SUBJECT: FPU Thermal Mathematical Model Specification

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CHANGE RECORD

ISSUE	DATE	SECTION	CHANGE
1	24-05-00	-	New Document

CONTENTS

1. SCOPE

The SPIRE FPU is mounted on the optical bench within the FIRST cryostat. This document describes the FPU thermal mathematical model, which is currently under construction at RAL.

2. APPLICABLE DOCUMENTS

2.1. Instrument Team Applicable Documents

ID	Title	Number
AD2.1.1	SPIRE Thermal Transient Cases for Cryostat Study	SPIRE-RAL-NOT-xxx (14-12-99)
AD2.1.2	Conceptual Design For the 300mK Thermal Strap	SPIRE-RAL-MOM-xxx (25-04-00)
AD2.1.3	The SPIRE Instrument For FIRST	SPIRE Meeting Munich vue graphs (29-03-00)
AD2.1.4	Array Design	SPIRE Technology Downselect Meeting JPL vue graphs (01-02-00)
AD2.1.5	PROVISIONAL SPIRE (FIRST) Interface Drawing	A1 5264 300 Issue 5 (21-03-00)
AD2.1.6	SPIRE Inputs For Cryostat and Instrument Thermal Modeling	RAL (15-5-00 -update)
AD2.1.7	SPIRE A Bolometer Instrument For FIRST	Proposal Submitted to ESA (Feb-98)

2.2. Dornier Applicable Documents

ID	Title	Number
AD2.2.1	FIRST Instrument I/F Study Final Report	FIRST-GR-B0000.009. Issue 1 (02-02-00)

2.3. ESA Applicable Documents

ID	Title	Number
AD2.3.1	FIRST Instrument I/F Study Final Report	PT-SPIRE-02124. Issue 0-4 BMS Mods (15-02-00)

3. INTRODUCTION

A thermal mathematical model of the SPIRE FPU is under creation in ESATAN v.8.4.2. The model is to be used to predict the following:

-The temperatures of the various components within the FPU, when under nominal conditions for each mode of operation.
-The time required for the FPU to settle to a stable operating temperatures after changing mode from Photometer to Spectrometer.
- The effect of thermal transients (e.g. cooler recycling) on the ultimate stability of the 300mK detector stage.
-The time required for the instrument parts to reach their nominal operating temperatures from ambient (i.e. initial cool down).

In order to analyse the above cases the thermal model requires the following characteristics:

-Transient analysis capability,
-Sufficiently fine nodal discretisation to analyse temperature gradients across the unit.
-Temperature dependant material properties (thermal conductivities, heat capacities) across the range from ambient to nominal operating temperatures.
-Account for effect of low temperatures on interface resistance across joints.
-Accurate modeling of the detector and cooler interfaces, as these are critical in predicting the absolute temperature and stability of the detectors.
-Accurate modeling of the interface between the FPU and the FIRST cryostat cooling system.

Information on the thermal characteristics of the 300mK System and the Helium Cooler is to be obtained from the design teams working in these areas at JPL and CEA respectively. Other information has been collated from various sources, including Dornier (FIRST- SPIRE Interfaces), MSSL (FPU Mechanical design) and RAL.

4. INSTRUMENT THERMAL REQUIREMENTS

4.1. FPU Structure

The 4K main structure is to be mounted off the 10K FIRST Optical Bench using isolating mounts, with a maximum heat leak of 6mW for a temperature difference of 6.8K (AD2.1.6). Similar materials are required for the structure and mirrors in order that differential thermal expansion does not cause alignment problems.

4.2. Mechanisms

TBD

4.3. Spectrometer and Photometer Calibration Sources

TBD

4.4. 300mK System

Supports

Maximum total heat leak down the Photometer 300mK supports = 0.6μW (AD2.1.2)
Maximum total heat leak down the Spectrometer 300mK supports = 0.4μW (AD2.1.2)

Detectors

Detector arrays be maintained at 300mK during operation.
Detector array stability = 150nK/√Hz between 0.03 and 25Hz.
The detector's warm mounting flange to be interfaced to the 2K structure.

Thermal Straps from Cooler to Detectors

Maximum temperature difference between cooler cold tip and detector arrays = 25mK.
Maximum temperature gradient along compliant links from bus bars to Cooler or detectors = 2mK/link (AD2.1.2).

4.5. Helium Cooler

Cooler structure to be mounted at 4K or below.
Maximum total heat load on Cooler = 10μW.
During recycling the evaporator temperature is to be maintained at 1.7K whilst the pump is heated to 40K. Following this the pump is to be cooled back to 2K, and the evaporator allowed to cool to 300mK.

5. MATERIAL PROPERTIES

5.1. Component Materials

Table 5.1 shows the materials used for the various FPU components, together with their relevant temperature ranges. Since the initial cool down from ambient is to be analysed, the material properties will be required up to the maximum start-up temperature of -30°C (AD2.3.1).

The majority of the structural components are manufactured from Aluminium Alloy 6061-T6, in order to match the thermal expansion of the mirrors (Ref AD 2.1.7).

Component	Material	Temperature Range (K)	
		min	max
Feet	Stainless Steel (spec TBD)	10	243
4K Structure	Aluminium 6061-T6	4	243
Optical Bench	Aluminium 6061-T6	4	243
Mirrors	Aluminium 6061-T6	2	243
BS Mechanism	Aluminium 6061-T6	4	243
FTS Mechanism	Aluminium 6061-T6	4	243
Calibration Source	Aluminium 6061-T6	4	243
4K Straps to GHe vent pipes	Copper	4	243
4K Harness	Copper	4	243
2K Boxes	Aluminium 6061-T6	1.7	243
2K Straps to He tank	OFHC Copper	1.7	243
2K Detector Flange	Aluminium 6061-T6	1.7	243
2K Harness	Stainless Steel or Brass (TBC)	1.7	243
300mK Bus Bars	OFHC Copper	0.3	243
Bus Bar Supports	Titanium 6Al-4V/ Kevlar Cord	0.3	243
300mK Straps to Bus Bars/Detectors	OFHC Copper	0.3	243
Detector Supports	Kevlar Thread	0.3	243
300mK Detector stage	Invar	0.3	243
300mK Detector Harness	Kapton	0.3	243

Table 5.1: Component Materials

5.2. Variation In Conductivity With Temperature

The thermal conductivity of the following materials are included in the model as functions of temperature:

-Aluminium 6061-T6
-Copper
-OFHC Copper
-Stainless Steel
-Titanium 6Al-4V
-Invar
-Kapton
-Kevlar

5.3. Variation In Specific Heat Capacity With Temperature

The specific heat capacities of the following materials are included in the model as functions of temperature:

-Aluminium 6061-T6
-Copper
-Stainless Steel
-Titanium 6Al-4V
-Invar

6. NODAL BREAKDOWN

The TMM consists of 86 diffuse nodes (representing the SPIRE FPU). These include 10 nodes to represent the walls of the Spectrometer and Photometer, 16 nodes for the Optical Bench and 5 nodes for the 2K boxes. The Photometer and Spectrometer bus bars are discretised along their lengths into five and four nodes respectively (due to their different lengths and number of supports). The mechanisms, calibration sources and mirrors are modeled as single nodes. The cooler is discretised into 3 nodes and each detector into 2 nodes.
A total of 7 boundary nodes are used to represent the FIRST Cryostat and the SPIRE JFET Box.
Table 6.1 gives a listing of all the nodes used within the model, together with their type and nominal operating temperature level.

NODE NUMBER	NODE NAME	TEMP LEVEL (K)	NODE TYPE
1000-1030, 1100-1130,1200-1230,1300-1330	optical bench	4	D
1500,1510,1520,1530,1540	spectrometer walls	4	D
1600,1610,1620,1630,1640	photometer walls	4	D
1700	aperture filter	4	D
2000	photo 3 mirror mount	4	D
2030	photo mirror 3	4	D
2040	photo mirror 4	4	D
2050	photo mirror 5	4	D
2060	photo mirror 6	4	D
2070	photo mirror 7	4	D
2080	photo mirror 8	4	D
2100	beam steering mechanism	4	D
2150,2160,2170,2180	photo 4k baffle	4	D
2400,2410,2420	photo 2k box	2	D
2450	photo 2k baffle	2	D
2500	photo dichroic 1	2	D
2510	photo dichroic 2	2	D
2520	photo mirror 9	2	D
2650,2655,2660,2665,2670	photo 300mK bus bar	0.3	D
2700	photo detector 1-2k	2	D
2750	photo detector 1-300mk	0.3	D
2800	photo detector 2 -2K	2	D
2850	photo detector 2 -300mk	0.3	D
2900	photo detector 3 -2K	2	D
2950	photo detector 3 -300mk	0.3	D

3000	spect input fold mirror	4	D
3010	spect collimator A	4	D
3020	spect collimator B	4	D
3030	spect beam divider 1	4	D
3040	spect fold mirror 1A	4	D
3050	spect fold mirror 2A	4	D
3060	spect fold mirror 1B	4	D
3070	spect fold mirror 2B	4	D
3080	spect rooftop mirror A	4	D
3090	spect rooftop mirror B	4	D
3100	spect beam divider 2	4	D
3110	spect camera mirror A	4	D
3120	spect camera mirror B	4	D
3200	spect mirror mechanism	4	D
3250	spect calibrator	4	D
3400,3410	spect 2k box	2	D
3450	spect 2k baffle	2	D
3650,3655,3660,3665	spect 300mK bus bar	0.3	D
3700	spect detector 1 -2k	2	D
3750	spect detector 1 -300mk	0.3	D
3800	spect detector 2 -2k	2	D
3850	spect detector 2 -300mk	0.3	D
4000	cooler 4k structure	4	D
4200	cooler 2k pump	2	D
4300	cooler evaporator	0.3	D
5000	JFET box	10	B
10000	first optical bench	10	B
11000	first cryostat walls		B
12000	first telescope	80	B
20000	first L0 helium tank	1.7	B
21000	first L1 vent pipe	4.0	B
22000	first L2 vent pipe	10	B

Table 6.1: SPIRE FPU Nodal Breakdown

7. CONDUCTIVE COUPLINGS

All conductive couplings are calculated using temperature dependant values for thermal conductivity. Conductances across bolted joints are also related to temperature, since the variation in this parameter at low temperatures is of critical concern for the thermal performance of the 300mK System.

7.1. Interface Conductive Couplings

Conductive Interface with FIRST Optical Bench:

The FPU is mounted off the 10K Optical Bench on three insulating stainless steel feet. The foot at the +z end of the box is cone shaped, attached to the FIRST Optical Bench using 4 M6 bolts. The remaining two feet at the –z end of the box have a blade design and are attached to the Optical bench using two M6 bolts.

Conductive Interface with JFET Box (10K) – Electrical Harness:

The tables below show a breakdown of the harnessing from individual components within the FPU to the FPU connector panel, and from the connector panel to the JFET Box (ref: AD2.3.1).

FROM	TO	NO. CONDUCTORS	CONDUCTOR SIZE	NO. SHIELDS	LENGTH (M)	MATERIAL
0.3K Structure	4K connector	40	(TBD)	10	(TBD)	copper
2K Housing	4K connector	8	(TBD)	2	(TBD)	copper
4K Housing	4K connector	8	(TBD)	2	(TBD)	copper
FTS Housing	4K connector	8	(TBD)	2	(TBD)	copper
FTS Mechanism	4K connector	18	(TBD)	2	(TBD)	copper
FTS BB Calibrator	4K connector	12	(TBD)	2	(TBD)	copper
Cooler Pump	4K connector	24	(TBD)	4	(TBD)	stainless / brass (TBC)
Cooler Evaporator	4K connector	20	(TBD)	4	(TBD)	stainless / brass (TBC)
BSM	4K connector	26	(TBD)	6	(TBD)	copper
Shutter	4K connector	16	(TBD)	2	(TBD)	copper
Phot BB Calibrator	4K connector	12	(TBD)	2	(TBD)	copper

Table 7.1: Harness Breakdown from FPU Internal components to FPU Connector Panel

FROM	TO	NO. CONDUCTORS	CONDUCTOR SIZE	NO. SHIELDS	LENGTH (M)	MATERIAL
4K connector	JFET Box	192	(TBD)	38	(TBD)	copper

Table 7.2: Harness Breakdown from FPU Connector Panel to JFET Box

Conductive Interface with FIRST Level 0 LHe Tank (1.7K) – Thermal Straps:

Three straps are used to connect the Cooler Pump, Cooler Evaporator and FPU 2K boxes to the FIRST HeII tank. The conceptual design for the Level 0 straps is described in AD2.2.1. The straps are manufactured from OFHC Copper (800W/mK @ 2K), and have a cross section of 20mm x 1mm. The length of these straps is (TBD)m.

Conductive Interface with FIRST Level 1 GHe Vent Line (4K) – Thermal Straps:

A single strap is used to connect the FPU main structure to the 4K GHe vent pipes. The conceptual design for the Level 1 straps is described in AD2.2.1. The strap is manufactured from ISO quality copper (140W/mK @ 2K), and has a cross section of 20mm x 1mm. The length of this strap is (TBD)m. The strap is attached to the box using the standard ISO mounting concept.
The modeling of this coupling is complicated by the changing temperature of the Helium vent line with changes in heat conducted to the LHe Tank.

FROM	TO	MATERIAL	CROSS SECTION (MM)	LENGTH (MM)
Cooler Pump	LHe Tank (L0)	OFHC Copper	20 x 1	(TBD)
Cooler Evaporator	LHe Tank (L0)	OFHC Copper	20 x 1	(TBD)
2K Boxes	LHe Tank (L0)	OFHC Copper	20 x 1	(TBD)
FPU Main Structure	GHe Vent (L1)	Copper	20 x 1	(TBD)

Table 7.3: FIRST Interface Strap Couplings Definition

7.2. Internal Conductive Couplings

Mirror Mounts:

The mirrors are mounted from their supports on 4mm diameter, Aluminium 6061stalks. The supports are also manufactured from Aluminium 6061, and are hard bolted to the Optical Bench.

Mechanism Mounts:

The Photometer Beam Steering Mirror Mechanism and the Calibrator are assumed to be hard bolted to the Optical Bench using six M5 screws. The FTS Mirror Mechanism is assumed to be hard bolted to the Optical Bench using eight M5 screws.

Cooler:

The Cooler structure is hard mounted to the 4K box. Internal couplings between the structure, Pump and Evaporator nodes are TBD.
Both the Evaporator and Pump are connected to individual 1.7K straps using gas-gap heat switches with a conductance of (TBD) W/K. During recycling the Evaporator heat switch is ON to maintained the temperature at 1.7K, whilst the Pump heat switch is OFF as it is heated to 40K (AD2.1.1). Following this, the Pump heat switch is turned ON and the Pump cools to 2K, whilst the Evaporator is turned OFF and cools to 300mK.

	MODE		
	OFF	ON	RECYCLING
Pump Heat Switch	OFF	ON	OFF
Evaporator Heat Switch	OFF	OFF	ON

Table 7.4: Cooler Gas Heat Switch Status

300mK Bus Bars:

Two bus bars are used to connect the cooler cold tip to the detectors. The conceptual design of the bus bars is defined in AD2.1.2. The Photometer bus bar links the cooler cold tip and the Photometer detectors (via thermal straps). The Spectrometer bus bar is coupled to the Photometer bus bar and Spectrometer detectors (also via straps). The bus bars are manufactured from OFHC Copper. Their nominal dimensions are given in Table 7.5.

FROM	TO	MATERIAL	DIAMETER (MM)	LENGTH (MM)
Cooler Cold Tip	Photometer Detectors	OFHC Copper	4	400
Photometer Bus Bar	Spectrometer Detectors	OFHC Copper	3	250

Table 7.5: Bus Bar Definition

300mK Straps:

The 300mK straps connect the bus bars to each other, the cooler cold tip and the detector arrays. The strap conceptual design is given in AD 2.1.2 and consists of a 20mm long, 2mm diameter, copper wire with M4 tags welded onto each end. A summary of the various straps is given in Table 7.6.

FROM	TO	MATERIAL	DIAMETER (MM)	LENGTH (MM)
Cooler Evaporator	Photometer Bus Bar	Copper	2	20
Photometer Bus Bar	Spectrometer Bus Bar	Copper	2	20
Photometer Bus Bar	Photometer Detectors 1	Copper	2	20
Photometer Bus Bar	Photometer Detectors 2	Copper	2	20
Photometer Bus Bar	Photometer Detectors 3	Copper	2	20
Spectrometer Bus Bar	Spectrometer Detector 1	Copper	2	20
Spectrometer Bus Bar	Spectrometer Detector 2	Copper	2	20

Table 7.6: Interface Strap Couplings Definition

Detectors:

The detector's 2K flange is mounted to the 2K box using eight M4 screws. The detector's 300mK stage is mounted from the 2K stage on a Titanium alloy and Kevlar thread system. Electrical connections between the detector and the 2K stage are made using a low conductivity Kapton cable with Ti/Au leads.

8. RADIATIVE COUPLINGS

8.1. Radiative Interface with FIRST Cryostat Walls

The 4K external walls of the FPU have a view factor to the warm cryostat walls. The resulting loads are calculated by hand and included in the model, assuming both surfaces to be polished aluminium with an emissivity of 0.1.

8.2. Radiative Interface with FIRST Optical Bench

The 4K external walls have a view factor to the 10K Optical Bench. The resulting loads are calculated by hand and included in the model. Calculations assume an emissivity of 0.1 for the FPU and (TBD) for the Optical Bench.

8.3. Radiative Interface with SPIRE JFET Box

The 4K external walls have a view factor to the 10K JFET Box. The resulting loads are calculated by hand and included in the model. Calculations assume an emissivity of 0.1 for the FPU and 0.2 for the JFET Box (AD 2.1.6).

8.4. Radiative Interface With FIRST Telescope

The 4K walls have a view factor to the FIRST Telescope at 80K. The resulting loads are calculated by hand and included in the model. Calculations assume an emissivity of 0.1 for the FPU and 0.04 for the Telescope.

9. COMPONENT POWER DISSIPATION

Detectors

Nominal power = 1.6μW per detector (AD2.1.2).
Noise Equivalent Power = 3E-17W/√Hz (AD2.1.3).

Helium Cooler

Nominal Power = 3mW (conducted down straps to FIRST Helium tank) (AD2.1.3)
Heater Power = 90mW (30minute duration during cooler recycling) (AD2.1.1)

FTS Mirror Drive Mechanism

Nominal Power = 2.4mW (average over full scan lasting 35 seconds – actual fluctuation defined in AD2.1.1).

Beam Steering Mechanism

Nominal Power = 4mW (AD2.1.1)

Photometer Calibrator

Nominal Power = 2mW (AD2.1.1)

Spectrometer Calibrator

Nominal Power = 5mW (AD2.1.1)

10. ANALYSIS CASES

10.1. Steady-State Cases

The SPIRE instrument operates in either Photometer or Spectrometer modes. Steady-state analysis of the FPU in both these modes will be performed in order to calculate absolute temperatures and heat flows within the instrument. The status of the instrument components during each mode is shown in Table 10.1 (Ref AD2.3.1).

10.2. Transient Cases

The critical transient cases to be analysed are as follows:

-Initial cool down from ambient, in order to predict cooldown time,
-Mode change from Photometer to Spectrometer, in order to predict detector stability and heat loads,
-Cooler recycling, in order to predict detector stability and heat loads.

The boundary conditions for each of these cases are given in Table 10.1, with the status of the various FPU components given in Table 10.2.

	Temperature (K)			
	Off (Pre Cooldown)	Cooler recycle	Photometer	Spectrometer
LHe Tank	1.7	1.7	1.7	1.7
GHe Vent	(TBD)	4*	4*	4*
FIRST Optical Bench	243	10	10	10
FIRST Cryostat Wall	243	80	80	80
JFET Box	243	10	10	10

*Varying with heat conducted to Level 0.

Table 10.1: Boundary Temperatures

	Mode			
	Off (Pre CoolDown)	Cooler Recycle	Photometer	Spectrometer
Detectors	OFF	ON	ON	ON
Photometer Calibration Source	OFF	ON	X	OFF
Spectrometer Calibration Source	OFF	ON	OFF	ON
Cooler	OFF	ON	ON	ON
BSM	OFF	ON	ON	ON
FTS Mechanism	OFF	ON	OFF	ON

X = ON or OFF depending on instrument configuration

Table 10.2: Component Status During Different Modes

11. SUMMARY

The thermal mathematical model of the SPIRE FPU is currently under construction. An outline description of the model in terms of nodal discretisation, conductive and radiative couplings and power dissipations has been presented, in addition to details of the various cases which the model will be used to analyse.

Some information on interfaces and detailed thermal aspects of several components is not yet defined, therefore assumptions have been made in these areas. Updated data will be incorporated into the model as it becomes available.