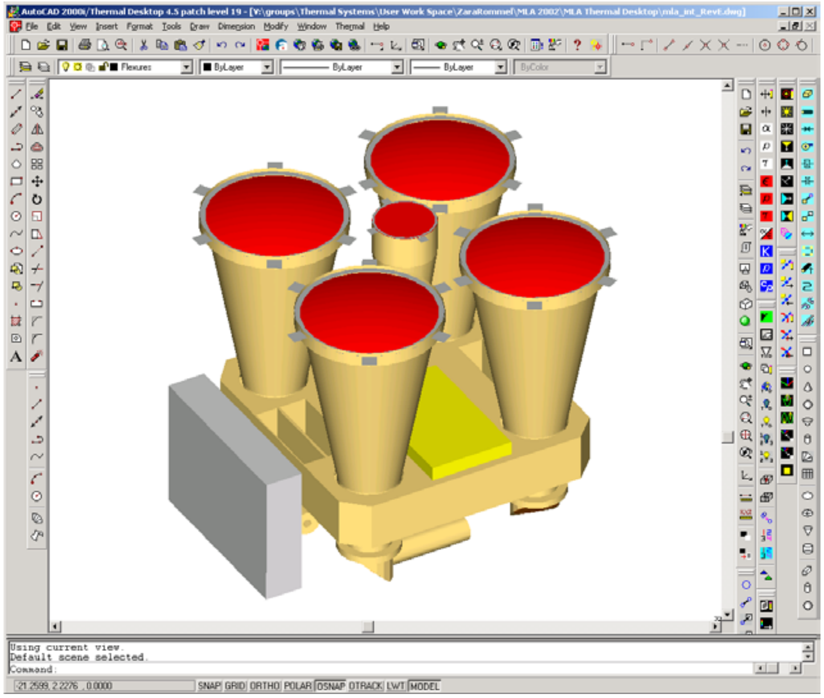
Cold Transient Timeline		
Cycle Time (Minutes)	**Instrument Power**	**Target Plate Temperature Setting (°C)**
0	Standby	10
60	Science	10
95	Keep Alive	10
112.5	Keep Alive	-140
300	Standby	-140
720	Standby	10

Table 5. MLA Cold Transient Cycling Timeline.

7 THERMAL BALANCE TEST MODEL AND ANALYSIS

7.1 Software

The thermal balance test model consists of a Thermal Desktop Geometry Model and a SINDA/FLUINT Math Model. The Geometry Model consists of over 2500 surfaces from which radiation couplings, conduction couplings, and thermal masses were generated. The Math Model consists of over 3000 nodes and 200,000 couplings.



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Using current view.
Default scene selected.
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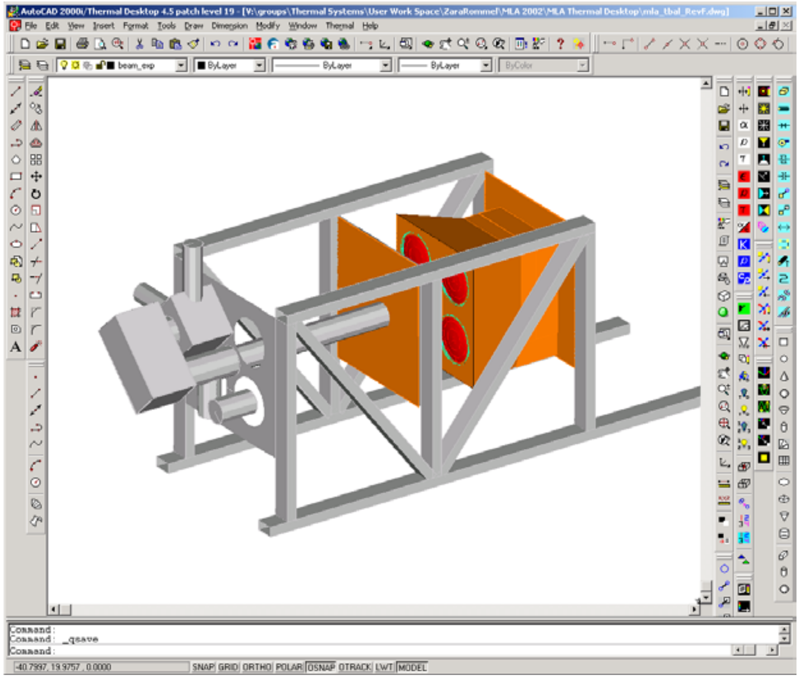
Figure 9. MLA Instrument Geometry Model



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Command:
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Figure 10. MLA Thermal Balance Test Geometry Model

7.2 Analysis and Assumptions

7.2.1 Material Properties

Material	Heat Capacitance (J/kg°C)	Conductivity (W/m°C)	Density (kg/m^3)
Beryllium	1880	150	1850
Sapphire	750	35	3960
Titanium	520	22	4430
Magnesium	1050	100	1800

Table 6. MLA Material Properties.

7.2.2 Optical Properties

Surface	Absorptivity	Emissivity
Kapton VDG	0.25	0.05
Kapton VDA	NA	0.03
Gold	NA	0.03
Sapphire	0.10	0.60
Black Anodize	NA	0.86
Polyimide (Circuit Boards)	NA	0.84
Dow no. 7	NA	0.65

Table 7. MLA Surface Properties.

7.2.3 Instrument Power Dissipation

COMPONENT	KA Power (Watts)	STBY Power (Watts)	SCI Power (Watts)
CPU	1.34	1.39	1.39
RMU	0.00	0.41	0.41
Detector	1.46	1.94	1.94
Detector (Heater)	0.00	2.00	2.00
Analog	0.29	0.30	0.30
LASER	0.59	0.60	5.50
LASER Elec	0.81	0.84	3.23
PCA	3.71	4.11	4.25
TOTAL	8.20	11.59	19.02

Table 8. MLA Instrument Power Dissipation.

7.2.4 Interface Conductors

Node I	Node J	Total Conduction (W/°C)
Receiver Tube	Main Housing	4.60
Receiver Flexure	Receiver Tube	4.20
Receiver Flexure	Receiver Lens	0.39
Receiver Lens	Receiver Tube	0.76
Beam Exp Tube	Laser Bench	0.55
Beam Exp Flexure	Beam Exp Tube	0.73
Beam Exp Flexure	Beam Exp Window	0.013
Beam Exp Window	Beam Exp Tube	0.0089
Laser Bench	Main Housing	0.40
PCA	SC Deck	4.20
MH Flexure	Main Housing	0.0052
MH Flexure	SC Deck	0.0052
Blanket e-star		0.03

Table 9. MLA Interface Conduction Couplings

7.2.5 Boundary Temperatures

Boundary Description	Boundary Node #	Hot Steady State (°C)	Cold Steady State (°C)
Planet Target plate	MLA.200002	-30	-90
Spacecraft Deck	MLA.8888	50	-20
Test Fixture	MLA.200006	20	20
Chamber Walls	MLA.9999	-90	-170
Instrument Power	NA	STBY (11.5 Watts)	KA (8.2 Watts)

Table 10. MLA Thermal Balance Test Steady State Boundary Conditions.

8 TEST RESULTS AND TEST MODEL COMPARISON AND ASESSMENT

8.1 Test and Model Power Comparison

	Test Voltage	Test Current	Test Power (Watts)	PER Model Power	Updated Model Power (Watts)
KA Power	32.5	0.252	8.2	7.0	8.2
STBY Power	32.5	0.355	11.5	9.6	11.6
SCI Power	32.5	0.589	19.1	18.0	19.0

Table 11. Test Power and Model Power

During the hot thermal balance test, the MLA temperatures were about 10 degrees warmer than predicted. Upon investigation, it was discovered that the instrument was dissipating about 30 percent more power than what was in the thermal model. The thermal model was then updated and a new set of temperature predictions was generated. The power numbers are listed in Table 11.

8.2 Steady State Test Results and Model Temperature Prediction Comparison

TC #	Node #	Location	Hot Predicts (°C)	Hot Results (°C)	ΔT (°C)	Cold Predicts (°C)	Cold Results (°C)	ΔT (°C)
1	MLA.15201	Receiver 1 Ti Flexure	21.2	OPEN	NA	-1.2	OPEN	NA
2	MLA.1052	Receiver 1 Tube Top	21.7	19.1	-2.6	-0.7	-0.3	0.5
3	MLA.1047	Receiver 1 Tube Bottom	23.9	22.7	-1.2	1.7	3.6	1.9
4	MLA.16201	Receiver 2 Ti Flexure	21.2	OPEN	NA	-0.7	OPEN	NA
5	MLA.2088	Receiver 2 Tube Top	21.6	19.2	-2.4	-0.3	-0.4	-0.1
6	MLA.2083	Receiver 2 Tube/MH interface nr Bolt	23.9	22.4	-1.5	2.3	3.2	0.9
7	MLA.5311	Receiver 2 Tube/MH interface on MH	26.3	23.2	-3.1	4.7	3.8	-1.0
8	MLA.2124	Receiver 2 Tube under MH	24.5	23.3	-1.2	2.9	3.5	0.7
9	MLA.2189	Receiver 2 Tube nr Fiber Optic Connector	24.5	23.7	-0.8	2.8	4.1	1.3
10	MLA.17201	Receiver 3 Ti Flexure	21.1	18.4	-2.8	-1.1	-2.6	-1.4
11	MLA.3052	Receiver 3 Tube Top	21.5	20.2	-1.4	-0.7	-0.4	0.3
12	MLA.3047	Receiver 3 Tube Bottom	23.8	23.7	0.0	1.7	3.4	1.7
13	MLA.18201	Receiver 4 Ti Flexure	22.0	18.7	-3.4	-1.3	-2.0	-0.6
14	MLA.4058	Receiver 4 Tube Top	22.4	OPEN	NA	-0.9	OPEN	NA
15	MLA.4056	Receiver 4 Tube Middle	23.2	21.4	-1.8	-0.1	1.0	1.1
16	MLA.4086	Receiver 4 Tube Middle (180 deg from 15)	23.2	21.1	-2.1	-0.1	0.8	0.9
17	MLA.4053	Receiver 4 Tube/MH interface nr Bolt	24.8	23.9	-0.9	1.5	3.7	2.1
18	MLA.5396	Receiver 4 Tube/MH interface on MH	26.6	24.8	-1.9	4.0	4.4	0.4
19	MLA.4124	Receiver 4 Tube under MH	25.5	24.4	-1.0	2.2	4.0	1.8
20	MLA.4192	Receiver 4 Tube nr Fiber Optic Connector	25.4	24.2	-1.3	2.2	3.7	1.5
21	MLA.15304	Beam Expander Ti Flexure	23.1	19.4	-3.7	9.8	5.9	-3.9
22	MLA.111949	Beam Expander Tube Top	23.7	21.1	-2.6	10.6	8.5	-2.1
23	MLA.111947	Beam Expander Tube Middle	24.4	22.3	-2.0	11.4	10.0	-1.4
24	MLA.111938	Beam Expander/Laser Bench Interface nr Bolt	26.1	23.4	-2.7	13.7	11.7	-2.0
25	MLA.101	Beam Expander/Laser Bench Interface on LB	26.7	23.6	-3.1	14.3	11.9	-2.5
26	MLA.5471	Mounting Flexure 1/MH Interface (on MH)	26.3	24.6	-1.7	2.9	3.2	0.3
27	MLA.7503	Mounting Flexure 1 Top	38.2	24.6	-13.6	-8.6	3.6	12.1
28	MLA.7503	Mounting Flexure 1 Bottom	38.2	40.4	2.2	-8.6	-14.4	-5.8
29	MLA.8888	Mounting Flexure 1/SC Deck Interface (on SC Deck)	50.0	47.8	-2.2	-20.0	-19.9	0.1
30	MLA.108	Laser Bench Top 1	26.7	23.8	-2.9	14.6	12.6	-2.0
31	MLA.105	Laser Bench/MH Interface 1 (on LB)	26.7	23.6	-3.1	14.6	11.5	-3.1
32	MLA.5170	Laser Bench/MH Interface 1 (on MH)	25.8	24.4	-1.4	4.3	5.9	1.5
33	MLA.112	Analog Cover Top 1	27.8	25.0	-2.7	4.7	5.3	0.6
34	MLA.114	Analog/MH Interface 1 (on Analog)	27.2	25.0	-2.1	3.6	4.8	1.2
35	MLA.5175	Analog/MH Interface 1 (on MH)	28.4	25.6	-2.8	4.3	5.2	0.9
36	MLA.6642	Main Housing nr Surv Thermostat A	27.8	OPEN	NA	5.4	OPEN	NA
37	MLA.6241	Main Housing nr Survival Heater 1	26.6	OPEN	NA	3.5	OPEN	NA
38	MLA.5577	Main Housing PCA side	26.2	26.4	0.2	4.0	6.0	2.0
39	MLA.6268	Main Housing (opposite 38)	26.8	26.1	-0.7	4.4	6.6	2.2
40	MLA.131	Detector +X	30.5	27.0	-3.4	5.1	6.8	1.7
41	MLA.132	Aft Optics	32.0	27.3	-4.7	6.0	3.5	-2.5
42	MLA.6707	Lower Electronics Housing Cover +Y	28.4	27.2	-1.2	5.8	7.3	1.4
43	MLA.6675	Lower Electronics Housing Side +Y	27.7	26.5	-1.2	5.4	6.5	1.2
44	MLA.6654	Lower Electronics Housing Side -X	27.9	26.8	-1.1	5.5	7.0	1.5
45	MLA.6567	Lower Electronics Housing/MH Interface 1 (on LEH)	27.1	25.6	-1.5	5.0	5.8	0.8
46	MLA.6310	Lower Electronics Housing/MH Interface 1 (on MH)	27.0	24.9	-2.1	5.0	5.4	0.4
47	MLA.11256	PCA Side +X (surv thermostat A)	51.5	54.9	3.4	-18.5	-3.7	14.8
48	MLA.11254	PCA Side +X (surv thermostat B)	51.1	53.5	2.3	-18.9	-9.0	9.9
49	MLA.11260	PCA Side -X	51.7	56.1	4.3	-18.3	-4.1	14.2
50	MLA.11242	PCA Side +Y	51.9	57.3	5.4	-18.1	-3.6	14.6
51	MLA.11247	PCA Side -Y	51.4	57.8	6.5	-18.7	-2.0	16.7
52	MLA.11282	PCA Top	52.2	53.0	0.8	-17.8	-1.7	16.2
53	MLA.11266	PCA Surv Htr 1	52.3	57.1	4.8	-17.7	-1.4	16.3
54	MLA.11263	PCA Surv Htr 2	52.2	56.1	3.9	-17.8	-1.8	16.0
55	MLA.11219	PCA/SC Deck Interface 1 (on PCA)	51.5	OPEN	NA	-18.6	OPEN	NA
56	MLA.8888	PCA/SC Deck Interface 1 (on SC Deck)	50.0	OPEN	NA	-20.0	OPEN	NA
57	MLA.11223	PCA/SC Deck Interface 2 (on PCA)	51.2	49.0	-2.2	-18.9	-19.1	-0.2
58	MLA.8888	PCA/SC Deck Interface 2 (on SC Deck)	50.0	OPEN	NA	-20.0	-19.0	1.0
59	MLA.8888	S/C Deck 1	50.0	49.3	-0.7	-20.0	OPEN	NA
62	MLA.200002	TVAC Target Plate 1	-30.0	OPEN	NA	-90.0	-90.2	-0.2
NA	MLA.999	Chamber Wall	-90.0	-89.0	-1.0	-170.0	-177.0	-7.0

Table 12. Test Results and Model Temperature Prediction Comparison.

The comparison in Table 12 shows that excluding the PCA, the MLA test results were within 3 °C of the model predictions for both hot and cold cases. This shows that the overall instrument heat balance in test matched closely with the model predictions. The PCA temperatures were about 5°C warmer in test for the hot case and about 15°C warmer for the cold case, but the interface temperature between the PCA and spacecraft deck closely matched the predicts (within 3°C). This means that the conduction through the magnesium structure of the PCA is less than what was modeled. Iterative changes to the PCA structural conduction were made to the model until the desired PCA temperatures were achieved. Hand calculations verified that the new conduction numbers are within a reasonable range. The results of these changes are in section 9.

8.3 Interface Delta T Comparison

Node Descrip. I	Node Descrip. J	Test Interface ΔT	Model Interface ΔT	Difference	TC I	TC J	Node I	Node J
Receiver Tube	Main Housing	0.9	1.8	0.9	23.8	24.7	24.8	26.6
Receiver Flexure	Receiver Tube	1.8	0.4	-1.4	18.3	20.1	22	22.4
Receiver Flexure	Receiver Lens	NA	NA	NA	18.3	NA	22	NA
Receiver Lens	Receiver Tube	NA	NA	NA	NA	20.1	NA	22.4
Beam Exp Tube	Laser Bench	0.2	0.6	0.4	23.3	23.5	26.1	26.7
Beam Exp Flexure	Beam Exp Tube	1.7	0.6	-1.1	19.4	21.0	23.1	23.7
Beam Exp Flexure	Beam Exp Window	NA	NA	NA	19.4	NA	23.1	NA
Beam Exp Window	Beam Exp Tube	NA	NA	NA	NA	23.3	NA	23.7
Laser Bench	Main Housing	0.8	0.9	0.1	23.5	24.3	26.7	25.8
PCA	SC Deck	0.1	1.2	1.1	50.3	50.4	51.2	50.0
MH Flexure	Main Housing	0.0	11.9	11.9	24.6	24.5	38.2	26.3
MH Flexure	SC Deck	7.8	11.8	4.0	41.3	49.0	38.2	50.0

Table 13. Hot Case Interface Delta T Comparison

Node Descrip. I	Node Descrip. J	Test Interface ΔT	Model Interface ΔT	Difference	TC I	TC J	Node I	Node J
Receiver Tube	Main Housing	0.6	2.5	1.9	3.5	4.1	1.5	4.0
Receiver Flexure	Receiver Tube	2.2	0.4	-1.8	-2.5	-0.4	-1.1	-0.7
Receiver Flexure	Receiver Lens	NA	NA	NA	-2.5	NA	-1.1	NA
Receiver Lens	Receiver Tube	NA	NA	NA	NA	-0.4	NA	-0.7
Beam Exp Tube	Laser Bench	0.1	0.6	0.5	11.7	11.8	13.7	14.3
Beam Exp Flexure	Beam Exp Tube	2.6	0.8	-1.8	5.9	8.5	9.8	10.6
Beam Exp Flexure	Beam Exp Window	NA	NA	NA	5.9	NA	9.8	NA
Beam Exp Window	Beam Exp Tube	NA	NA	NA	NA	11.7	NA	10.6
Laser Bench	Main Housing	5.7	10.3	4.6	11.6	5.9	14.6	4.3
PCA	SC Deck	0.2	1.1	0.9	-19.2	-19.4	-18.9	-20.0
MH Flexure	Main Housing	0.4	11.5	11.1	3.4	3.0	-8.6	2.9
MH Flexure	SC Deck	5.5	11.4	5.9	-14.5	-20.0	-8.6	-20.0

Table 14. Cold Case Interface Delta T Comparison

Tables 13 and 14 show the interface Delta Ts for test and model for hot and cold cases. There is a discrepancy in the Laser Bench and Main Housing Interface in the cold case. That discrepancy is corrected for in the model correlation. Another discrepancy is in the Main Housing Flexure to Main Housing Interface. This discrepancy is due to the nodal breakdown difference in the model versus the thermocouple locations in the test. The model had one node for the flexure whereas there were 2 thermocouples on the flexure in the test. Averaging the temperatures of the two thermocouples on the flexure yields 32.5°C for the hot case and –5.6°C for the cold case. This results in a difference in Delta T of 4.0°C in the hot case and 5.2°C in the cold case, which is a significant improvement from the 11.9°C and 11.5°C values listed in the tables. The rest of the MLA interface couplings in the model closely matched what was seen in the test.

8.4 Operational Heater Duty Cycle Comparison

The operational heater on the Laser Bench was originally specified as a proportional heater. During the test, however, it was confirmed that the operational heater is controlled thermostatically. Table 15 shows the duty cycles for test and model cases. The results indicate that there is a larger heat loss in the laser bench than what was modeled. This heat is probably lost to the Main Housing, which is the main conductive path from the laser bench. This is corrected for in the correlated model using parametric SINDA analysis on the Laser Bench to Main Housing coupling.

Laser Bench Op Heater	**Duty Cycle (%)**			
	Cold Balance	**Hot Balance**	**Cold Transient**	**Hot Transient**
Test	100	0	89	42
Model	66	0	56	33

Table 15. Laser Bench Heater Duty Cycle Comparison.

8.5 Survival Heater Verification

The survival heaters on the Main Housing and PCA were verified during the Thermal Vacuum portion of the test. During Cold Survival Plateau, the main housing survival heater circuit A turned on at –12.5°C and off at –5.0°C. The Main Housing survival heater circuit B turned on at –20°C and off at –12.5°C. The PCA survival heater circuit A turned on at –7.8°C and off at 1.2°C. The PCA survival heater circuit B turned on at –13.7°C and off at –6.5°C.

8.6 Thermistor Performance Verification

The thermal performances of the MLA flight thermistors were verified during thermal vacuum testing by comparison to nearby test thermocouples. Of the fourteen thermistors, ten were in locations that allowed thermocouples to be placed nearby. The remaining four thermistors were located on the Laser Oscillator, RMU, CPU, and the Detector Boards. No thermocouples could be located on these components.

The comparisons of the thermistor temperatures to the measured thermocouple temperature for the five hot and five cold plateaus taken during the thermal vacuum test are shown in Table 1. Also shown in this table are the differences or “delta” between thermistor and thermocouple for each plateau. Comparison of data shows that the performance of most of the MLA thermistors agrees well with the thermocouples. The thermistors are within ± 1 °C of the thermocouples. This is within the accuracy of the thermocouple. The PCA and Oscillator thermistors however, do show a greater difference than can be explained by the accuracy of the thermocouples accuracy. Investigation into this difference can be explained in the actual location of the thermocouple versus the location of the thermistor. For the PCA, the thermistor was located on the case next to the printed circuit board. As this board was dissipating heat it drove the thermistor warmer than the thermocouple, which was located on the outer case of the PCA. This explanation also applied to the Oscillator thermistor in that the thermistor was located closer to the heat dissipation component than the thermocouple.

The two thermistors that had the largest difference to their thermocouples were the Main housing and the Receiver Base. The difference was as large as 10°C for the hot plateaus. The only explanation for this occurrence was that the Main housing and Receiver thermistors may be labeled incorrectly. When the Main housing thermistor data was compared to the Receiver Base thermocouple data a good fit was observed. This was also observed when the Receiver Base thermistor data was compared to the Main housing thermocouple. This comparison is shown in Table 16. Thus it is recommended that the software screen data be checked to verify that the Main housing and Receiver Base thermistors are labeled correctly.

Thermistor to TC comparison

	1ST HOT (1BC)		2ND HOT (6)		3RD HOT (10)		4TH HOT (12)		5TH HOT (14)		delta 1	delta 2	delta 3	delta 4	delta 5	AVG
	6/5,11:00	6/5,11:00	6/9,18:10	6/9,18:10	6/11.23:30	6/11.23:30	6/13,1:30	6/13,1:30	6/19,7:45	6/19,7:45						
	Thermistor	TC	Thermistor	TC	Thermistor	TC	Thermistor	TC	Thermistor	TC						
Alt Dect	28.5	29.5	38.5	39.9	33.6	34.5	38.5	38.7	36.8	37.4	-1	-1	-1	0	-1	-1
Anal Board	28.5	29	38.5	38.7	34	33.6	37.7	37.5	36.4	36.2	-1	0	0	0	0	0
OSC	28.5	29.1	41.6	39.7	35.6	34.8	42.5	38.5	41.1	37.5	-1	2	1	4	4	2
Laser Elec	28.5	29.3	37.2	37.3	32.9	32.9	36.8	36.1	36	35.4	-1	0	0	1	1	0
Laser	24.1	25	27.1	28.7	27.5	28.1	27.8	28.4	29.2	29.6	-1	-2	-1	-1	0	-1
PCA	60.5	57.7	58.6	57.3	58	55.2	59.3	57.1	59.3	57.8	3	1	3	2	2	2
Beam X	31.7	32.4	36	36.4	31.7	32.3	34.8	35.1	31.4	31.8	-1	0	-1	0	0	0
Rcvr Lens	25.1	25.3	28.5	28.6	28.2	27.9	28.9	28.2	29.6	29.5	0	0	0	1	0	0
Rcvr Base	28.5	27.5	37.7	29	33.2	27.9	38.1	28.6	36.4	28.2	1	9	5	10	8	7
Main Hsg	27.5	31.2	28.9	38.8	28.2	34.4	29.2	37.7	28.2	36.8	-4	-10	-6	-9	-9	-7
Reversing Main Housing Thermistor with Receiver Base Thermistor																
Main Hsg	28.5	31.2	37.7	38.8	33.2	34.4	38.1	37.7	36.4	36.8	-3	-1	-1	0	0	-1
Rcvr Base	27.5	27.5	28.9	29	28.2	27.9	29.2	28.6	28.2	28.2	0	0	0	1	0	0

	1ST COLD (4)		2ND COLD (9)		3RD COLD (11)		4TH COLD (13)		5TH COLD (15)		delta 1	delta 2	delta 3	delta 4	delta 5	AVG
	6/7,12:00	6/7,12:00	6/11,11:14	6/11,11:14	6/12,12:12	6/12,12:12	6/18.18:07	6/18.18:07	6/19,17:00	6/19,17:00						
	Thermistor	TC	Thermistor	TC	Thermistor	TC	Thermistor	TC	Thermistor	TC						
Alt Dect	7.7	7.5	7.3	7.1	4.6	4.2	9	9.6	8.7	8.4	0	0	0	-1	0	0
Anal Board	7.7	5.9	7.3	5.7	4.6	2.7	9.3	7.8	8.7	6.8	2	2	2	2	2	2
OSC	11.9	8	11.6	5.9	8.3	4.8	13.5	10.5	12.8	9.2	4	6	4	3	4	4
Laser Elec	6.7	5.8	7.3	7.7	3.5	2.8	9	6.2	8.7	7.2	1	0	1	3	2	1
Laser	11.6	9.3	11.3	9	12.2	9.5	11.9	10.2	12.5	10.6	2	2	3	2	2	2
PCA	-25.3	-23.6	-22.9	-20.4	-23.5	-22	-22.3	-19.6	-22.9	-20.1	-2	-3	-2	-3	-3	-2
Beam X	0.2	0.1	0.2	-0.2	-3.4	-3.4	2.1	2.1	1.3	0.8	0	0	0	0	1	0
Rcvr Lens	10.3	9.5	10	9.4	10.6	9.8	10.6	10.3	11.6	10.9	1	1	1	0	1	1
Rcvr Base	7.3	6.5	6.7	6	3.9	6.2	8.7	7.4	8	7.5	1	1	-2	1	1	0
Main Hsg	6.7	6.4	6.3	6.3	6.3	3.3	7	9.1	7.3	7.8	0	0	3	-2	-1	0
Reversing Main Housing Thermistor with Receiver Base Thermistor																
Main Hsg	7.3	6.4	6.7	6.3	3.9	3.3	8.7	9.1	8	7.8	1	0	1	0	0	0
Rcvr Base	6.7	6.5	6.3	6	6.3	6.2	7	7.4	7.3	7.5	0	0	0	0	0	0

Table 16. Thermistor Performance Verification

8.7 Transient Test and Model Temperature Comparison

The transient cases provided temperature change rates for thermal capacitance correlation. The temperature change rates seen during the test closely matched the rates seen in the model and therefore no changes to the model were made. The plot comparisons are listed in Appendix B.

9 MODEL CORRELATION

9.1 PCA Correlation

Two main changes were made to the MLA thermal model to reduce the discrepancy seen during the test. The first change made was to the PCA internal conduction. The PCA was seen running about 5°C warmer than predicts in the hot case and 11°C warmer in the cold case. At first, it was suspected that the interface coupling used in the model was in error. But thermocouple data shows that the interface temperatures predicted in the model matched the test results. Thus the internal conduction in the PCA was reduced iteratively using parametric SINDA runs. The internal power was also shifted to the Output Board of the PCA to match the thermal gradient seen during test. In addition the heat gained/lost (hot case/cold case) from the top of the PCA to the Main Housing via the connector cables were added. The results of these changes brought the PCA model temperatures to within 4°C of test results. The summary of the PCA model changes are listed in Table 17.

Coupling Description		Old Conductance	New Conductance	Factor
PCA Feet	PCA Panels	2.13	0.21	0.10
PCA Feet	PCA Bottom Plate	3.28	0.33	0.10
PCA Feet	PCA Center Panel	1.14	0.46	0.40
PCA Top Plate	Main Housing	0.00	0.20	NA

Table 17. PCA Model Changes.

9.2 Laser Bench to Main Housing Interface Correlation

The second change made to the model is in the Laser Bench and Main Housing interface coupling. The results indicated that the delta T in this interface was larger in the model (10.3°C in the model vs. 5.6°C in test) than in the test. The Laser Bench heater duty cycle was also 30% less in the model than in the test. Since the Main Housing serves as the Laser Bench sink, the coupling between them must be higher than what was modeled. Iterative changes to the interface coupling between the Laser Bench and Main Housing showed that increasing the interface coupling by a factor of 1.5 brought the model delta T to within 2°C of the test results. In addition, the Laser Bench duty cycle in the model is now within 5% of test results. The correlated heater duty cycles are listed in Table 19.

9.3 Blanket Effective Emissivity Correlation

Correlation of the PCA and Laser Bench caused an overall increase in the instrument temperature of about 2°C. To offset this increase, the blanket effective emissivity was increased from 0.03 to 0.05 to bring the average instrument model temperatures back down to within 3°C of test results. Table 18 shows the correlated model temperatures versus the test temperatures. Table 20 shows the correlated model interface delta Ts versus the test interface delta Ts.

TC #	Node #	Location	Hot Predicts (°C)	Hot Results (°C)	ΔT (°C)	Cold Predicts (°C)	Cold Results (°C)	ΔT (°C)
1	MLA.15201	Receiver 1 Ti Flexure	20.9	OPEN	NA	1.9	OPEN	NA
2	MLA.1052	Receiver 1 Tube Top	21.3	19.1	-2.2	2.4	-0.3	-2.6
3	MLA.1047	Receiver 1 Tube Bottom	23.7	22.7	-1.0	5.0	3.6	-1.4
4	MLA.16201	Receiver 2 Ti Flexure	20.9	OPEN	NA	2.4	OPEN	NA
5	MLA.2088	Receiver 2 Tube Top	21.3	19.2	-2.2	2.9	-0.4	-3.3
6	MLA.2083	Receiver 2 Tube/MH interface nr Bolt	23.8	22.4	-1.4	5.6	3.2	-2.5
7	MLA.5311	Receiver 2 Tube/MH interface on MH	26.3	23.2	-3.1	8.2	3.8	-4.5
8	MLA.2124	Receiver 2 Tube under MH	24.4	23.3	-1.1	6.2	3.5	-2.7
9	MLA.2189	Receiver 2 Tube nr Fiber Optic Connector	24.4	23.7	-0.7	6.1	4.1	-2.0
10	MLA.17201	Receiver 3 Ti Flexure	20.7	18.4	-2.3	2.0	-2.6	-4.6
11	MLA.3052	Receiver 3 Tube Top	21.1	20.2	-1.0	2.5	-0.4	-2.8
12	MLA.3047	Receiver 3 Tube Bottom	23.5	23.7	0.2	5.0	3.4	-1.6
13	MLA.18201	Receiver 4 Ti Flexure	21.5	18.7	-2.9	1.6	-2.0	-3.6
14	MLA.4058	Receiver 4 Tube Top	22.0	OPEN	NA	2.1	OPEN	NA
15	MLA.4056	Receiver 4 Tube Middle	22.8	21.4	-1.4	2.9	1.0	-1.9
16	MLA.4086	Receiver 4 Tube Middle (180 deg from 15)	22.7	21.1	-1.6	2.9	0.8	-2.1
17	MLA.4053	Receiver 4 Tube/MH interface nr Bolt	24.4	23.9	-0.5	4.6	3.7	-1.0
18	MLA.5396	Receiver 4 Tube/MH interface on MH	26.4	24.8	-1.6	7.3	4.4	-2.9
19	MLA.4124	Receiver 4 Tube under MH	25.1	24.4	-0.7	5.3	4.0	-1.3
20	MLA.4192	Receiver 4 Tube nr Fiber Optic Connector	25.1	24.2	-0.9	5.3	3.7	-1.7
21	MLA.15304	Beam Expander Ti Flexure	21.6	19.4	-2.2	8.7	5.9	-2.8
22	MLA.111949	Beam Expander Tube Top	22.5	21.1	-1.4	9.7	8.5	-1.2
23	MLA.111947	Beam Expander Tube Middle	23.3	22.3	-1.0	10.8	10.0	-0.8
24	MLA.111938	Beam Expander/Laser Bench Interface nr Bolt	25.5	23.4	-2.1	13.5	11.7	-1.8
25	MLA.101	Beam Expander/Laser Bench Interface on LB	26.2	23.6	-2.6	14.3	11.9	-2.5
26	MLA.5471	Mounting Flexure 1/MH Interface (on MH)	26.0	24.6	-1.4	6.1	3.2	-2.9
27	MLA.7503	Mounting Flexure 1 Top	38.0	24.6	-13.4	-7.0	3.6	10.5
28	MLA.7503	Mounting Flexure 1 Bottom	38.0	40.4	2.3	-7.0	-14.4	-7.4
29	MLA.8888	Mounting Flexure 1/SC Deck Interface (on SC Deck)	50.0	47.8	-2.2	-20.0	-19.9	0.1
30	MLA.108	Laser Bench Top 1	26.3	23.8	-2.4	14.7	12.6	-2.1
31	MLA.105	Laser Bench/MH Interface 1 (on LB)	26.3	23.6	-2.6	14.4	11.5	-2.9
32	MLA.5170	Laser Bench/MH Interface 1 (on MH)	25.7	24.4	-1.3	7.9	5.9	-2.1
33	MLA.112	Analog Cover Top 1	27.6	25.0	-2.6	7.9	5.3	-2.6
34	MLA.114	Analog/MH Interface 1 (on Analog)	26.8	25.0	-1.8	6.7	4.8	-2.0
35	MLA.5175	Analog/MH Interface 1 (on MH)	28.2	25.6	-2.6	7.5	5.2	-2.3
36	MLA.6642	Main Housing nr Surv Thermostat A	27.9	OPEN	NA	8.8	OPEN	NA
37	MLA.6241	Main Housing nr Survival Heater 1	26.6	OPEN	NA	6.8	OPEN	NA
38	MLA.5577	Main Housing PCA side	26.3	26.4	0.0	7.3	6.0	-1.3
39	MLA.6268	Main Housing (opposite 38)	26.6	26.1	-0.5	7.8	6.6	-1.2
40	MLA.131	Detector +X	30.3	27.0	-3.3	8.4	6.8	-1.6
41	MLA.134	Aft Optics	30.0	27.3	-2.7	8.0	3.5	-4.5
42	MLA.6707	Lower Electronics Housing Cover +Y	28.4	27.2	-1.2	9.3	7.3	-2.0
43	MLA.6675	Lower Electronics Housing Side +Y	27.8	26.5	-1.3	8.7	6.5	-2.2
44	MLA.6654	Lower Electronics Housing Side -X	27.8	26.8	-1.0	9.0	7.0	-2.0
45	MLA.6567	Lower Electronics Housing/MH Interface 1 (on LEH)	27.3	25.6	-1.7	8.3	5.8	-2.5
46	MLA.6310	Lower Electronics Housing/MH Interface 1 (on MH)	27.1	24.9	-2.2	8.4	5.4	-3.0
47	MLA.11256	PCA Side +X (surv thermostat A)	56.4	54.9	-1.5	-7.8	-3.7	4.1
48	MLA.11254	PCA Side +X (surv thermostat B)	54.8	53.5	-1.4	-10.6	-9.0	1.6
49	MLA.11260	PCA Side -X	56.3	56.1	-0.2	-7.6	-4.1	3.5
50	MLA.11242	PCA Side +Y	55.6	57.3	1.7	-8.1	-3.6	4.6
51	MLA.11241	PCA Side -Y	55.8	57.8	2.0	-6.2	-2.0	4.2
52	MLA.11282	PCA Top	58.3	55.0	-3.3	-3.8	-1.7	2.2
53	MLA.11266	PCA Surv Htr 1	58.5	57.1	-1.5	-3.8	-1.4	2.4
54	MLA.11263	PCA Surv Htr 2	58.6	56.1	-2.4	-3.8	-1.8	2.0
55	MLA.11219	PCA/SC Deck Interface 1 (on PCA)	50.8	OPEN	NA	-18.6	OPEN	NA
56	MLA.8888	PCA/SC Deck Interface 1 (on SC Deck)	50.0	OPEN	NA	-20.0	OPEN	NA
57	MLA.11223	PCA/SC Deck Interface 2 (on PCA)	50.8	49.0	-1.8	-18.6	-19.1	-0.5
58	MLA.8888	PCA/SC Deck Interface 2 (on SC Deck)	50.0	OPEN	NA	-20.0	-19.0	1.0
59	MLA.8888	S/C Deck 1	50.0	49.3	-0.7	-20.0	OPEN	NA
62	MLA.200002	TVAC Target Plate 1	-35.0	OPEN	NA	-90.0	-90.2	-0.2
NA	MLA.9999	Chamber Wall	-90.0	-89.0	1.0	-170.0	-177.0	-7.0

Table 18. Test Results and Correlated Model Temperature Comparison.

	Duty Cycle (%)			
Laser Bench Op Heater	**Cold Balance**	**Hot Balance**	**Cold Transient**	**Hot Transient**
Test	100	0	89	42
Correlated Model	100	0	80	35

Table 19. Test Results and Correlated Model Heater Duty Cycle Comparison.

Node Descrip. I	Node Descrip. J	Test Interface ∆T	Model Interface ∆T	Difference	TC I	TC J	Node I	Node J
Receiver Tube	Main Housing	0.9	2.0	1.1	23.8	24.7	24.4	26.4
Receiver Flexure	Receiver Tube	1.8	0.4	1.4	18.3	20.1	20.7	21.1
Receiver Flexure	Receiver Lens	NA	NA	NA	18.3	NA	NA	NA
Receiver Lens	Receiver Tube	NA	NA	NA	NA	20.1	NA	NA
Beam Exp Tube	Laser Bench	0.2	0.7	0.5	23.3	23.5	25.5	26.2
Beam Exp Flexure	Beam Exp Tube	1.7	0.8	0.8	19.4	21.0	21.6	22.5
Beam Exp Flexure	Beam Exp Window	NA	NA	NA	19.4	NA	NA	NA
Beam Exp Window	Beam Exp Tube	NA	NA	NA	NA	23.3	NA	NA
Laser Bench	Main Housing	0.8	0.6	0.2	23.5	24.3	26.3	25.7
PCA	SC Deck	0.1	0.8	0.6	50.3	50.4	50.8	50.0
MH Flexure	Main Housing	0.0	12.0	12.0	24.6	24.5	38.0	26.0
MH Flexure	SC Deck	7.8	12.0	4.2	41.3	49.0	38.0	50.0

Table 20. Hot Case Correlated Interface Delta T Comparison.

Node Descrip. I	Node Descrip. J	Test Interface ∆T	Model Interface ∆T	Difference	TC I	TC J	Node I	Node J
Receiver Tube	Main Housing	0.6	2.7	2.1	3.5	4.1	4.6	7.3
Receiver Flexure	Receiver Tube	2.2	0.5	1.7	-2.5	-0.4	2.0	2.5
Receiver Flexure	Receiver Lens	NA	NA	NA	-2.5	NA	NA	NA
Receiver Lens	Receiver Tube	NA	NA	NA	NA	-0.4	NA	NA
Beam Exp Tube	Laser Bench	0.1	0.8	0.7	11.7	11.8	13.5	14.3
Beam Exp Flexure	Beam Exp Tube	2.6	1.0	1.6	5.9	8.5	8.7	9.7
Beam Exp Flexure	Beam Exp Window	NA	NA	NA	5.9	NA	NA	NA
Beam Exp Window	Beam Exp Tube	NA	NA	NA	NA	11.7	NA	NA
Laser Bench	Main Housing	5.7	6.5	0.8	11.6	5.9	14.4	7.9
PCA	SC Deck	0.2	1.4	1.2	-19.2	-19.4	-18.6	-20.0
MH Flexure	Main Housing	0.4	13.0	12.6	3.4	3.0	-7.0	6.1
MH Flexure	SC Deck	5.5	13.0	7.6	-14.5	-20.0	-7.0	-20.0

Table 21. Cold Case Correlated Interface Delta T Comparison.

10 CONCLUSION

The MLA Thermal Balance Test provided us with sufficient data to validate our thermal model assumptions and to validate our thermal control system design. Overall, the thermal model temperature predictions were close (within 3°C) to the test results. Thermal masses were correct and heaters and thermistors were verified. A couple of discrepancies were seen in the PCA temperatures and the Laser Bench/Main Housing interface delta Ts, but the causes of those discrepancies were studied, understood, and corrected for in the correlated model.

11 APPENDIX A: THERMOCOUPLE LOCATIONS

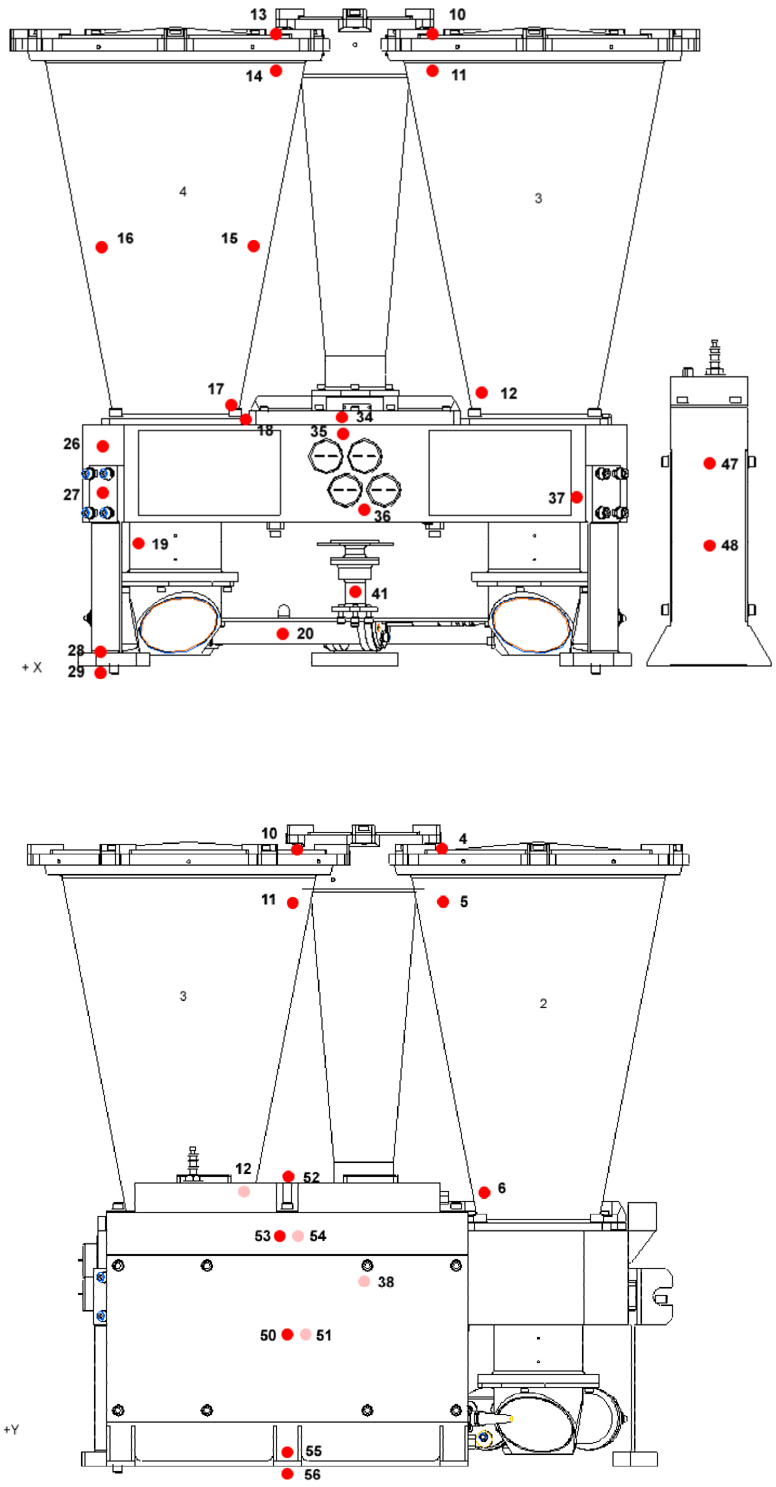

Figure A-1. MLA Thermocouple Locations 1

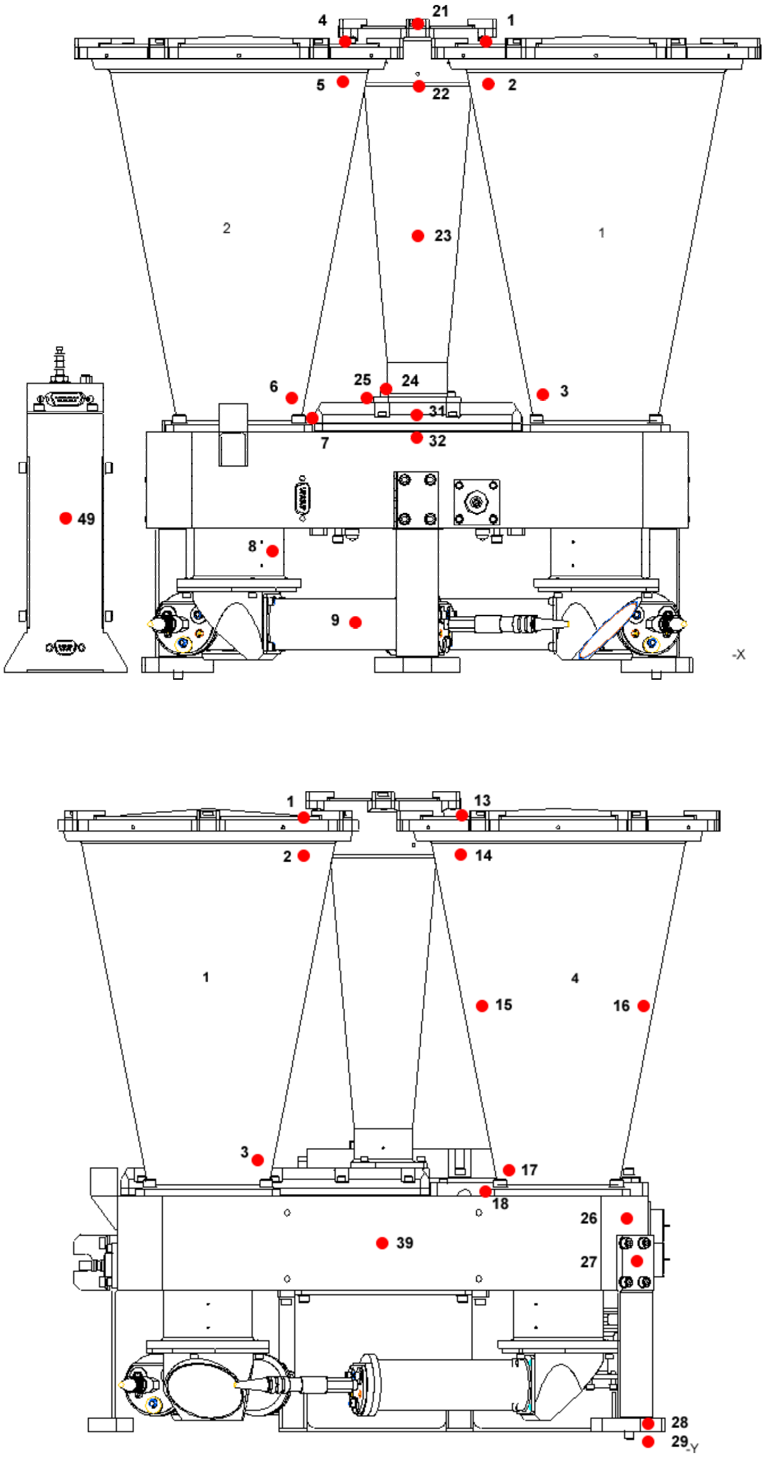

Figure A-2. MLA Thermocouple Locations 2

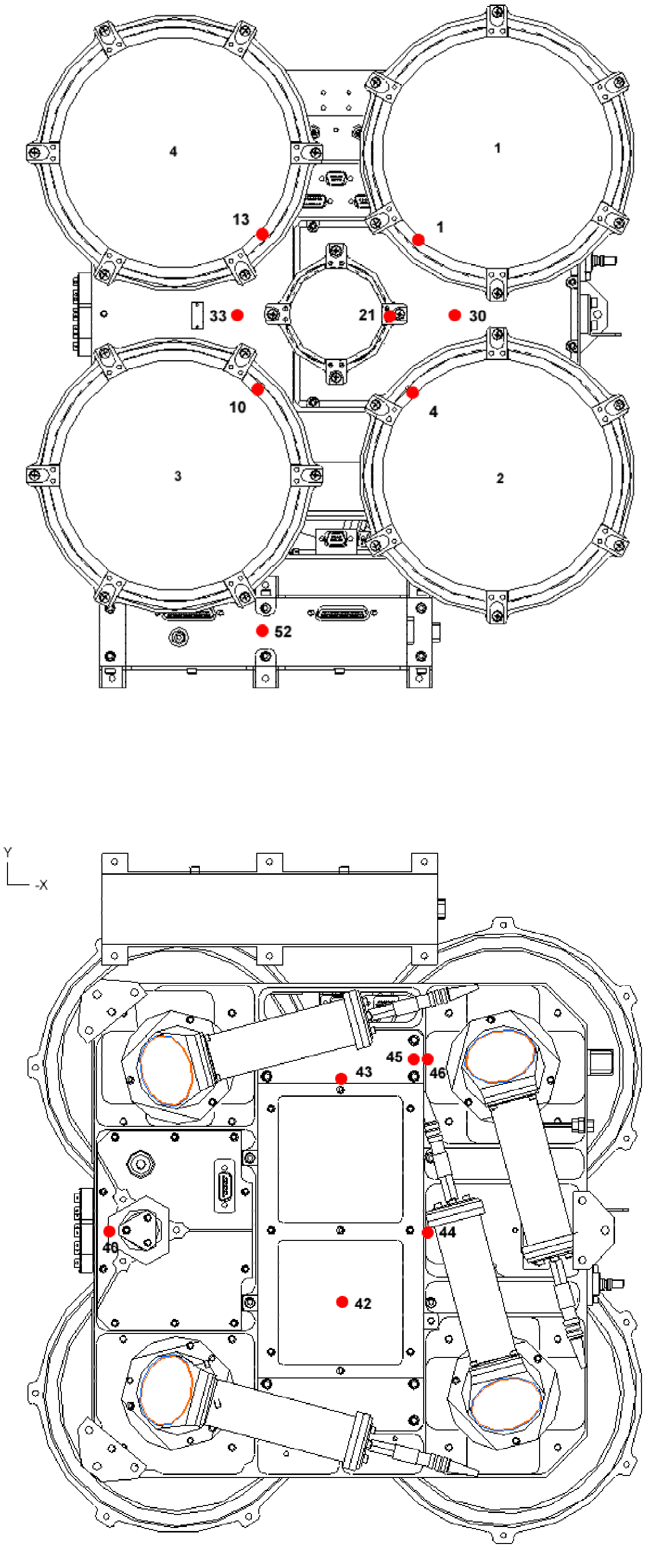

Figure A-3. MLA Thermocouple Locations 3.

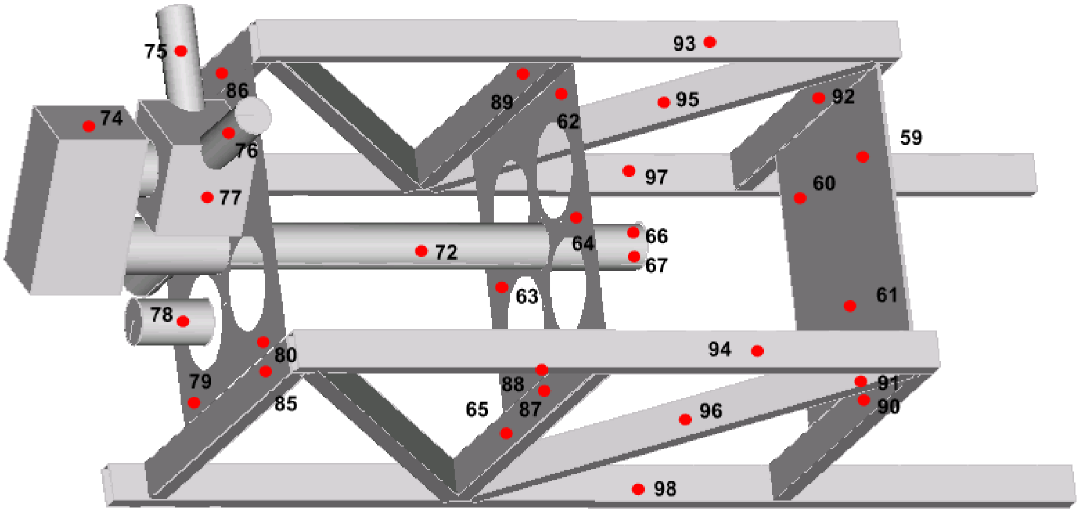

Figure A-4. MLA Test Stand Thermocouple Locations.

12 APPENDIX B: TRANSIENT TEST AND MODEL PLOT COMPARISONS

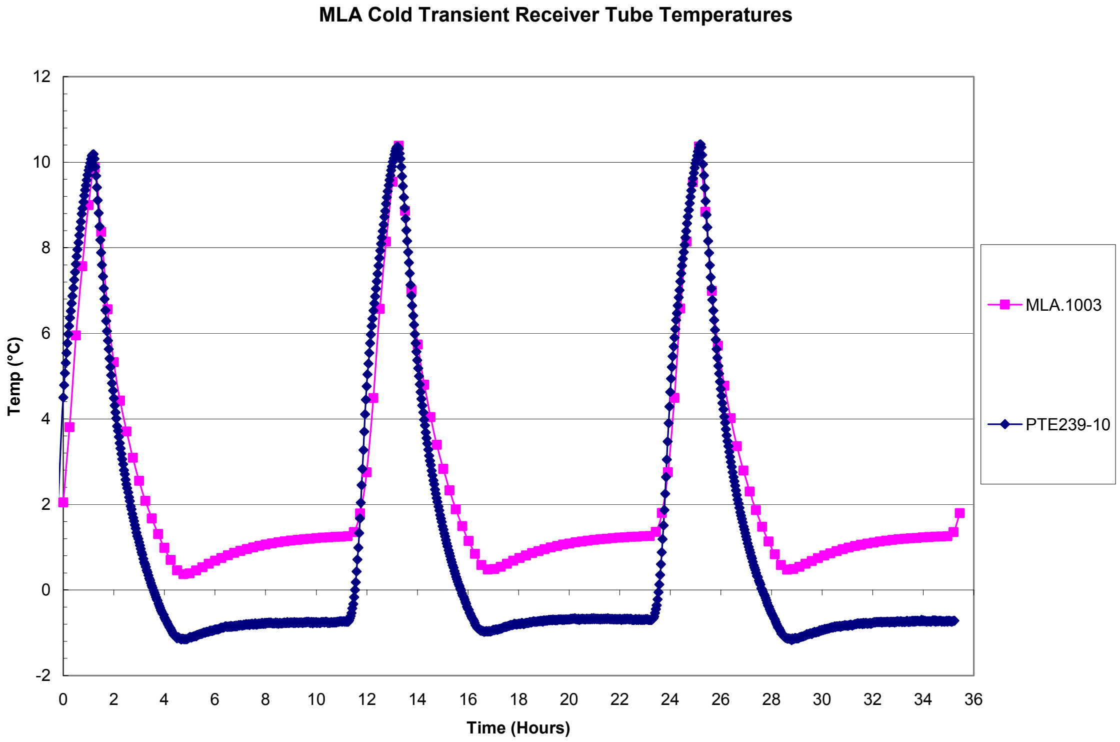

Figure B-1. MLA Cold Transient Receiver Tube Prediction and Test Results.

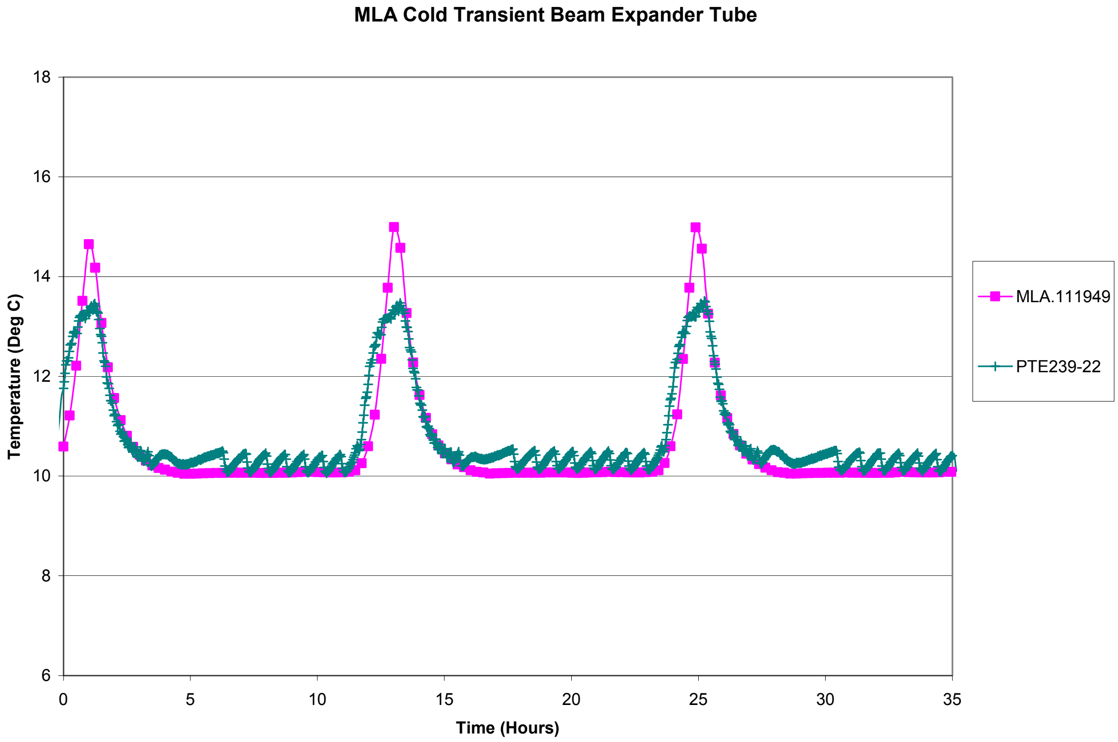

Figure B-2. MLA Cold Transient Beam Expander Tube Prediction and Test Results.

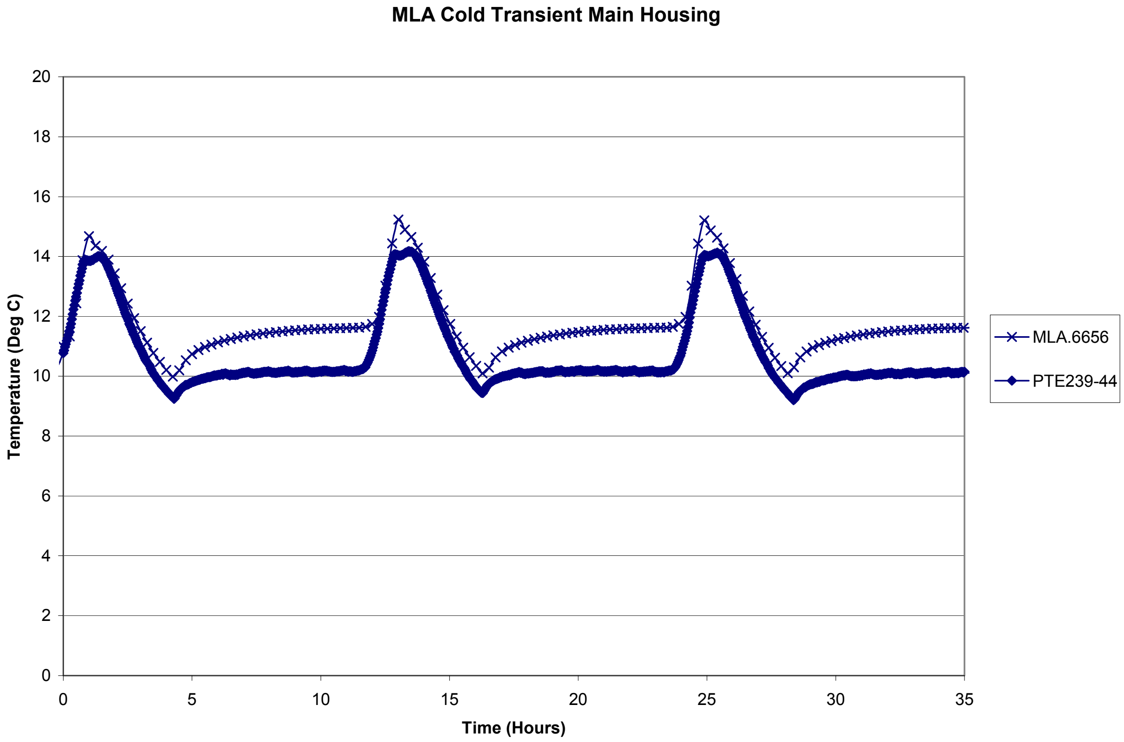

Figure B-3. MLA Cold Transient Main Housing Prediction and Test Results.

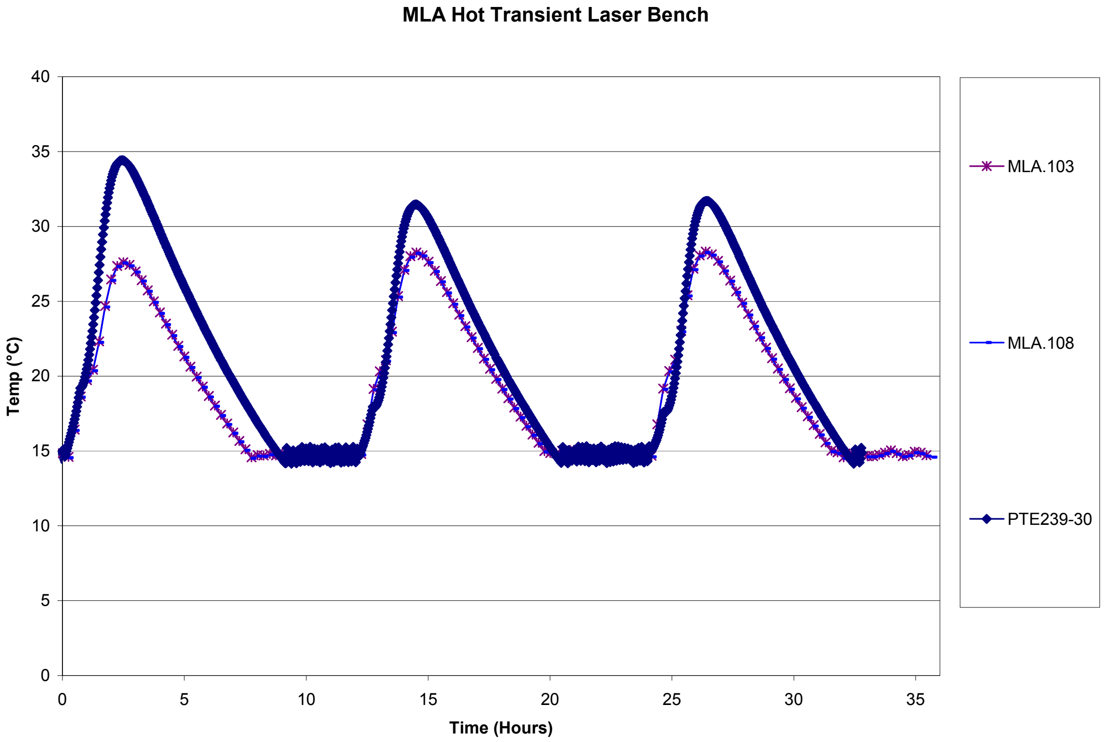

Figure B-4. MLA Hot Transient Laser Bench Prediction and Test Results.

13 APPENDIX C: MLA THERMAL BALANCE TEST PHOTOS

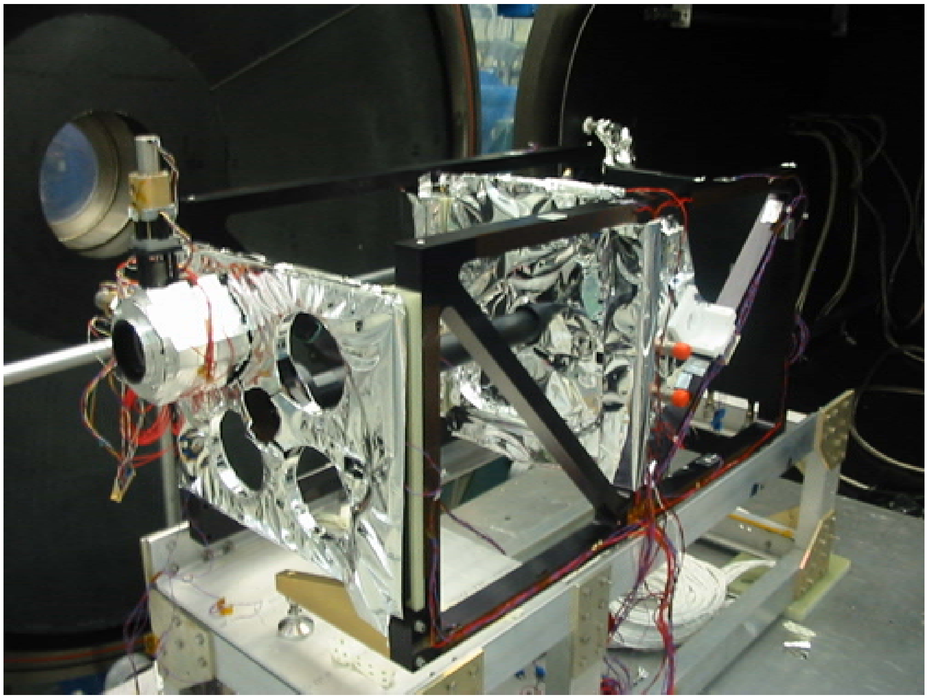

Figure C-1. MLA Test Stand.

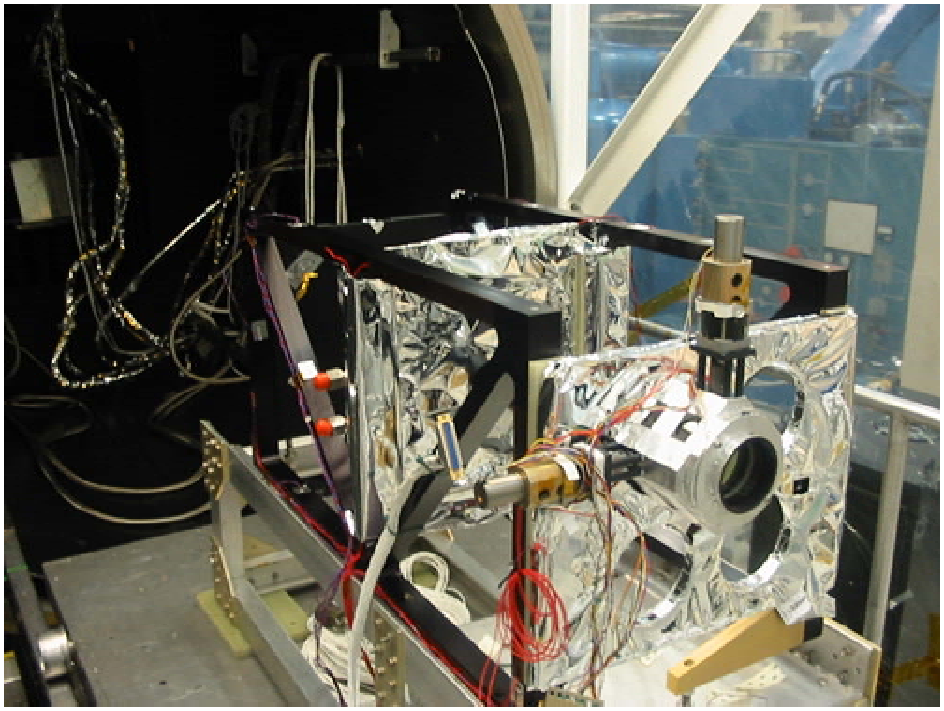

Figure C-2. MLA Test Stand Assembly.

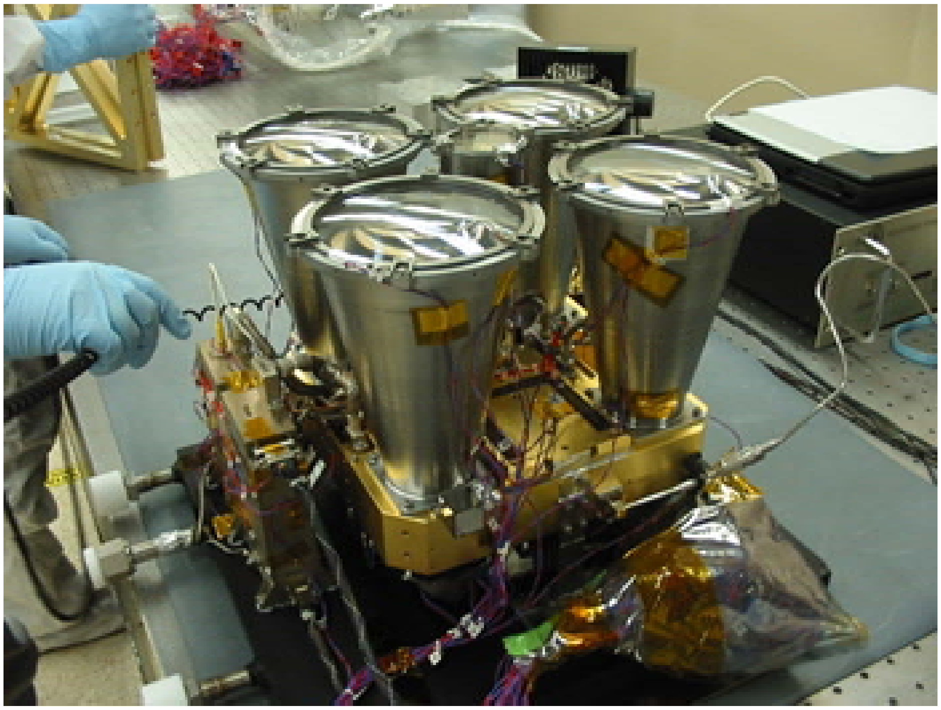

Figure C-3. MLA Instrument.

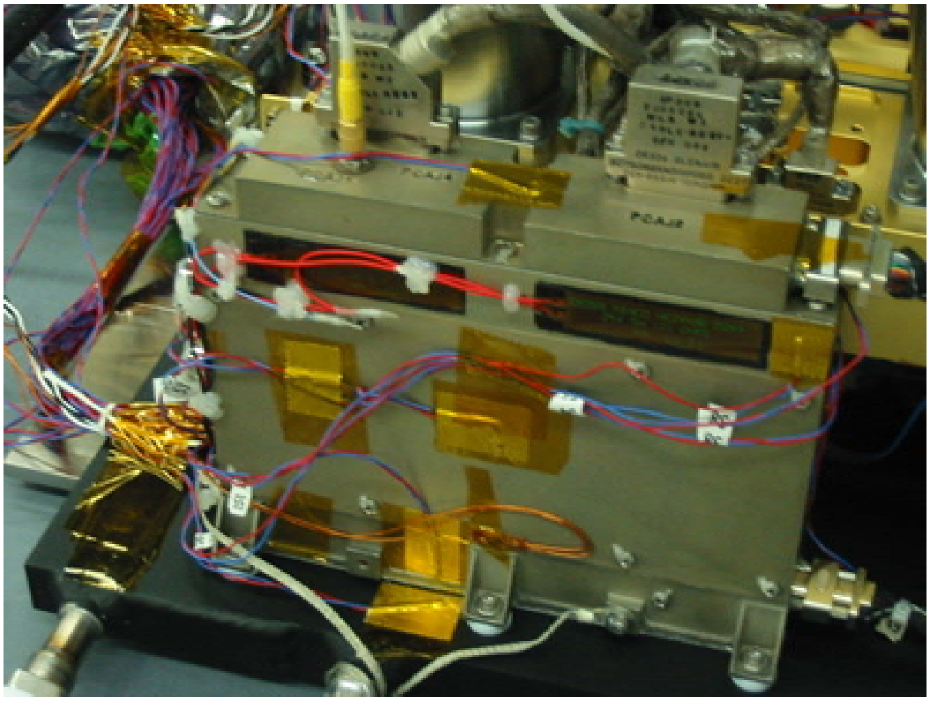

Figure C-4. MLA PCA.

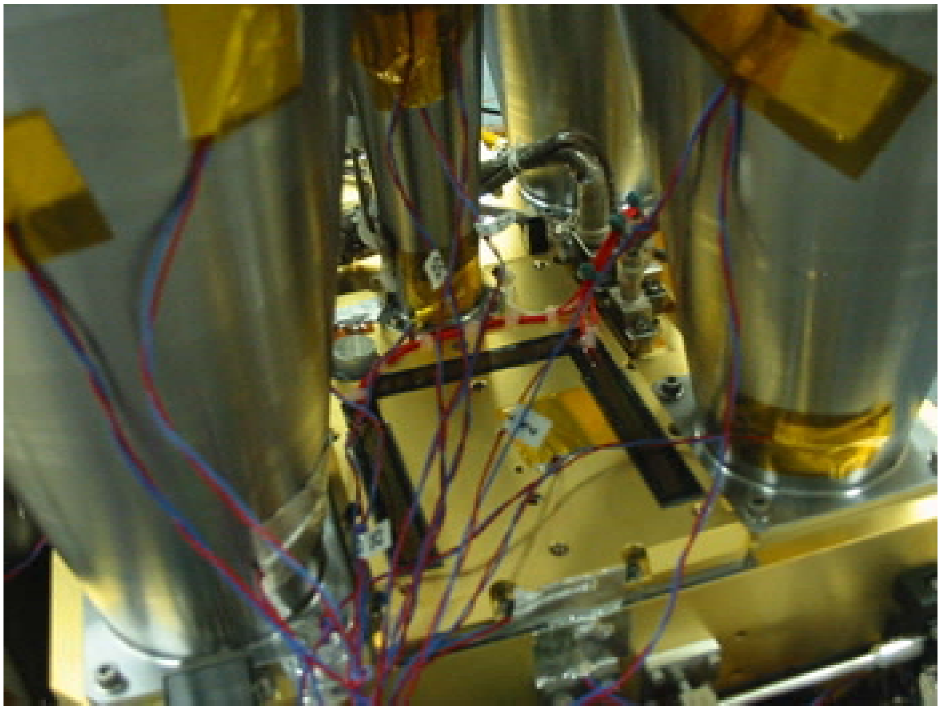

Figure C-5. MLA Laser Bench.