Spectrometer Calibrator (SCAL)

Subsystem Design Description

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List of Acronyms

Term	Meaning	Term	Meaning
AD	Applicable Document	IR	Infrared
ADC	Analogue to Digital Converter	IRD	Instrument Requirements Document
AIV	Assembly, Integration and Verification	IRTS	Infrared Telescope in Space
AME	Absolute Measurement Error	ISM	Interstellar Medium
AOCS	Attitude and Orbit Control System	JFET	Junction Field Effect Transistor
APART	Arizona's Program for the Analysis of Radiation Transfer	ISO	Infrared Space Observatory
APE	Absolute Pointing Error	LCL	Latching Current Limiter
ASAP	Advanced Systems Analysis Program	LIA	Lock-In Amplifier
ATC	Astronomy Technology Centre, Edinburgh	LVDT	Linear Variable Differential Transformer
AVM	Avionics Model	LWS	Long Wave Spectrometer (an instrument used on ISO)
BDA	Bolometer Detector Array	MAC	Multi Axis Controller
BFL	Back Focal Length	MAIV	Manufacturing, Assembly, Integration and Verification
BRO	Breault Research Organization	MCU	Mechanism Control Unit = HSMCU
BSM	Beam Steering Mirror	MGSE	Mechanical Ground Support Equipment
CBB	Cryogenic Black Body	M-P	Martin-Puplett
CDF	Cardiff, Department of Physics & Astronomy	NEP	Noise Equivalent Power
CDMS	Command and Data Management System	NTD	Neutron Transmutation Doped
CDMU	Command and Data Management Unit	OBS	On-Board Software
CDR	Critical Design Review	OGSE	Optical Ground Support Equipment
CEA	Commissariat a l'Energie Atomique	OMD	Observing Modes Document
CMOS	Complimentary Metal Oxide Silicon	OPD	Optical Path Difference
CoG	Centre of Gravity	PACS	Photodetector Array Camera and Spectrometer
CPU	Central Processing Unit	PCAL	Photometer Calibration source
CQM	Cryogenic Qualification Model	PFM	Proto-Flight Model
CVV	Cryostat Vacuum Vessel	PID	Proportional, Integral and Differential (used in the context of feedback control loop architecture)
DAC	Digital to Analogue Converter	PLW	Photometer, Long Wavelength
DAQ	Data Acquisition	PMW	Photometer, Medium Wavelength
DCU	Detector Control Unit = HSDCU	POF	Photometer Observatory Function
DDR	Detailed Design Review	PROM	Programmable Read Only Memory
DM	Development Model	PSW	Photometer, Short Wavelength
DPU	Digital Processing Unit = HSDPU	PUS	Packet Utilisation Standard
DSP	Digital Signal Processor	RAL	Rutherford Appleton Laboratory,
DQE	Detective Quantum Efficiency	RD	Reference Document
EDAC	Error Detection and Correction	RMS	Root Mean Squared
EGSE	Electrical Ground Support Equipment	SCAL	Spectrometer Calibration Source
EM	Engineering Model	SCUBA	Submillimetre Common User Bolometer Array
EMC	Electro-magnetic Compatibility	SED	Spectral Energy Distribution
EMI	Electro-magnetic Interference	SMEC	Spectrometer Mechanics
ESA	European Space Agency	SMPS	Switch Mode Power Supply
FCU	FCU Control Unit = HSFCU	SOB	SPIRE Optical Bench
FIR	Far Infrared	SOF	Spectrometer Observatory Function
FIRST	Far Infra-Red and Submillimetre Telescope	SPIRE	Spectral and Photometric Imaging Receiver
FOV	Field of View	SRAM	Static Random Access Memory
F-P	Fabry-Perot	SSSD	SubSystem Specification Document
FPGA	Field Programmable Gate Array	STP	Standard Temperature and Pressure
FPU	Focal Plane Unit	SVM	Service Module
FS	Flight Spare	TBC	To Be Confirmed
FTS	Fourier Transform Spectrometer	TBD	To Be Determined
FWHM	Full Width Half maximum	TC	Telecommand
GSFC	Goddard Space Flight Center	URD	User Requirements Document
HK	House Keeping	UV	Ultra Violet
HOB	Herschel Optical Bench	WE	Warm Electronics
HPDU	Herschel Power Distribution Unit	ZPD	Zero Path Difference
HSDCU	Herschel-SPIRE Detector Control Unit		
HSDPU	Herschel-SPIRE Digital Processing Unit		
HSFCU	Herschel-SPIRE FPU Control Unit		
HSO	Herschel Space Observatory		
IF	Interface		
IID-A	Instrument Interface Document - Part A		
IID-B	Instrument Interface Document - Part B		
IMF	Initial Mass Function		

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1 Scope of this document

This document describes the design of the Herschel-SPIRE Spectrometer Calibrator (SCAL) subsystem. The intention of this document is to present all design information available at a given release date and will be updated as and when changes to the design are made under configuration control.

2 Document list

2.1 Applicable documents

All applicable documents are listed in the AD chapter of the CIDL (HSO-CDF-LI-029).

3 Outline description of the Spectrometer CALibrator (SCAL)

The SPIRE Fourier Transform Spectrometer (FTS) uses two broadband, high-efficiency, intensity beam splitters in a Mach-Zender configuration. This configuration has two input ports, and the measured spectrum represents the difference between the two radiant inputs at these ports. One input is located at a 26-mm diameter pupil image of the telescope, at which the radiant input will be dominated by the emission from the telescope itself (several pW of power over the FTS range), with the signal from all except the brightest astronomical sources being negligible by comparison. The Spectrometer Calibrator (SCAL) is located at a complementary pupil at the second input port of the FTS, as shown in Figure 1 and Figure 2, and its function is to provide a thermal input that mimics the dilute 80-K black body emission of the telescope. This allows the large telescope background to be nulled, thereby reducing the dynamic range requirements for the detector sampling: ideally, if the telescope spectrum is perfectly nulled, the dynamic range is then dictated by the (much smaller) power from the astronomical source.

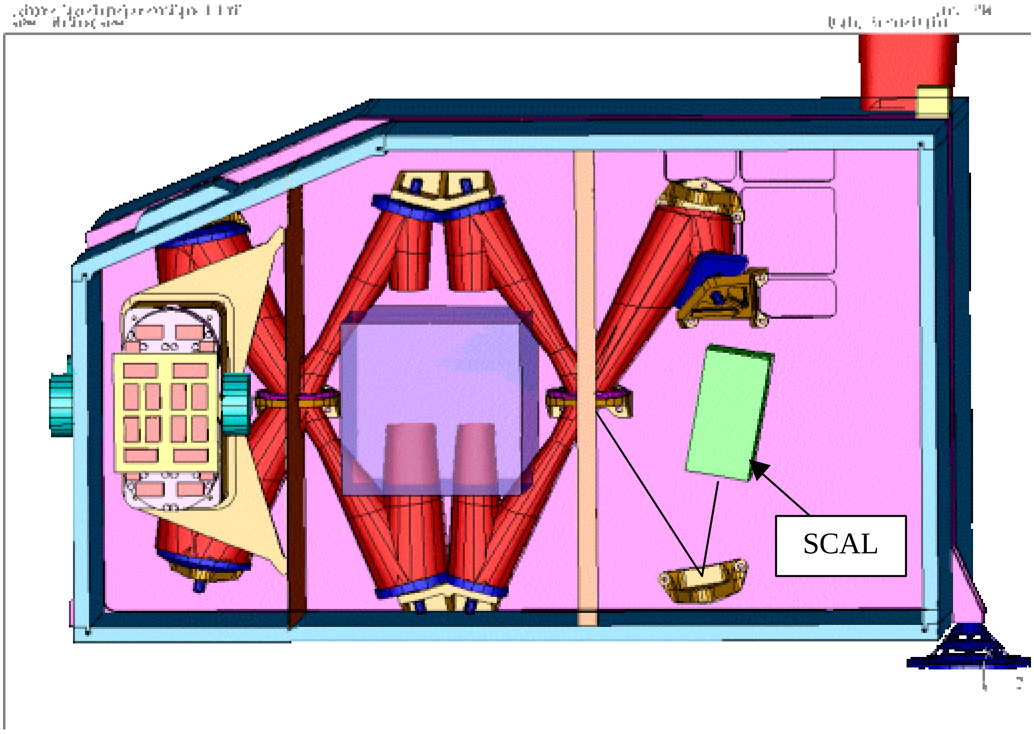


Figure 1 Layout of the SPIRE spectrometer, showing the location of SCAL.

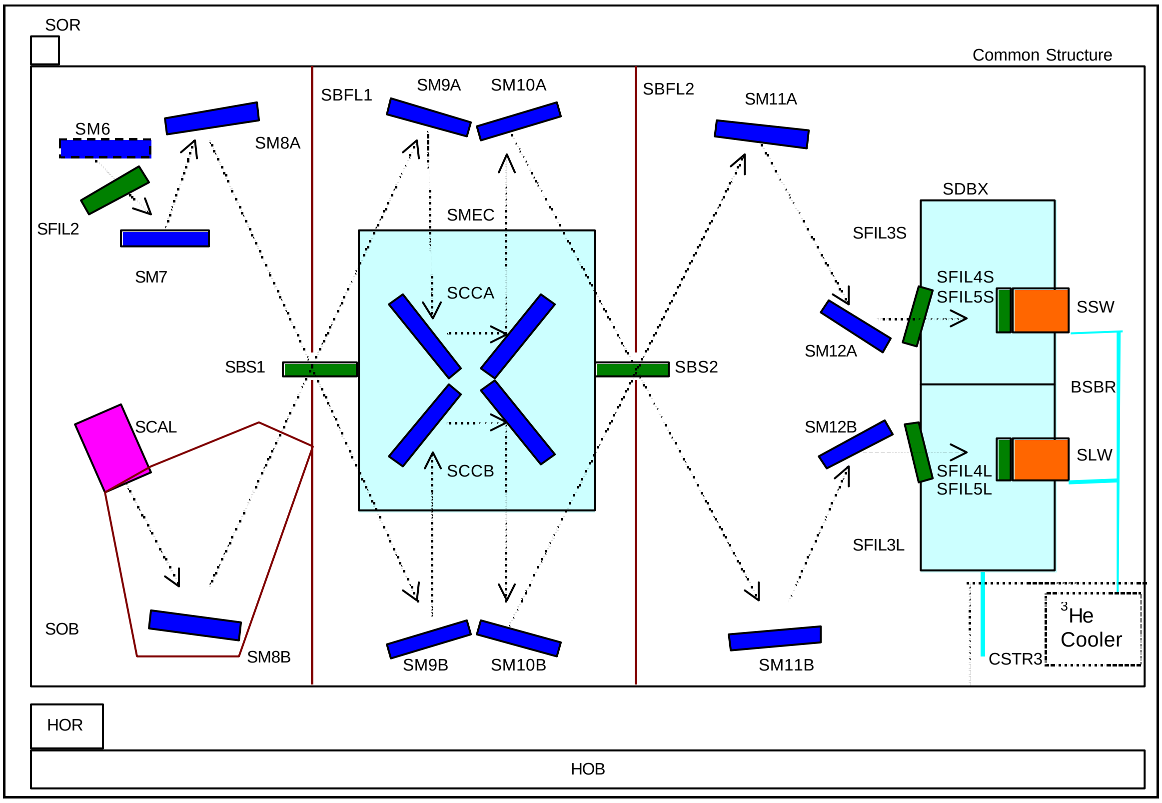


Figure 2 Topological diagram of spectrometer side of the SPIRE instrument showing the position of SCAL, and the baffle to which it interfaces.

4 SCAL requirements

The following tables summarise the SCAL requirements, as stated in the SPIRE Instrument Requirements Document and the System Budgets Document, taking into account the changes requested by (July 25 2001) and the response of the SPIRE Instrument Scientist (e-mail, August 30 2001). Each requirement is discussed individually below.

The main design drivers for SCAL are derived from the Instrument Requirements Document (AD11) and from the SCAL ICD (AD 27).

SCAL Performance Requirements		
Requirement ID	**Description**	**Value**
IRD-CALS-R01	Radiated spectrum	Null the central maximum to accuracy of 5% (goal 2%) [TBC] Replicate the dilute spectrum of the telescope to an accuracy of better than 20% (goal 5%) [TBC] over 200-400 μm.
IRD-CALS-R02	Beam pattern	Replicate the appropriate beam pattern at the second input port pupil image. *This requirement has been deleted as SCAL can be designed as a Lambertian emitter.*
IRD-CALS-R03	Adjustability:	Zero - maximum in 256 steps
IRD-CALS-R04	Uniformity	The uniformity of the intensity from the calibration source across the second input port pupil image shall be better than TBD%. *Deletion of this requirement has been requested and is currently under consideration.*
IRD-CALS-R05	Repeatability and drift	The output intensity of the calibration source shall drift by

		no more than 1% over one hour of continuous operation. The absolute change in the output intensity of the source shall be no more than 15% over the mission lifetime
IRD-CALS-R06	Operation	The calibration source shall be capable of continuous operation for periods of up to 2 hours with no loss of operational performance.
IRD-CALS-R07	Number of operations	The calibration source shall be capable of up to 12000 operational cycles
IRD-CALS-R08	Transient response	SCAL should take no longer than 30 minutes (15 goal) to heat to operating temperature from 4 K, and no more than 3 hrs (30 min. goal) to cool from operating temperature to 4 K. *New requirement proposed by Cardiff.*

SCAL System Requirements		
Requirement ID	**Description**	**Value**
IRD-CALS-R09	Operating Voltage	No more than 28 V DC
IRD-CALS-R10	Power dissipation in the focal plane	Shall be within the specification given in . . . . *What is this specification?Systems Budgets now states that total budget for spectroscopy is 8.4mW. This does not show the breakdown for SMEC and SCAL.*
IRD-CALS-R11	Mechanical envelope	The SCAL unit shall fit within a volume envelope to be specified by MSSL
IRD-CALS-R12	Thermal Isolation	The temperature of the SCAL housing and surrounding structure shall rise by no more than 1 K over the temperature of the FPU structure after one hour of continuous operation. To ensure that this requiremetn can be met, provision shll be made for a direct thermal strap fro the SCAL housing to the SPIRE optical bench *The above change to this requirement has been requested by Cardiff team.*
IRD-CALS-R13	Operating Temperature	< 6 K
IRD-CALS-R14	Redundancy	Fully redundant systems shall be provided for the active elements.
IRD-CALS-R15	Thermometry	Thermometers shall be provided on the spectrometer calibrator.

SCAL Technical Requirements		
Requirement ID	**Description**	**Value**
SCAL-T1	Mass	< 200 gm

4.1 SCAL requirements descriptions

4.1.1 CALS-R01 (radiated spectrum)

The dynamic range is set by the intensity of the central maximum of the interferogram, which is in turn determined by the difference in the total power received from the two ports. The origin of this requirement is that in order to carry out low-resolution spectrophotometry with SPIRE, the central maximum must be nulled to a high level to prevent phase errors associated with inadequate sampling from affecting the spectrum.

Besides reducing the dynamic range, it is also desirable that the spectrum of the calibrator be identical or nearly identical to that of the telescope. Ideally they will be the same, resulting in a null interferogram when viewing blank sky. The requirement covers the range 200-400 µm, which is the prime band for the FTS. Nulling over the 400 - 670 µm range should be as good as possible but is not the subject of a specific requirement.

4.1.2 CALS-R02 (beam pattern)

Requirement deleted: SCAL has been designed as a non-reflective Lambertian emitter with the appropriate spectral properties.

4.1.3 CALS-R03 (adjustability)

In the design and modelling of the SPIRE instrument, the telescope is assumed to be at 80 K and to have an effective emissivity of 0.04. These values are both subject to uncertainty. The temperature is expected to be in the range 60-80 K. The emissivity is subject to much larger uncertainty - it could easily be a factor of two lower or higher - and the value will not be known until after launch. SCAL must therefore be adjustable in order to provide the required nulling and spectral matching over a wide range of conditions.

4.1.4 CALS-R04 (uniformity)

It was originally envisaged that the SCAL pupil would have to be uniformly bright. Analysis of the FTS performance shows that this is not the case. Being located at a pupil, the detectors view all parts of SCAL with the same angular distribution. *The Cardiff team has therefore requested that this requirement be deleted and the current design of SCAL assumes that the pupil does not need to be uniformly bright.*

4.1.5 CALS-R05 (repeatability and drift)

A typical long integration with the FTS may comprise a sequence of interferograms (each taking around one minute), repeated for an our or more. It is important that the power received from the calibrator not vary significantly on the timescale of an observation.

The in-orbit telescope temperature and emissivity are not expected to change significantly even on timescales of months. It is envisaged that the optimum settings for SCAL will be determined empirically early in the mission and should need only occasional checking and adjustment. A calibrator output drift less than 15% over the mission lifetime means that only occasional re-adjustment of the calibrator excitation levels will be needed.

4.1.6 CALS-R06 (operation)

SCAL operation . . .

4.1.7 CALS-R07 (number of operations)

In order to define the life-test requirement for SCAL, it is necessary to specify the number of operations that SCAL must be able to tolerate. This is derived using the following conservative assumptions:

Mission operational lifetime:	4.5 years
Fraction of lifetime for which SPIRE operates:	33%
Fraction of SPIRE time for which SCAL used:	50%
Number of operational hours per day:	21
Frequency with which SCAL is powerd down/up	Once every 2 hours

Margin factor (and allowing for ground operation):	1.5

These assumptions result in a total operation time of 238 days and a number of cycles of 4300 (a factor of three less than the 12,000 operations specified).

The Cardiff team therefore requests that IRD-CALS-R06 be changed to 4,500 operations instead of 12,000

Note: A continuous accelerated life test with 15-minutes per cycle will achieve 4500 cycles in approximately 47 full 24-hr days (the need for such a test is TBD).

4.1.8 CALS-R08 (transient response)

To minimise set-up time, it is desirable that SCAL can be warmed up or cooled down as quickly as possible. The envisaged operational scenario for Herschel and SPIRE involves each instrument being operated for substantial periods of time (e.g., one cooler cycle - equivalent to 48 hrs). During such a period when SPIRE is operating, the FTS or photometer are also likely to be used continuously for long periods of time (typically hours). The warm-up and cool-down time should therefore be on the order of minutes or tens of minutes. There is a trade-off here between stability (requiring a long time constant) and short warm-up time (requiring a short time constant).

Note that when SCAL is switched off to allow change-over from SPIRE FTS to photometer operation, there will be a settling time of at least 15 minutes associated with the JFETs, and in any case SCAL cannot be viewed by the photometer detectors. It should therefore be possible to start photometer operation as soon as the JFETs are warmed up without any delay imposed by SCAL cool-down.

4.1.9 CALS-R09 (operating voltage)

This requirement is dictated by maximum voltage that the warm electronics can provide.

4.1.10 CALS-R10 (power dissipation in the focal plane)

SCAL will be powered up continuously while the FTS is operating, and its dissipation will load the Level-1 (4-K) stage, the temperature of which is to a large extent determined by the total FPU dissipation. It is important that this load be as small as possible to avoid the Level-1 temperature being raised too much (and to maximise the Herschel lifetime).

4.1.11 CALS-R11 (mechanical envelope)

SCAL must fit within the available volume, which will be defined in the Structure Interface Control Document.

4.1.12 CALS-R12 (thermal isolation)

When SCAL is switched on, almost all of the electrical power will be conducted to the SCAL mounting (only a tiny fraction is actually radiated by the device). The rise in temperature of the environment must be small to avoid changes in the radiated power by the structure affecting the overall sensitivity of the system. The mounting and FPU structure must thus be designed to be able to conduct efficiently this power into the Herschel cryostat 4-K strap. In case it proves necessary, the SCAL housing and the SPIRE optical Bench must be equipped with appropriate lugs to allow a direct thermal strap to be fitted.

4.1.13 CALS-R12 (operating temperature)

The SOB temperature determines the nominal temperature of the SCAL housing. The current SPIRE thermal model predicts that this should be about 5 K. In practice this temperature could rise by one or two degrees depending on the total power dissipation of the SPIRE FPU. This will have no significant impact on the operation of SCAL.

4.1.14 CALS-R12 (redundancy)

SCAL is vital to the correct functioning of several key observing modes. It must therefore have fully redundant heaters and thermometers.

4.1.15 CALS-R12 (thermometry)

To null the telescope spectrum it is not strictly necessary to know the temperature of SCAL, merely to be able to adjust it to a suitable value. However, instrument calibration will be greatly assisted if the temperature is known.

5 Description of the SCAL design

SCAL will employ two sources at the second input port to the FTS. As this port is a pupil, the effective can be control emissivity by using a geometrical fill factor. A black (emissivity ~ 1) source (SCAL_A(P)) that fills only 4% of the pupil area, produces an effective emissivity of ~ 4%. A second, smaller source (SCAL_B(P)) is provided to accommodate the possibility that the telescope emissivity is lower than the nominal 4%. This source will have an effective geometric emissivity of ~ 2%. If the telescope emissivity is higher than expected, both sources can be used together to match the telescope spectrum to within the requirements (although not necessarily meeting the SCAL overall dissipation requirements in this case). In order to provide full redundancy, two secondary sources (SCAL_A(R), SCAL_B(R)) are included, which are identical to the primary sources. Radiation shields are used between the sources to minimise radiant heating of passive sources by the active source(s). The plate to which the source assemblies are mounted forms the back plane of a cavity at Level-1 temperature (which we take here to be ~ 5 K), and is also blackened. SCAL is thus non-reflecting, avoiding any potential standing waves that could be set up between the detectors and SCAL.

Each source consists of an Aluminium end cap, with embedded heater and thermometer, on a Torlon strut for thermal isolation. The main design features of SCAL are shown in Figure 3.

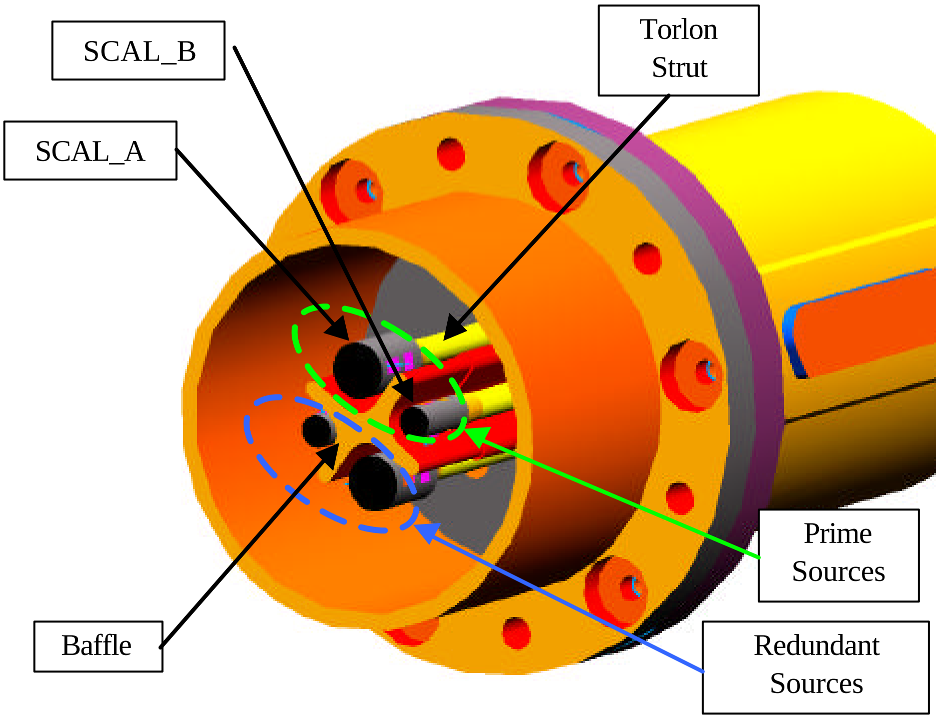


Figure 3 Model of SCAL assembly showing prime and redundant sources and baffle.

The SCAL assembly will bolt directly to a baffle, provided by MSSL, which also houses SM8B (see Figure 4, Figure 5 and Figure 6). To ensure adequate heat sinking, provision will be made for the attachment of a thermal strap.

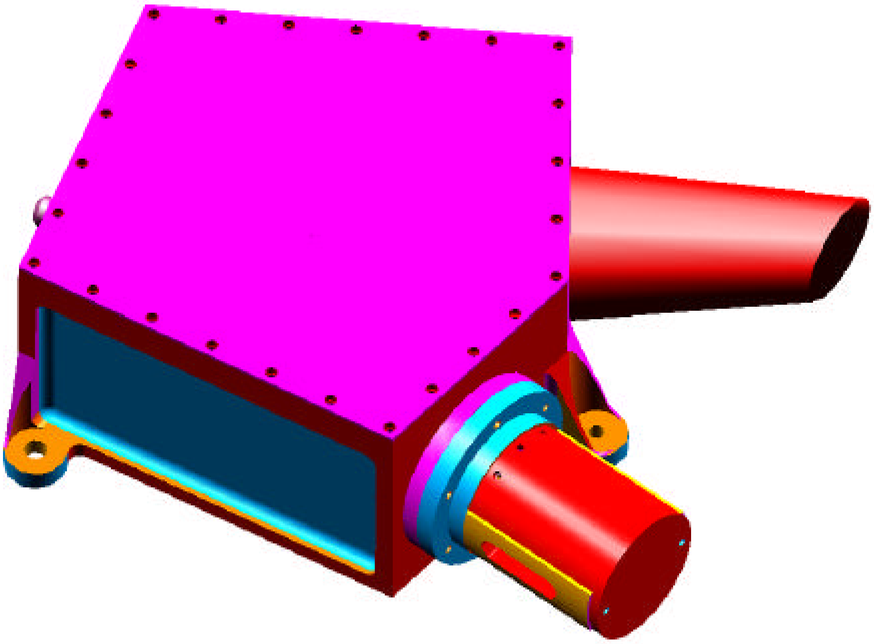


Figure 4 Isometric view of SCAL interface to baffle.

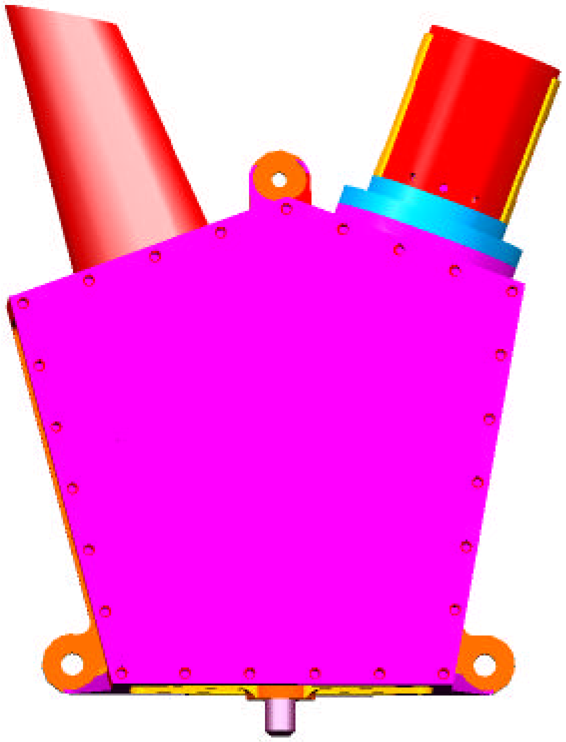


Figure 5 Plan view of SCAL and baffle.

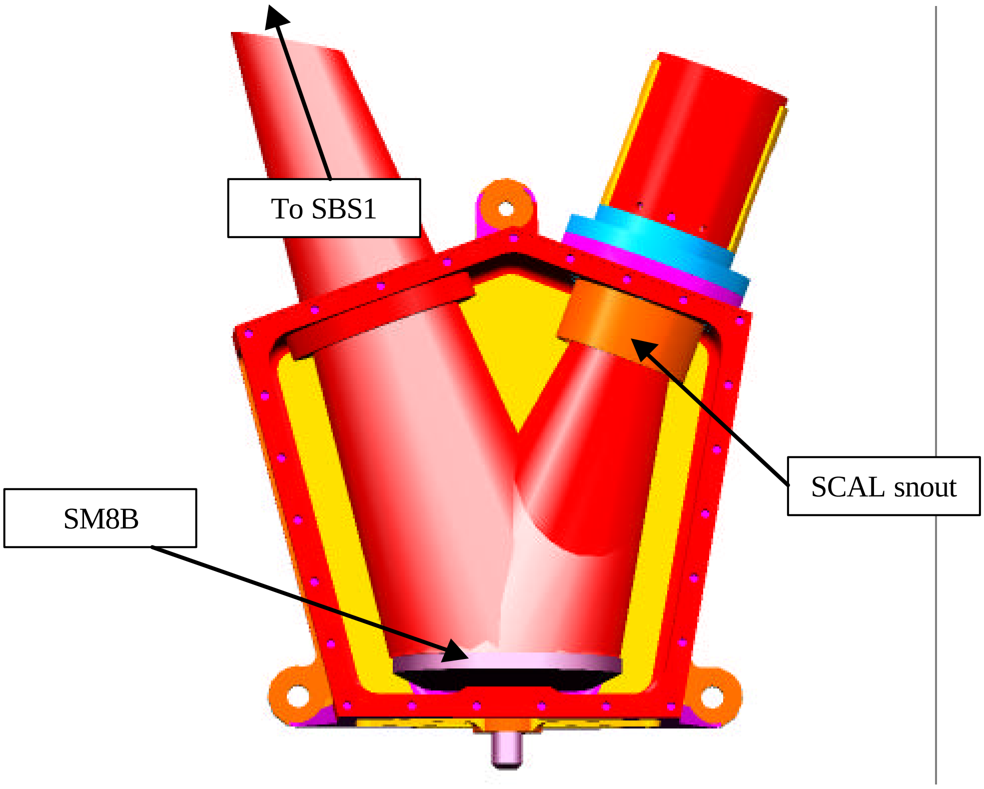


Figure 6 Plan view of SCAL and baffle. Top cover has been removed to show SM8B and beams.

A photometric model of SCAL and how it is viewed by the detectors (discussed further in Section 6) has shown that the configuration needed for optimal spectral matching, as well as maximum flexibility to cope with variations in the telescope temperature and emissivity from the specifications, is as shown in Table 1 and Figure 7.

Table 1 Optimal configuration for SCAL sources

Source	**SCAL_A(P), SCAL_A(R)**	**SCAL_B(P), SCAL_B(R)**
Diameter (mm)	5	3
Distance from source centre to pupil centre (mm)	5	5

The detectors view the 26-mm diameter pupil with an approximately Gaussian illumination profile with an edge taper of approximately 8 dB. Ideally, all sources would be placed at the pupil centre for maximum illumination efficiency. The source distribution to be used, illustrated in Figure 7, is the best compromise due to mechanical constraints.

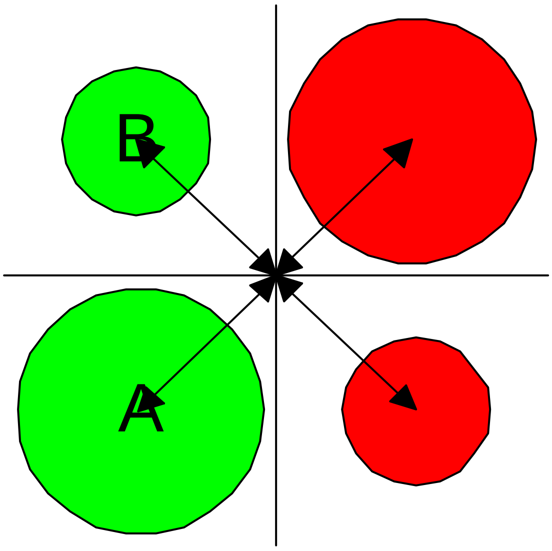


Figure 7 Optimal layout of the thermal sources for SCAL. Prime sources are shown in green, redundant in red. The centre of each source is 5mm from the pupil centre, and the minimum gap between adjacent sources is 3.07mm.

6 Computer simulation and modelling

6.1 Nulling of telescope emission

A MathCAD model has been produced (Appendix - A.1.1) to predict the degree of spectral matching attainable with different source dimensions, distributions, and temperatures, for different telescope temperature/emissivity scenarios. It takes into account the difference in transmission between the telescope and detectors, and SCAL and the detectors, due to the different number of filters in the paths. It also accounts for an assumed wavelength dependent emissivity of the black source coating, and for the Gaussian illumination of the pupil. It assumes that the telescope emissivity is wavelength independent - an explicit variation with wavelength can easily be incorporated, but at present there is no available information on this.

Model results are presented below for the source configuration shown in Figure 7 for a variety of telescope temperatures and emissivities.

80 K, 4% emissivity: Optimum spectral matching for an 80K, 4% emissivity telescope is achieved with the following parameters:

- SCAL_A temperature = 13 K
- SCAL_B temperature = 105 K

This produces the following nulling errors:

- 200 µm – 1.3%

- 400 µm – 1.4%

The nulling ratio as a function of wavelength is shown in Figure 8.

The spectral matching goal can also be achieved by running SCAL_A at 5K (i.e. unpowered) and SCAL_B at 108K, although the nulling isn't quite as good (200µm – 3.4%, 400µm – 3.0%).

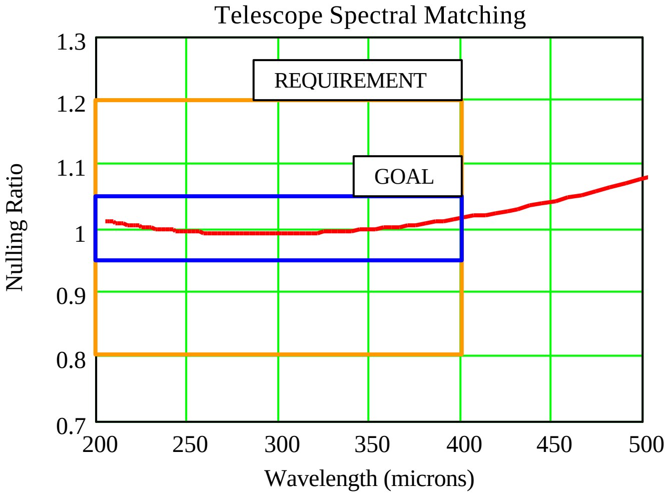


Figure 8 Telescope matching achievable for an 80-K, 4% emissivity telescope.

80 K, 2% emissivity: Optimum spectral matching for an 80-K, 2% emissivity telescope is achieved with the following parameters:

- SCAL_A temperature = 5 K
- SCAL_B temperature = 64 K

This produces the following nulling errors:

- 200 µm – 5.5%
- 400 µm – 4.9%

The nulling ratio as a function of wavelength is shown in Figure 9. In this scenario, it is not possible to achieve the spectral matching goal, but the requirement is easily met.

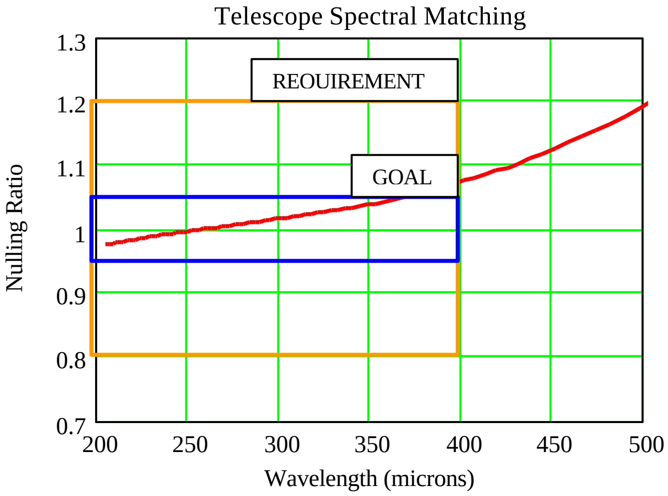


Figure 9 Telescope matching achievable for an 80-K, 2% emissivity telescope.

80 K, 8% emissivity: Optimum spectral matching for an 80-K, 8% emissivity telescope was achieved with the following parameters:

- SCAL_A temperature = 84 K
- SCAL_B temperature = 5 K

This produces the following nulling errors:

- 200 µm – 1.7%
- 400 µm – 0.4%

The nulling ratio as a function of wavelength is shown in Figure 10. The spectral matching goal is easily achieved in this scenario.

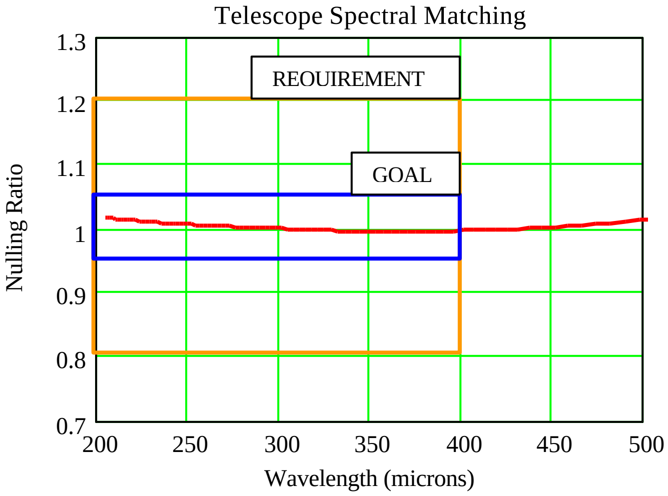


Figure 10 Telescope matching achievable for an 80-K, 8% emissivity telescope.

65 K, 4% emissivity: Optimum spectral matching for a 65-K, 4% emissivity telescope was achieved with the following parameters:

- SCAL_A temperature = 12 K
- SCAL_B temperature = 84 K

This produces the following nulling errors:

- 200µm –1.5%
- 400µm – 1.8%

The nulling ratio as a function of wavelength is shown in Figure 11. The spectral matching goal is easily achieved in this scenario.

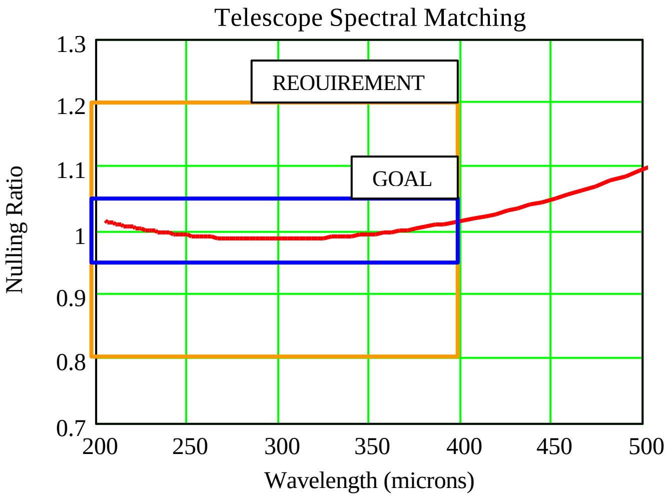


Figure 11 Telescope matching achievable for a 65-K, 4% emissivity telescope.

Optimum spectral matching for a 65-K, 2% emissivity telescope was achieved with the following parameters:

- SCAL_A temperature = 5 K
- SCAL_B temperature = 53 K

This produces the following nulling errors:

- 200µm – 5.6%
- 400µm – 5.9%

The nulling ratio as a function of wavelength is shown in Figure 12. The spectral matching goal is not met in this scenario, although the requirement is comfortably met.

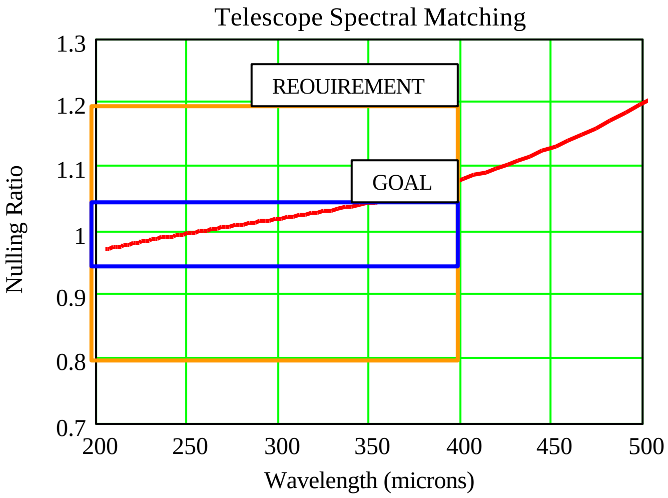


Figure 12 Telescope matching achievable for a 65-K, 2% emissivity telescope.

65 K, 4% emissivity: Optimum spectral matching for a 65-K, 8% emissivity telescope was achieved with the following parameters:

- SCAL_A temperature = 68 K

- SCAL_B temperature = 13 K

This produced the following nulling errors:

- 200µm – 0.6%
- 400µm – 0.8%

The nulling ratio as a function of wavelength is shown in Figure 13. The spectral matching goal is easily achieved in this scenario.

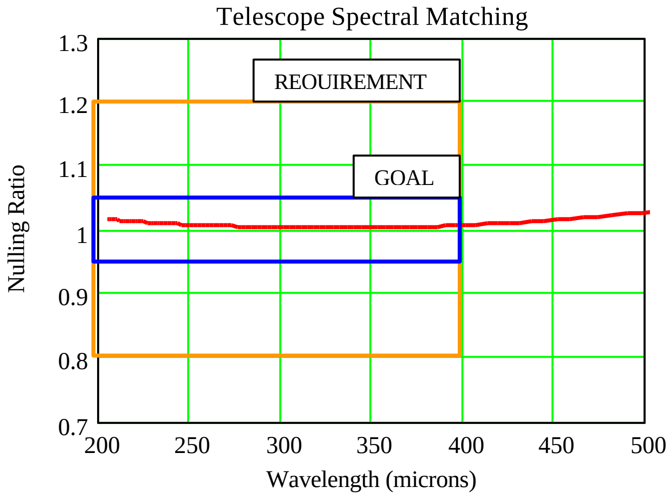


Figure 13 Telescope matching achievable for a 65-K, 8% emissivity telescope.

6.2 Thermal Modelling

A thermal model (appendix A.1.2) has been produced to simulate the thermal behaviour of the SCAL sources. Thermal data has been extracted from extensive literature surveys and, where possible, been verified and added to by experiments in our laboratory. The model uses an iterative program loop in a MathCAD worksheet. The algorithm takes as its input a designated constant power applied to the heater at a set base temperature, and for a small time interval, calculates the temperature rise. The next time interval is then calculated according to the slope of the warm-up curve, and the temperature rise in this interval is then calculated using temperature-dependant heat capacities and thermal conductivities for all components. Once equilibrium has been achieved (slope set by user), the power is switched off, and the cool-down curve is calculated in the same way. This model has been validated by tests in the lab on thermal prototypes.

Warm-up and cool-down curves are shown for SCAL_A and SCAL_B in Figure 14 and Figure 15 respectively. These models show the predicted thermal behaviour for a variety of applied powers.

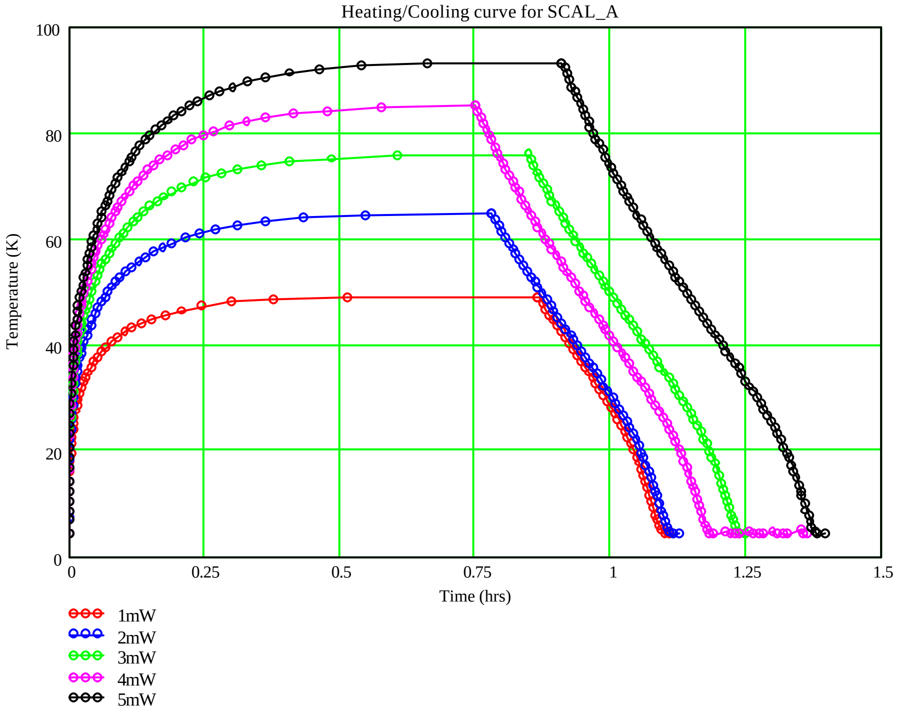


Figure 14 Heating/cooling for SCAL_A (5 mm diameter x 7 mm deep)

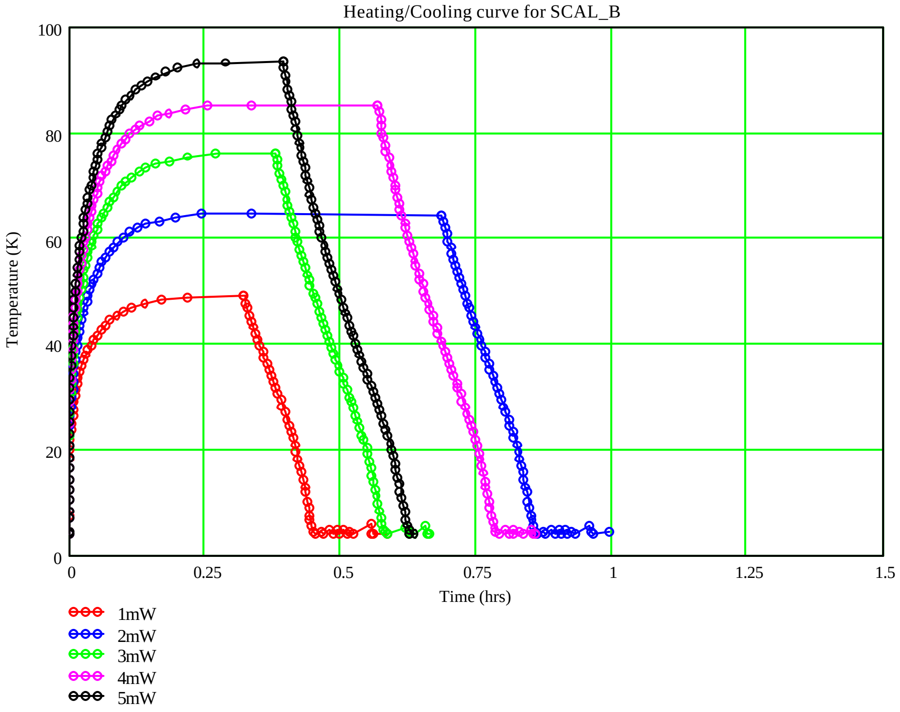


Figure 15 Heating/cooling curve for SCAL_B (3 mm diameter x 7 mm deep).

This model has been used in conjunction with the spectral matching model to estimate the power required to null the telescope emission to within the requirements. The most demanding case is where we have a telescope temperature of 80 K with 4% emissivity (Section TBD). The spectral matching model predicts that SCAL_B needs to be run at 105K, with SCAL_A at 13 K to get the best spectral match. The thermal model predicts that 6.6 mW and 0.06mW needs to be applied to SCAL_B and SCAL_A respectively to achieve these temperatures. These curves are shown in Figure 16 and Figure 17.

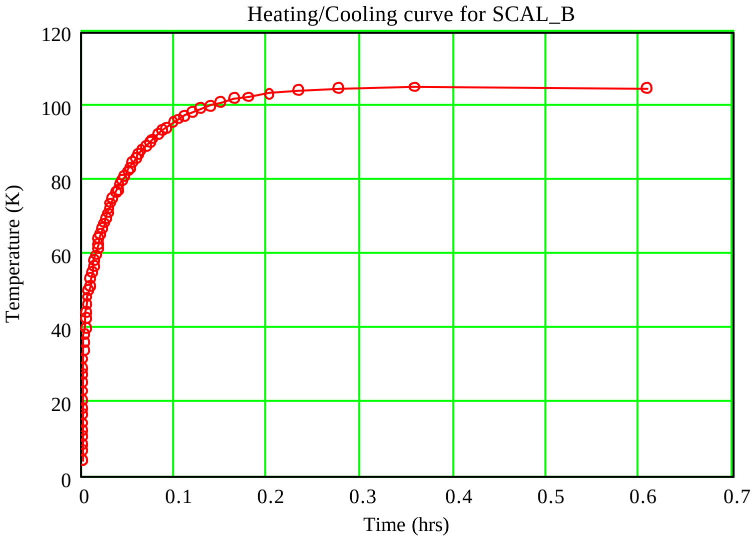


Figure 16 Warm-up curve for SCAL_B for an applied power of 6.6 mW

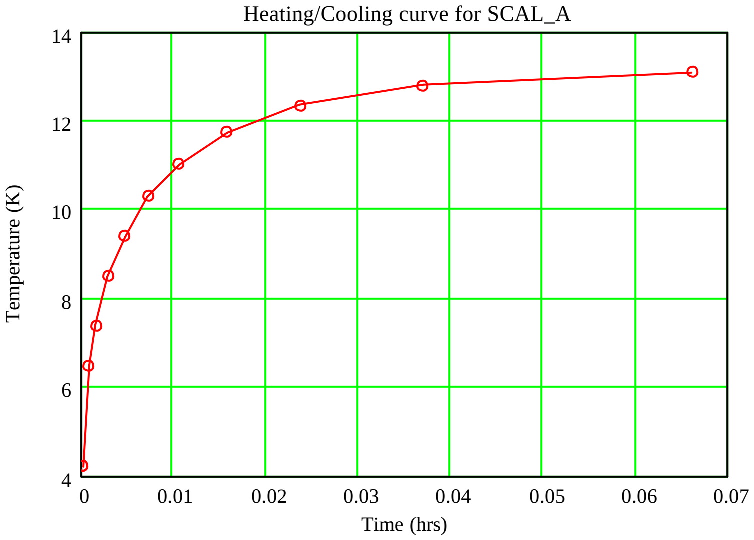


Figure 17 Warm-up curve for SCAL_A for an applied power of 0.06 mW

The case shown above is the required emitter temperatures for excellent spectral matching, to within 1.4%, across the 200-µm to 400-µm band. This requires applying a total power of 6.6 mW. However, a very good spectral match (to within 7.8%) can also be achieved by running only SCAL_A at 52.5 K, as shown in Figure 18.

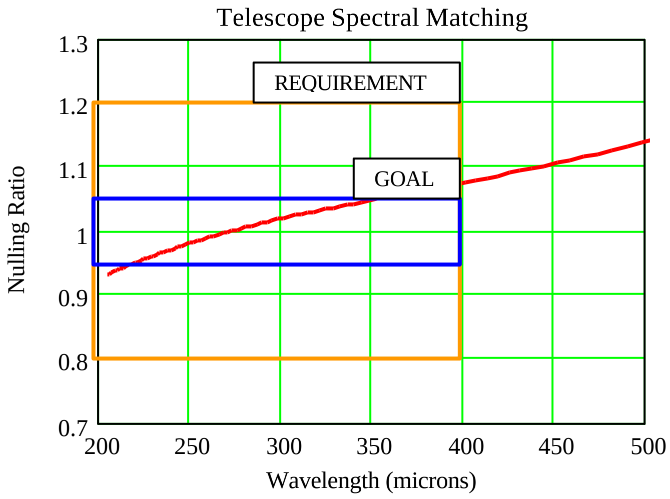


Figure 18 Telescope matching for 80-K, 4% emissivity telescope – matching achievable with reduced power dissipation.

Running SCAL_A at 52.5 K will require an applied power of 1.2 mW, as shown in Figure 19.

This discussion shows that there are numerous possibilities for combinations of source temperatures to meet the spectral matching requirement. It also shows that in some cases, there is a trade-off between the goodness of the match and power dissipation.

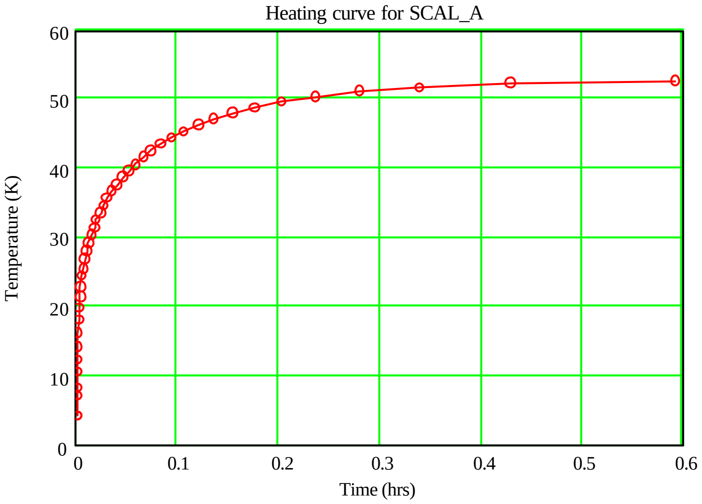


Figure 19 Heating curve for SCAL_A for an applied power of 1.2 mW

6.3 Mechanical modelling

At the time of writing, mechanical modelling has been restricted to analysis of the sources on the Torlon rods due to time constraints. A full mechanical FEA will be carried out on the whole system before the SPIRE instrument DDR.

Source deflection under load: A MathCAD model has been produced to predict the maximum expected deflection of the sources on the Torlon legs for different launch accelerations. Details of this model are presented in Appendix A.1.3 and results are presented and discussed in Section 7.7.1.

Resonant Frequency Calculation: A simple MathCAD worksheet has been produced to calculate the first resonant frequency of the system, treating the system as a mass on a spring, and as a mass on a cantilever. For this analysis, the shear modulus was used (worst case) to predict the first resonant frequency, using the mass as the total mass of the aluminium end cap and Torlon leg (overestimate). Details of this worksheet are presented in Appendix A.1.4 and results are presented and discussed in Section 7.7.1.

Static Load Bearing Capacity: A simple MathCAD worksheet has been produced to calculate the static load bearing capacity of the Torlon legs. Details of this worksheet are presented in appendix A.1.4 and results are presented and discussed in Section 7.7.1.

Mechanical FEA: A full mechanical FEA will be carried out on the entire system before the SPIRE instrument IBDR.

7 Detailed Design Description

7.1 Thermal Sources

Two prime heated sources are used, one of 5 mm diameter (~ 4% pupil area) and one of 3 mm diameter (~ 2% pupil area), and are referred to as SCAL_A(P) and SCAL_B(P) respectively. This configuration provides flexibility to compensate for uncertainties in the telescope emissivity and temperature (see Section 6.1). Full redundancy is provided by two additional sources, SCAL_A(R) and SCAL_B(R).

7.1.1 Source Assembly – Heater Body

Each source consists of an aluminium end cap, with embedded heater (Vishay CHPHR 0505 chip resistor) and thermometer (Cernox-1030), on a Torlon rod. The face of the Aluminium end cap is treated with carbon-loaded Epotek-920 epoxy to produce a high emissivity finish.

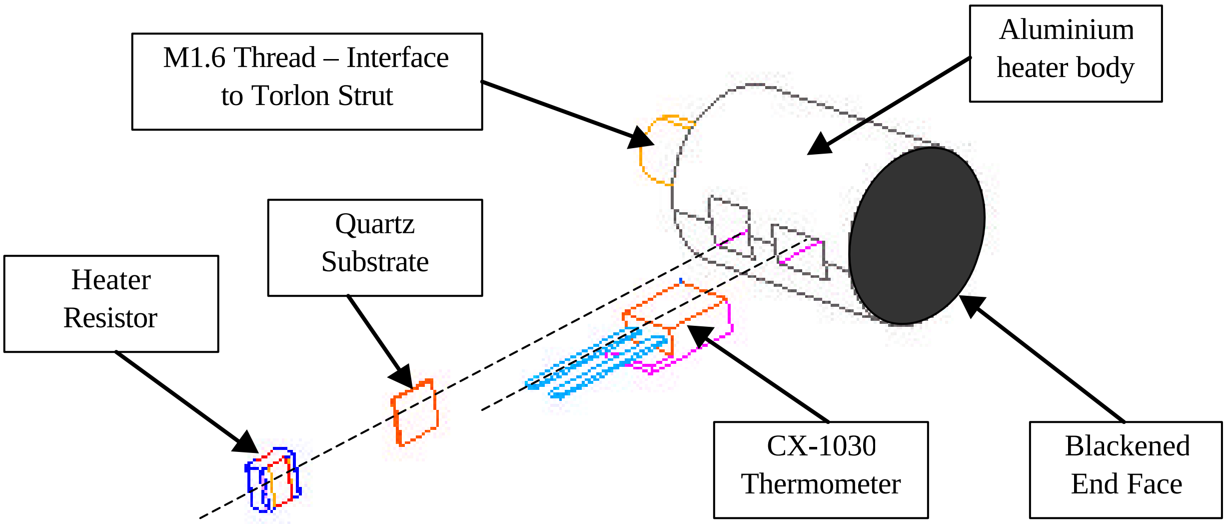
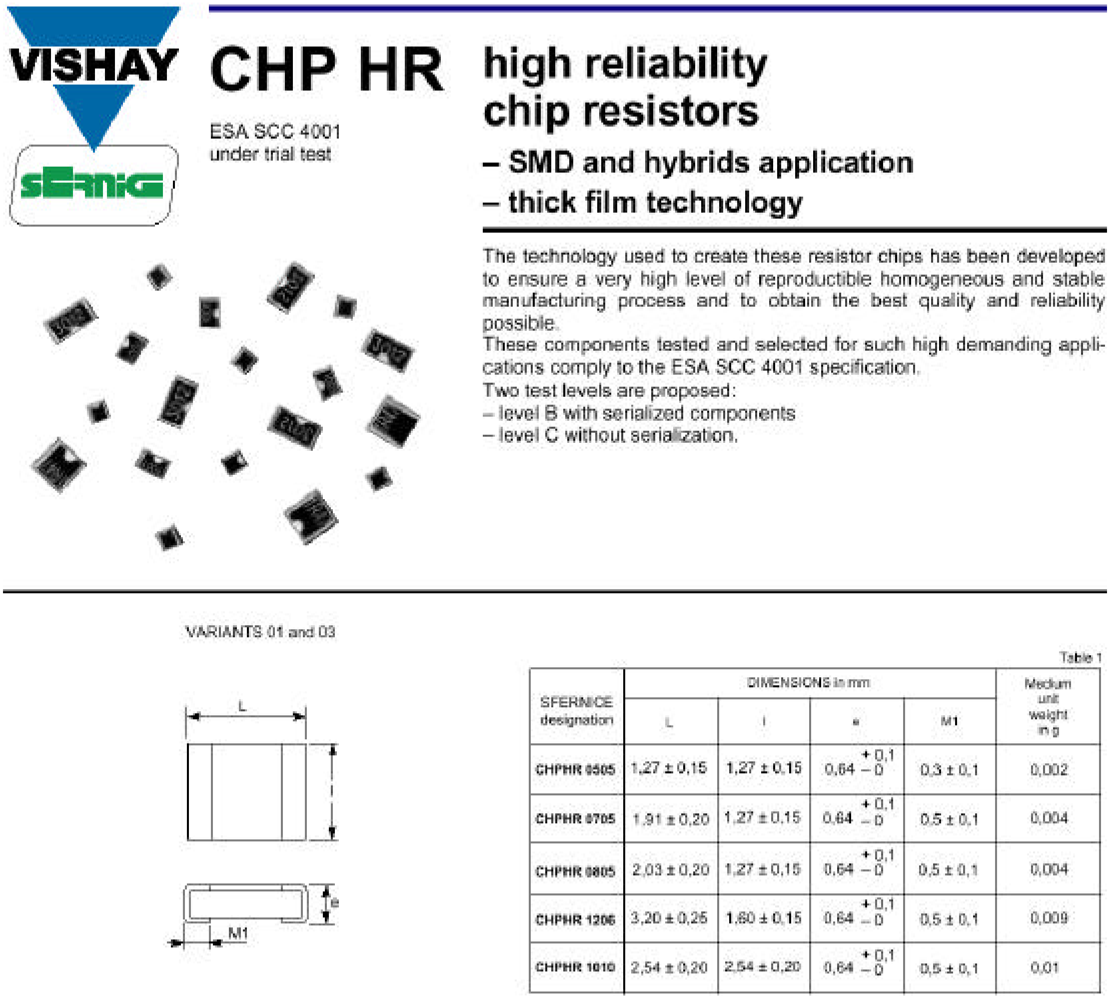


Figure 20 Details of aluminium heater body and assembly

7.1.2 Heater Details

The heaters to be used are 0.125-W, 500-Ω high reliability chip resistors (CHPHR 0505), manufactured by Vishay/Sfernice. These components are on the ESA preferred parts list, but have not been qualified for use at 4 K (TBC) – samples will be tested in the Cardiff lab between September and November 2001. Details of these components are shown in Figure 21. The heater resistor will be mounted on a 100-µm thick Quartz or Sapphire substrate (Goodfellow) using Epotek 920 epoxy.

The heater on its substrate will be mounted in a slot in each heater body, as shown in Figure 20. Wires will be bonded to the end caps of the heater resistor using silver loaded conductive epoxy (Epotek H20-S).



CHP HR

ESA SCC 4001
under trial test

high reliability chip resistors

– SMD and hybrids application
– thick film technology

The technology used to create these resistor chips has been developed to ensure a very high level of reproductible homogeneous and stable manufacturing process and to obtain the best quality and reliability possible.
These components tested and selected for such high demanding applications comply to the ESA SCC 4001 specification.
Two test levels are proposed:
– level B with serialized components
– level C without serialization.

VARIANTS 01 and 03

Table 1

SFERNICE designation	DIMENSIONS in mm				Medium unit weight in g
	L	l	e	M1	
CHPHR 0505	1,27 ± 0,15	1,27 ± 0,15	$0{,}64\ ^{+0{,}1}_{-0}$	0,3 ± 0,1	0,002
CHPHR 0705	1,91 ± 0,20	1,27 ± 0,15	$0{,}64\ ^{+0{,}1}_{-0}$	0,5 ± 0,1	0,004
CHPHR 0805	2,03 ± 0,20	1,27 ± 0,15	$0{,}64\ ^{+0{,}1}_{-0}$	0,5 ± 0,1	0,004
CHPHR 1206	3,20 ± 0,25	1,60 ± 0,15	$0{,}64\ ^{+0{,}1}_{-0}$	0,5 ± 0,1	0,009
CHPHR 1010	2,54 ± 0,20	2,54 ± 0,20	$0{,}64\ ^{+0{,}1}_{-0}$	0,5 ± 0,1	0,01

Figure 21 Details of the heaters to be used for SCAL (CHPHR 0505)

7.1.3 Thermometer details

The thermometers to be used in the heater bodies are Lakeshore Cernox 1030 sensors. These components have been selected as they have the performance required by the SCAL subsystem (Figure 23), and for commonality with the rest of the SPIRE systems, drive electronics and software. They are also of a convenient size to fit into the small thermal source assemblies (Figure 22).

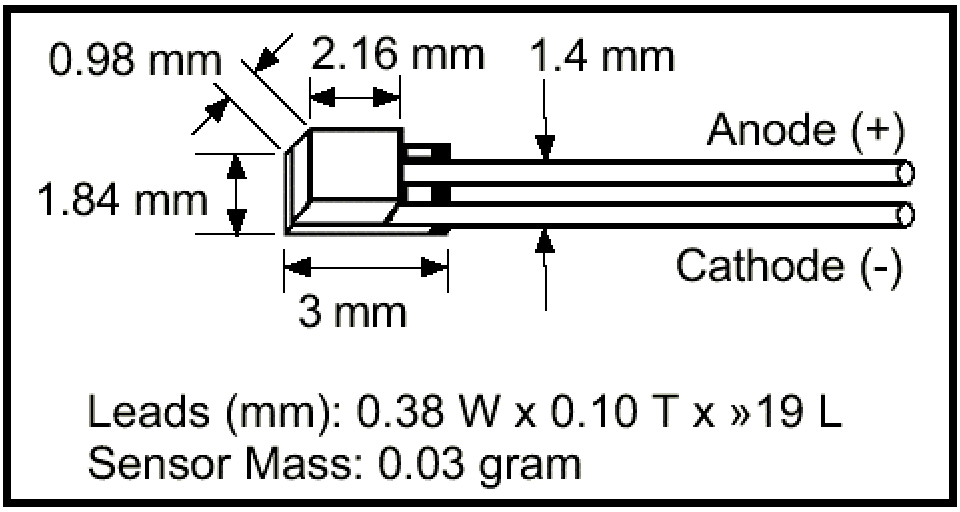


Figure 22 Package details for Cernox 1030 SD sensor

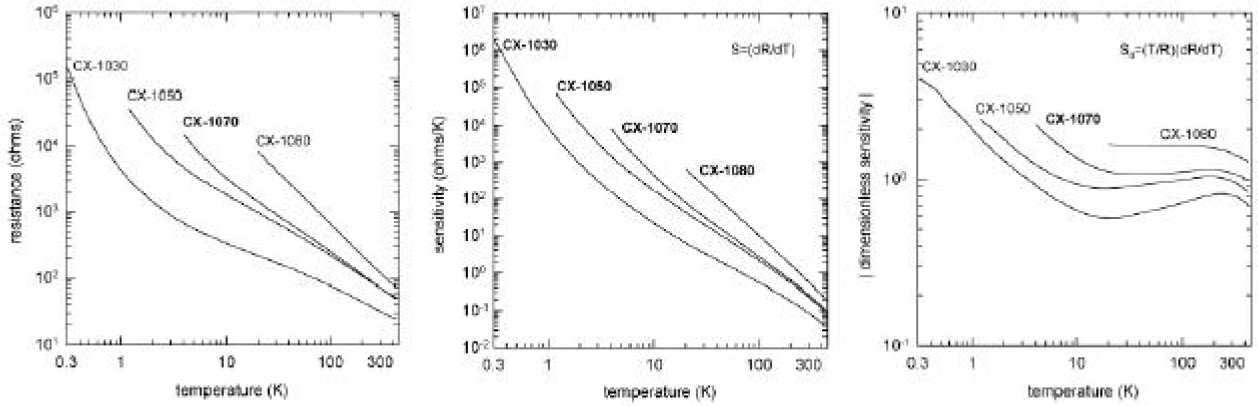


Figure 23 Typical resistance and sensitivity values for Cernox 1000 family sensors

7.1.4 Strut Details

Details of the Torlon support struts are shown in Figure 24. Each strut is machined from a single piece of Torlon.

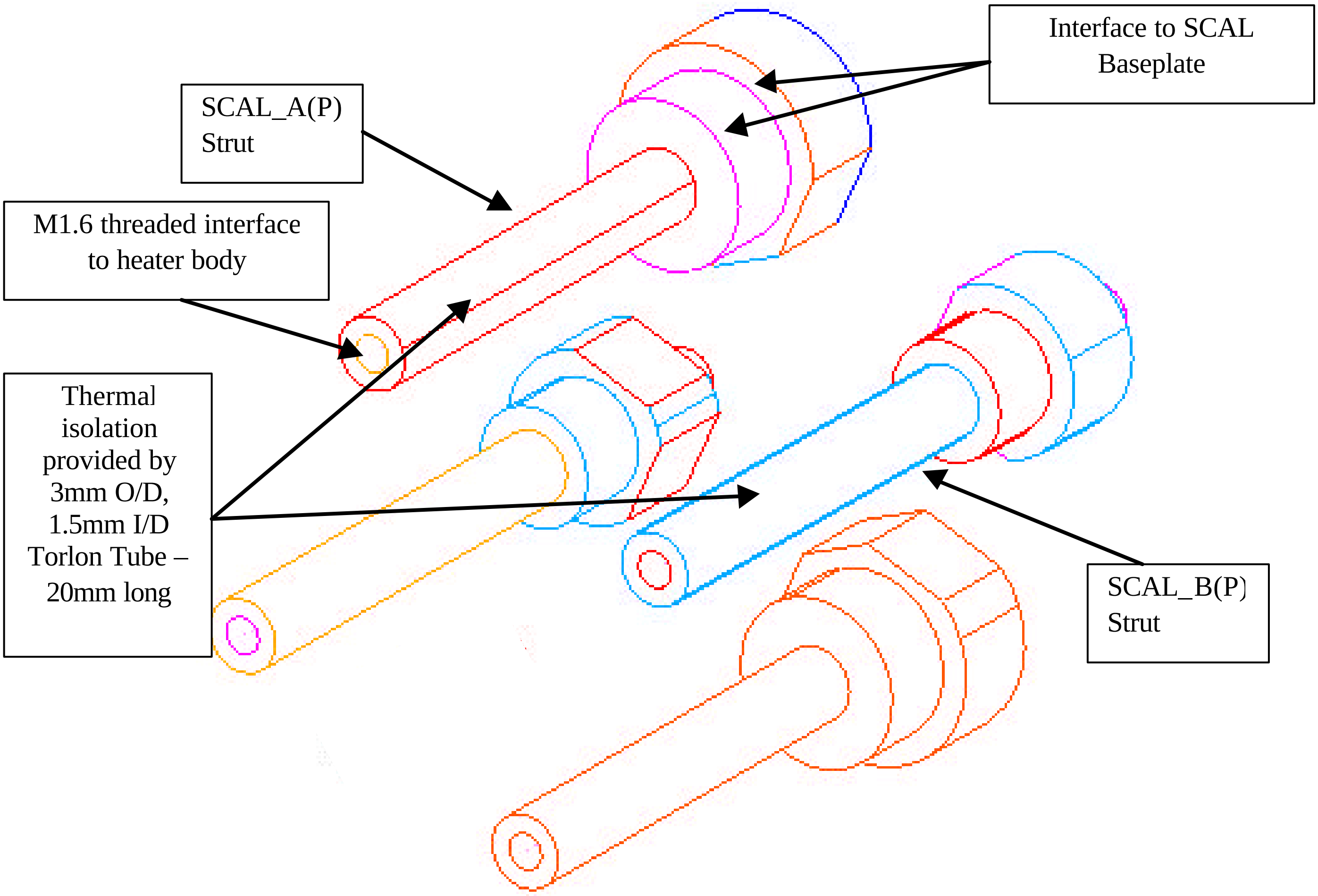


Figure 24 Details of Torlon Struts.

Wires will be wrapped helically around the legs to gain sufficient wiring length for thermal isolation purposes. Near the base of each strut will be a hole in the tube wall through which wiring will be routed to the tube cavity, and potted with epoxy (Figure 38).

7.2 SCAL Baseplate

The SCAL baseplate is shown in Figure 25 and Figure 26. During thermal prototype tests, a degree of radiant heating of passive sources by the active source was noticed. Therefore the SCAL baseplate features a baffle, shown in Figure 26, which is machined as one part with the SCAL baseplate for optimal heatsinking. The rear of the SCAL baseplate has four shouldered holes to accept the thermal source assemblies. These holes are 7 mm and 5 mm diameter for SCAL_A and SCAL_B sources respectively, with a larger diameter shoulder for retention of the Torlon struts. These oversized holes enable pre-assembly of the thermal sources prior to feeding the completed assemblies through the holes from the rear of the baseplate. The source assemblies are then clamped in place with the strut retaining plate, as shown in Figure 27.

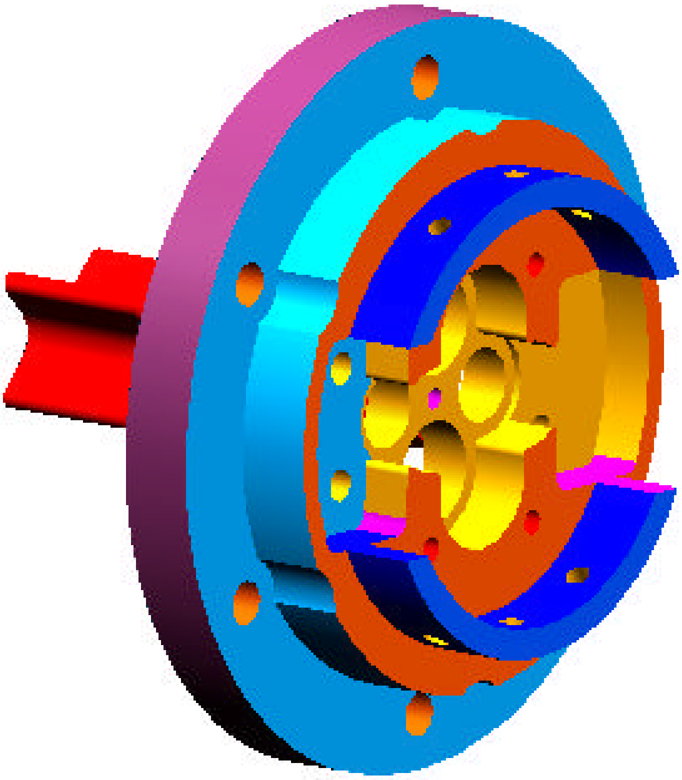


Figure 25 Rear view of SCAL baseplate.

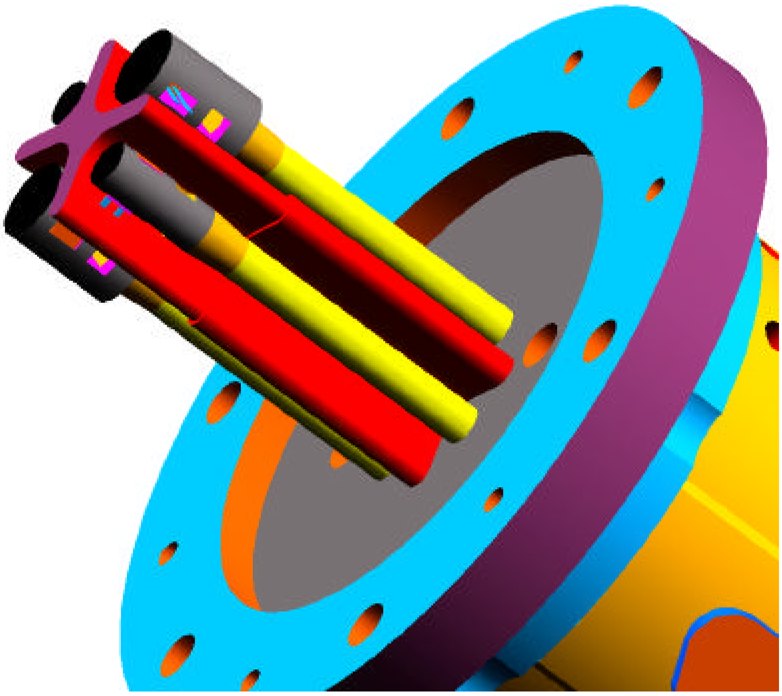


Figure 26 Front view of SCAL showing details of baffle.

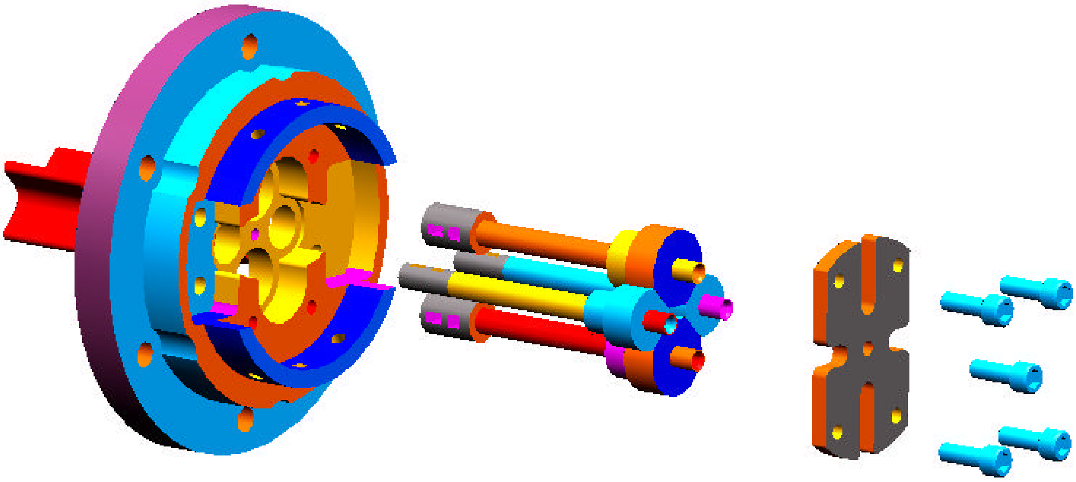


Figure 27 Details of integration of thermal source assemblies and strut retention plate.

7.3 Attachment of Thermal Sources to Torlon Legs

The interface of the aluminium heater bodies to the Torlon struts is critical, as if a heater body breaks free, it could affect other subsystems and, possibly, compromise the operation of the spectrometer. At the time of writing design modification is underway which involves placing a cover – either a filter or just polypropylene – over the front face of SCAL to contain any failed components.

The heater bodies are attached to the Torlon struts using an M1.6 thread, together with Epotek 920 epoxy as shown in Figure 28. The static load bearing capacity of this arrangement is considered in Section 7.7.1. This interface will be the subject of a series of mechanical tests and thermal cycles on test pieces.

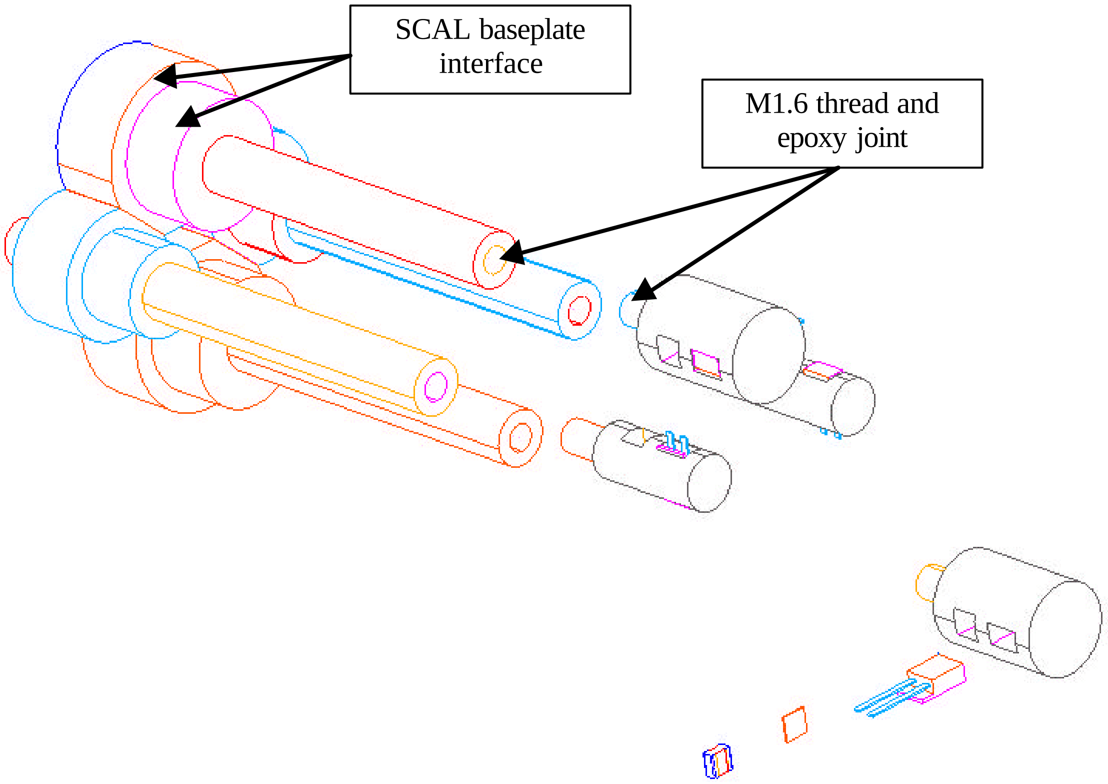


Figure 28 Details of aluminium-Torlon interface.

7.4 Attachment of Torlon Struts to SCAL Baseplate

The interface for the Torlon struts is illustrated in Figure 27, Figure 28 and Figure 29. The interface consists of shouldered holes, as discussed in Section 7.2, and a retaining plate. Figure 30 shows a rear view of the baseplate with the thermal source assemblies in place and held with the retaining plate. The retaining plate has machined slots to fit around the bases of the Torlon struts. The strut bases also serve as wiring channels, and these slots enable assembly without damaging the wires.

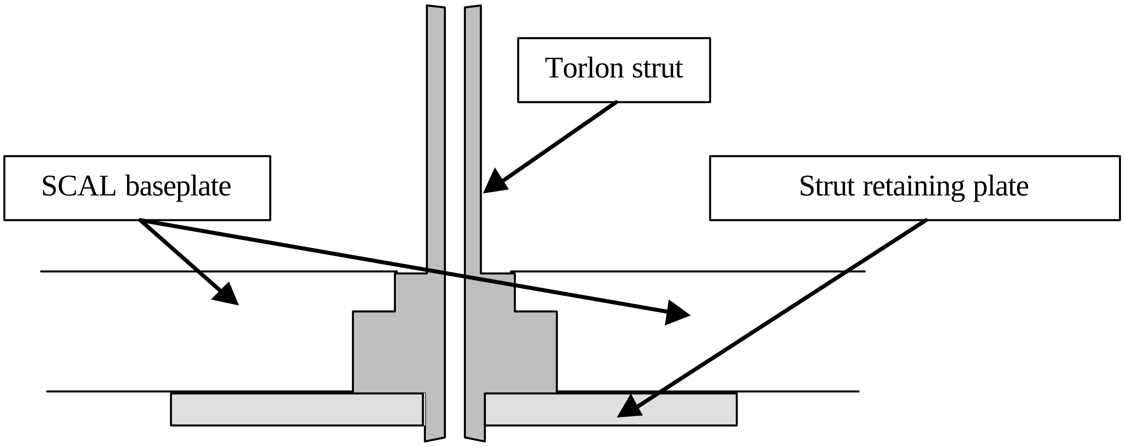


Figure 29 Schematic of strut interface to SCAL baseplate.

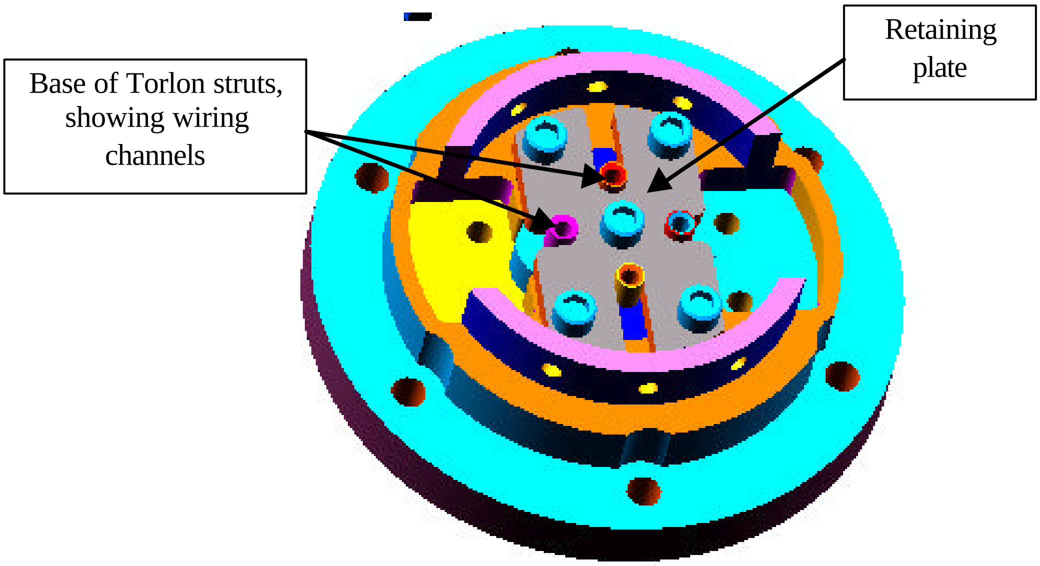


Figure 30 View of baseplate with integrated thermal sources and retaining plate.

7.5 Connector Brackets and Rear Cover

The electrical connectors (MDM37 PSB) are mounted on brackets as shown in Figure 32. These brackets have slots milled to accept the rear cover, as shown in Figure 32 and Figure 33

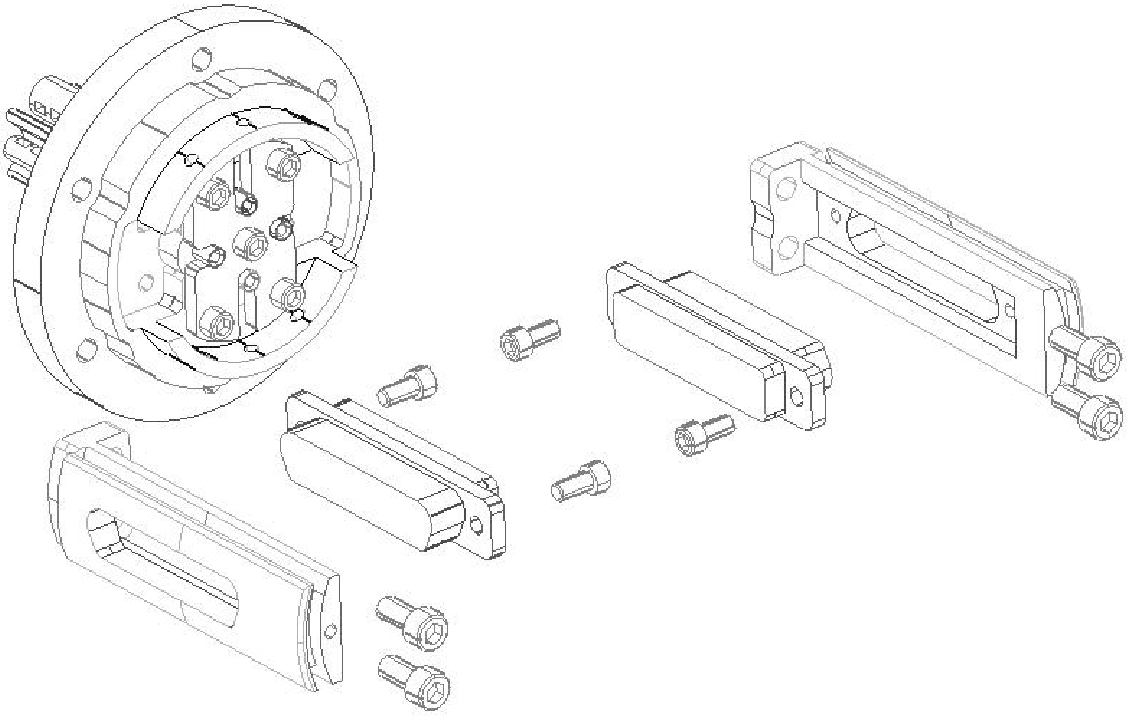


Figure 31 Assembly of electrical connector brackets on SCAL baseplate

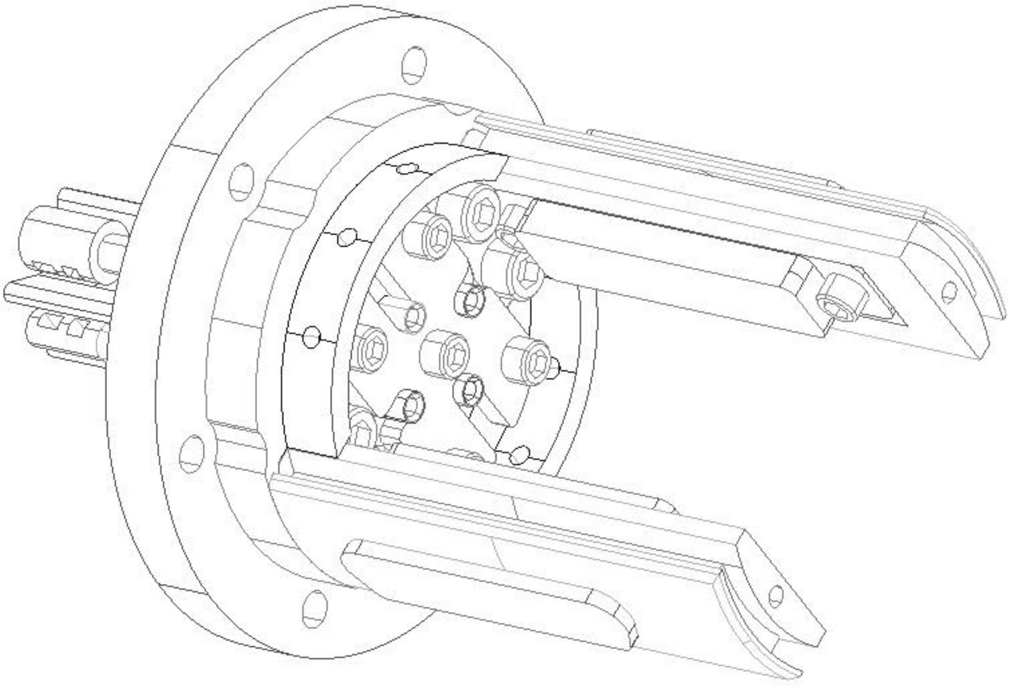


Figure 32 Details of connector mounting to rear of SCAL baseplate.

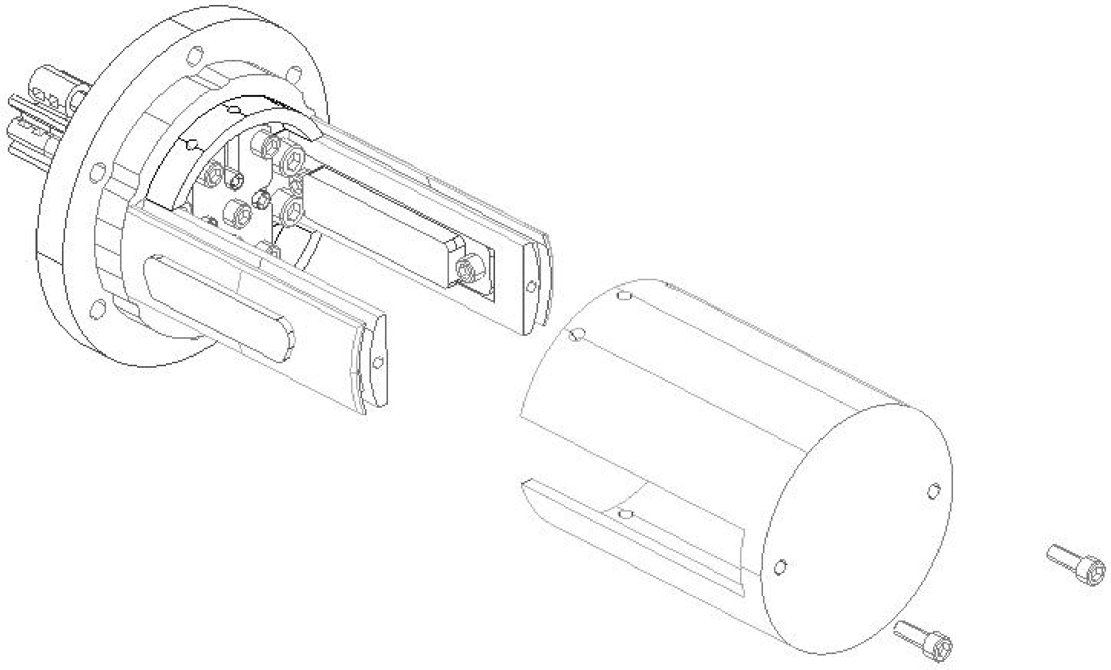


Figure 33 SCAL rear cover mounting

7.6 SCAL Snout

The front face of SCAL is protected by a snout, as shown in Figure 34. The front flange of this snout also forms the mating interface to the SCAL/SM8B baffle (provided by MSSL). This interface is further discussed in section 7.7.6. We are currently investigating the possibility of placing a filter or cover over the open SCAL face. This would make SCAL completely self-contained, and confine any catastrophic failure mode (e.g. heater body coming adrift) to SCAL.

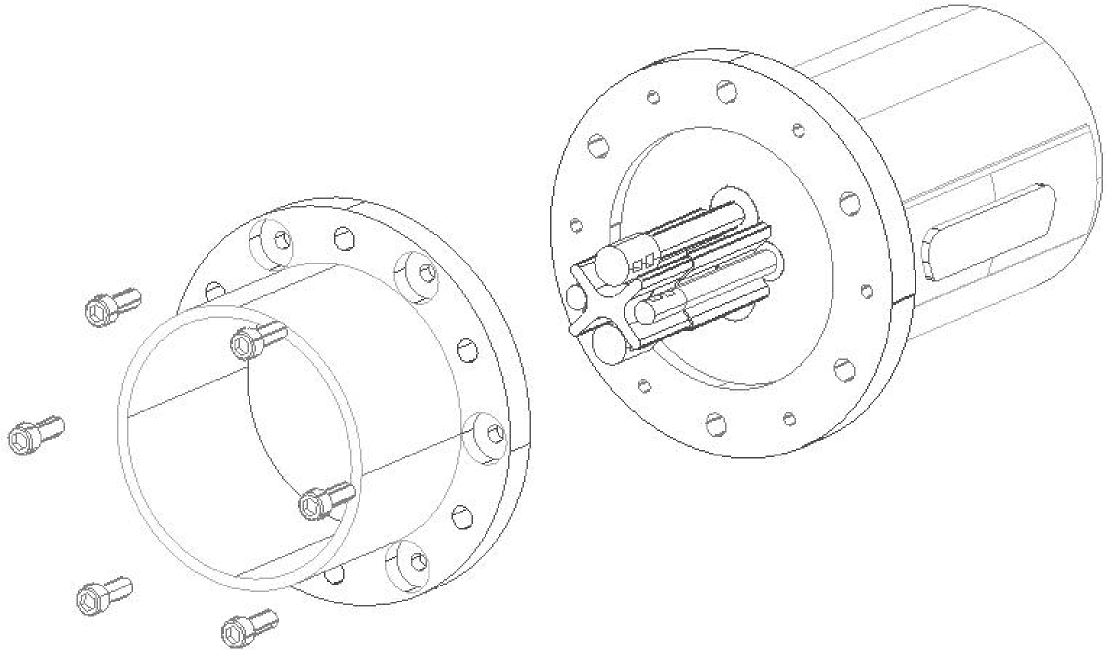


Figure 34 Illustration of SCAL snout.

7.7 Mechanical Interface

7.7.1 Launch Environment

The requirements from the SPIRE mechanical dictate that SCAL should withstand a maximum launch accelerations of 100 g (static) in the X, Y and Z directions. This section details a preliminary analysis of the system to get a first order estimate of the mechanical parameters. A full FEA analysis of the whole system will be performed before the instrument IBDR, as well as all necessary mechanical tests on prototypes to prove the design.

7.7.2 Maximum Deflection of Sources:

A MathCAD model has been produced (appendix A.1.3) to predict the maximum expected deflection of the sources on the Torlon legs for different launch accelerations. This analysis has been conducted only for the SCAL_A sources, as these are the sources that will experience the most severe forces (largest). It was also assumed that the acceleration was in a plane perpendicular to the rods (worst case).
The results are summarised in Table 2.

Table 2 Predicted peak source deflection as a function of launch acceleration. The final row (*) shows the predicted deflection of a 2.5 mm diameter solid rod for the quoted acceleration.

Launch Acceleration (g)	Peak Deflection (mm)
20	0.011
50	0.029
100	0.057
150	0.086
200	0.115
300	0.172
500	0.286
1350*	1.503*

7.7.3 Experiment to Verify Mechanical Model

An experiment was carried out to verify these predictions. A piece of 2.5mm diameter Torlon 4203 rod was clamped in a bench vice, with 22mm protruding as shown in Figure 35.

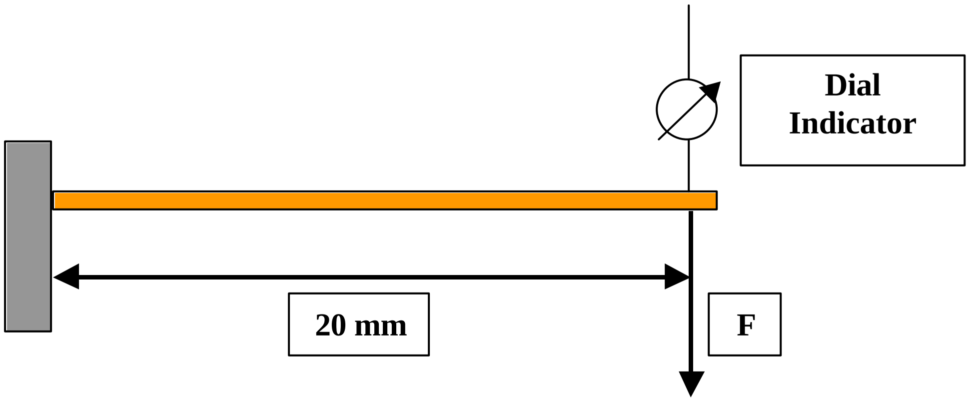


Figure 35 Simple experiment to determine maximum beam deflection under load.

In this experiment, with reference to Figure 35, the force, F, was applied by a 0.5kg mass hanging 20mm from the clamp point. The point of deflection measurement was at the point of application of this force. The deflection measured, for four different Torlon 4203 samples in the configuration shown above, was 1.58±0.15mm.

A mass of 0.5kg corresponds to a launch acceleration of 1350g. The final row of Table 2 shows the predicted deflection for this acceleration to be 1.503mm, in excellent agreement with the experimental result.

7.7.4 Static Load Bearing Capability:

- **Torlon** –Using data from the BP/AMOCO Torlon designers handbook for the shear strength of Torlon 4203, the static load strength limit corresponds an acceleration of 7.86×10^4g. However, this is the predicted acceleration needed for the Torlon itself to break. The weak point of the system will be the glued interface to the aluminium end caps.
- **Glued aluminium/Torlon interface**:- The BP/AMOCO Torlon designers handbook quotes a value for the shear strength of a Torlon-aluminium 2024 interface joined with epoxy as 4000 psi. This translates into a maximum acceleration of 1.70×10^4g.
- **Screw holding strength**:- The screw pull-out strength for a 4-40 UNC bolt in a 4.8 mm thick Torlon block has been quoted as 240 kg. This equates to an acceleration of around 6×10^5g.
- The SCAL sources will be fixed to the struts with an M1.4 thread and also fixed with epoxy, as described in section 7.3. A series of test pieces will be constructed to verify the pull-apart strength of this joint.

7.7.5 Resonant Frequency Calculation:

The first resonant frequency of the thermal sources is calculated using the following expressions:-

$$k\_tor := EC \cdot \frac{A\_tor}{L\_tor} \qquad freq1 := \frac{1}{2 \cdot \pi} \cdot \left(\frac{k\_tor}{m\_disc + m\_tor} \right)^{0.5}$$

where EC is the compressive modulus of elasticity (strictly, we should use the flexural modulus, but we use EC as this has the lowest value of the quoted moduli – worst case), A_tor and L_tor are the cross-sectional area and length of the Torlon strut, and m_tor and m_disc are the masses of the Torlon and aluminium end cap respectively.

This calculation gives a first resonant frequency of the SCAL_A source (most massive) as 5.97×10^3 Hz.

It should be noted that this calculation is for a simple mass on a spring. The system is more closely modelled by a mass on a cantilever, in which case the above quoted frequency should be multiplied by a factor of Pi. It is also made assuming the weakest of the quoted moduli, and assumes that the “mass on the spring” is the total mass of the aluminium cap and the whole Torlon strut.

7.7.6 Interface to SCAL/SM8B baffle

The SCAL mechanical interface consists of six 4-40 UNC bolts on a 42.5 mm PCD as illustrated in Figure 36. Full details of this interface are contained in AD27 (SCAL ICD, HSO-CDF-ICD-012).

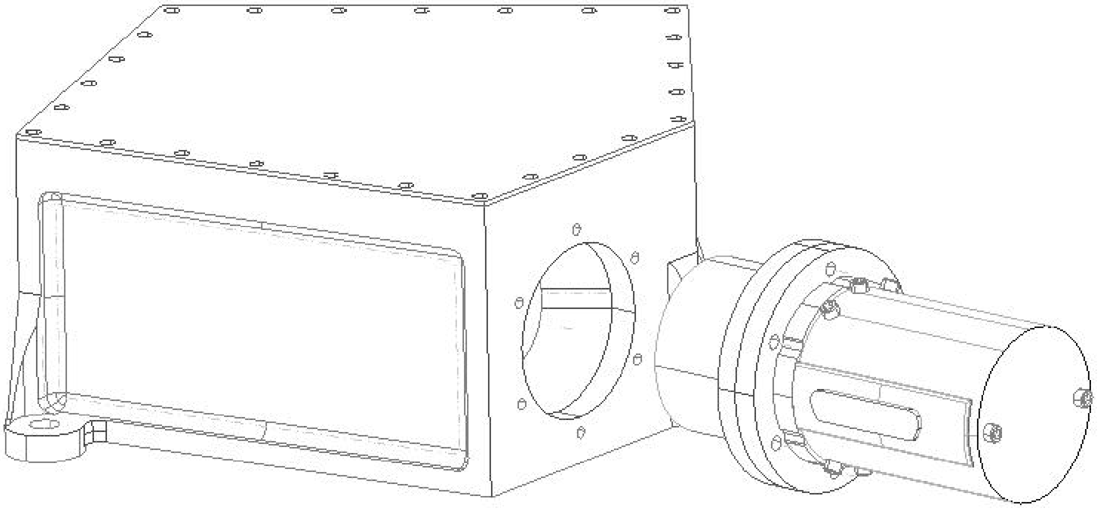


Figure 36 Illustration of interface to SCAL/SM8B baffle.

7.8 Thermal Design Details

A thermal model has been produced (appendix A.1.2) which models the thermal behaviour of the sources as a function of applied power. The components considered in this model are encompassed by the yellow shaded area in Figure 37. In the model, it is assumed that the SCAL baseplate is at 4.2 K. This model takes into account the temperature dependant heat capacity and thermal conductivity of all components shown, and has been validated by experiments in the lab with thermal prototypes.

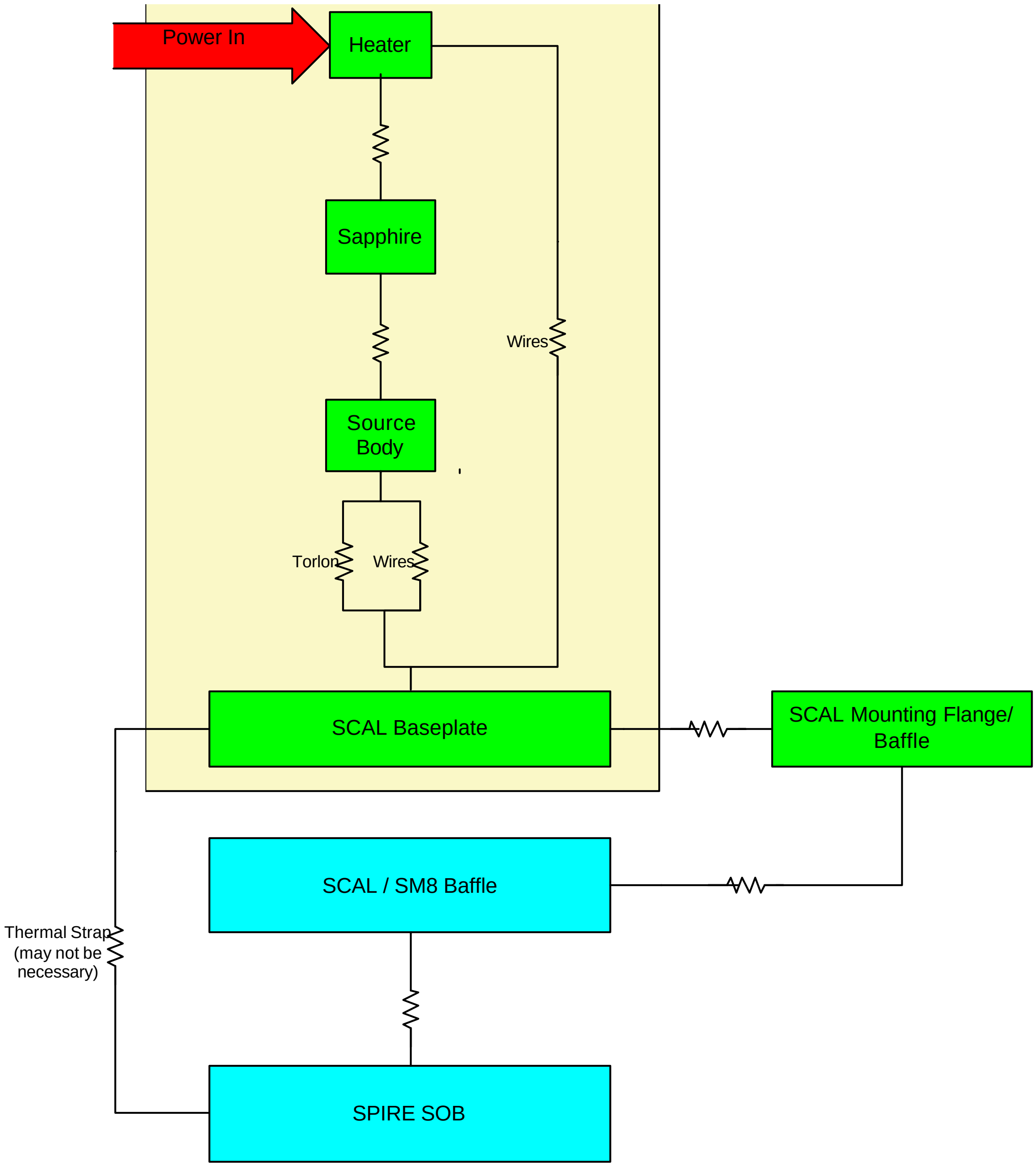


Figure 37 Thermal block diagram for SCAL (one source). Green indicates Cardiff supplied SCAL components, blue indicates MSSL supplied components.

7.8.1 Wire Heatsinking

Special care will be taken to ensure adequate heatsinking of all wires. This will be achieved by fixing wires to the heatsink points with Epotek 920 epoxy.

7.8.2 Baffling

A degree of radiant heating of passive sources by the active source was observed during preliminary lab tests. Therefore SCAL will have a baffle to separate the sources, as shown in Figure 26. This baffle will be machined with the baseplate as a single part to ensure good heatsinking. In addition, the baffle will be coated with a low emissivity finish (carbon loaded Epotek 920).

7.9 Thermal Interface

There is no direct thermal interface with SCAL and the SPIRE optical bench, as SCAL is mounted off the SCAL/SM8 baffle (Figure 36). In the unlikely event of heat sinking through the baffle to the SOB

proving insufficient, provision is made for a thermal strap from the SCAL baseplate directly to the SOB. This strap will be in the form of a well annealed, gold plated 99.999% pure copper strip.
The temperature of the SCAL interface with the baffle will be monitored by a thermometer on the SCAL baseplate.

7.10 Optical Design Details

- Talk to Kjetil – need verification that partial filling of pupil OK – need more info. on the true illumination of the pupil.
- Stray light – Tony

7.11 Optical Interface

To be written – need to consult with Kjetil & Tony

7.12 Electrical Design Details

7.12.1 Wiring

All heaters and thermometers will be wired in a four-wire configuration with manganin wire. Wiring for each source will be passed through holes in the SCAL strut where they will be anchored with epoxy, and then wrapped down the strut as shown in Figure 38 to gain sufficient wire length for thermal isolation purposes. At the base of each strut, the wires are passed through another hole through the tube wall, and into the centre of the strut. At the point where they emerge from the base of the strut, they will be anchored with epoxy.

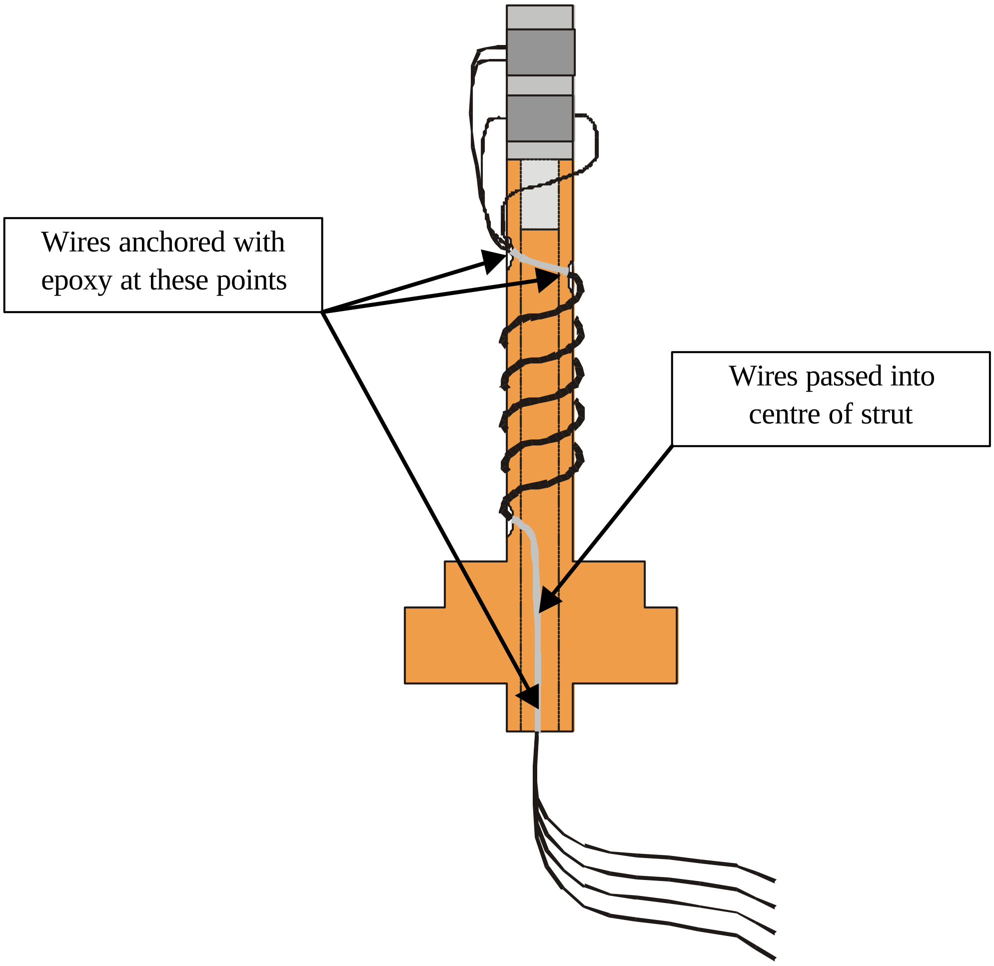


Figure 38 Routing of thermal source wiring.

After integration of the thermal sources to the SCAL baseplate, the wires are soldered directly to the prime and redundant MDM37PSB connectors. The mounting of the connectors is illustrated in Figure 32, and an indication of the wiring is shown in Figure 39. Connector savers will be employed for the CQM, PFM and FS models, and mate/demate log books kept.

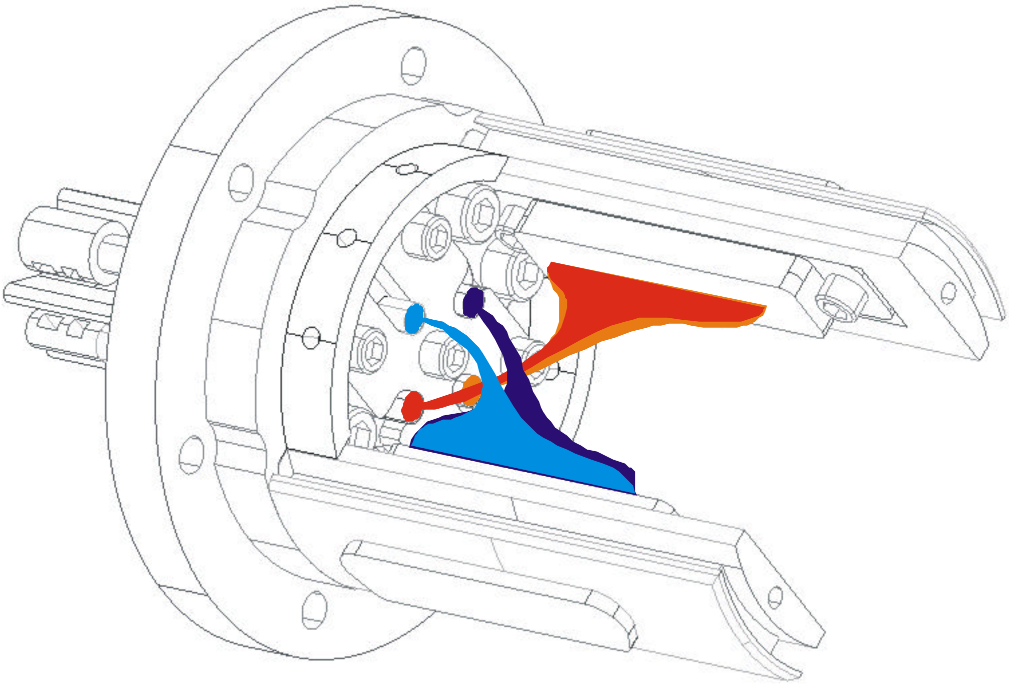


Figure 39 Illustration of wiring to connectors. The wiring for the prime sources is shown in blue, redundant in red.

7.12.2 Connector Pin-Outs and Harness Definition

A schematic of the SCAL harness is shown in Figure 40. This harness, to be supplied by Cardiff with SCAL, is isothermal, and runs between SCAL and the RF filter box. All conductors will be made from copper, and the harness length and routing is to be defined by MSSL. The pin allocation for the MDM37 PSB connectors (prime and redundant) is illustrated by Figure 41, and wiring details of the SPIRE cryoharness, C10, are shown in Table 3 and Figure 40.

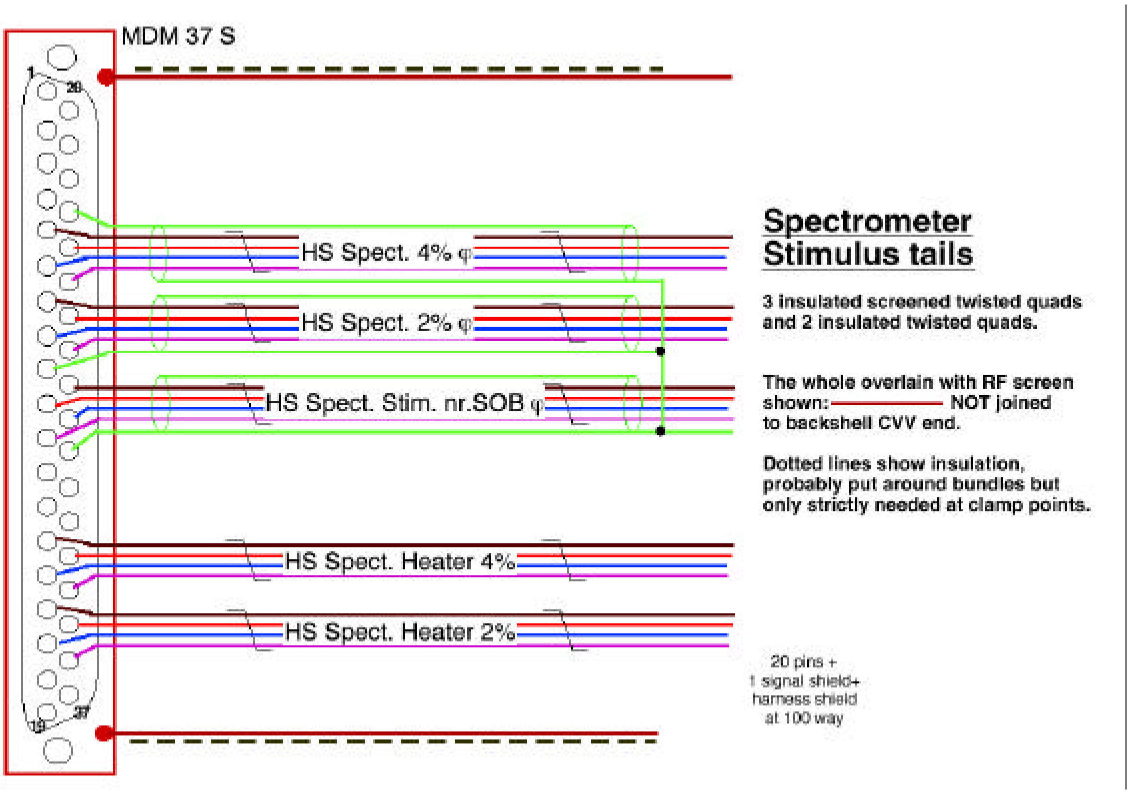


Figure 40 Schematic of SCAL harness wiring scheme. The same scheme is used for prime and redundant harnesses.

Table 3 Wiring details for SPIRE cryoharness, C10.

Function	**37way J21**	**Max. current**	**Wire lay-up**	**Max Ohms**	**100way #10**
HS Spect. 4% temperature I+ **SCAL_A**	5	1 µA	Insulated screened twisted quad	1000	
HS Spect. 4% temperature V+	6	N/A		1000	
HS Spect. 4% temperature V-	24	N/A		1000	
HS Spect. 4% temperature I-	25	1 µA		1000	
HS Spect. 4% temperature shld*	23	N/A		N/A	
HS Spect. 2% temperature I+ **SCAL_B**	7	1 µA	Insulated screened twisted quad	1000	
HS Spect. 2% temperature V+	8	N/A		1000	
HS Spect. 2% temperature V-	26	N/A		1000	
HS Spect. 2% temperature I-	27	1 µA		1000	
HS Spect. 2% temperature shld*	9	N/A		N/A	
HS Spect. Stim near SOB temperature I+	10	1 µA	Insulated screened twisted quad	1000	
HS Spect. Stim near SOB temperature V+	11	N/A		1000	
HS Spect. Stim near SOB temperature V-	28	N/A		1000	
HS Spect. Stim near SOB temperature I-	29	1 µA		1000	
HS Spect. Stim near SOB temperature shld*	30	N/A		N/A	
HS Spect. 4% heater I+ **SCAL_A**	14	9 mA	Twisted quad	30	
HS Spect. 4% heater V+	15	9 mA		30	
HS Spect. 4% heater I-	33	9 mA		30	
HS Spect. 4% heater V-	34	9 mA		30	
HS Spect. 2% heater I+ **SCAL_B**	16	7 mA	Twisted quad	30	
HS Spect. 2% heater V+	17	7 mA		30	
HS Spect. 2% heater I-	35	7 mA		30	
HS Spect. 2% heater V-	36	7 mA		30	

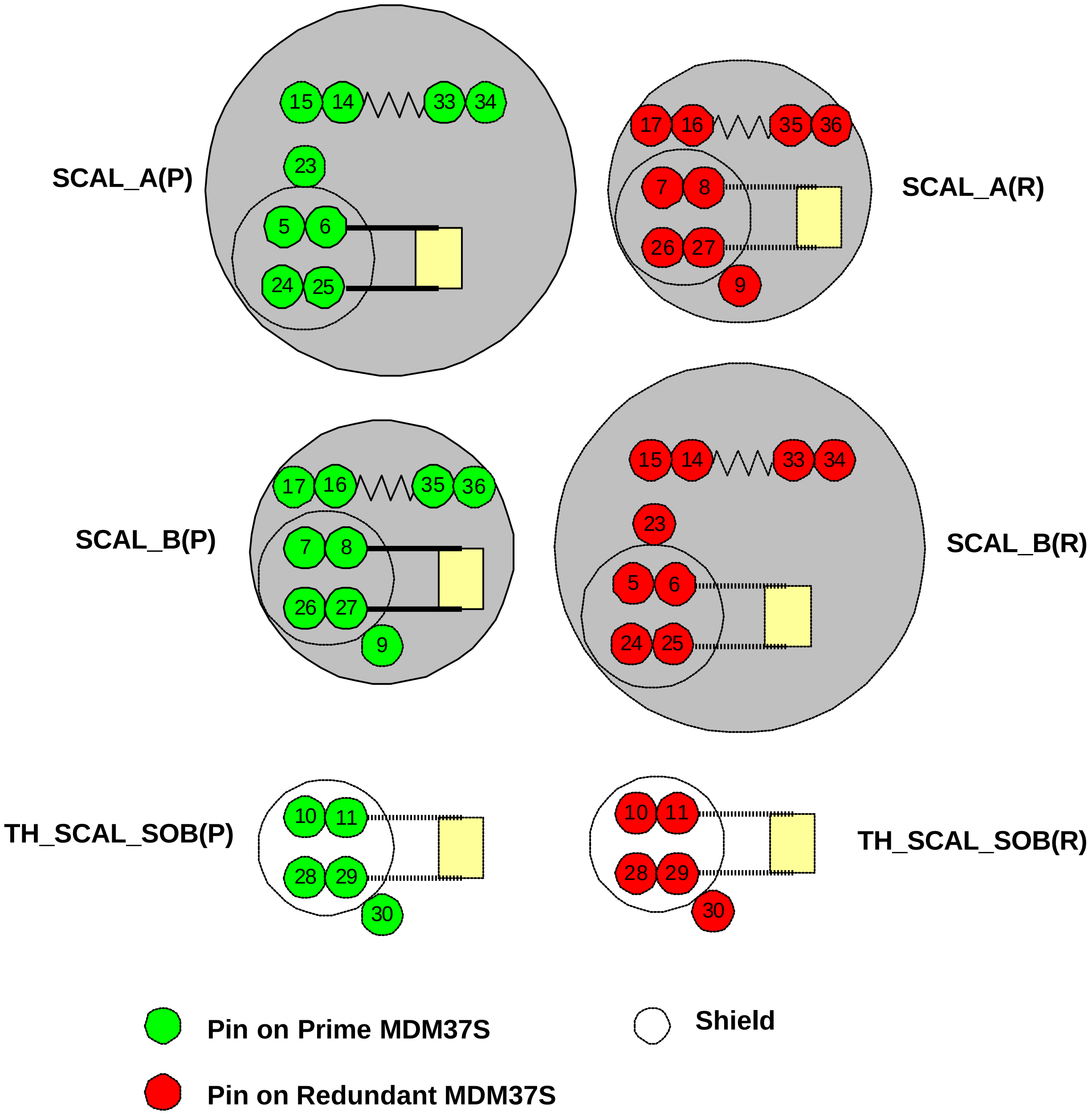


Figure 41 Schematic of pin allocation on SCAL prime and redundant connectors

7.13 Electrical Interface

Current drive for the SCAL heaters was agreed at the SPIRE interface review in November 2000. The requirements listed below assume a final heater impedance of 500 Ω and wiring impedance of 30 Ω per wire. The design of SCAL has changed significantly since the interface review. There is a need for two more thermometry channels (one prime, one redundant) over what was agreed at the review. We need to verify with the warm electronics providers (CEA-SAp) that this is not a problem.

7.13.1 Maximum Drive Current

Maximum power is specified as 5mW (goal - TBC), but we may want to run at higher power. Therefore we have allowed for a maximum power dissipation of 15mW. Assuming a 500 Ω heater resistor, this gives a required drive current of 5.5mA.

7.13.2 Adjustability of the drive current

12-bit resolution (minimum) is required in the range 0 – 5.5mA. This will give a minimum of 2275 adjustment steps in the target operating range.

7.13.3 Required Maximum Drive Voltage

The required maximum drive voltage, assuming a 30 Ω harness impedance in each direction, is 3.08 V. The voltage drop across the heater in this situation will be 2.75 V.

7.13.4 Drive Current Stability

The required repeatability for calibrator radiant power is 1%.

The stability and repeatability of the drive current should be within 5μA or 0.5% of the drive current, whichever is the greater.

7.13.5 Power Supply Redundancy

Separate power supplies are required for each SCAL heater – 2 prime, 2 redundant. Completely independent circuits will drive the prime and redundant SCAL heaters.

7.13.6 Requirements on Thermometry Accuracy

In deriving these requirements, we have made the following assumptions:

(1) Cernox 1030 thermometer with properties close to generic example in Lakeshore catalogue.
(2) Required temperature measurement range = 4 K – 120 K
(3) Nominal operating temperature range = 5 – 90 K (to match dilute 80 K telescope Rayleigh-Jeans telecope spectrum).
(4) Goal temperature accuracy & stability = 1% in nominal range, 2% at 80 K. Note: this is not stated in the IRD, but internally decided.

Based on these assumptions, we have created a MathCad spreadsheet (Cernox_spec.mcd) to analyse the corresponding warm electronics requirements for the SCAL thermometers, which are:

(1) Constant current drive
(2) Drive current in the range 10 – 30 μA. Currents above this range may cause unacceptable self-heating.
(3) 16-bit ADC resolution.
(4) Stability: 1% on drive current required, driving through resistances of (500+2000)Ω (2kΩ from two harness wires), up to ~35kΩ.

8 Hardware Tree

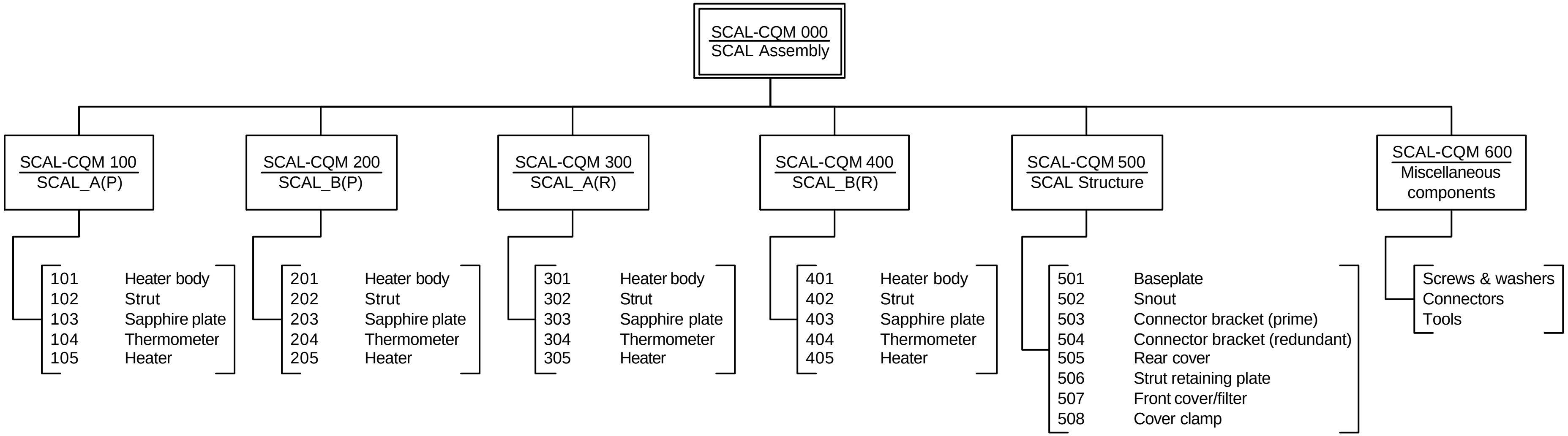


Figure 42 Hardware tree

9 Mass Breakdown

The mass breakdown of all SCAL components is shown in Table 4 below.
This breakdown does not include the option of fitting a front cover over the snout to protect other SPIRE subsystems from SCAL component failure. Therefore we request that the current mass budget allocation of 200g remains in place until further notice.

Table 4 SCAL mass breakdown

SCAL COMPONENT MASS CALCULATION

Component	**Total mass**	**Single part mass**
REAR COVER	0.0263716 Kg	
- top retaining hex (2)	0.000653416 Kg	0.000326708 Kg
- base retaining hex (4)	0.001120766 Kg	0.0002801915 Kg
CONNECTOR BRACKET (2)	0.01183558 Kg	0.00591779 Kg
- retaining hex (4)	0.002544804 Kg	0.000636201 Kg
CONNECTOR (Ali 6061) (2)	0.01085444 Kg	0.00542722 Kg
- retaining hex (4)	0.001120736 Kg	0.000280184 Kg
STRUT CLAMP 0.0014163		
- retaining hex (5)	0.00163354 Kg	0.000326708 Kg
STRUT 5mm (2) (Torlon 5030)	0.001538742 Kg	0.000769371 Kg
STRUT 3mm (2) (Torlon 5030)	0.001006218 Kg	0.000503109 Kg
BASE	0.0342416 Kg	
- retaining hex (6)	0.00665784 Kg	0.00110964 Kg
SNOUT	0.0212208 Kg	
- retaining hex (6)	0.001960248 Kg	0.000326708 Kg
SOURCE 5mm (2)	0.000659434 Kg	0.000329717 Kg
SOURCE 3mm (2)	0.000235732 Kg	0.000117866 Kg
HEATER (4)	0.0000098782 Kg	2.46955E-006 Kg
THERMOMETER (4)	0.0000021168 Kg	5.292E-007 Kg
SAPPHIRE PLATE (4)	0.000046638 Kg	1.16587E-006 Kg

Main assembly (Rear Cover, Connector Brackets, Strut Clamp, Base, Snout) = 93.08588 g

Entire assembly = 126.2 g

10 Reliability & Redundancy

10.1 Reliability Block Diagram

RELEX models to be included

10.2 Fault Tree Analysis

RELEX models to be included

10.3 Single Point Failures

No single point failure modes have been identified

10.4 FMECA

A failure modes effects and criticality analysis has been performed (Table 5) on all functional elements of SCAL (excluding structural elements whose integrity has been assessed with stress analysis and fracture mechanics analysis as necessary) which can cause failure effects within the experiment or cause damage to or interfere with, the proper functioning of the HERSCHEL spacecraft.

Each failure effect identified has been given a criticality category according to the definition below:

- Category 1**:** The failure effect is not confined to the subsystem. When this failure results also in loss or degradation of the instruments function this shall be stated.
- Category 2: The failure results in loss or degradation of the subsystems function but the effect is confined to the subsystem.
- Category 3: Minor internal subsystem failures.

The following attributes have been added to the criticality category as appropriate:

- "R", if the design contains a redundant item which can perform the same function
- "SH", if the failure effect causes a safety hazard
- "SPF" if the failure is caused by a single point failure.

The following failure modes have been considered: -

Premature operation
Failure to operate (at the prescribed time)
Failure to cease operation (at the prescribed time)
Failure during operation
Degradation or out of tolerance operation
For failure at component level e.g. hardware interface
  - short circuit
  - open circuit
  - incorrect function e.g. from single event upset - ex: latch-ups.

Incorrect commands or sequence of commands
Incorrect software functions
Mechanical failure

Design specifications, descriptions functional diagrams etc. used in the preparation of the FMECA shall be attached or referenced.

10.5 Critical Components Identification

Table 5 Failure Modes Effects and Criticality Analysis (FMECA) for the SCAL system

FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS (FMECA)

Product: SPIRE Instrument
Project/Phase: Herschel
System/Subsystem/Equipment: SCAL
Mission phase/Operational Mode: Space Flight
Prepared by: P.Hargrave
Approved by:
Date: 25/08/01
Document reference:
Issue:

Id number	Item/ block	Function	Failure mode	Failure cause	Failure effects a. Local effects b. End effects	Severity	Failure detection method/ observable symptoms	Compensation provisions	Correction actions	Remarks
000.001	SCAL Assembly		Input power short to ground (source A or B)	Connector Failure	a. Loss of SCAL_A or SCAL_B sources b. Degraded dynamic range for spectrometer detectors	2R	No source heating for one of the prime sources	Switch to redundant side	Can run second prime source – impaired telescope nulling	There are two prime sources with full redundancy. Running the other prime source will still allow some degree of telescope nulling with perhaps increased power dissipation
000.002	SCAL assembly		Input power open circuit (source A or B)	Connector Failure	a. Loss of SCAL_A or SCAL_B sources b. Reduced dynamic range for spectrometer detectors	2R	No source heating for one of the prime sources	Switch to redundant side	Can run second prime source – impaired telescope nulling	There are two prime sources with full redundancy. Running the other prime source will still allow some degree of telescope nulling with perhaps increased power dissipation
000.003	SCAL assembly		Thermometry short (source A or B)	Connector Failure	a. Inability to monitor SCAL_A or SCAL_B temperatures b. Loss of thermometry data for source	3R	Low impedance reading on source thermometer	Switch to redundant side	Can still run source “blind” based on experimental data until we maximise the central peak in the interferogram	

FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS (FMECA)

Product: SPIRE Instrument
Project/Phase: Herschel
System/Subsystem/Equipment: SCAL
Mission phase/Operational Mode: Space Flight
Prepared by: P.Hargrave
Approved by:
Date: 25/08/01
Document reference:
Issue:

Id number	Item/ block	Function	Failure mode	Failure cause	Failure effects a. Local effects b. End effects	Severity	Failure detection method/ observable symptoms	Compensation provisions	Correction actions	Remarks
000.004	SCAL assembly		Thermometry open circuit (source A or B)	Connector Failure	a. Inability to monitor SCAL_A or SCAL_B temperatures b. Loss of thermometry data for source	3R	Open circuit reading for thermometer	Switch to redundant side	Can still run source “blind” based on experimental data until we maximise the central peak in the interferogram	
100.001	SCAL_A(P) – prime 4% source assembly	Radiant source for telescope nulling	Heater body breaks off strut	Manufacturing error. Part failure.	a. Loss of SCAL_A(P) source b. Degraded dynamic range for spectrometer detectors. Possible damage to other subsystem and instrument components (e.g. SM8B, beam splitter)	1R	Open circuit reading for thermometer and heater	a. Switch to redundant side b. None	Can run second prime source – impaired telescope nulling	
101.001	SCAL_A(P) – heater body		Loss of black coating	Manufacturing error.	a. Reduced emissivity of source – increased power dissipation to achieve required level of nulling. Impaired nulling. b. Possible damage to other subsystem and instrument components (e.g. SM8B, beam splitter) from coating fragments	1R		a. Switch to redundant side b. None	Can run second prime source – impaired telescope nulling	May not be possible to match spectrum within requirements
102.001	SCAL_A(P) – strut	Supports heater body – provides thermal isolation	Breaks	Material failure	a. Loss of source b. Reduced dynamic range for spectrometer detectors. Possible damage to other subsystem and instrument components (e.g. SM8B, beam splitter)	1R		a. Switch to redundant side b. None	Can run second prime source – impaired telescope nulling	

FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS (FMECA)

Product: SPIRE Instrument
Project/Phase: Herschel
System/Subsystem/Equipment: SCAL
Mission phase/Operational Mode: Space Flight
Prepared by: P.Hargrave
Approved by:
Date: 25/08/01
Document reference:
Issue:

Id number	Item/ block	Function	Failure mode	Failure cause	Failure effects a. Local effects b. End effects	Severity	Failure detection method/ observable symptoms	Compensation provisions	Correction actions	Remarks
103.001	SCAL_A(P) – sapphire plate	Provides electrical isolation for heater resitor & good thermal path to heater body	Cracks	Manufacturing error. Differential thermal contraction	a. Impaired thermal path to heater body – increased warm-up time b. Longer warm-up	3R		Switch to redundant side		May be detectable by performing cross-calibration with redundant side sources.
104.001	SCAL_A(P) – thermometer	Monitors source temperature	Short	Manufacturing error. Part failure.	a. Inability to monitor SCAL_A temperature b. Loss of thermometry data for source	3R	Low impedance reading on source thermometer	Switch to redundant side	Can still run source “blind” based on experimental data until we maximise the central peak in the interferogram	
104.002			Open	Manufacturing error. Part failure.	a. Inability to monitor SCAL_A temperature b. Loss of thermometry data for source	3R	Open circuit reading for thermometer	Switch to redundant side	Can still run source “blind” based on experimental data until we maximise the central peak in the interferogram	
104.003			Erratic output	Manufacturing error. Part failure.	a. Inability to monitor SCAL_A temperature b. Loss of thermometry data for source	3R		Switch to redundant side	Can still run source “blind” based on experimental data until we maximise the central peak in the interferogram	

FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS (FMECA)

Product: SPIRE Instrument
Project/Phase: Herschel
System/Subsystem/Equipment: SCAL
Mission phase/Operational Mode: Space Flight
Prepared by: P.Hargrave
Approved by:
Date: 25/08/01
Document reference:
Issue:

Id number	Item/ block	Function	Failure mode	Failure cause	Failure effects a. Local effects b. End effects	Severity	Failure detection method/ observable symptoms	Compensation provisions	Correction actions	Remarks
104.004			No output	Manufacturing error. Part failure.	a. Inability to monitor SCAL_A temperature b. Loss of thermometry data for source	3R		Switch to redundant side	Can still run source “blind” based on experimental data until we maximise the central peak in the interferogram	
105.001	SCAL_A(P) – Heater resistor	Heater for source	Open	Manufacturing error. Part failure.	a. Loss of source b. Reduced dynamic range for spectrometer detectors	2R	No source heating	Switch to redundant side	Can run second prime source – impaired telescope nulling	There are two prime sources with full redundancy. Running the other prime source will still allow some degree of telescope nulling with perhaps increased power dissipation
105.002			Short	Manufacturing error. Part failure.	a. Loss of source b. Reduced dynamic range for spectrometer detectors	2R	No source heating	Switch to redundant side	Can run second prime source – impaired telescope nulling	There are two prime sources with full redundancy. Running the other prime source will still allow some degree of telescope nulling with perhaps increased power dissipation
105.003			Changed value	Manufacturing error. Part failure.	a. Change in drive requirements b. None	3R	Monitor I/V values for heater (4 wire configuration)	Change drive current Switch to redundant side?	Change drive current	

11 Assembly, Integration & Verification

A Manufacturing, Assembly, Integration and Verification (MAIV) flow chart has been prepared (HSO-CDF-FC-014) and will be updated under configuration control.
A full AIV plan is in preparation at the time of writing.

11.1 General

An overall exploded view of the SCAL assembly is shown in Figure 43.

11.2 Assembly

A full AIV plan is in preparation at the time of writing.

11.3 Integration

A full AIV plan is in preparation at the time of writing.

11.4 Verification

A full AIV plan is in preparation at the time of writing.

11.5 Transport & Storage

SCAL will be delivered in a nitrogen purged box for storage. SCAL will be supplied with a cover for the normally open emitter face. We require that this cover remains in place unless the cleanliness of the environment is class 10,000 or better. For the purposes of integration to the instrument, it is permissible to remove the SCAL cover in a class 100,000 environment for short periods. We assume there will be no need to disassemble SCAL once delivered to RAL. If that need arises, members from Cardiff must be present.

11.6 Handling

For the purposes of integration to the instrument, it is permissible to remove the SCAL cover in a class 100,000 environment for short periods. We assume there will be no need to disassemble SCAL once delivered to RAL. If that need arises, members from Cardiff must be present.

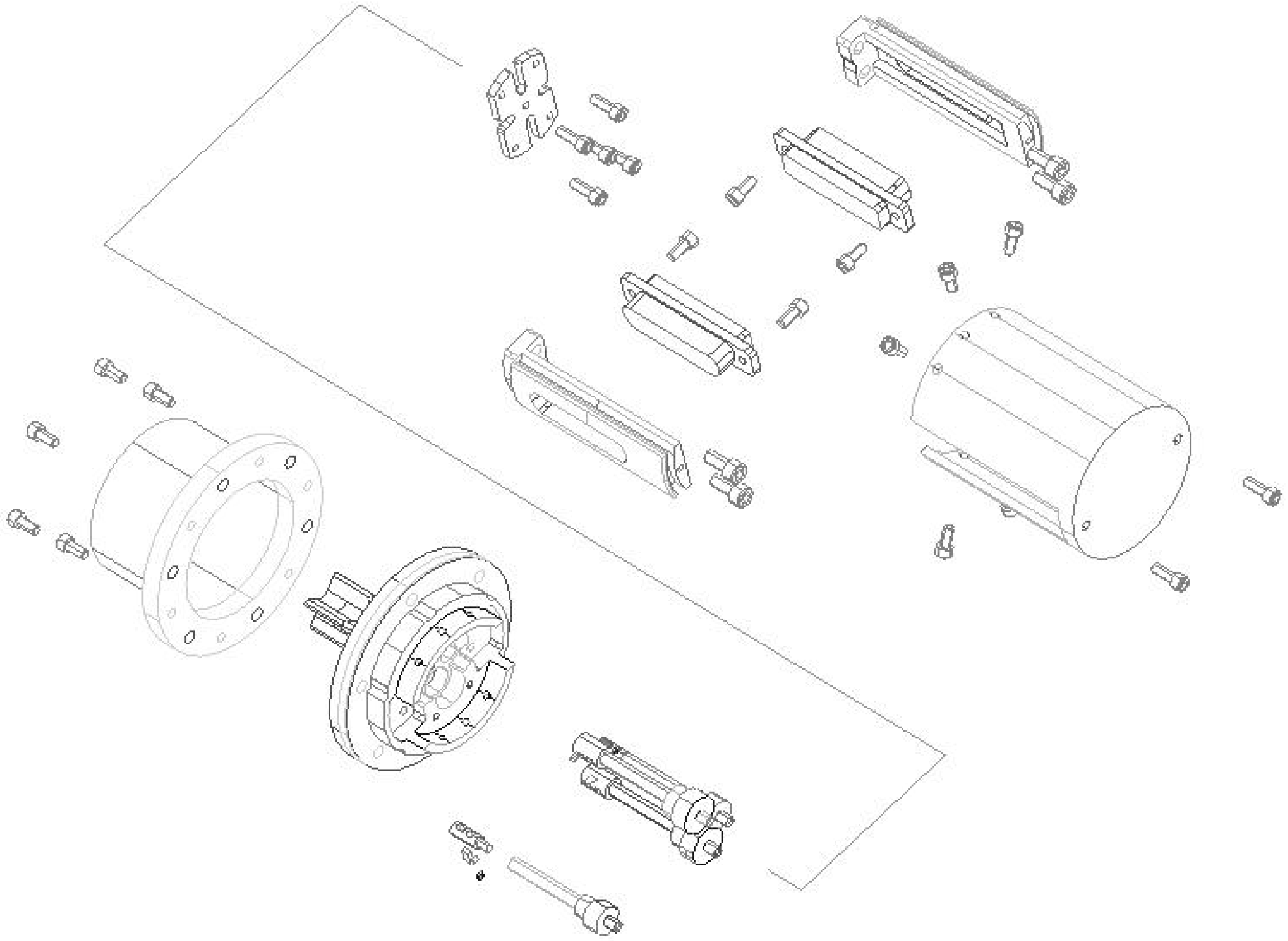


Figure 43 Exploded view of SCAL components.

A. Appendices

A.1. Appendix 1 – Details of Computer Models

A.1.1. Nulling of Telescope Emission Spectrum

SCAL photometric model **SCAL_Nulling.mcd** **8 August 2001**

Constants $h \equiv 6.626 \cdot 10^{-34}$ $c \equiv 3 \cdot 10^{8}$ $kb \equiv 1.38 \cdot 10^{-23}$

Planck function $B(nu,T) := \dfrac{2 \cdot h \cdot (nu)^3}{c^2 \cdot \left[e^{\left(\frac{h \cdot nu}{kb \cdot T} \right)} - 1 \right]}$

Telescope temperature $Ttel := 80$

Telescope emissivity

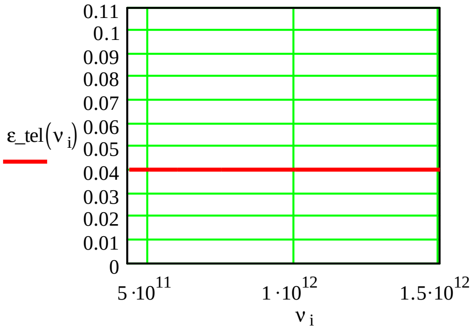
The emissivity and its wavelength dependence are both highly uncertain. Here we assume a constant value across the band, but make provision for a wavelength dependence being incorporated later

Nominal emissivity $\varepsilon tel\_o := 0.04$

$i := 1, 2 .. 6$ $\nu_i := \dfrac{c}{\lambda_i \cdot 10^{-6}}$

$\lambda_i :=$	$\varepsilon\_tel\_rel_i :=$
700	1
600	1
500	1
400	1
300	1
200	1

$\varepsilon\_tel(nu) := \text{linterp}(\nu, \varepsilon\_tel\_rel, nu) \cdot \varepsilon tel\_o$



Wavelength depedence can be incorporated by editing this ε_tel_rel table

Transmission between telescope and detector $t\_tel := 0.164$

Transmission between calibrator and detector $t\_cal := 0.203$

Figures are from SPIRE_FTS_3.mcd (see IIDR)

Coupling factors for telescope and calibrators (see below) $Tel\_factor := 0.457$ $Cal\_factor := 0.761$

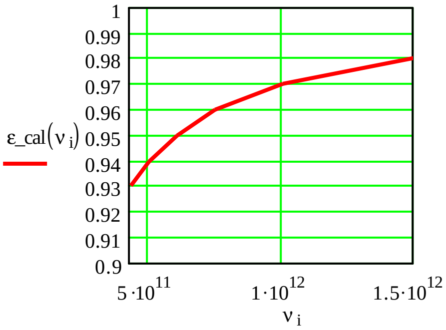
Pupil diameter and radius (mm) $D := 26$ $R := 0.5 D$

Calibrator black coating emissivity vs. wavelength

Here we assume a linear variation from 0.93 at 700 µm to 0.98 at 200 µm. This should be updated later with the best available information on the black coating.

$\lambda_i =$	$\varepsilon\_coating_i :=$
0	0.93
0	0.94
0	0.95
0	0.96
0	0.97
0	0.98

$\varepsilon\_cal(nu) := \text{linterp}(\nu, \varepsilon\_coating, nu)$



Calibrator A Diameter (mm) Effective emissivity

$dA := 5$ $\quad \varepsilon\_eff\_A(nu) := \left(\frac{dA}{D}\right)^2 \cdot \varepsilon\_cal(nu)$ $\quad \varepsilon\_eff\_A(\nu_1) = 0.0344$

$\varepsilon\_eff\_A(\nu_6) = 0.0362$

Calibrator B $dB := 3$ $\quad \varepsilon\_eff\_B(nu) := \left(\frac{dB}{D}\right)^2 \cdot \varepsilon\_cal(nu)$ $\quad \varepsilon\_eff\_B(\nu_1) = 0.0124$

$\varepsilon\_eff\_B(\nu_6) = 0.0130$

Calibrator C
(the 5-K background)

$$\varepsilon\_eff\_C(nu) := \varepsilon\_cal(nu) \cdot \left[1 - \left(\frac{dA}{D}\right)^2 - \left(\frac{dB}{D}\right)^2\right]$$

Calibrator Temperatures (K) $T\_A := 52.5$ $\quad T\_B := 5$ $\quad T\_C := 5$

Telescope spectrum nulling ratio

$j := 1, 2 .. 100$ $\quad k := 1, 2 .. 72$ $\quad \lambda 1 := 200$ $\quad \lambda 2 := 670$

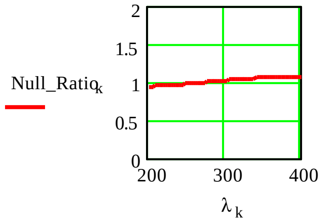
$$\nu 1 := \frac{c}{\lambda 1 \cdot 10^{-6}} \qquad \nu 2 := \frac{c}{\lambda 2 \cdot 10^{-6}} \qquad \nu_j := \nu 1 + \frac{j}{100} \cdot (\nu 2 - \nu 1) \qquad \lambda_j := \frac{c}{\nu_j} \cdot 10^6$$

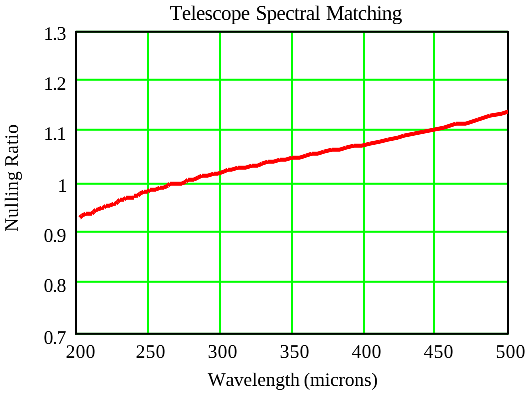
$$Ratio_j := \frac{\left[B(\nu_j, T\_A) \cdot \varepsilon\_eff\_A(\nu_j) \cdot t\_cal + \left(B(\nu_j, T\_B) \cdot \varepsilon\_eff\_B(\nu_j) \cdot t\_cal\right) + B(\nu_j, T\_C) \cdot \varepsilon\_eff\_C(\nu_j) \cdot t\_cal\right] \cdot Cal\_factor}{B(\nu_j, Ttel) \cdot \varepsilon\_tel(\nu_j) \cdot t\_tel \cdot Tel\_factor}$$

$Null\_Ratio_j := Ratio_j$ $\quad Null\_Ratio\_to\_400_k := Ratio_k$ $\quad Null\_Ratio\_to\_400_0 := Ratio_1$

Nulling errors at
200 and 400µm

$|1 - \min(Null\_Ratio\_to\_400)| = 0.0713$ $\quad |1 - \max(Null\_Ratio\_to\_400)| = 0.0777$





Optimum settings for 4/2.5 mm

1. 80 K 4% 57 K 5 K
 14 K 108 K
2. 80 K 2% 5 K 66 K
3. 80 K 10% 109 K 5 K
 99 K 50 K

1. 60 K 4% 44 K 5 K (goal not met)
 13 K 78 K
2. 60 K 2% 5 K 50 K
3. 60 K 10% 49 K 100 K

Optimum settings for 5/2.5 mm

1. 80 K 4% 10 K 110 K
2. 80 K 2% 15 K 57 K (goal not met)
3. 80 K 10% 78 K 5 K

Optimum settings for 5/3.5 mm

1. 80 K 4% 5 K 68 K
2. 80 K 2% 5 K 43 K (goal not met)
3. 80 K 10% 78 K 5 K

Optimum settings for 5/2 mm

1. 80 K 4% 14 K 152 K
2. 80 K 2% 5 K 91 K
3. 80 K 10% 78 K 5 K

Effect of 8-dB Gaussian illumination profile on the pupil

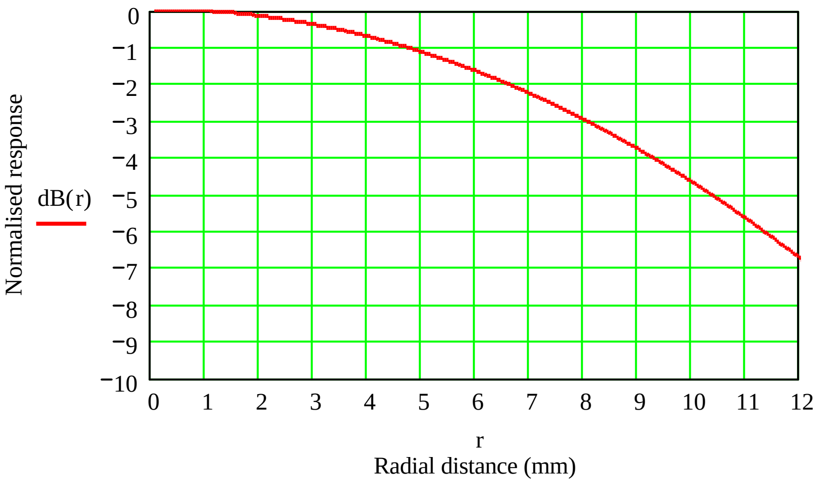
The two pupils (telescope and calibrator) are illuminated by the FTS feedhorns with a nominal edge taper of 8 dB. The power received from the pupil is therefore weighted according to this illumination profile.

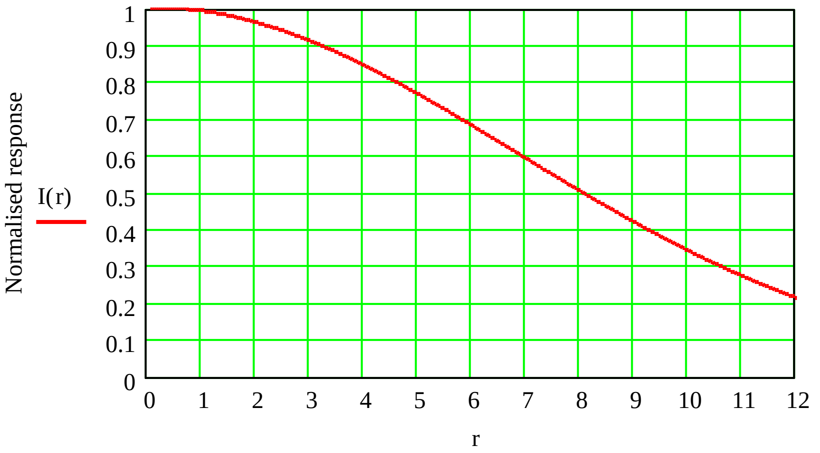
Pupil edge taper (dB) $\text{taper\_dB} := 8$

Pupil edge taper (linear) $\text{taper\_lin} := 10^{\frac{\text{taper\_dB}}{10}}$ $\text{taper\_lin} = 6.3$

Define Gaussian illumination pattern

$$\text{ro} := \frac{R}{\left(-\ln\left(\frac{1}{\text{taper\_lin}}\right)\right)^{0.5}} \qquad \text{ro} = 9.58 \qquad I(r) := \exp\left[-\left(\frac{r}{\text{ro}}\right)^2\right] \qquad \text{dB}(r) := 10\log(I(r))$$





A.1.2. Source Thermal Model

SCAL Thermal Model

SCAL_Thermal_model_1_PH.mcd
Worksheet created on 29/06/01
Last Modified by PH
Last modified on 21/8/01

Constants:

$h \equiv 6.626 \cdot 10^{-34}$ $kb \equiv 1.3806 \cdot 10^{-23}$ Plank function: $B(\nu, T) := \frac{2 \cdot h \cdot \nu^3}{c^2 \cdot \left[\exp\left(\left(\frac{h \cdot \nu}{kb \cdot T} \right) \right) - 1 \right]}$

$c \equiv 2.998 \cdot 10^{8}$ $\sigma := 5.67 \cdot 10^{-8}$

$NA := 6.02 \cdot 10^{23}$

Environment

Bath temperature $T0 := 4.2$ K

Function definitions

Integral thermal conductivity... $ik(k, T_L, T_U) := \int_{T_L}^{T_U} k(x)\, dx$ W/m

SCAL properties

Wires

Wire diameter $w_{diam} := 0.000125$ m

Wire length $w_{length} := 60 \cdot 10^{-3}$ m

Wire cross sectional area $w_{area} := \pi \cdot \frac{w_{diam}^2}{4}$ $w_{area} = 1.227 \times 10^{-8}$ m^2

Number of wires $w_{count} := 8$

Integral k for wires $ki_{wires}(x) := ik(k_{man}, T0, x)$

$ki_{wires}(x) := ik(kCu, T0, x)$

Power loss through the wires $P_{wires}(x) := \frac{w_{area} \cdot w_{count}}{w_{length}} \cdot ki_{wires}(x)$ W $P_{wires}(20) = 5.846 \times 10^{-5}$

Support (Torlon rods)

Torlon diameter $tor_{diam} \equiv 2.5 \cdot 10^{-3}$ m $torbore := 0 \cdot 10^{-3}$

Torlon Density $tor_{dens} := 1.41 \frac{g}{cm^3}$ $tor_{dens} := tor_{dens} \cdot 0.001 \cdot 100^3$ $tor_{dens} = 1.41 \times 10^3 \frac{kg}{m^3}$

Length of Torlon support $tor_{length} \equiv 20 \cdot 10^{-3}$ m Number... $tor_{count} \equiv 1$

Cross sectional area $tor_{area} := \pi \cdot \frac{tor_{diam}^2}{4} - \pi \cdot \frac{torbore^2}{4}$ $tor_{area} = 4.909 \times 10^{-6}$ m^2

$tor_{vol} := tor_{area} \cdot tor_{length}$ $tor_{mass} := tor_{vol} \cdot tor_{dens} \cdot tor_{count}$ $tor_{mass} = 1.384 \times 10^{-4}$

Torlon Heat Capacity

$C_{torlon}(x) := c_{tor}(x) \cdot tor_{mass} \frac{J}{K}$

Integral k for torlon support $ki_{tor}(x) := ik\left(k_{tor}, T0, x\right)$ $ki_{tor}(20) = 0.362$ W/m

Power loss through torlon supports $P_{tor}(x) := \frac{tor_{area} \cdot tor_{count}}{tor_{length}} \cdot ki_{tor}(x)$ $P_{tor}(20) = 8.882 \times 10^{-5}$ W

$P_{tor}(x) := \frac{tor_{area} \cdot tor_{count}}{tor_{length}} \cdot kkev(x)$

Aluminum disc

Density of aluminium $Al_{\rho} := 2.7 \cdot 10^3$ kg/m^3 Emmisivity $Al_{\varepsilon} := 0.9$

Diameter of disc $Al_{diam} \equiv 5 \cdot 10^{-3}$ m Thickness $Al_{thick} \equiv 0.007$ m

Cross sectional area (emmiting area) $Al_{area} := \pi \cdot \frac{Al_{diam}^2}{4} \cdot 0.55$ m^2 $Al_{area} = 1.08 \times 10^{-5}$

Disc volume $Al_{vol} := Al_{area} \cdot Al_{thick}$ m^3 $Al_{vol} = 7.559 \times 10^{-8}$

Disc mass $Al_{mass} := Al_{\rho} \cdot Al_{vol}$ $Al_{mass} = 2.041 \times 10^{-4}$ kg

$M_{epo} := 0$

Mass of epotek $M_{epo} := 1.5 \cdot 10^{-3}$ kg

Heat capacity of the disc $C_{disc}(x) := Al_{mass} \cdot Clin_{Al}(x) + M_{epo} \cdot C_{epo}(x)$

$$C_{disc}(x) := Al_{mass} \cdot Clin_{Al}(x) + M_{epo} \cdot C_{epo}(x) + \frac{C_{torlon}(x)}{3}$$

Power losses

Conductive losses

$P_{con}(x) := P_{wires}(x) + P_{tor}(x)$ W $P_{con}(20) = 1.473 \times 10^{-4}$

Radiative losses

$P_{rad}(x) := Al_{area} \cdot \sigma \cdot \left(x^4 - T0^4\right) \cdot Al_{\varepsilon}$ W $P_{rad}(20) = 8.8 \times 10^{-8}$

Total losses

$P_{loss}(x) := P_{rad}(x) + P_{con}(x)$ W $P_{loss}(20) = 1.474 \times 10^{-4}$

The simulation (Thermal model from Pete)

Function **simTi(P,T0,sp)** returns the **heating/cooling profiles** in a two dimensional array. The first column contains the time from start **sec**, and the second temperature in **Kelvin**.

The function requires 3 arguments. These are:

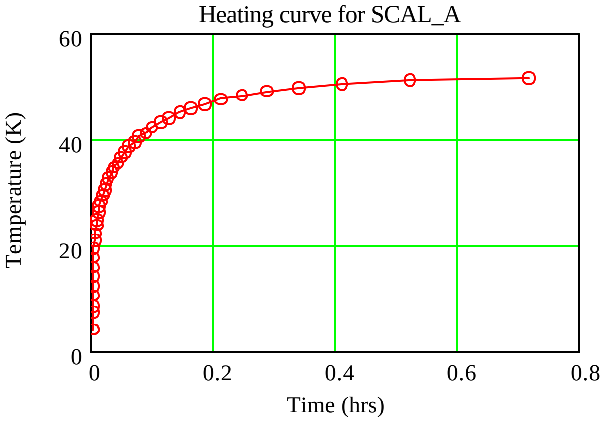
P - The supplied power to the heater
T0 - The starting temperature of the calibrator
P$_{\mathbf{loss}}$ - Is the function that returns the total power losses due to conduction and radiation
C$_{\mathbf{disc}}$ - Is the function that returns the heat capacity of the disc (+ epotek + kapton...)
sp - The value of the profile angle (in degrees) for which equilibrium is considered

The algorithm works as follows:
The profile is stored in matrix **s**, to which the first values are added (0, T0). Δ**t** is first set to **10**$^{\mathbf{-3}}$ **sec**, and dynamicaly adjusted according to the current slope. At each iteration, the slope of the profile is calculated and compared to **tan(sp)**, if it is smaller, equilibrium is assumed and the loop ends

```
$simTi(P, T0, P_{loss}, C_{disc}, sp) :=$
    $s_{0,0} \leftarrow 0$
    $s_{0,1} \leftarrow T0$
    $oldy \leftarrow T0$
    $\Delta t \leftarrow 10^{-3}$
    $j \leftarrow 1$
    $slp \leftarrow \tan\left(sp \cdot \frac{\pi}{180}\right) + 10$
    while $slp \ge \tan\left(sp \cdot \frac{\pi}{180}\right)$
        $y \leftarrow oldy + \frac{P - P_{loss}(oldy)}{C_{disc}(oldy)} \cdot \Delta t$
        if $y < 4.0$
            $\Delta t \leftarrow \max\left(\frac{\Delta t}{1.3}, 10^{-3}\right)$
            continue
        $s_{j,0} \leftarrow s_{j-1,0} + \Delta t$
        $s_{j,1} \leftarrow y$
        $slp \leftarrow \frac{abs(y - oldy)}{\Delta t}$
        $oldy \leftarrow y$
        $j \leftarrow j + 1$
        $\Delta t \leftarrow \frac{2.0 \cdot \sin(atan(slp)) + 1}{slp}$
    s
```

$P_{loss}(5) = 3.988 \times 10^{-6}$

$iSim := simTi(0.0012, T0, P_{loss}, C_{disc}, 0.05)$



The equilibrium temperature is...

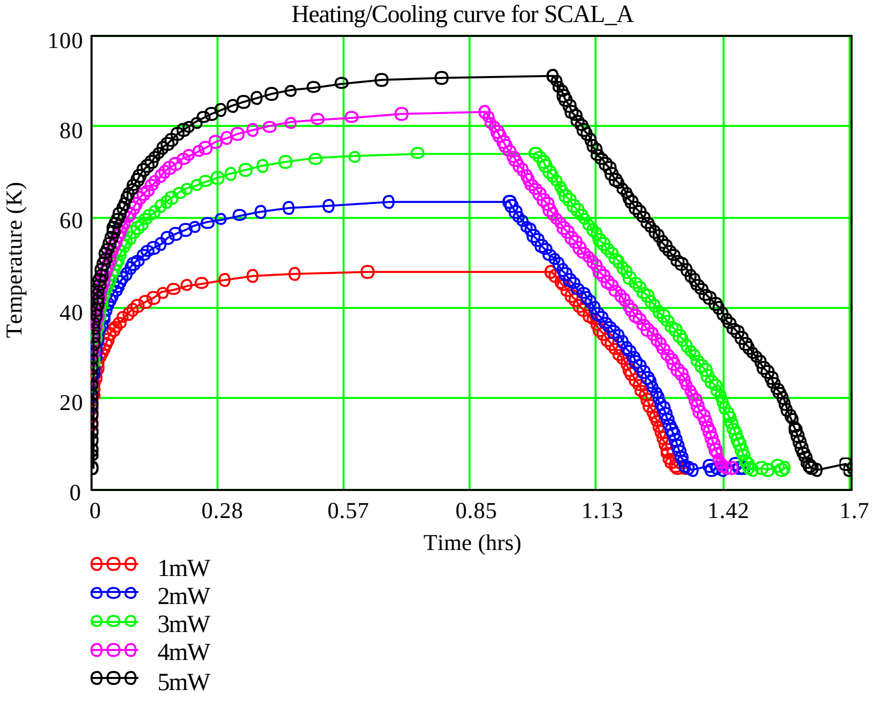
$iSim_{rows(iSim)-1,1} = 51.526$ K

$aSim_{rows(aSim)-1,1} =$ K

$$
Model(P,T) := \left|
\begin{array}{l}
s1 \leftarrow simTi(P, T, P_{loss}, C_{disc}, 0.037) \\
s2 \leftarrow simTi(0.0, s1_{rows(s1)-1,1}, P_{loss}, C_{disc}, 0.2) \\
s2^{\langle 0 \rangle} \leftarrow s2^{\langle 0 \rangle} + s1_{rows(s1)-1,0} \\
s \leftarrow stack(s1, s2)
\end{array}
\right.
$$

$N := 5 \quad i := 0..\, N-1$

$D_i := Model[0.001 \cdot (i+1), T0]$



A.1.3. Source Deflection Under Load

SCAL Mechanical model SCAL_torlon_bend.MCD 29 August 2001

Model to predict the maximum deflection expected of the sources on Torlon legs under various loads

Aluminium end cap

Diameter (mm) $d\_disc := 5$

Thickness (mm) $tdisc := 7$

Density (kg m-3) $\rho\_Al := 2.7 \cdot 10^{3}$

Mass (kg) $m\_disc := \left(tdisc \cdot 10^{-3}\right) \cdot \frac{\pi \cdot \left(d\_disc \cdot 10^{-3}\right)^{2}}{4} \cdot \rho\_Al \quad m\_disc = 3.7 \times 10^{-4}$

Torlon support rod

Diameter (m) $d\_tor := 2.5 \cdot 10^{-3} \quad r\_tor := 0.5 \cdot d\_tor$

Length (m) $L\_tor := 20 \cdot 10^{-3}$

Area (m^2) $A\_tor := \pi \cdot (r\_tor)^{2} \quad A\_tor = 4.909 \times 10^{-6}$

Density (kg m-3) $\rho\_tor := 1.45 \cdot 10^{-3} \cdot 10^{6} \quad \rho\_tor = 1.45 \times 10^{3}$

Mass (kg) $m\_tor := (L\_tor) \cdot \pi \cdot (r\_tor)^{2} \cdot \rho\_tor \quad m\_tor = 1.42 \times 10^{-4}$

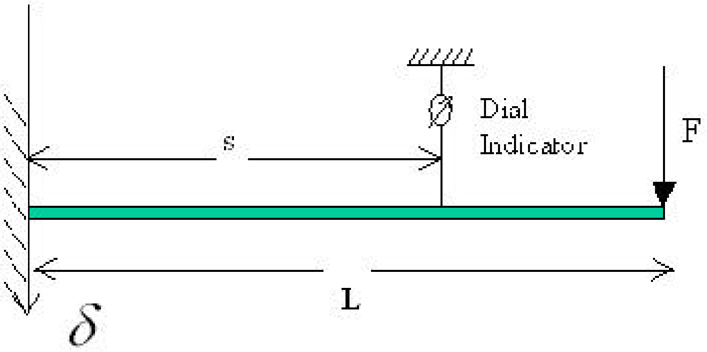
Data from http://www.mtpinc-exporter.com/plastic/data4.htm

$cf := 6.89 \cdot 10^{3}$

Torlon properties (room temp) of Torlon 4203
Values are given in PSI and multiplied here by 6.89E3 to convert to Pa

			Values (PSI) for Torlon 4301
Tensile Strength (Pa)	$TS := 26900 \cdot cf$	$TS = 1.85 \times 10^{8}$	19600
Flexural Strength (Pa)	$FS := 30700 \cdot cf$	$FS = 2.12 \times 10^{8}$	26400
Compressive Strength (Pa)	$CS := 32000 \cdot cf$	$CS = 2.20 \times 10^{8}$	30000
Shear strrength (Pa)	$SS := 18500 \cdot cf$	$SS = 1.27 \times 10^{8}$	16000
Tensile Modulus of Elasticity (Pa)	$ET := 730000 \cdot cf$	$ET = 5.03 \times 10^{9}$	
Compressive Modulus of Elasticity (Pa)	$EC := 450000 \cdot cf$	$EC = 3.10 \times 10^{9}$	680000
Flexural Modulus of Elasticity (Pa)	$EF := 660000 \cdot cf$	$EF = 4.55 \times 10^{9}$	920000

Model of Torlon Cantilever



Moment of Inertia of Torlon Rod (circular cross-section)

$$I := \frac{\pi \cdot (d\_tor)^4}{64}$$

Deflection measurement point

$$s := L\_tor$$

In these calculations, the flexural modulus of elasticity has been used, as recommended in the BP/AMOCO Torlon designers guide. The value of this modulus at 4K is not known.

Launch acceleration (design value)

$g := 9.81 \qquad Load := 100g \qquad F := m\_disc \cdot Load$

Deflection at measurement point (m)

$$\delta := \frac{-F \cdot s^2}{6 \cdot EF \cdot I} \cdot [3 \cdot (L\_tor) - s] \qquad \delta = -1.113 \times 10^{-4}$$

Peak deflection for range of launch accelerations

$$i := 0, 1 .. 7 \qquad Acc_i := \begin{array}{|c|}\hline 20 \\ \hline 50 \\ \hline 100 \\ \hline 150 \\ \hline 200 \\ \hline 300 \\ \hline 500 \\ \hline 1350 \\ \hline \end{array}$$

Launch accelerations (multiples of g)

$$F_i := Acc_i \cdot g \cdot m\_disc$$

$$\delta_i := \frac{-F_i \cdot s^2}{6 \cdot EF \cdot I} \cdot (3 \cdot L\_tor - s)$$

$$\delta = \begin{pmatrix} -2.227 \times 10^{-5} \\ -5.567 \times 10^{-5} \\ -1.113 \times 10^{-4} \\ -1.67 \times 10^{-4} \\ -2.227 \times 10^{-4} \\ -3.34 \times 10^{-4} \\ -5.567 \times 10^{-4} \\ -1.503 \times 10^{-3} \end{pmatrix}$$

Peak Deflection (m)

A.1.4. Resonant Frequency and Static Load Bearing Calculation

SCAL Mechanical model

SCAL is here modelled as a mass on a single solid Torlon rod

Density of Aluminium (kg m-3) $\rho := 2.7 \cdot 10^{3}$

Diameter of disc (mm) $d\_disc := 5$

Thickness of disc (mm) $tdisc := 4$

Mass of disc (kg) $m\_disc := \left(tdisc \cdot 10^{-3}\right) \cdot \frac{\pi \cdot \left(d\_disc \cdot 10^{-3}\right)^{2}}{4} \cdot \rho$ $m\_disc = 2 \times 10^{-4}$

Torlon support rod

Diameter (mm) $d\_tor := 2.4$ $r\_tor := 0.5 \cdot d\_tor$

Length (mm) $L\_tor := 20$

Area (m^2) $A\_tor := \pi \cdot \left(r\_tor \cdot 10^{-3}\right)^{2}$ $A\_tor = 5 \times 10^{-6}$

Density (kg m-3) $\rho\_tor := 1.51 \cdot 10^{-3} \cdot 10^{6}$ $\rho\_tor = 1.51 \times 10^{3}$

Mass (kg) $m\_tor := \left(L\_tor \cdot 10^{-3}\right) \cdot \pi \cdot \left(r\_tor \cdot 10^{-3}\right)^{2} \cdot \rho\_tor$

$m\_tor = 1.37 \times 10^{-4}$

Data from http://www.mtpinc-exporter.com/plastic/data4.htm

Torlon properties (room temp) of Torlon 4203
Values are given in PSI and multiplied here by 6.89E3 to convert to Pa $cf := 6.89 \cdot 10^{3}$

			Values for Torlon 4301
Tensile Strength (Pa)	$TS := 26900 \cdot cf$	$TS = 1.85 \times 10^{8}$	19600
Flexural Strength (Pa)	$FS := 30700 \cdot cf$	$FS = 2.12 \times 10^{8}$	26400
Compressive Strength (Pa)	$CS := 32000 \cdot cf$	$CS = 2.20 \times 10^{8}$	30000
Shear strrength (Pa)	$SS := 18500 \cdot cf$	$SS = 1.27 \times 10^{8}$	16000
Tensile Modulus of Elasticity (Pa)	$ET := 730000 \cdot cf$	$ET = 5.03 \times 10^{9}$	680000
Compressive Modulus of Elasticity (Pa)	$EC := 450000 \cdot cf$	$EC = 3.10 \times 10^{9}$	920000
Flexural Modulus of Elasticity (Pa)	$EF := 660000 \cdot cf$	$EF = 4.55 \times 10^{9}$	

Resonant frequency

Spring constant (N m-1)

(using lowest of the above moduli)

$$k\_tor := EC \cdot \frac{A\_tor}{L\_tor \cdot 10^{-3}} \qquad k\_tor = 7 \times 10^{5}$$

Resonant frequency for lumped mass on a massless spring is f = (1/2 π)*(k/m)^0.5

Resonant frequency for a distributed mass (rod) is f = (1/2)*(k/m)^0.5

Take worst cases - use total mass

Resonant frequency (Hz)
(mass on spring)

$$freq1 := \frac{1}{2 \cdot \pi} \cdot \left(\frac{k\_tor}{m\_disc + m\_tor} \right)^{0.5} \qquad freq1 = 7.1 \times 10^{3}$$

Resonant frequency (Hz)
(cantilever)

$$freq1 := \frac{1}{2} \cdot \left(\frac{k\_tor}{m\_disc + m\_tor} \right)^{0.5} \qquad freq1 = 2.2 \times 10^{4}$$

Static load-bearing capability

Max tolerable acceleration = (Strength)(Area)/(Mass)

Assume worst case: use total mass and use lowest strength value above

Max acceleration (g)

$$a\_max := \frac{SS \cdot A\_tor}{m\_disc + m\_tor} \cdot \frac{1}{9.81} \qquad a\_max = 1.69 \times 10^{5}$$