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In-Orbit thermal control system performance results from LISA Pathfinder LEOP and Thermal Commissioning

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The LISA Pathfinder spacecraft is a technology demonstration mission for detecting gravity waves launched in 2015. It is funded by the European Space Agency (ESA) with Airbus Defence and Space as prime contractor. The spacecraft has a challenging thermal design including a tight temperature stability requirement for the sensitive laser interferometer instrument and micro-propulsion payloads during science operations on-station at Earth-Sun Lagrange Point 1 (L1). This has led to extra constraints on the thermal design and operation of the thermal control system where multiple trim heaters have to be operated constantly in various combinations instead of cycling heaters. Also some payloads need to be controlled within a narrow temperature window of 6 °C. This paper reviews the in-orbit thermal control system operation compared to the thermal analysis predictions throughout the varying thermal environments of Launch and Early Phase (LEOP) operations, to transfer to L1 and arrival on-station. This includes comparing the duty cycling of the heaters during the non-science phases and a review of the spacecraft in-orbit temperature trends.

Nomenclature

ADC = Analogue to Digital Converter
AOS = Acquisition of Signal
AST = Star Tracker
ARM = Apogee Raising Manoeuvre
CGS = Cold Gas System
CPS = Chemical Propulsion System
DFACS = Drag-Free Attitude Control System
DRS = Disturbance Reduction System
DSS = Digital Sun Sensor
FDIR = Failure Detection, isolation and Recovery
FDV = Fill and Drain Valve
FEE = Front-End Electronics
HC = Heater Circuit
ITO = Indium Tin Oxide
L1 = Lagrange Point 1
LAB = Laser Control Unit
LCA = LTP Core Assembly
LCM = Launch Composite Module
LCU = Laser Control Unit
LEOP = Launch and Early Phase Operations
LISA = Laser Interferometer Space Array
LMU = LTP Laser Modulation Unit
LPF = LISA Pathfinder
LTP = LISA Technology Package
MEF = Main Engine Firing
MLI = Multi-Layer Insulation

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MPE = Micro-Propulsion Electronics
OBSW = On-Board Software
OSR = Optical Solar Reflector
PCDU = Power Conditioning and Distribution Unit
PID = Proportional-integral-derivative
PMU = LTP Phase Measurement Unit
PRM = Propulsion Module
PSD = Power Spectral Density
RCT = Reaction Control Thruster
RLU = LTP Reference Laser Unit
SAU = Sensor and Actuation Unit
SCM = Science Module
SLI = Single Layer Insulation
STM = Structural/Thermal Model
TCS = Thermal Control System
TCM = Trajectory Correction Manoeuvre
TRP = Temperature Reference Point
UFP = Uncertainty Flight Prediction
ULU = LTP Ultraviolet Lamp Unit
VDA = Vacuum Deposited Aluminium

I. Introduction

LISA Pathfinder (LPF), funded by the European Space Agency with Airbus Defence and Space as main contractor, was successfully launched on 3rd December 2015 from Kourou, French Guiana, on the VEGA launcher. The purpose of the LISA Pathfinder (LPF) mission is to provide in-orbit validation of the critical technology necessary for the e-LISA mission and thereby provide confidence for its success. The critical packages that have been identified for demonstration are the ESA-provided LISA Technology Package (LTP), which is the main inertial sensor; the Drag-Free Attitude Control System (DFACS); and the micro-propulsion technologies including the NASA-provided Disturbance Reduction System (DRS) Colloid thrusters. The LTP payload consists of Test Masses enclosed in Inertial Sensors with Optical Benches for Laser interferometry, and Electronics assemblies.

The LPF spacecraft is divided into two distinct sections (see Figure 1): the science module (SCM, including the LTP and DRS payloads) and the propulsion module (PRM). The LPF mission occurs in a periodic halo orbit about the L1 Earth-Sun Lagrange point requiring station keeping. The SCM was placed into this orbit by the PRM and the two modules separated on halo orbit insertion.

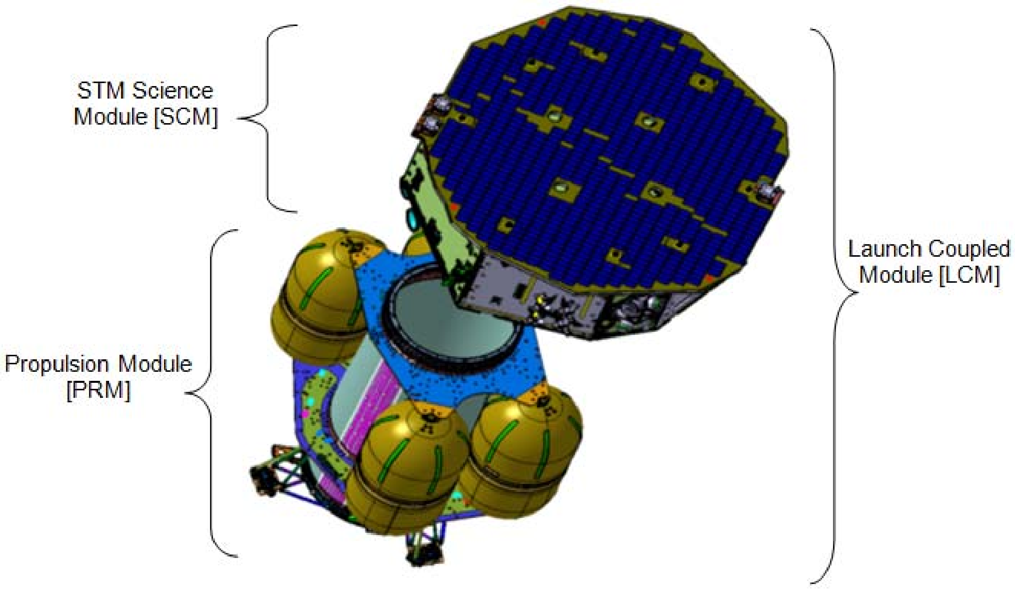


Figure 1. Diagram of LISA Pathfinder (MLI not shown).

The spacecraft has a challenging thermal design including a tight temperature stability requirement for the sensitive laser interferometer instrument and micro-propulsion payloads during science operations on-station at Earth-Sun Lagrange Point 1 (L1). This is in comparison to other missions with cryogenic instruments requiring high thermal stability using high resolution thermometry[1] or PID law software controlled heating lines[2]. The

LPF temperature stability requirement has led to extra constraints on the thermal design and operation of the thermal control system where multiple trim heaters have to be operated constantly in various combinations instead of cycling heaters. The LTP Core Assembly (LCA) interfaces have to be kept stable below 10^{-3} K/√Hz over the frequency window of 10^{-3} Hz to 10^{-1} Hz. Also some payloads need to be controlled within a temperature window of 6 °C without using any switching heaters on the whole science module. This has led to extended analysis and thermal test campaigns to design and verify the thermal stability performance[3].

A. Details of LPF Thermal Design

The LPF thermal control subsystem (TCS) is responsible for maintaining the equipments of the LPF spacecraft within their specified temperature limits and for meeting the thermal stability requirements during launch and all in-orbit mission phases. To achieve this, the thermal control subsystem employs passive thermal control techniques such as black painted interior to maximise internal radiative heat transfer, white painted radiator areas of external surfaces of panels to reject heat dissipated by units, and multi-layer insulation (MLI) to minimise heat losses from other external surfaces, as well as the use of two sets of 32 heaters (a set each for prime and redundant).

Active heaters are not permitted during the payload science operations as the transient variations in temperature that happen as a heater switches can interfere with the payload measurements. Heat pipes have been avoided as it is not possible to include some gravity compensation for the transfer of mass through the pipes while on station as this will not be known before flight, again causing payload interference.

The majority of the SCM internal units are mounted on internal panels and not directly to radiator panels as seen in Figure 2. To improve the heat rejection from the units to the external environment, the majority of internal units and structure all have high infrared emissivity surface finishes to maximise radiative heat transfer within the platform.

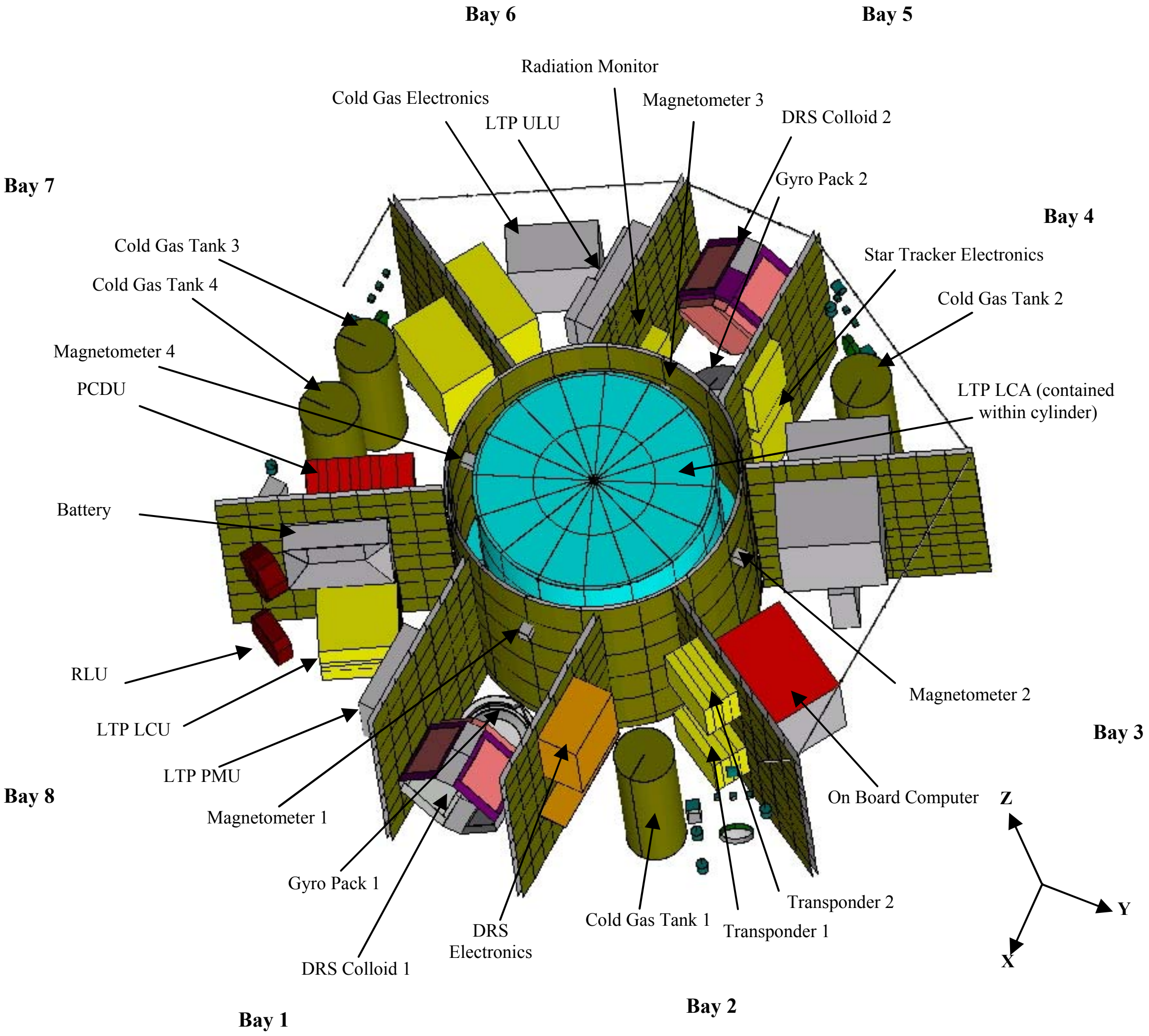


Figure 2. Internal view of LISA Pathfinder Science Module
Shown with all external panels removed

The external SCM radiator surfaces are white painted to enable efficient rejection of the heat generated by the units. White paint has been selected due to the high infrared emissivity of this surface finish. The higher solar absorptivity of this finish (compared with OSR mirror tiles or silverised Teflon tape) has a minimal impact on the TCS design, as the on-station orbit at Lagrange point 1 has no significant Earth flux and the spacecraft is pointing such that the closure panels are not exposed to the solar environment. During LEOP the radiators are exposed to solar flux, however extra heat absorbed does not impact the thermal design as the total dissipation of the SCM is reduced due to the payloads not operating. Where not required as radiators, the external surfaces of the SCM are covered by MLI blankets to minimise heat loss. All the external thermal finishes are adequately protected against atomic oxygen for the LEOP phase of the mission. ITO Kapton MLI on the SCM and VDA MLI on the PRM is used to prevent a charge build-up on the spacecraft during the mission.

The required isolation of the LTP Core Assembly in the SCM is achieved with low conductance strut mounts and a low emissivity finish of the thermal shield. The design of the structure that supports the LCA is a “cage” (cylinder) around the unit. A single VDA Kapton foil covers the external surfaces of the cage to reduce the thermal noise from external sources on the payload interface. At the top of the cylinder, the SCM top closure panel MLI provides isolation from the external heat flux.

The SCM Micro Propulsion Thrusters are mounted on individual brackets, on the external side of the external closure panels, each equipped with heaters for control of the thrusters’ conductive interfaces. The Micro Thruster assemblies are covered with an MLI tent and VDA Kapton SLI underneath on the panel, and the thrusters’ brackets are decoupled from the panel with low conductivity washers, in order to isolate the thruster assemblies to enable a consolidated heater operation whilst on-station. The space-exposed parts of the thrusters’ nozzles are coated with low emissivity VDA Kapton tape. Also resistor type heaters have been mounted to the thrusters’ pipework to allow for heating of the pipe and Nitrogen gas at the entry to the thrusters.

The SCM Micro Propulsion equipments are generally insulated on external panels which are covered by MLI. The exception are the equipments on the PXPY panel due to space limitations where these equipments are attached to the other side of the external panel radiator needed for the high dissipation Transponders and DRS IAU. So where necessary, these equipments have been decoupled from the external panel via low conductivity washers and the application of black tape to increase the radiative exchange with the centre of the spacecraft.

As there are very few dissipating components on the PRM (2.5 W total during non-firing), the PRM has been designed to absolutely minimise its heat loss with no exposed radiators. The outer MLI surfaces reject heat directly to space, and performance is selected to minimise the heat loss and hence TCS heater power consumption. The minimum necessary heater power is applied in the cold cases so that the lower temperatures of the CPS components are maintained towards the bottom of their allowable range allowing for control uncertainty.

The PRM CPS components are primarily mounted on the lower floor of the PRM, utilising both the upper and lower surfaces of the floor. The floor is then heated to maintain the required temperatures of the CPS equipment and an enclosure is created to retain heat from the lower surface of the floor. All PRM heaters are controlled through hardware thermostats.

The PRM main engine heat shield has been optimised to maximise the heat rejection during MEF to maintain the engine temperature within limits. Internal surfaces are highly reflective to additionally increase radiative couplings and heat loss from the engine valves during MEF.

B. Details of phases of the mission

The LPF mission has been broken down into three phases: LEOP, transfer and on-station. During the LEOP and transfer phases, the PRM is attached to the SCM and provides the propulsive elements to place the SCM in the operational orbit. Once on-station, the PRM is detached and the SCM continues with the operational phases of the mission.

The LEOP phase of the mission includes all activities from Launch until the first trajectory correction manoeuvre (TCM) is performed after the spacecraft has been injected on to its transfer to L1 following the final main engine burn of the PRM.

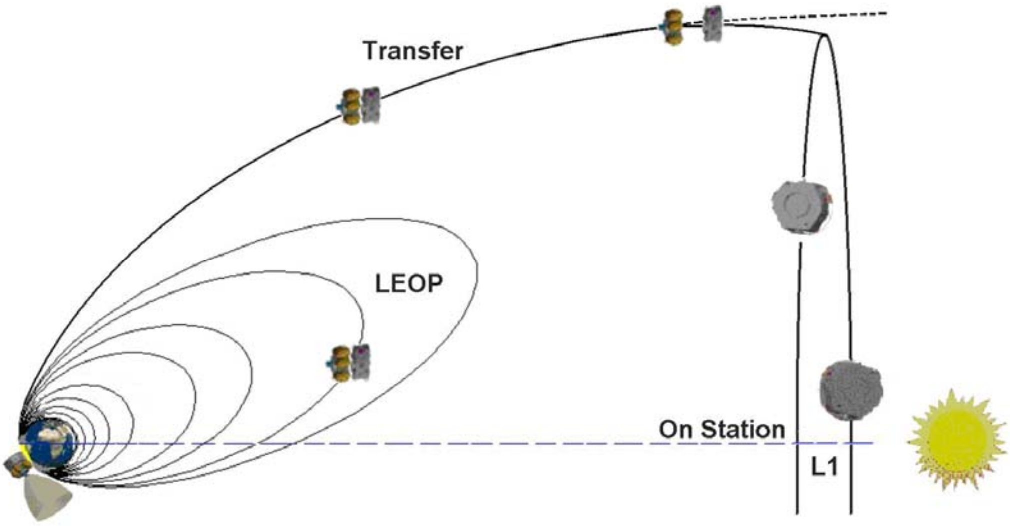


Figure 3. Diagram of the LISA Pathfinder Mission

Approximately 30 days after injection into the transfer, the composite is close to L1 and executes a further dispersion correction manoeuvre sequence prior to separation of the Science Spacecraft from the Propulsion Module. The LCM is spun up via the PRM thrusters, and the SCM/PRM umbilical connectors are heated to above 0 °C to ensure that there is no interference from any ice present within the connectors. After separation from the PRM the SCM is de-spun over an extended duration using the CGS thrusters with the DRS colloids as backup.

The LTP demonstration phase comprises the power-up of the payload subsystem followed by a series of science runs applying specific driving signals or measurement sequences. Including initialisation, charge control, transitions, and measurements, each run is expected to last for a significant time and requires a stable thermal environment.

II. LEOP Thermal Performance

C. LEOP Timeline

The following main thermal events occurred during LPF LEOP:

Day	dd/mm/yy	Time (Z)	Phase	Activity
336	02/12/2015	19:04:00	Pre-Launch	Spacecraft is powered on
336	02/12/2015	19:37:00	Pre-Launch	Check heater and thermistor settings
336	02/12/2015	23:04:00	Pre-Launch	Check propellant tank, main engine, DSS temperatures
337	03/12/2015	00:50:00	Pre-Launch	Check heater and thermistor settings same as PRM Low Power
337	03/12/2015	03:49:00	Pre-Launch	Spacecraft switch to internal power
337	03/12/2015	03:54:00	Pre-Launch	Thermal GO/NO GO on temps
337	03/12/2015	03:56:00	Pre-Launch	Thermal check on manual heaters
337	03/12/2015	04:03:30	Pre-Launch	Launcher Auto Sequence
337	03/12/2015	04:03:52	Pre-Launch	Abort disabled
337	**03/12/2015**	**04:04:00**	**LAUNCH**	**LAUNCH**
337	03/12/2015	04:08:03	Post Launch	Fairing Separation
337	03/12/2015	05:49:33	Post Launch	Spacecraft Separation
337	03/12/2015	06:11:00	Post Launch	TCS Initialisation
337	03/12/2015	07:08:00	Post Launch	Authorise AST switch on with TRP at 6.3 °C & thermistor update
338	04/12/2015	04:16:00	LEOP	Authorise transition to PRM High Power Mode (nominal)

Day	dd/mm/yy	Time (Z)	Phase	Activity
338	04/12/2015	07:43:00	LEOP	Concern on battery with PRM High Power Mode, move to PRM Low Power
338	04/12/2015	23:51:00	LEOP	Slew for practice manoeuvre
339	05/12/2015	06:10:00	LEOP	Mission Review Board on PRM Heating during MEFs
340	06/12/2015	03:30:00	Engine Burn	Test Burn
341	07/12/2015	05:01:00	Engine Burn	ARM #1
341	07/12/2015	17:20:00	Engine Burn	ARM #2
342	08/12/2015	07:30:00	Engine Burn	ARM #3
342	08/12/2015	21:01:00	Engine Burn	ARM #4
344	10/12/2015	00:33:00	Engine Burn	ARM #5
346	12/12/2015	05:18:00	Engine Burn	ARM #6 (Escape Burn)
347	13/12/2015	02:00:00	Engine Burn	TCM #1
347	**13/12/2015**	**04:00:00**	**LEOP**	**LEOP successfully completed**

Table 1. LEOP Thermal Specific Timeline

As seen in Table 1, the LEOP involved a large number of Main Engine Firings over a relatively short time. This resulted with 30 major LPF heater updates and 6 major LPF thermistor setting updates applied during the LEOP. These were to meet operational requirements and ensure the spacecraft remained within its temperature limits.

D. Launch / Fixed Heaters

LISA Pathfinder successfully launched from Kourou on a VEGA launcher. In the ten minute window before launch, the planned number of spacecraft heaters were manually switched on.

- PRM thruster heater circuits 28 and 60 (prime and redundant) to be manually switched on and will cycle using the thermostats.
- SCM prime heaters 3, 4, 6, 7, 9, 13, 29 to be manually switched on to ensure the nearby equipments are maintained within their temperature limits.

When the PRM thruster heaters were switched on the main engine flange was seen to quickly rise in temperature as expected (to 56.6 °C by the time of lift-off). All pre-launch thermal checks were completed successfully. Analysis of the PRM thruster heater circuit power demand showed the expected values of 41.9 W and 41.6 W for prime and redundant, showing that the FDV and Upper Pipe heater circuits were not active as their local thermostats were at ambient temperature and so above the switch on set point of 18 °C.

First AOS after launch showed that unheated parts of the spacecraft were slowly cooling. TCS Initialisation occurred as planned with only a low heater power demand initially as set-points had not been triggered for a large number of heater circuits with the starting temperature conditions before launch. The battery was seen to rise in temperature as expected but stayed within its 35 °C temperature limits.

E. PRM / Firing

There were a number of heater setting updates for the PRM over the LEOP period due to the operational requirements and Apogee Raising Manoeuvres. The PRM RCTs and Main Engine heater circuits (HC28 and HC60) were operated from before launch in hot redundant with prime and redundant heater constant on. The propulsion equipments cycled on their local thermostats as intended. Software control was used for the PRM Tank and Lower Floor heater circuits (HC27 and HC59) due to power constraints during eclipses and main engine firings and requirements from propulsion. Only one of these heater circuits were active at any one time. The thermostats were still active so there were occasions when the heater circuit was enabled but the heater was not active due to the thermostat. Note there was no change in heater control before, during or after MEF. All heater updates were controlled around the slews.

In general for the PRM there were 4 different “modes” of heater operation for the PRM Tank heaters:

“OFF”: used to ensure minimum power demand during MEF with no possibility of tank heater switch-on without FDIR trigger.

“Low Power Mode”: where the PRM Tank heater circuit was controlled off the lower floor thermistors. This mode was used after launch, during initial eclipses and after initial MEFs in order to conserve power. This mode allowed for increased safety for the PRM heater operation.

“Medium Power Mode”: where the PRM Tank heater circuit was controlled off the Helium pressurant tank thermistors. In practice this allowed for software cycling of the PRM Tank heater circuit coupled with the thermostat cycling. This mode was used during LEOP as cycling off the Lower Floor (Low Power Mode) was not producing the desired cycling due to the nearby thermal capacitance on the propellant tanks. This mode was used after ARM#2 in order to conserve power but still allow for heater cycling on the PRM Tanks. This allowed the Helium tank and Lower Floor heater mats to cycle on both software and thermostats whilst the Propellant tank heaters generally cycled only off the software control as the thermostat set points were not reached.

“High Power Mode”: where the PRM Tank heater circuit was set to ON CONSTANT and therefore completely controlled off the thermostats for each set of thermostats. This was the highest dissipation PRM tank heater power mode. This mode was used when there were no constraints on propellant pressures or power demand.

			During Burns			
PHASE	**In sun**	**In eclipse**	**Before first slew**	**After final slew**	**During subsequent orbits**	**Comment**
Launch	HC27 / CONST / OFF (PRM (tanks) OFF for Launch)	No change	N/A	N/A	N/A	No tank heaters are operated during launch due to power constraint
TCS Init and Early LEOP	HC27 / AUTO / ON (PRM Low Power controlled off the lower floor)	No change	N/A	N/A	N/A	PRM is in "Low Power" but effectively HC27 OFF
First LEOP Orbits with PRM High Power Mode	HC27 / CONST / ON (PRM High Power)	No change	N/A	N/A	N/A	All tank heaters turn ON. Prop tanks do not cycle and remain ON constantly.
Middle LEOP Orbits with PRM Low Power Mode in eclipse	HC27 / CONST / ON (PRM High Power) by time tag	HC27 / AUTO / ON (PRM Low Power) by time tag	N/A	N/A	N/A	Due to power constraints in eclipse, effectively turned HC27 OFF during eclipse
Test Burn	N/A	N/A	HC27 / CONST / OFF (PRM OFF for MEF) by time tag	HC27 / CONST / ON (PRM High Power) by time tag	N/A	Configuration for Test Burn
ARM#1 (1704s)	N/A	N/A	HC27 / CONST / OFF (PRM OFF for MEF) by time tag	HC27 / AUTO / ON (PRM Low Power) by time tag	Change to following within <u>second</u> orbit after burn: HC27 / CONST / ON (PRM High Power) in sun direct command	Configuration for ARM#1
ARM#2 (2007s)	N/A	N/A	HC27 / CONST / OFF (PRM OFF for MEF) by time tag	HC27 / AUTO / ON (PRM Low Power) by time tag	Change to following with <u>first</u> orbit after burn: HC27 / CONST / ON (PRM High Power) in sun direct command	Configuration for ARM#2
After ARM#2 with PRM High Power Mode	HC27 / CONST / ON (PRM High Power)	HC27 / AUTO / ON (PRM Low Power) by time tag	N/A	N/A	N/A	Due to power constraints in eclipse, effectively turned HC27 OFF during eclipse
Just before ARM#3 from 342 05:30	HC27 / AUTO /ON controlled by He tank sensor (PRM Medium Power)	N/A	N/A	N/A	N/A	Due to CPS concerns on difference in pressure, this effectively turned HC27 OFF just before ARM#3 in order to: 1) avoid further increase of the NTO tank temp (as for CPS request) 2) keep the He tank above 10degC
ARM#3 (1863s)	N/A	N/A	HC27 / CONST / OFF (PRM OFF for MEF) by time tag	HC27 / AUTO / ON (PRM Low Power) by time tag	We keep the settings in order to avoid further warming up of the NTO tank.	-
4hr after ARM#3 end	HC27 / AUTO /ON controlled by He tank sensor (PRM Medium Power)	No change	N/A	N/A	N/A	Effectively turns on HC27 to warm He tank before next ARM
ARM#4 (2012s)	N/A	N/A	HC27 / CONST / OFF (PRM OFF for MEF) by time tag	HC27 / AUTO / ON (PRM Low Power) by time tag	We keep the settings in order to avoid further warming up of the NTO tank.	-
After ARM#4 when the the bottom of the prop tanks have started cooling (~6 hrs)	HC27 / AUTO /ON controlled by He tank sensor (PRM Medium Power)	No change as eclipse period relatively shorter at this stage of LEOP	N/A	N/A	N/A	Effectively turns on HC27 to warm He tank before next ARM
ARM#5 (895s)	N/A	N/A	HC27 / CONST / OFF (PRM OFF for MEF) by time tag	HC27 / AUTO / ON (PRM Low Power) by time tag	HC27 / AUTO /ON controlled by He tank sensor (PRM Medium Power)	-
ARM#6 (536 s) - Escape Burn	N/A	N/A	HC59 / CONST / OFF (PRM OFF for MEF) by time tag	HC59 / AUTO / ON (PRM Low Power) by time tag	Immediately: HC59 / CONST / ON (PRM High Power)	Set to PRM High Power for Transfer

Table 2. PRM LEOP Thermal Settings Index

The observed Helium tank temperature drop as a result of each Main Engine Firing was always within the requirement with margin of between 15 and 25%. The coldest the Helium tank became after a firing was for ARM#4. The Helium tank dropped to -6.4 °C which still had sufficient clearance from the -10 °C temperature limit.

F. Thermal Comparison

At the end of the LPF LEOP, the thermal control system was performing as expected. All units were within temperature limits and the majority were close to their predicted temperatures and heater powers. The PRM thermostats were cycling as expected given the adjustments due to using the software control which allowed for greater flexibility for the PRM thermal control and successful completion of the eight Main Engine Firing burns and test burns.

III. Thermal Commissioning & Transfer Thermal Performance

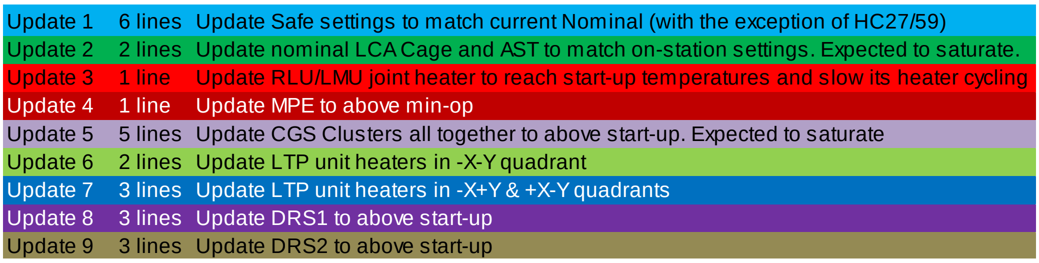
G. Overview

There were a large number of major LPF heater updates and major LPF thermistor setting updates applied during the transfer and thermal commissioning. This covered testing each individual heater circuit in the thermal commissioning, setting up the correct thermal environment for the payload commissioning and separation whilst meeting operational requirements and ensuring the spacecraft remained within its temperature limits.

H. Warm-up

The first stage of the Thermal Commissioning at the start of the Transfer phase was to warm up the spacecraft to enable Payload Commissioning. This was covered by nine heater updates over the course of 14th December 2015. Warm up was successful with no issues seen.

LEGEND:



Update 1	6 lines	Update Safe settings to match current Nominal (with the exception of HC27/59)
Update 2	2 lines	Update nominal LCA Cage and AST to match on-station settings. Expected to saturate.
Update 3	1 line	Update RLU/LMU joint heater to reach start-up temperatures and slow its heater cycling
Update 4	1 line	Update MPE to above min-op
Update 5	5 lines	Update CGS Clusters all together to above start-up. Expected to saturate
Update 6	2 lines	Update LTP unit heaters in -X-Y quadrant
Update 7	3 lines	Update LTP unit heaters in -X+Y & +X-Y quadrants
Update 8	3 lines	Update DRS1 to above start-up
Update 9	3 lines	Update DRS2 to above start-up

IN DATAPOOL ONLY

		SCV_CONFIG_NOM							SCV_CONFIG_SAFE						
		Operating State	Control State	Temperature sensors			Temperature limits		Operating State	Control State	Temperature sensors			Temperature limits	
		- ON - OFF	- CONSTANT - AUTO	Id 1	Id 2	Id 3	min (on)	max (off)	- ON - OFF	- CONSTANT - AUTO	Id 1	Id 2	Id 3	min (on)	max (off)
Circuit	Purpose	SC_NomHtrOpsSt	SC_NomHtrCtrlSt	SC_NomHtrTSId1	SC_NomHtrTSId2	SC_NomHtrTSId3	SC_NomHtrMinTemp	SC_NomHtrMaxTemp	SC_SafeHtrOpsSt	SC_SafeHtrCtrlSt	SC_SafeHtrTSId1	SC_SafeHtrTSId2	SC_SafeHtrTSId3	SC_SafeHtrMinTemp	SC_SafeHtrMaxTemp SC_Health_Heate
Heater 1	LCA Trimming	ON	AUTO	2	4	5	24	26	OFF	AUTO	2	4	5	8	11
Heater 2	AST	ON	AUTO	20	21	22	-3	-1	OFF	AUTO	20	21	22	-34	-30
Heater 3	Colloid 1 Nozzles	ON	AUTO	35	35	35	15	20	OFF	AUTO	35	35	35	6	9
Heater 4	Colloid 1 Op	ON	AUTO	26	27	28	14	16	OFF	AUTO	26	27	28	7	12
Heater 5	Colloid 1 Non-Op	ON	AUTO	26	27	28	18	20	OFF	AUTO	26	27	28	7	12
Heater 6	Colloid 2 Nozzles	ON	AUTO	37	37	37	15	20	OFF	AUTO	38	38	38	6	9
Heater 7	Colloid 2 Op	ON	AUTO	29	30	31	14	16	OFF	AUTO	29	30	31	7	12
Heater 8	Colloid 2 Non-Op	ON	AUTO	29	30	31	18	20	OFF	AUTO	29	30	31	13	16
Heater 9	RLU Non-Op On Station	OFF	AUTO	12	15	16	0	5	OFF	AUTO	12	15	16	0	5
Heater 10	LMU Non-Op On Station	ON	AUTO	11	13	14	-4	-1	OFF	AUTO	11	13	14	-4	-1
Heater 11	RLU Trimming 1	OFF	AUTO	12	15	16	0	5	OFF	AUTO	12	15	16	0	5
Heater 12	RLU Trimming 2	OFF	AUTO	12	15	16	0	5	OFF	AUTO	12	15	16	0	5
Heater 13	LMU Trimming 1	OFF	AUTO	11	13	14	0	5	OFF	AUTO	11	13	14	0	5
Heater 14	LMU Trimming 2	OFF	AUTO	11	13	14	0	5	OFF	AUTO	11	13	14	0	5
Heater 15	RLU/LMU Non-Op	ON	AUTO	12	15	16	16	20	OFF	AUTO	12	15	16	-4	-1
Heater 16	LTP Equipment Non-Op 1	ON	AUTO	61	62	64	0	5	OFF	AUTO	61	62	64	-10	-7
Heater 17	CG Cluster 1 Cluster Non-Op	ON	AUTO	32	32	32	25	30	OFF	AUTO	49	32	34	-20	-15
Heater 18	LTP SAU 2 Non-Op	ON	AUTO	7	7	7	6	10	OFF	AUTO	7	7	7	-14	-11
Heater 19	LTP SAU 1 Non-Op	ON	AUTO	8	8	8	6	10	OFF	AUTO	8	8	8	-14	-11
Heater 20	CG Cluster 2 Cluster Non-Op	ON	AUTO	47	53	54	25	30	OFF	AUTO	50	53	54	-20	-15
Heater 21	Battery	ON	AUTO	23	24	25	6	10	OFF	AUTO	23	24	25	6	10
Heater 22	CG Cluster 3 Cluster Non-Op	ON	AUTO	51	55	56	25	30	OFF	AUTO	51	55	48	-20	-15
Heater 23	MPE	ON	AUTO	87	87	87	5	10	OFF	AUTO	86	86	86	-24	-21
Heater 24	SCM Sep, Umbilical Heating	OFF	AUTO	82	83	84	-10	-5	OFF	AUTO	82	83	84	-10	-5
Heater 25	LCA Trimming	ON	AUTO	2	4	5	25	27	OFF	AUTO	2	4	5	9	14
Heater 26	LTP Equipment Non-Op 2	ON	AUTO	65	65	65	0	4	OFF	AUTO	9	10	65	-10	-7
Heater 27	PRM Tanks	OFF	CONSTANT	144	144	144	-175	175	OFF	AUTO	119	120	121	10	13
Heater 28	PRM Equipment	ON	CONSTANT	144	144	144	-175	175	ON	CONSTANT	144	144	144	-175	175
Heater 29	PXPY Trim Panel Heater	ON	AUTO	45	45	45	0	5	OFF	AUTO	45	45	45	-20	-15
Heater 30	ULU	ON	AUTO	71	71	71	15	20	OFF	AUTO	71	71	71	-14	-11
Heater 31	Thruster Pipe Work	ON	AUTO	41	44	46	25	30	OFF	AUTO	41	44	46	25	30
Heater 32	SPARE	OFF	CONSTANT	144	144	144	-175	175	OFF	CONSTANT	144	144	144	-175	175
Heater 33	LCA Trimming	OFF	AUTO	2	4	5	8	11	ON	AUTO	2	4	5	14.5	16
Heater 34	AST	OFF	AUTO	17	18	19	-29	-25	ON	AUTO	17	18	19	-29	-27
Heater 35	Colloid 1 Nozzles	OFF	AUTO	36	36	36	6	9	ON	AUTO	35	35	35	6	9
Heater 36	Colloid 1 Op	OFF	AUTO	26	27	28	7	12	OFF	AUTO	26	27	28	7	12
Heater 37	Colloid 1 Non-Op	OFF	AUTO	26	27	28	7	12	ON	AUTO	26	27	28	7	12
Heater 38	Colloid 2 Nozzles	OFF	AUTO	39	39	39	6	9	ON	AUTO	37	37	37	6	9
Heater 39	Colloid 2 Op	OFF	AUTO	29	30	31	7	12	ON	AUTO	29	30	31	9	12
Heater 40	Colloid 2 Non-Op	OFF	AUTO	29	30	31	13	16	ON	AUTO	29	30	31	13	16
Heater 41	RLU Non-Op On Station	OFF	AUTO	12	15	16	0	5	OFF	AUTO	12	15	16	0	5
Heater 42	LMU Non-Op On Station	OFF	AUTO	11	13	14	-4	-1	ON	AUTO	11	13	14	-4	-1
Heater 43	RLU Trimming 1	OFF	AUTO	12	15	16	0	5	OFF	AUTO	12	15	16	0	5
Heater 44	RLU Trimming 2	OFF	AUTO	12	15	16	0	5	OFF	AUTO	12	15	16	0	5
Heater 45	LMU Trimming 1	OFF	AUTO	11	13	14	0	5	OFF	AUTO	11	13	14	0	5
Heater 46	LMU Trimming 2	OFF	AUTO	11	13	14	0	5	OFF	AUTO	11	13	14	0	5
Heater 47	RLU/LMU Non-Op	OFF	AUTO	12	15	16	-4	-1	ON	AUTO	12	15	16	-4	-1
Heater 48	LTP Equipment Non-Op 1	OFF	AUTO	61	62	64	-10	-7	ON	AUTO	61	62	64	-10	-7
Heater 49	CG Cluster 1 Cluster Non-Op	OFF	AUTO	49	32	34	-20	-15	ON	AUTO	32	32	32	-20	-17
Heater 50	LTP SAU 2 Non-Op	OFF	AUTO	7	7	7	-14	-11	ON	AUTO	7	7	7	0	3
Heater 51	LTP SAU 1 Non-Op	OFF	AUTO	8	8	8	-14	-11	ON	AUTO	8	8	8	0	3
Heater 52	CG Cluster 2 Cluster Non-Op	OFF	AUTO	50	53	54	-20	-15	ON	AUTO	47	53	54	-20	-15
Heater 53	Battery	OFF	AUTO	23	24	25	6	10	ON	AUTO	23	24	25	6	10
Heater 54	CG Cluster 3 Cluster Non-Op	OFF	AUTO	51	55	48	-20	-15	ON	AUTO	51	55	56	-20	-15
Heater 55	MPE	OFF	AUTO	87	87	87	-24	-21	ON	AUTO	87	87	87	-20	-17
Heater 56	SCM Sep, Umbilical Heating	OFF	AUTO	82	83	84	-10	-5	OFF	AUTO	82	83	84	-10	-5
Heater 57	LCA Trimming	OFF	AUTO	2	4	5	9	14	ON	AUTO	2	4	5	16	19
Heater 58	LTP Equipment Non-Op 2	OFF	AUTO	9	10	65	-10	-7	ON	AUTO	65	65	65	-10	-7
Heater 59	PRM Tanks	ON	CONSTANT	144	144	144	-175	175	ON	CONSTANT	144	144	144	-175	175
Heater 60	PRM Equipment	ON	CONSTANT	144	144	144	-175	175	ON	CONSTANT	144	144	144	-175	175
Heater 61	PXPY Trim Panel Heater	OFF	AUTO	143	143	143	-20	-15	ON	AUTO	45	45	45	-20	-15
Heater 62	ULU	OFF	AUTO	146	146	146	-14	-11	ON	AUTO	71	71	71	-14	-11
Heater 63	Thruster Pipe Work	OFF	AUTO	41	44	46	25	30	OFF	AUTO	41	44	46	25	30
Heater 64	SPARE	OFF	CONSTANT	144	144	144	-175	175	OFF	CONSTANT	144	144	144	-175	175

Table 3. Thermal Commissioning Warm-Up on 14th December 2015

I. Heater checks

At the request of the Operations Centre, every heater which had not been operated whilst in flight was activated one at a time on 15th December 2015. This was covered by datapool updates only as there was no functional need to use the safeguard memory upload method. All the heaters were operated for three minutes, a temperature response was seen and the heater power measured. All heaters were within 10% of expected power dissipations apart from HC45 where the error in the predictions increases due to the small size of the heater.

J. Maximum Solar Array Power Check

After the individual heater checks were completed on 15th December 2015, a short investigation into the maximum power generating capacity of the Solar Array was carried out. The methodology was to gradually turn on more heaters, increasing the overall bus load until the array capacity was reached which would be detected by the battery starting to discharge.

From the starting warm-up configuration the following heaters were switched on in order:

- Heater 24; SCM Sep, Umbilical Heating
- Heater 50; LTP SAU 2 Non-Op
- Heater 51; LTP SAU 1 Non-Op
- Heater 58; LTP Equipment Non-Op 2
- Heater 48; LTP Equipment Non-Op 1

The battery was seen to discharge on the enabling of Heater 48 and so the maximum Solar Array capacity was between 738 W (the load with no battery discharge) and 755 W. Therefore the maximum Solar Array capacity limit was taken as 738 W which would allow some margin as the actual peak was analysed to be about halfway between the two load points.

K. Transfer details

For the Cold Gas commissioning tests, the redundant heater of the Cold Gas PXPY panel was switched ON to warm-up the pressure regulators of Cold Gas Feed Branch 1.

The spacecraft was successfully warmed up for the Payload Commissioning (DRS, CGS, LTP) during Transfer. Cycling heaters were used for the majority of the duration of Transfer as this was the safest configuration. Use of cycling heaters was minimised during LTP commissioning. There was also a request at this stage to reach a stable temperature target of 23 °C on the RLU pump head for the start of RLU power scan on 13th January 2016. This was achieved by using different combinations of the trim heaters to hit 23.0 °C at the start of the pass on 14th January 2016. At the same time the RLU TRP was 22.0 °C and the LMU TRP was 26.0 °C.

L. Thermal Comparison

At the end of the LPF Transfer prior to SCM-PRM separation, the thermal control system was performing as expected. The spacecraft was successfully warmed up to enable payload commissioning, the thermal control system was further commissioned and an investigation into the maximum power available on the Solar Array was carried out. The PRM thermostats continued to cycle as expected during transfer. All units were within temperature limits and the majority were close to their predicted temperatures and heater powers. The temperature requirements for the RLU pump head sensor for payload commissioning before separation were successfully met.

IV. Separation and On-Station Thermal Performance

M. Separation

SCM-PRM Separation occurred successfully on 22nd January 2016 at 11:30z.

In advance of separation, the umbilical heaters had been activated to cycle between 5 °C and 10 °C at 21st January 2016 (021) at 11:26z. They were adjusted to CONSTANT operation at 12:20z in order for all umbilicals to warm above 0 °C as the umbilical heater had started cycling but not all umbilicals were above 0 °C at that time. Before separation it was confirmed that all the umbilicals were above 0 °C as required.

The following thermal actions occurred on the 22nd January 2016 for separation:

022, 08:30z PRM Thermistors marked as failed, still able to receive telemetry before separation
022, 11:25z PRM heater circuits are commanded CONSTANT OFF (HC28,59,60).
022, 11:30z SCM-PRM Separation

The spacecraft was observed to cool slowly after separation but the bottom of the –Z LCA Cage remained above 10 °C even with being exposed to space after separation.

N. LCA Outgassing

After separation on the 22nd and 23rd January 2016, the LCA Cage heater set-points were raised to enable outgassing from the LCA Cage and the associated thermistor alarms were raised to avoid any erroneous FDIR triggers. The LCA Cage prime heaters (HC01, 25) were used on the 22nd January 2016 and at the request of the Operations Centre the next day the LCA Cage redundant heaters (HC33, 57) were used as well. Once the LTP payload within the cage was seen to warm up to 30 °C the heater settings were relaxed to avoid exceeding any temperature limits for the LTP.

O. Constant heaters & stable environment

After SCM-PRM separation, a safe mode was intentionally triggered by ground after upload of OBSW6.1 to enable the software patching. Therefore thermal Safe was used for a short time. In the days after the separation from 25th January 2016, the cycling heaters on the SCM were gradually changed to CONSTANT operation or effectively CONSTANT operation as planned to enable a stable thermal environment for the sensitive LTP payload. This has been completed successfully and the required environment has been reached. All units are within their operating temperature limits. High resolution thermistors were used to monitor the thermal stability of the payload.

The spacecraft was measured as very stable, taking 24th February 2016 (Day 055 in the year) as a representative sample for stability assessment during science operations. The standard deviation of the temperature profile over a 24-hour period for each of the thermistors attached to LTP equipments was as small as 0.0045 K:

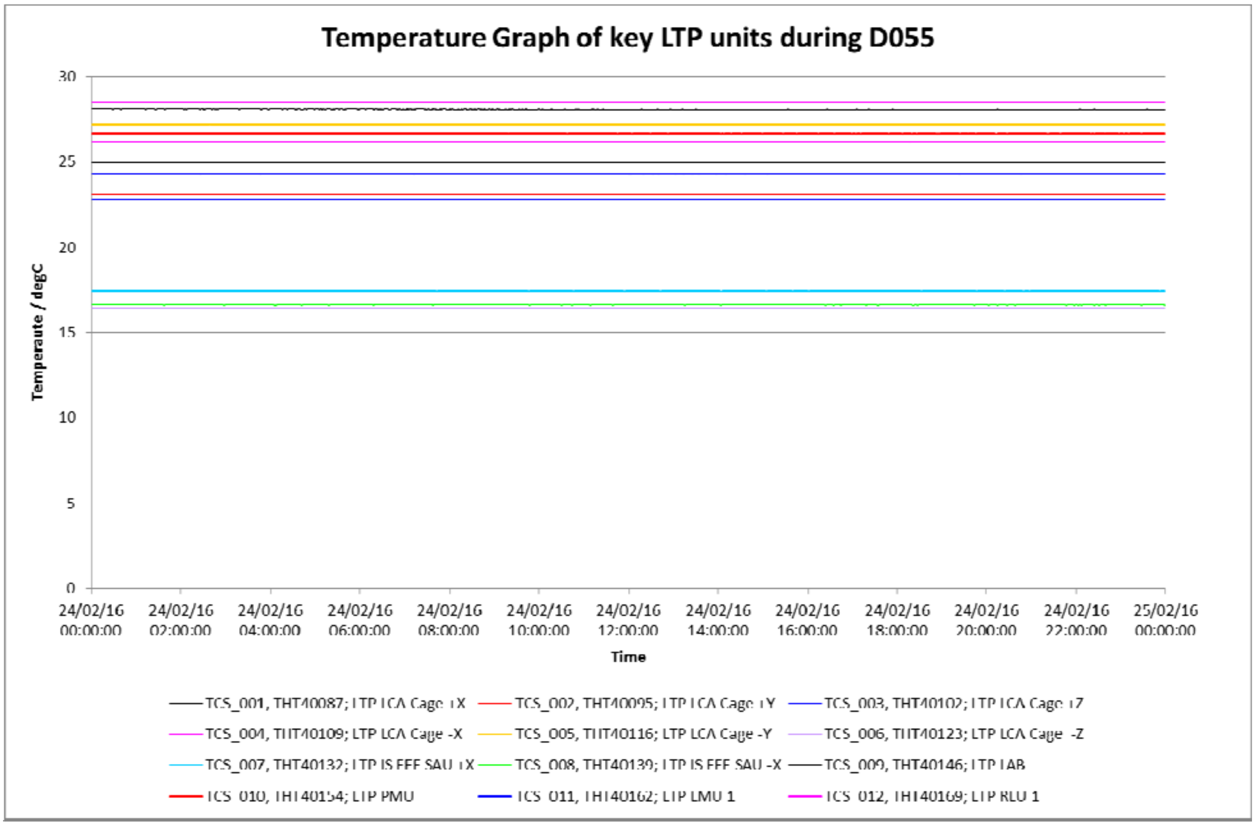


Figure 4. Temperature Profile of key LTP units during science operations on 24th February 2016, showing the high level of thermal stability over the period of a day

Sensor Type	Min of 1σ	Max of 1σ	Average of 1σ
1. LTP	0.0005	0.0099	0.0045
2. Platform	0.0041	0.0172	0.0084
3. Thrusters	0.0000	0.0103	0.0043
4. External	0.0013	0.0656	0.0194

Table 4. Table of range of standard deviations for the four main groups of thermistors for 24th February 2016 during science operations – showing the high level of stability throughout the spacecraft.

Type	TM Id	Mean	1σ	Min	Max	Range	Op Min	Op Max
1. LTP	TCS_001, THT40087; LTP LCA Cage +X	28.091	0.010	28.085	28.106	0.021	10.0	30.0
1. LTP	TCS_002, THT40095; LTP LCA Cage +Y	26.656	0.003	26.636	26.656	0.021	10.0	30.0
1. LTP	TCS_003, THT40102; LTP LCA Cage +Z	22.737	0.003	22.736	22.756	0.020	10.0	30.0
1. LTP	TCS_004, THT40109; LTP LCA Cage -X	28.499	0.001	28.478	28.520	0.041	10.0	30.0
1. LTP	TCS_005, THT40116; LTP LCA Cage -Y	27.174	0.001	27.174	27.195	0.021	10.0	30.0
1. LTP	TCS_006, THT40123; LTP LCA Cage -Z	16.397	0.002	16.378	16.398	0.020	10.0	30.0
1. LTP	TCS_007, THT40132; LTP IS FEE SAU +X	17.421	0.002	17.402	17.421	0.020	10.0	30.0
1. LTP	TCS_008, THT40139; LTP IS FEE SAU -X	16.594	0.003	16.575	16.594	0.020	10.0	30.0
1. LTP	TCS_009, THT40146; LTP LAB	24.941	0.002	24.941	24.961	0.020	0.0	40.0
1. LTP	TCS_010, THT40154; LTP PMU	23.091	0.001	23.071	23.091	0.020	-10.0	40.0
1. LTP	TCS_011, THT40162; LTP LMU 1	24.302	0.010	24.291	24.311	0.020	23.0	29.0
1. LTP	TCS_012, THT40169; LTP RLU 1	26.160	0.002	26.159	26.180	0.021	23.0	29.0

Table 5. Table of range of standard deviations for a number of thermistors next to each type of equipment for 24th February 2016 during science operations – showing the high level of stability throughout the spacecraft.

Units in °C

Table 4, Table 5 & Figure 4 show the temperature profile over 24th February 2016 for the key LTP units. The range of the temperatures can be seen to be constrained by the sensor accuracy of ~20 mK.

The LTP Core Assembly (LCA) interfaces have to be kept stable below 10^{-3} K/√Hz and the FEE SAU units have to be kept stable below 10^{-1} K/√Hz over the frequency window of 10^{-3} Hz to 10^{-1} Hz. This is generally demonstrated in Figure 5 and Figure 6 where the LCA Cage is still cooling after the temperature was raised before separation in order to promote faster outgassing of the structure. The stability of the LCA has increased over time so that the stability requirements are consistently achieved.

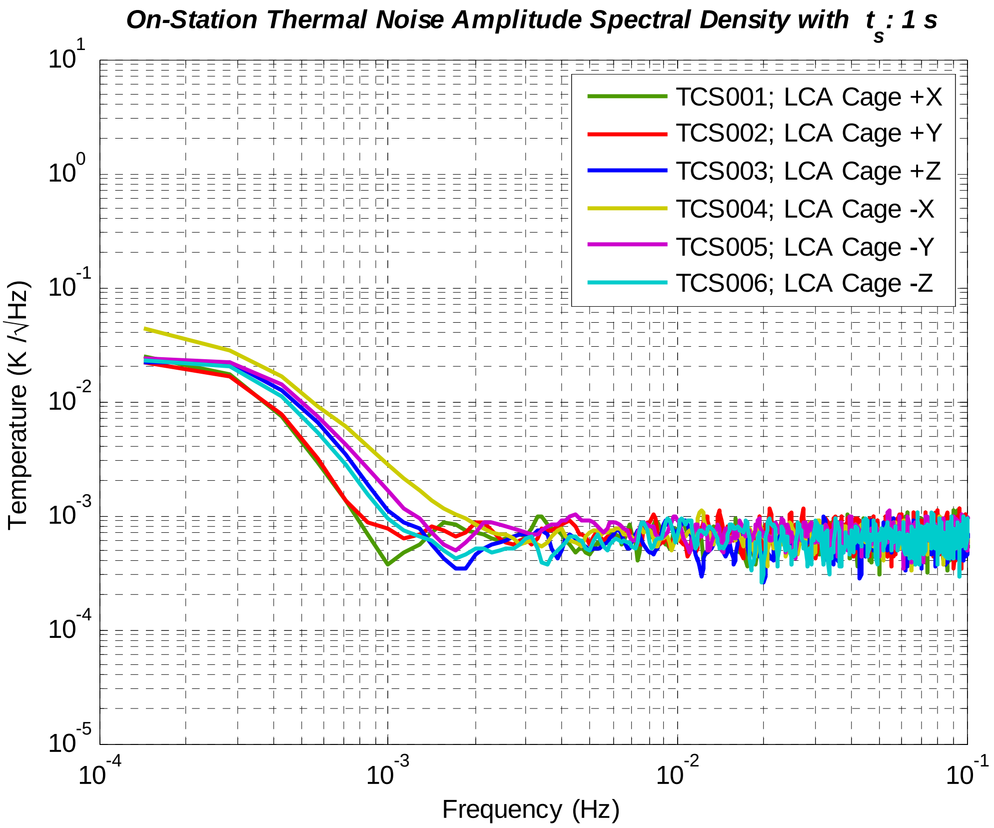


Figure 5. On-Station Thermal Noise Amplitude Spectral Density for the main LCA Cage for 24th February 2016 showing the average stability below the required 10^{-3} K/√Hz between 10^{-3} Hz to 10^{-1} Hz.

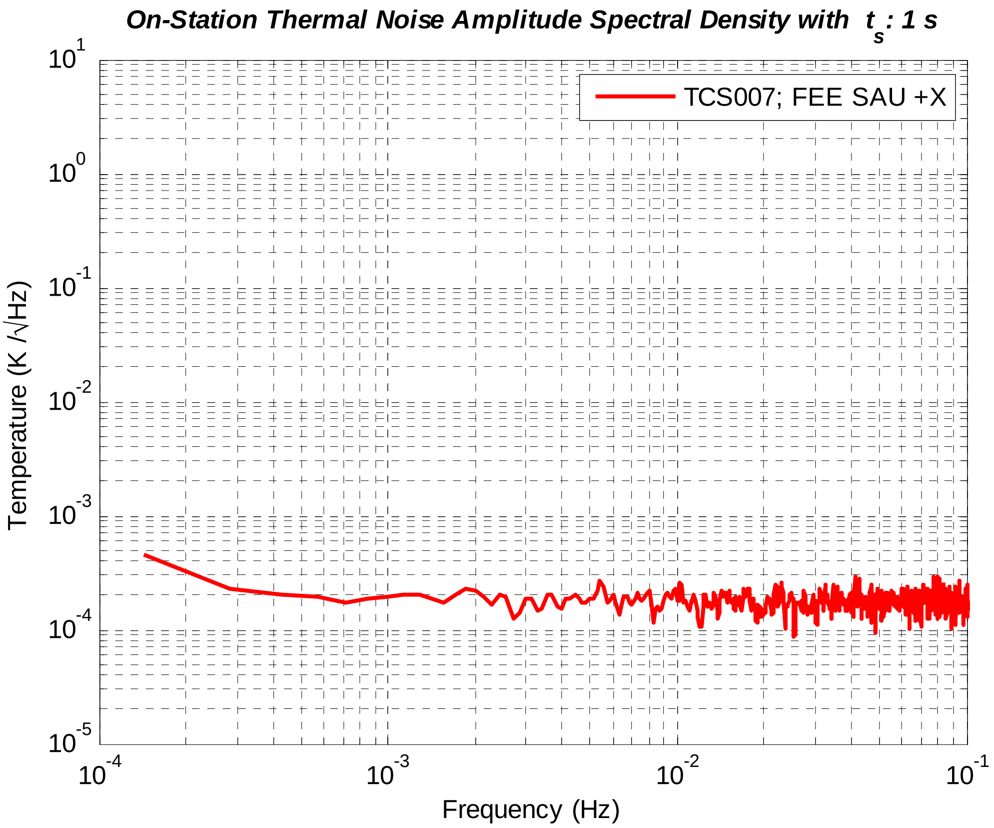


Figure 6. On-Station Thermal Noise Amplitude Spectral Density for a key LTP equipment for 24th February 2016 showing the average stability below the required 10^{-1} K/√Hz between 10^{-3} Hz to 10^{-1} Hz.

This data shows that the method of using discrete trim heaters for very stable operation of the LCA Cage and the RLU and LMU units to tight temperature limits does work as required. However, it should be understood that this method requires extra analysis and test verification for the discrete heaters and that there are only discrete temperature shifts possible from using the different heater combinations. Also, the constraints on the location of many heaters on small units needs to be considered.

V. Conclusions

This paper outlines the in-orbit thermal control system performance results from LISA Pathfinder LEOP and Thermal Commissioning. The LPF thermal control system has fully met its design requirements, providing thermal control during the intensive apogee raising manoeuvres in LEOP, to a thermally stable environment for the sensitive payload on-station. The LTP Core Assembly (LCA) interfaces have been shown to be kept stable below 10^{-3} K/√Hz over the frequency window of 10^{-3} Hz to 10^{-1} Hz. Also the method of using multiple trim heaters for controlling a unit to within a tight 6 °C temperature band at a temperature stability of less than 20 mK variation over 24 hours has been verified in flight.

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