# In-Flight Calibration Sources for Herschel-SPIRE

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## ABSTRACT

SPIRE, the Spectral and Photometric Imaging Receiver, will be a bolometer instrument for ESA's Herschel satellite. The instrument comprises a three-band imaging photometer covering the 250-500 μm range, and an imaging Fourier Transform Spectrometer (FTS) covering 200-670 μm. This paper presents the requirements for and design of the photometer and spectrometer calibration/illumination sources, and the results of laboratory tests on prototypes. The photometer calibrator is an electrically heated thermal source of submillimetre radiation, the purpose of which is to provide a repeatable signal for in-flight monitoring of health and responsivity of the SPIRE photometer detectors. It is not required to provide absolute calibration or uniform illumination of the arrays, but it may be used as part of the overall calibration scheme. The spectrometer calibrator is located at a pupil at the second input port of the FTS. It is designed to enable matching of the telescope emission for a range of telescope temperature (60-90 K) and emissivity (2% - 10%). By matching the telescope emission at this port, the high background from the Herschel telescope emission can be nulled to a high degree, resulting in an interferogram in which the contribution from the astronomical source is not overwhelmed by the telescope offset. The flexibility for telescope matching inherent in the design is important, as the exact telescope parameters will be unknown until the satellite is in operation. The FTS calibrator will also be used to assist in the absolute calibration scheme for SPIRE FTS observations.

Keywords: Herschel, SPIRE, Calibration, Fourier Transform Spectrometer, Photometer, Submillimetre, Illuminator, Bolometer

## 1. THE SPIRE INSTRUMENT

SPIRE [1], the Spectral and Photometric Imaging Receiver, is a bolometer instrument for ESA's Herschel Space Observatory [2]. Its main scientific goals are deep extragalactic and galactic imaging surveys and spectroscopy of star-forming regions in our own and nearby galaxies. The instrument comprises a three-band imaging photometer covering the 250-500 μm range, and an imaging Fourier Transform Spectrometer (FTS) covering 200-670 μm. The photometer has a field of view of 4 x 8 arcminutes, which is observed simultaneously at 250, 350 and 500 μm with dichroic beam dividers separating the three spectral bands. The angular resolution is determined by the telescope diffraction limit, with FWHM beam widths of approximately 17, 24 and 35 arcseconds at 250, 350 and 500 μm respectively. An internal beam steering mirror can be used for spatial modulation of the telescope beam, and observations can also be made by scanning the telescope without chopping, providing better sensitivity for source confusion-limited deep surveys. The FTS has a field of view of 2.6 arcminutes, and an adjustable spectral resolution of 0.04 – 2 $\text{cm}^{-1}$ ($\lambda/\Delta\lambda = 20 – 1000$ at 250 μm). It employs a dual-beam configuration with novel broad-band intensity beam dividers to provide high efficiency and separated output and input ports. The following sections give a brief summary of the photometer and spectrometer. A detailed description of the SPIRE instrument can be found in Griffin et al (2000)[1].

### 1.1. PHOTOMETER

The SPIRE photometer, illustrated in Figure 1, is an all-reflective system except for two dichroic beam dividers used to direct the three wavelength bands onto the bolometer arrays[3], and various transmissive edge filters to reject out-of-band radiation. The optical design is optimized to give almost diffraction-limited imaging across a 4 x 8 arcminute field of

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view, simultaneously observed by all three detector arrays. The detector bodies and dichroics are supported from a 2-K enclosure, with the rest of the photometer elements mounted to an optical bench panel at 4-K. The detector arrays, feedhorns, and the final filter are thermally isolated from the 2-K structure by Kevlar wires, and are cooled to ~300-mK by a thermal strap to a $^3$He refrigerator[4]. Both the spectrometer and photometer fields of view can be steered by a beam steering mirror (BSM)[5], which also houses a thermal source. This source is discussed in more detail in section 2.

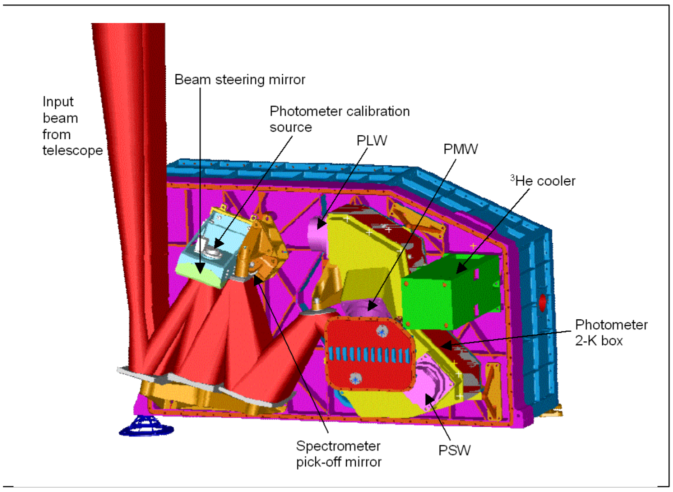


*Figure 1 General view and schematic of the SPIRE photometer (covers removed). PSW, PMW and PLW denote the short, medium and long wavelength detector arrays respectively.*

## 1.2. SPECTROMETER

The photometer input optics are shared by the spectrometer up to a pick-off mirror where the separate spectrometer field of view is directed through a hole in the optical bench panel to the other side of the instrument. The layout of the FTS is shown in Figure 2. The FTS employs two broadband high-efficiency intensity beam splitters in a Mach-Zehnder configuration, rather than the traditional polarizing beam dividers. This configuration has the advantage that all four ports are separately accessible, but the throughput is a factor of two higher than the classical Martin-Puplett polarising FTS, owing to the fact that none of the incoming radiation is rejected. The performance of the beam dividers, and of a bench-top implementation of this design has been demonstrated[6], and a more detailed description of the SPIRE FTS is given by Swinyard et al[7].

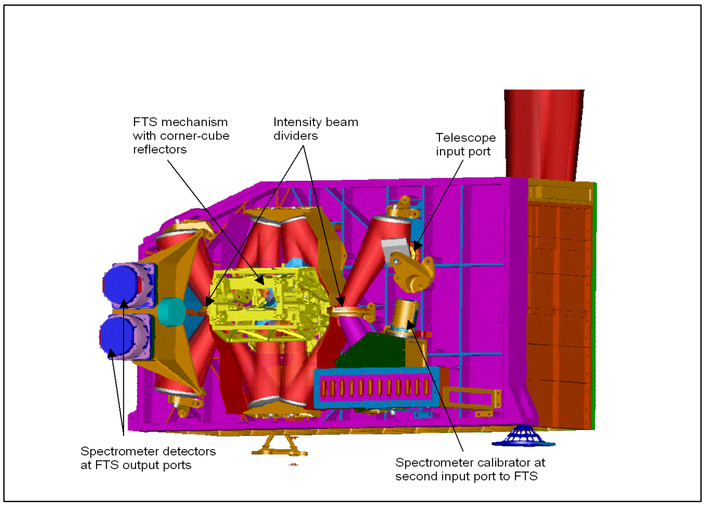


*Figure 2 General view and schematic of the SPIRE spectrometer (covers removed).*

Two band-limited detector arrays are placed in the two output ports, covering 200-300 µm and 300-670 µm. A back-to-back corner-cube mirror mechanism serves both arms of the interferometer, with a very low friction carriage mechanism using double parallelogram linkage and flex pivots. The FTS design is optimized for the 200-400 µm band, but coverage is extended to 15 $cm^{-1}$ (670 µm) to give access to the 609 µm line of CI in our own and nearby galaxies, and to increase the range over which the spectral energy distribution of sources can be measured in the FTS low-resolution mode. A filtering scheme similar to the one employed for the photometer is used to restrict the passband of the instrument, with filters on the bolometer arrays themselves defining the passband for each array.

A thermal calibrator is located at a pupil image in the second input port of the FTS, and provides a thermal input that mimics the dilute 80-K black body emission of the telescope signal in the first input port. This allows the large telescope background to be nulled, thereby reducing the dynamic range requirements for the detector sampling. Details of the FTS calibration source are given in section 3.

## 2. PHOTOMETER CALIBRATION SOURCE

The photometer calibrator (PCAL) is an electrically heated thermal source of submillimetre radiation, the purpose of which is to provide a repeatable signal for monitoring the health and responsivity of the SPIRE photometer detectors. It is not required to provide absolute calibration or uniform illumination of the array, although it may be used as part of the overall calibration scheme in flight. PCAL will be located behind a hole in the centre of the BSM, which is at a pupil image, as shown in Figure 3. Although PCAL is optimised for the photometer, it can also be viewed by the FTS detector arrays.

The active component of PCAL is a pair of thermal sources (two sources are used to provide redundancy) developed to meet the SPIRE requirements based on an initial source design by Haller-Beeman associates[8,9]. Each source is essentially a "reverse bolometer". Early devices consisted of a NiCr thin film deposited on a sapphire substrate, suspended on nylon wires from a copper mounting ring, as shown in Figure 4. However, these devices did not meet the SPIRE requirements on the speed of response within the strict power dissipation budget. Therefore a new device was developed which employs a thin NiCr film on a thin mica substrate, forming a resistive heater with high emissivity. This device does not use the nylon suspension and is supported solely by the electrical leads to NiCr film. As the suspended mass is so small, these devices should survive cryogenic vibration testing. A prototype source is also shown in Figure 4.

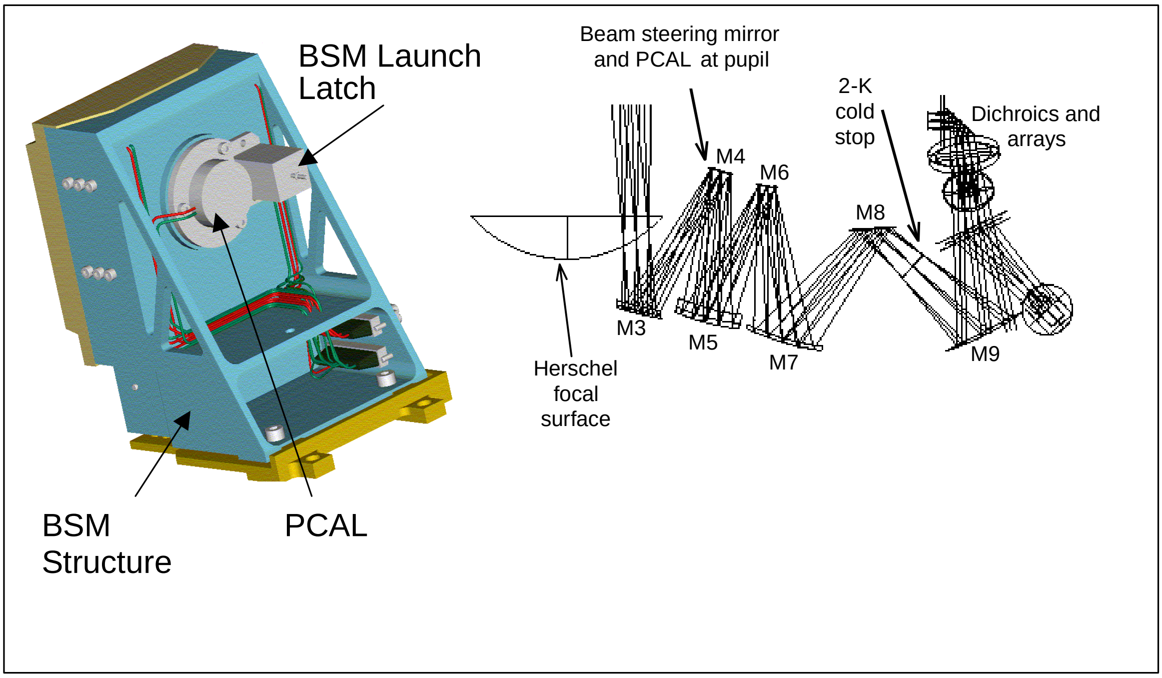
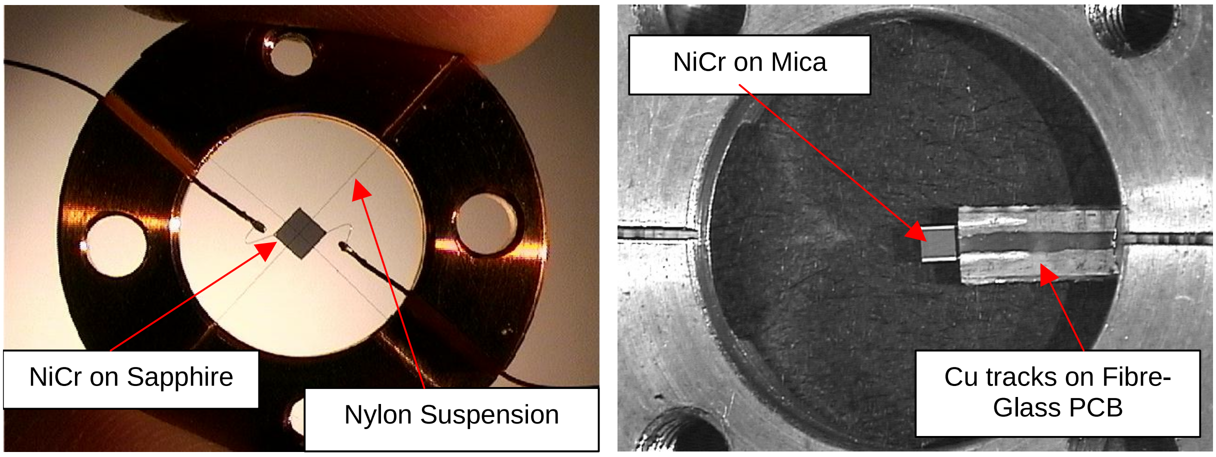


*Figure 3 Location of the photometer calibrator on the BSM (rear view), and the location in the photometer optical layout.*



A. Original Design

B. SPIRE design concept

*Figure 4 Haller-Beeman emitters used as a basis for the SPIRE PCAL source design.*

## 2.1. PERFORMANCE REQUIREMENTS

The main performance requirements and system constraints that have driven the design of PCAL are listed in Table 1 below.

*Table 1 SPIRE system constraints and performance requirements that have driven the design of PCAL*

| Requirement ID | Requirement Details |
|---|---|
| Nominal operating output | Equivalent to $\varepsilon T$ = 40 K for 200 < $\lambda$ < 700 $\mu$m |
| Time constant | In response to a step change in applied electrical power, the 90% settling time of the radiant power output shall be less than 350 ms (requirement); 70 ms (goal) |
| Volume envelope | This shall be compatible with the space available within the BSM enclosure |
| Repeatability | RMS better than 1% over 20 operations equi-spaced over a period of 12 hours, with uniform base temperature and drive current. |
| Operation | Nominally once per hour for no more than 10 seconds |
| Thermal isolation | The temperature of the PCAL housing shall rise by no more than 1 K over the temperature of the BSM structure after 10 seconds when the calibrator is operated unmodulated at nominal power output. |
| Operating temperature | 4 K |
| Cold power dissipation | Calibrator power dissipation in the focal plane unit when operating continuously at nominal radiant output shall be less than 4 mW (requirement); 2 mW (goal) |
| Operating voltage | Less than 28 V at input power level of 5 mW |
| Redundancy | Cold redundancy is required for the thermal source |
| Number of operations / lifetime | The calibration source shall be capable of up to 300,000 operational cycles at the nominal electrical power. |

## 2.2. THERMAL SOURCE DESIGN

Early tests of the nylon-suspended Haller-Beeman sources showed that the performance requirements listed in Table 1 could not all be met in the same device. For example, we could design a device optimized for speed of response, but then the power consumption would be too great to attain the required photometric output / source temperature. We varied the conductivity (G) of the electrical wires to alter the time constant, but there was an obvious trade-off between speed and power dissipation, and we could not achieve one goal without going out of the limits for the other. Therefore the self-supporting “cantilever” type devices, shown in Figure 4(B), were developed. The goal was to reduce the thermal mass and hence the heat capacity (C) of the suspended components in order to decrease the thermal time constant without increasing the thermal conductivity of the suspension, which in this case is just the electrical wires. Details of the SPIRE sources, which will be built by Haller-Beeman Associates, are shown in Figure 5.

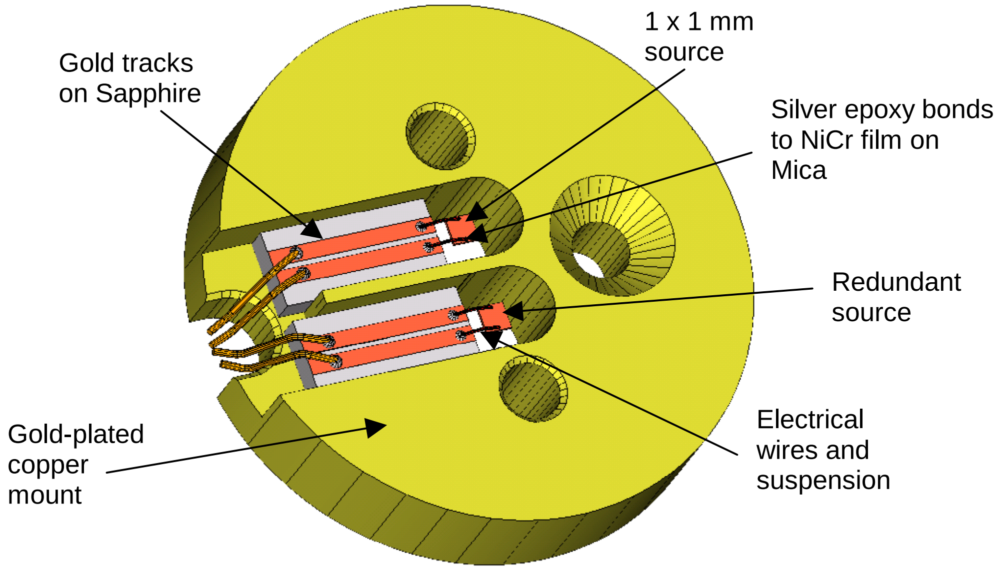


*Figure 5 Details of thermal source for PCAL.*

## 2.3. PHOTOMETER CALIBRATOR ASSEMBLY

The thermal source shown in Figure 5 will be mounted in a gold-plated aluminium enclosure, as shown in Figure 6.

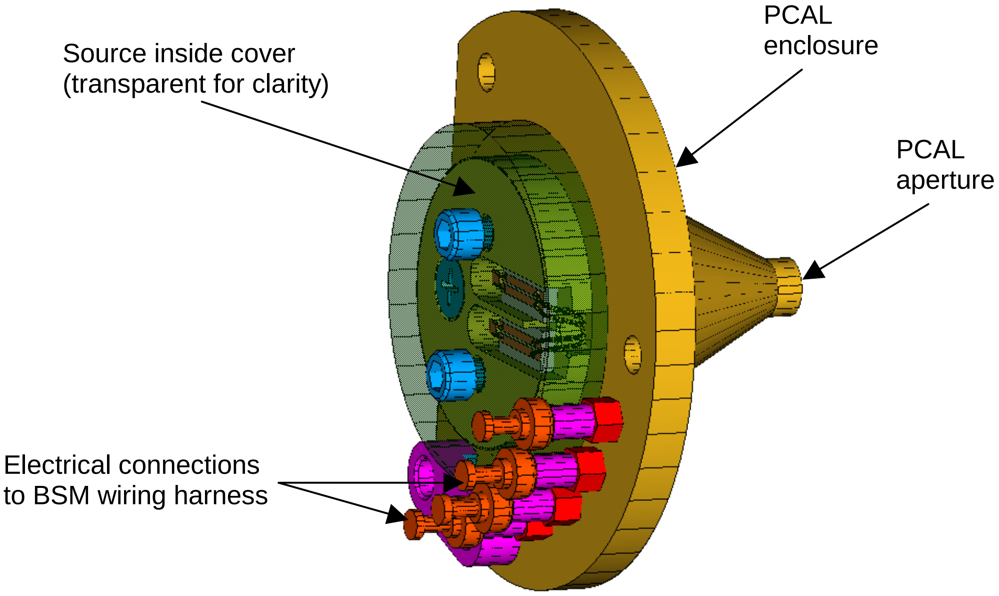


*Figure 6 PCAL assembly.*

The PCAL enclosure incorporates light-pipes to couple the emission from the sources to the PCAL aperture. The 3mm diameter PCAL aperture is placed 5-mm behind the central hole in the BSM. The PCAL aperture pipe then bifurcates into two 2.5mm diameter pipes which link the axial aperture pipe with the source cavities, as shown in Figure 7.

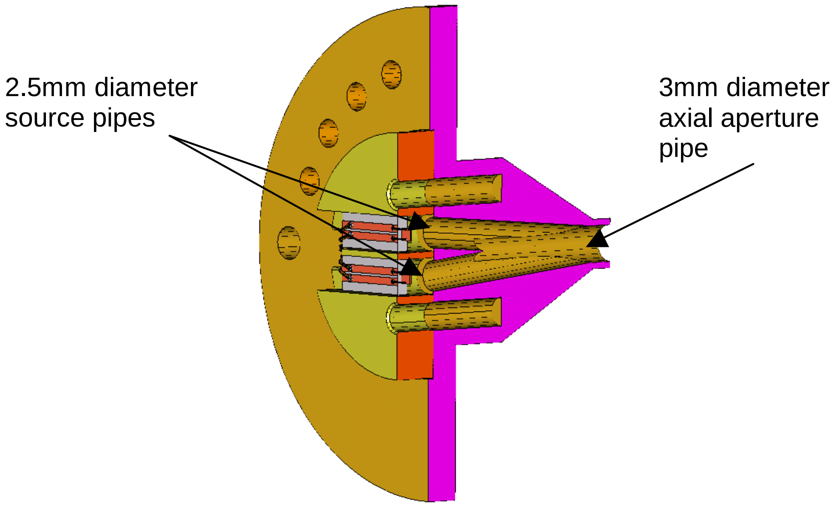


*Figure 7 Sectional view of the PCAL enclosure with the source, showing the geometry of the light-pipes.*

### 2.4. THERMAL SOURCE TESTS

A variety of source architectures have been tested as prototypes for SPIRE in order to find one that meets the instrument requirements (photometric efficiency, speed of response etc.).

### PHOTOMETRIC TESTS

The photometric output for each of the prototype devices has been determined as a function of applied power using a low-background bolometer test facility[10] with a well-calibrated cryogenic blackbody (CBB) source. A $^3$He bolometer is enclosed by a shield and filter stack, also at ~300-mK, and the whole assembly is then surrounded by a radiation shield at 4.2-K. A filter stack covers an aperture in the 4.2-K shield, and the aperture is closed with the CBB source. The CBB has a 1-mm diameter aperture. Load curves are then taken as a function of CBB temperature in order to obtain a photometric power calibration for the bolometer system. The CBB is then replaced by the source to be tested, which is placed in a mount with a 1-mm diameter aperture at the same position in space as the CBB aperture. Bolometer load curves are then taken as a function of applied source power. Analysis of the load curves gives the radiant power absorbed by the detector in each case, and comparison of the absorbed power for the CBB and the test source gives us an effective blackbody temperature for the test source. Typical results are shown in Figure 8.

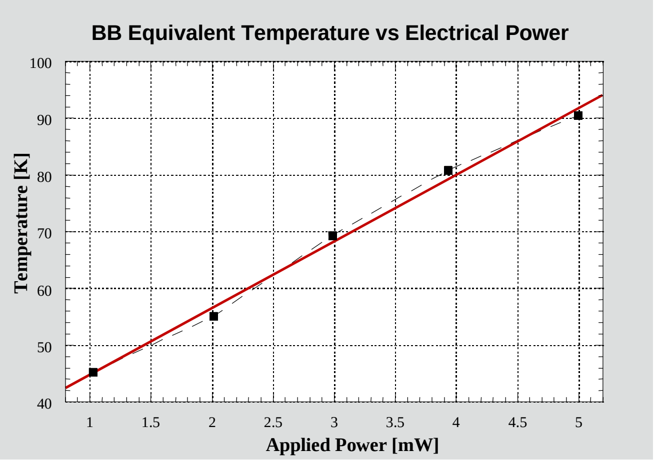


*Figure 8 Blackbody equivalent temperature as a function of applied power for one of the SPIRE prototype sources (HB1).*

Because the cycle-time of the large $^3$He test cryostat is rather long, and the speed of response of the bolometer is too slow to allow time constant measurements, a small test cryostat employing a $^4$He-cooled unstressed Ge-Ga photoconductor detector was also constructed, as shown in Figure 9. The spectral band was defined by two filters and by the detector cut-off frequency in the range 82 - 145 µm. A Trans-Impedance Amplifier circuit was used to read the detector signals. The amplifier consists of a cold dual-JFET unit mounted close to the detector on the $^4$He work surface and a room temperature external preamplifier. Careful choice of the value of the feedback resistor (1-2.5 GΩ) resulted in a time constant of ~1 ms for the detector system.

This photoconductor detector test cryostat was given a secondary calibration by applying a known power to some of the sources previously calibrated in the $^3$He test cryostat, and recording the detector output, as shown in Figure 10. The resulting detector voltage output could then be translated to an equivalent blackbody temperature. This system allowed rapid photometric tests to be made on the prototype sources following other tests (e.g. warm vibration) as a health check. Absolute photometric calibration of the flight sources will be carried out using the $^3$He bolometer test cryostat.

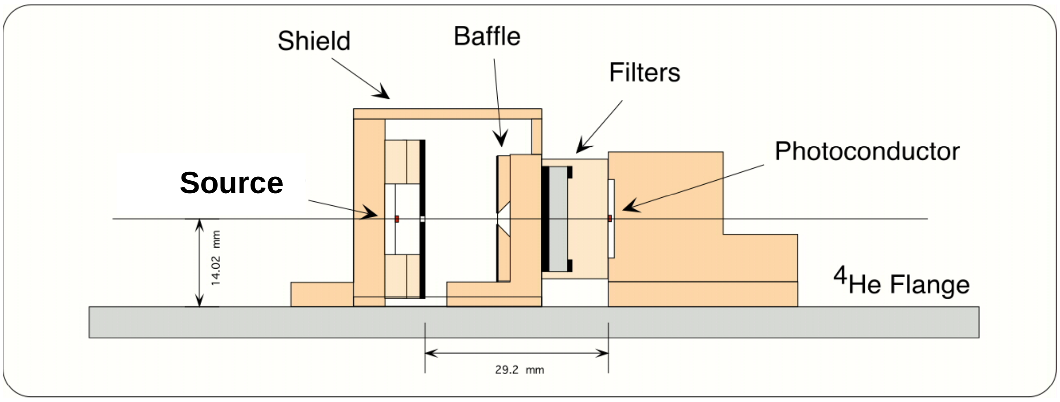


*Figure 9 Schematic of photoconductor detector test cryostat.*

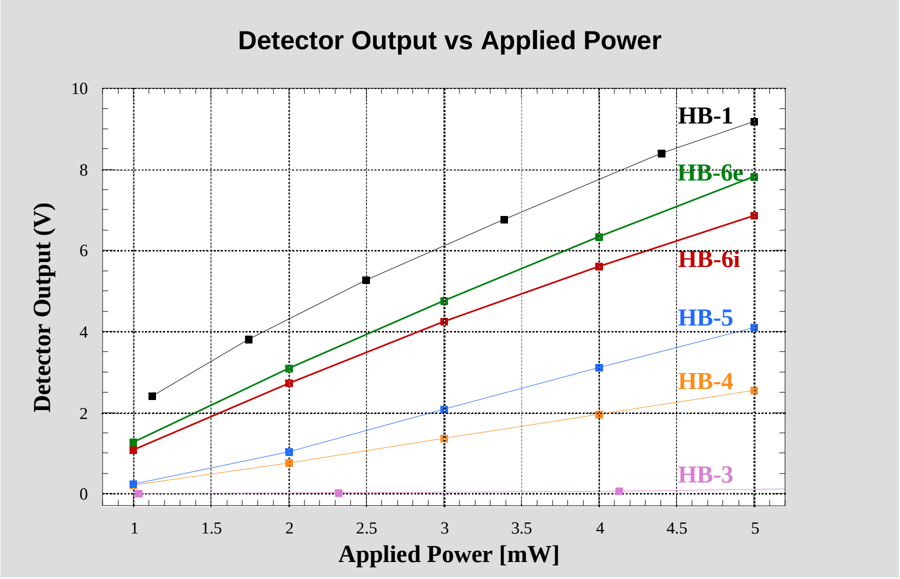


*Figure 10 Photodetector output vs power applied to source. A signal of 2V equates to a blackbody equivalent temperature of 45-K at the source aperture.*

The baseline source architecture selected for SPIRE is similar to that of the sources marked HB-6 in Figure 10. This design gives an equivalent blackbody temperature of ~45-K for an applied power of 1.5mW, which comfortably exceeds the instrument requirements (εT = 40-K for applied power < 2mW).

### TIME CONSTANT TESTS

The photoconductor detector response to step inputs to the sources of various voltage levels was recorded on a spectrum analyzer in the time domain. The 90% settling time constants are shown in Figure 11. As previously mentioned, the selected architecture for SPIRE is similar to that of HB-6. This source has a time constant of ~210ms for an applied power of 1.5mW, the power required for εT = 45-K. This easily exceeds the instrument requirements (< 350ms), and is the architecture that will be implemented in the SPIRE cryogenic qualification model. Further development work will continue to improve the time constant in an attempt to meet the instrument goal time constant of < 70ms, while not straying outside the photometric efficiency goal. If successful, this modified architecture will be implemented for the SPIRE flight model

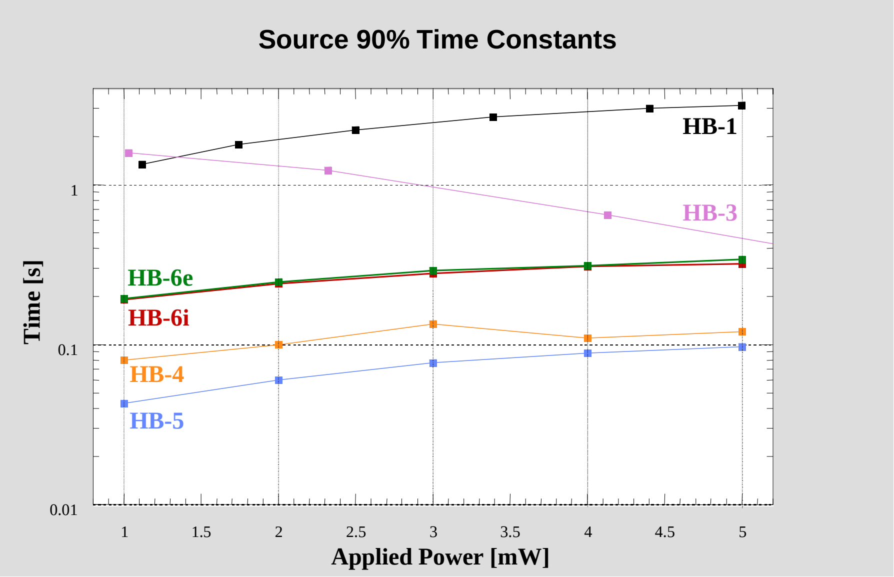


*Figure 11 Settling time constants (90%) for prototype SPIRE sources.*

### WARM VIBRATION TESTS

Two cantilever-type devices, similar to HB-6, have undergone the following sequence of warm vibration tests:-

- Sine survey – 0.5G 5Hz-2kHz
- Sine sweep, 40G 5Hz - 110 Hz, velocity and displacement limited
- Sine survey – 0.5G 5Hz-2kHz
- Random – 18G rms, 5Hz – 2kHz

Both sources survived, and indicated no subsequent degradation in their performance. Cryogenic vibration of these devices are expected to be successful, as these sources have also undergone many cryogenic cycles before and after the warm vibration tests.

## 3. SPECTROMETER CALIBRATION SOURCE

The Spectrometer Calibrator (SCAL) is located at a complementary pupil at the second input port of the FTS, as shown in Figure 12, 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.

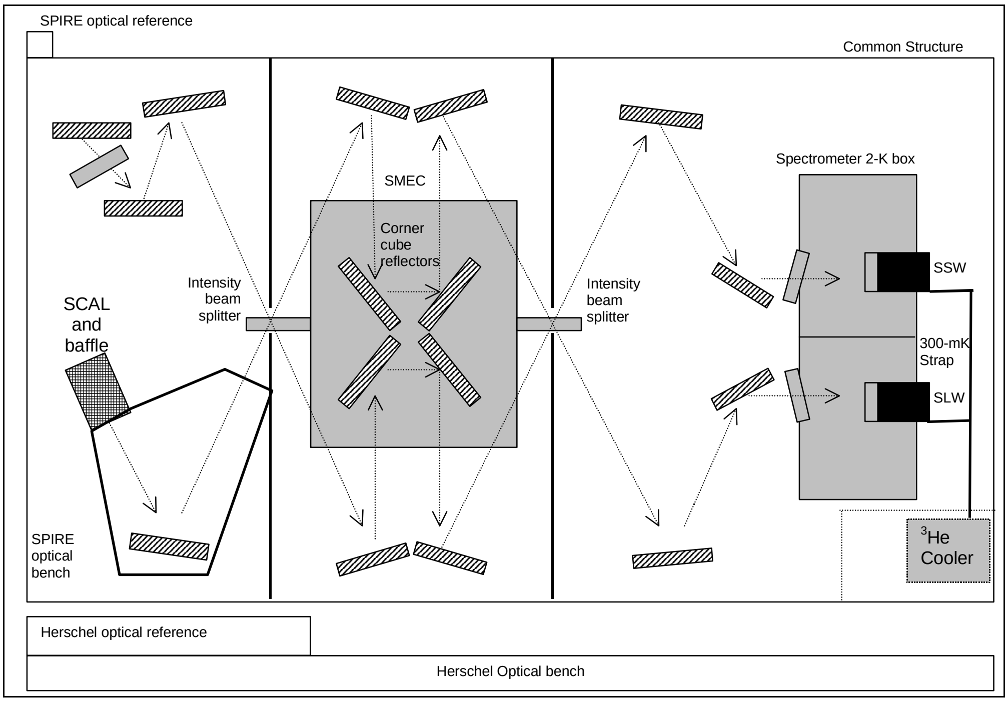


*Figure 12 Schematic of SPIRE FTS layout*

### 3.1. PERFORMANCE REQUIREMENTS

The main performance requirements and system constraints that have driven the design of SCAL are listed in Table 2 below.

*Table 2 SPIRE system constraints and performance requirements that have driven the design of SCAL*

| Requirement ID | Requirement |
|---|---|
| Radiated spectrum | Null the central maximum to accuracy of 5% (goal 2%)<br>Replicate the dilute spectrum of the telescope to an accuracy of better than 20% (goal 5%) over 200-400 µm. |
| 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 |
| Operation | The calibration source shall be capable of continuous operation for periods of up to 2 hours with no loss of operational performance. |
| Number of operations | The calibration source shall be capable of up to 12000 operational cycles |
| 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. |
| Operating Voltage | No more than 28 V DC |
| Power dissipation in the focal plane | Less than 5mW |
| 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. |
| Operating Temperature | < 6 K |
| Redundancy | Fully redundant systems shall be provided for the active elements. |

### 3.2. SPECTROMETER CALIBRATOR DESIGN

SCAL will employ two sources at the second input port to the FTS. As this port is a pupil, one can control the effective emissivity by using a geometrical fill factor. A black (emissivity ~ 1) source that fills only 4% of the pupil area, produces an effective emissivity of ~ 4%. A second, smaller source is provided to accommodate the possibility that the telescope emissivity is lower than the nominal 4%. This source has 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 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 the spacecraft 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. The main design features of SCAL are shown Figure 13.

Each source consists of an Aluminium end cap, with embedded heater (Vishay HR 0603 series) and thermometer (Cernox CX-1030), on a Torlon strut for thermal isolation. Manganin wires are affixed to the heater chips and thermometers using silver-loaded conductive epoxy (Epotex H20-S), and fed down the axial bore of the Torlon struts through to the backplane of SCAL where they are soldered to the prime and redundant MDM-37 pin connectors.

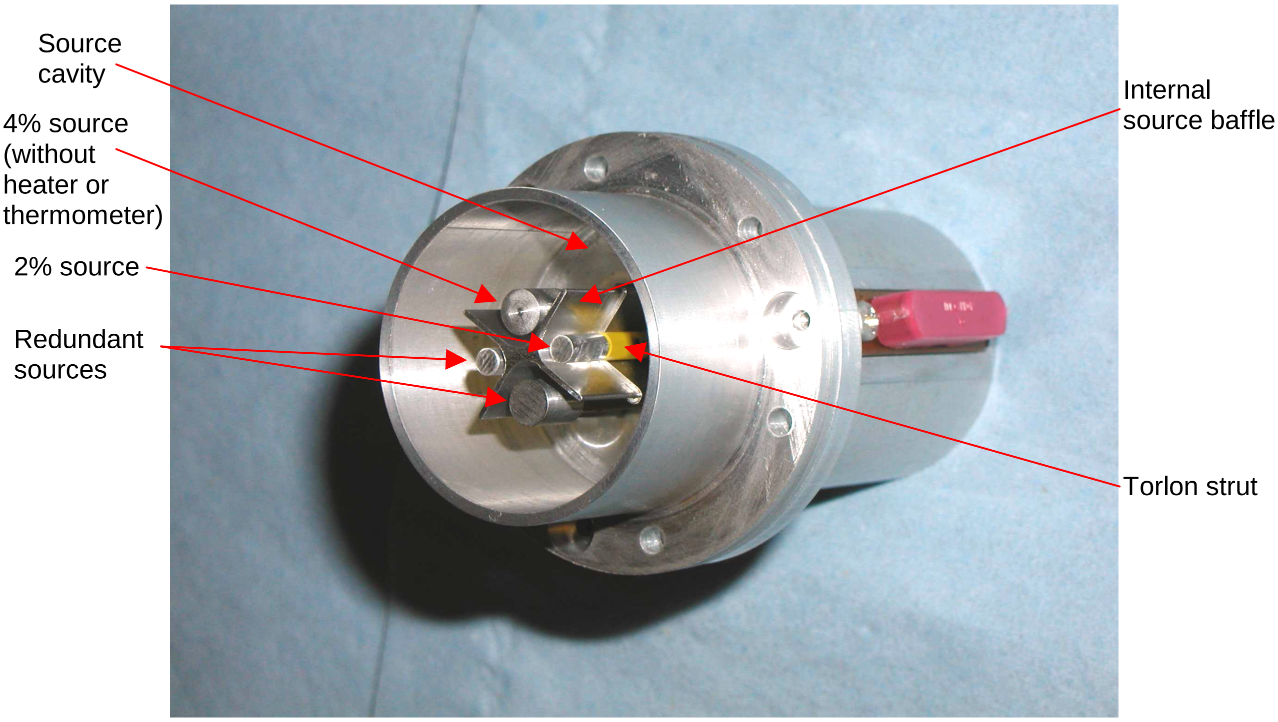


*Figure 13 Prototype model of SCAL showing salient design features. Note – the sources, baffle and cavity will all have a high emissivity coating applied.*

### 3.3. TELESCOPE MATCHING

A computer model has been produced 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 in Figure 14, for the source configuration shown in Figure 13, for a variety of telescope temperatures and emissivities. These results show the flexibility inherent in the design to cope with uncertainties in the telescope effective temperature.

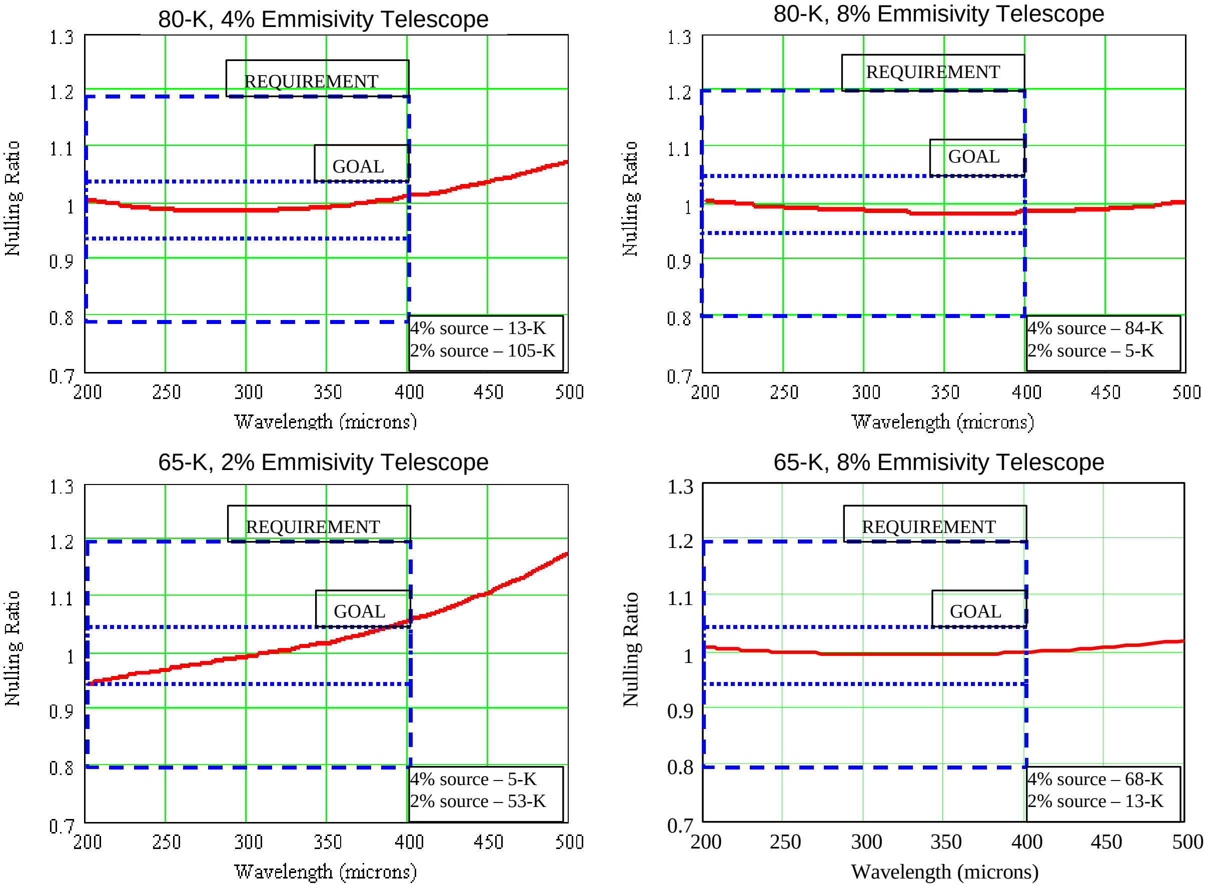


*Figure 14 Efficiency of telescope signal nulling for different telescope parameters.*

## 3.4. THERMAL PERFORMANCE

Several thermal and mechanical prototype sources have been built and tested. Typical results are shown in Figure 15. Constant power (2, 5 and 8-mW) was applied to the source until equilibrium was reached, and then the power was removed, and the source allowed to cool. It can be seen that the warm-up time for constant applied power is rather long, taking approximately two hours to reach 100-K for an applied power of 5-mW. In SPIRE, the sources will be heated under PID control using a pre-determined warm-up sequence that will apply a higher initial peak power. In this way, equilibrium can be reached very quickly, and certainly within the 30-minute requirement. The important parameter, which can only be controlled by design, is the passive cool-down from operating temperature to 4-K after a sequence of spectrometer operations. Cool-down of the prototype source shown in Figure 15 takes around 50 minutes from 100-K to 4-K which is easily within the requirement of less than 3 hours. Thermal modeling indicates that the cool-down of the actual SPIRE SCAL sources, which have heavier gauge wire, will take around 25 minutes over the same temperature range.

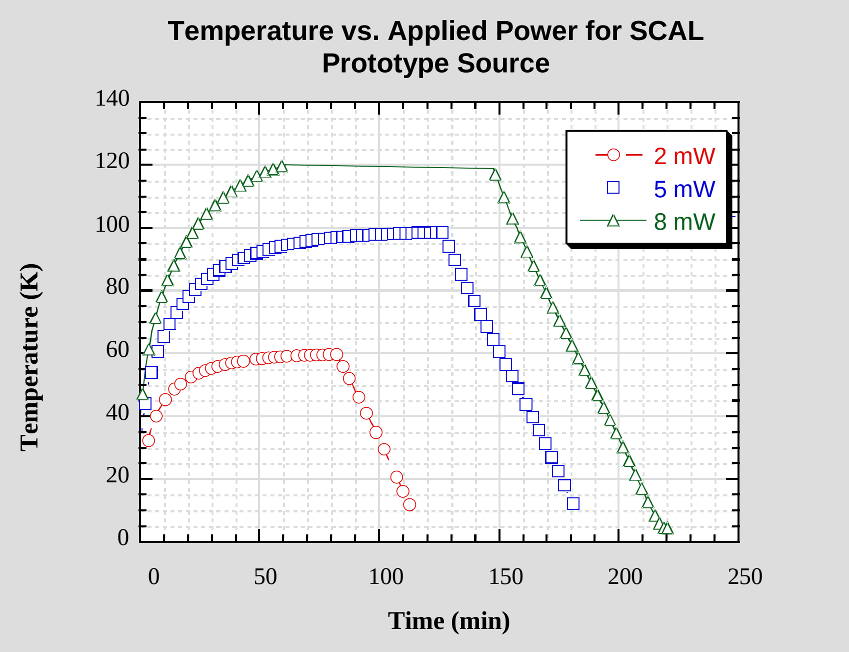


*Figure 15 Measured transient response of a prototype SCAL source. The flattened crest of the 8-mW curve is due to the source going out of the calibrated range of the Cernox-1030 thermometer used for this experiment.*

## 4. ACKNOWLEDGEMENTS

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