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A Ground Calibration Facility for HERSCHEL-SPIRE

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ABSTRACT

We describe the requirements and the main design features of the ground test and calibration facility for the Herschel SPIRE instrument. SPIRE has a large cold focal plane unit (approx 700 x 400 x 400 mm) with several internal temperature stages, and is designed to operate in orbit viewing a low emissivity 80-K telescope. The calibration facility is designed to allow all aspects of instrument behaviour, performance, calibration, and optimisation of observing modes to be investigated under flight representative conditions. The facility includes the following features:

- A large test cryostat replicating the in-orbit thermal environment
- An external telescope simulator and sub-millimetre sources allowing the instrument to be fed with a beam that accurately simulates the beam from the Herschel telescope.
- Internal cold black body for absolute radiometric and flat field calibration
- Cold neutral density filters and an internal shutter for control of the photon background conditions
- A far infrared laser used for spectral calibration of the SPIRE spectrometer channel and to present a source with well understood beam modes to the instrument.
- An external FTS to characterise the spectral response of the instrument in both the camera and spectrometer channel

The ground test facility will be used to evaluate the flight model before delivery and will also be used to house and carry out tests on the flight spare focal plane unit both before launch and during mission operations.

Keywords: Instrumentation, Far Infrared, Ground Test Facility.

1. INTRODUCTION

The HERSCHEL mission[1] is dedicated to observing the cosmos at wavelengths from 85 to 700 mm. It consists of a 3.5 m telescope at a temperature of 80 K with a suite of focal plane instruments cooled to <11K in a liquid helium cryostat. The SPIRE (Spectral and Photometric Imaging REceiver) instrument[2] is one of the three focal plane instruments for HERSCHEL. The focal plane unit of SPIRE is operated at cryogenic temperature (<11 K) and the NTD Germanium 'spiderweb' bolometer feedhorn arrays[3] are operated at ~300 mK. This temperature is provided by a $_3$He sorption cooler. The instrument has two sub-instruments: a multi-frequency imaging photometer using three separate bolometer arrays with resolving power of about $\lambda/\Delta\lambda \sim 3$, and an imaging Fourier Transform Spectrometer (FTS) that provides a maximum resolving power of 1000 at 250 mm.

The photometer[2] will simultaneously image a 4x8 arcmin field of view onto spectral bands nominally centred on 250, 350 and 500 mm. A beam steering mirror will be used to move or spatially modulate the source image at the detector arrays. To give complete spatial sampling of the field of view the image needs to be sequentially stepped by fractions of the Airy pattern diameter. The spectrometer[4] uses two bolometer arrays to give spectrally resolved images of a small (~2.6 arcmin) area of sky. The two bolometer arrays have nominal optical bands of 200-300 and 300-670 mm. The spectrometer shares the input optics of the instrument with the photometer, including the beam steering mechanism.

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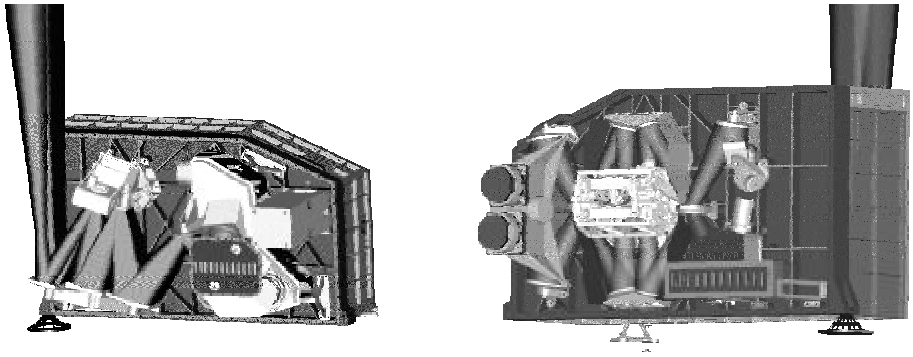

Figure 1: SPIRE Photometer (left) and Spectrometer (right)

A ground calibration, or AIV (Assembly, Integration and Verification) facility[5] is required such that the SPIRE instrument can, as far as possible, be shown to satisfy its scientific requirements[6] and is designed to enable the successful pre-flight calibration and characterisation of the SPIRE instrument. The outputs from the AIV programme will be data calibration tables required in order to process data taken in flight as well as detailed characterisations of the detectors at pixel and array level enabling the operation of the instrument under optimal conditions and training of operations staff. We present the facility, it's requirements, design and expected performance.

2. FACILITY OVERVIEW

The facility is required to provide SPIRE with an operating environment representative of that on board the HERSCHEL satellite and to provide the necessary test equipment to perform the tests required in order that the instrument is calibrated and characterised satisfactorily.

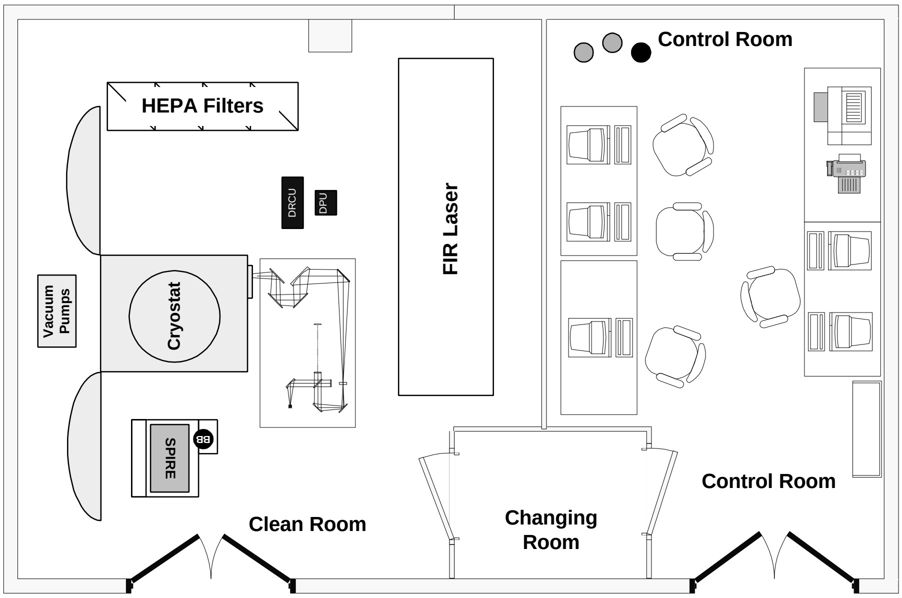

Figure 2: SPIRE AIV Facility Plan

Figure 2 shows a plan view of the SPIRE AIV facility with all of the major items represented. The facility consists of three rooms: A clean room that houses SPIRE, the facility cryostat and all associated optics, a control room for all control and monitoring equipment and a changing room where staff can prepare to enter the clean environment. The clean room is at class 10,000 except in the area of the cryostat where the class is 1000.

The clean room houses the test cryostat, a liquid nitrogen vessel surrounding a pumped ^{4}He vessel which provides the required 77 K, 10 K, 4.2 K and 1.7 K temperature stages. The NTD bolometric arrays operate at 0.3 K provided by a ^{3}He sorption pump provided as a part of SPIRE instrument. Various radiation sources are coupled to SPIRE via a 300 K telescope simulator, situated on a low level optical bench next to the cryostat. Sources include a variable temperature hot blackbody source, used both as the input source to a test FTS also on the low level optical bench and as a separate source for extended source measurements. An Edinburgh Instruments PL295 Far Infrared laser, pumped by a PL5 CO_2 laser, is situated on a separate optical bench adjacent to the telescope simulator bench. A far infrared Fabry-Perot interferometer and pinhole aperture spatial filter are used to ensure single-moded output from the laser. An Edinburgh Instruments laser stabilisation system is used to promote constant power output. All of these sources are coupled with SPIRE via the telescope simulator. In order to perform flat-field measurements on the arrays a cryogenic blackbody source, variable from 4.2 K to 40 K, is provided, situated subsequent to all cryostat filtering. This source will use a flip mirror to place itself in the beam and will fill the beam of SPIRE.

3. TEST CRYOSTAT

The cryostat in Figure 3 will accommodate SPIRE, two JFET units and the cryogenic blackbody source. The requirement of the cryostat is to provide SPIRE with a thermal environment that is representative of that which it will experience on board the HERSCHEL satellite. Four temperature stages are required:

- 77 K provided by the liquid Nitrogen tank
- 10 K provided by the helium boil-off gas
- 4.2 K provided by the liquid helium tank
- 1.7 K by pumping on the liquid helium

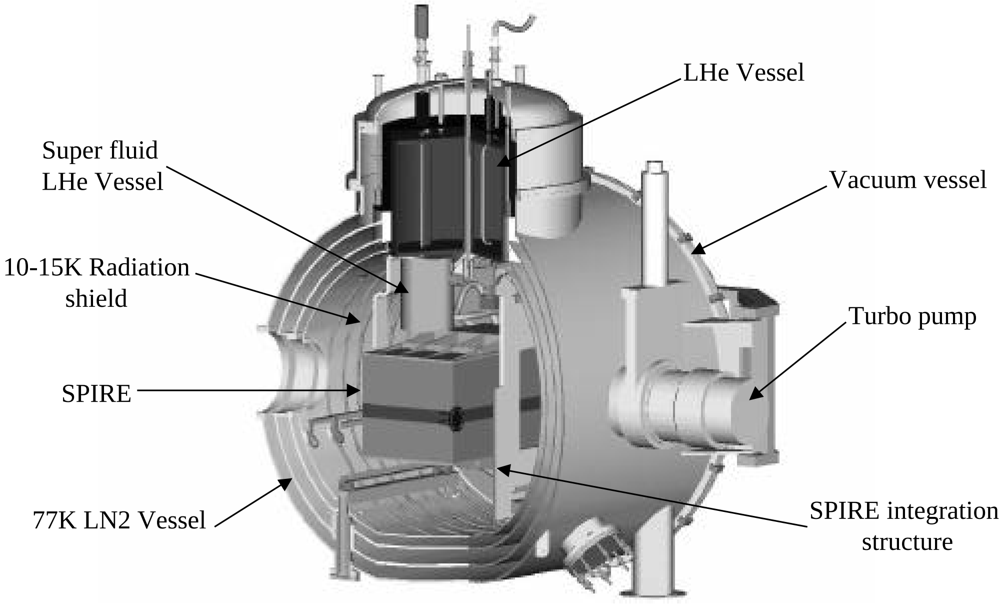

Figure 3: Test Cryostat Conceptual Drawing showing SPIRE, Cryogenic Blackbody Source and external Telescope Simulator re-imaging optics

The main vacuum chamber will be a stainless steel vessel approximately 1.2m in diameter that can be pumped to a pressure of <10-6 mbar. Prior to filling the cryogen tanks. Three separate tanks containing LN_2, ^{4}He and superfluid ^{4}He are designed to hold for >72 hours when at operating temperature. Pre-cooling of tanks with LN_2 will reduce time necessary for cool-down. In order to reduce thermal loading, the instrument is surrounded by a 10 K shield provided by Helium boil-off from the 4 K tank (the actual temperature is variable depending on rate of boil-off). Temperature of 77 K, 4.2 K and 1.7 K stages will be monitored at various positions using Cernox™ resistance thermometers.

The instrument is integrated into the cryostat by means of a support frame, which is locked into position within the cryostat. The frame will also have the cryogenic blackbody mounted on it. Due to space restrictions within the AIV clean room SPIRE will be mounted on the support frame in a separate facility before transit to the AIV facility for integration with the cryostat.

As well as recreating the HERSCHEL thermal environment it is also important to recreate the background power levels expected in flight that is incident upon the detector arrays. In flight this is dominated by the 80 K HERSCHEL telescope but in the AIV facility it is the room temperature (~290 K) cryostat window. Low-pass blocking filters are mounted at each temperature interface and 4.2 K neutral density filtering reduces the background power levels to those expected in flight. All filters are angled to avoid unwanted ghost images from back reflections.

The cryostat window is large, approximately 300mm in diameter in order to accommodate the full instrument FOV (field-of-view) without clipping (as well as allowing visual access to instrument alignment reference points), and while it would be ideal to have one window that transmits both visible and far infrared radiation efficiently (e.g. Sapphire), this proves prohibitively expensive. For optical alignment the window will be a wedged quartz plate which will then be swapped for a HDPE (High Density Polypropylene) window for instrument testing at FIR/submm wavelengths.

TELESCOPE SIMULATOR

The telescope simulator system has to deliver to the instrument a test beam similar to the output beam at the focal plane of the Herschel telescope. This requires the geometric (F-number=8.68) and diffractive (obscuration pattern) characteristics of the Herschel telescope beam at any SPIRE wavelengths to be replicated at smaller lab scale.

As one of its main functions, our telescope simulator is required to provide point source imaging across the whole SPIRE FOV, in order to test the spatial response of the instrument. A 1:1 imaging system, based on the design used to simulate UKIRT by Duncan et al in 1993[7] is employed. In this design a single imaging optic is used to produce the required pupil as a virtual image of a real stop.

In Figure 4, M1 is the pupil mask, providing an obscuration pattern similar to the Herschel telescope one, and M2 is an ellipsoidal re-imaging mirror. The flat mirrors F2 and F3 provide a coupled 2-axis scanning system scanning. The Herschel telescope focal plane is actually parabolic in shape and this requires the telescope simulator to scan in three dimensions. F1 and F2 are mounted and move linearly together to provide the focus depth control. The cryostat window and blocking filters are also shown. For verification of scan mode mechanisms and characterisation of the telescope simulator, a visible trace beam is directed into the system with a portion of this beam picked-off before the cryostat window towards a screen and detector. The optical bridge is necessary due to the height differences between the FIR laser and simulator benches. The later one being adapted to the height of the instrument aperture when inside the calibration cryostat.

The instrument will receive the test beam as it was coming from a (virtual) pupil similar in size and distance as the real telescope one (i.e. the secondary mirror of the Herschel telescope). This will be of use when measuring the telescope pupil illumination function i.e. how the real telescope pupil is actually “seen” by the instrument, allowing verification of the SPIRE out-of-field straylight rejection capabilities.

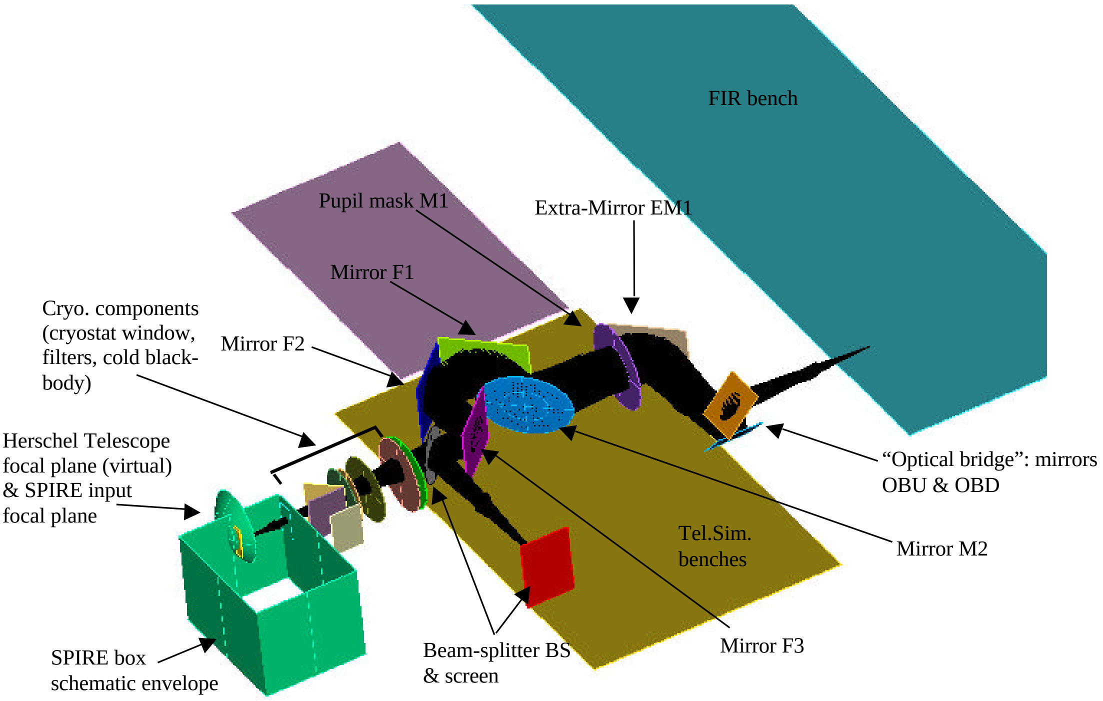

Figure 4: Test Telescope Simulator Optical Layout

SIMULATOR SIZING

To accurately scale the representation of the HERSCHEL pupil maintaining the Fraunhofer far-field approximation, the minimum dimension of any diffractive aperture within the telescope simulator must be many times (typically >10 times) our longest wavelength[7]. This is the diameter of the mask's obscuration, D_{M1} given by

$$D_{M1} = \frac{N l}{OBSC},$$

where $N > 10$, OBSC is the HERSCHEL telescope obscuration factor given by the ratio of mirror sizes D_{SM}/D_{PM} and l = 0.7mm. The distance of M1 from the source is then,

$$L_{M1} = D_{M1} \cdot F\#.$$

The size of the simulator is governed by the required wavefront radius of curvature *ROC* given by

$$ROC = 2 \cdot L_{M1} \cdot L_{PUP} \frac{1}{(L_{M1} + L_{PUP})}$$

where L_{PUP} is the pupil distance to be simulated. For our simulator, *ROC* is approximately 2m and is set to be the mirror-to-focii distance of the telescope simulator M2 mirror.

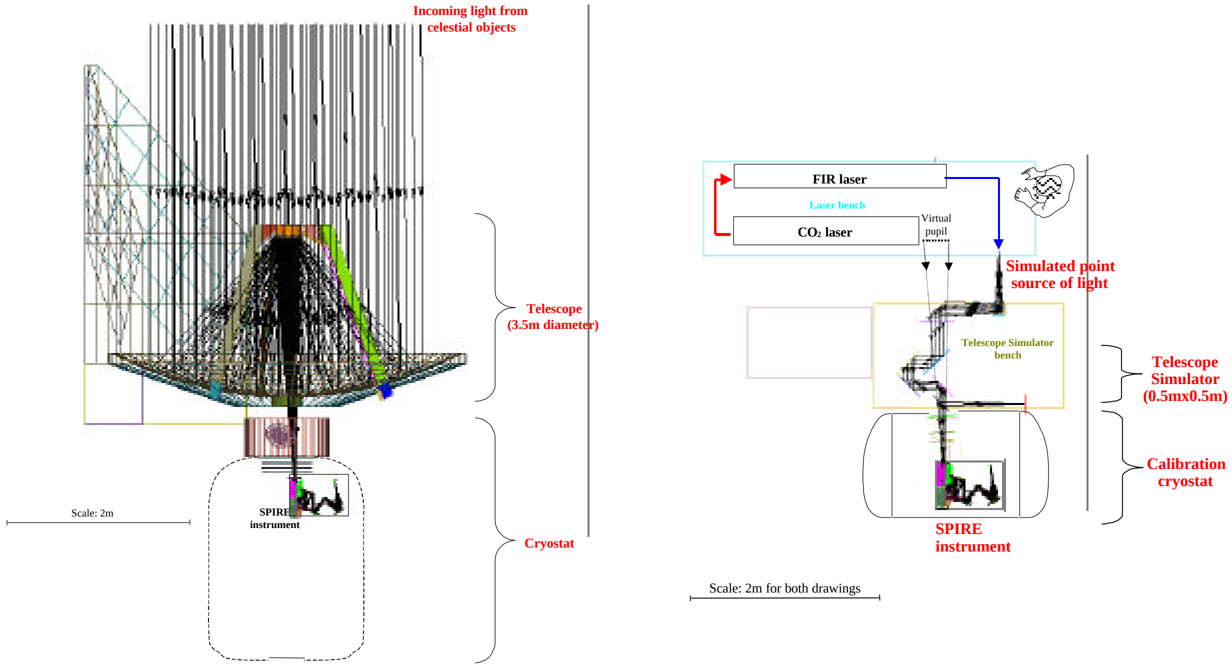

Figure 5: Comparison Between the HERSCHEL Telescope and Test Simulator. (Virtual pupil is shown in simulator)

SOURCES

A number of calibration sources are currently being developed or adapted for the SPIRE test facility. The primary source are going to be:

- A Far Infrared laser providing long wavelength radiation at high power levels, up to 100mW.
- A cryogenic blackbody source for absolute temperature calibration and flat field measurements.
- A bench-top test Fourier Transform Spectrometer for spectral response measurements and the detection of internal fringing.
- A variable hot blackbody source for use as a point-source like input to the FTS or as a standalone point-like or extended source.

FAR INFRARED LASER

The laser here is the same as was used in the ground calibration of the Infrared Space Observatory (ISO)[8] Long Wavelength Spectrometer (LWS)[9] instrument. It consists of an Edinburgh Instruments FIR PL295 FIR gas laser optically pumped by a PL5 Carbon Dioxide laser (also manufactured by Edinburgh Instruments) in a configuration as shown in Figure 6.

The FIR laser gives a range of laser lines from 10.6μm to 2mm and there are hundreds of lines[10] covering the whole of the SPIRE band. A few of these have been chosen for use during ground testing of SPIRE, the selection criteria being dependent upon gas required and strength of line. There are many more lines than this available but the gases used for these may be hazardous and so require special handling and/or storage facilities, or the line produced may be weak. The FIR laser has an output power, depending upon the line used, of between 1 and 10's of milliwatts. This power is crucial when trying to overcome the atmospheric absorption experienced in the lab at these wavelengths over such a long path length (>3m). If the water vapour absorption proves problematic then we have the option of purging the optical benches with dry air.

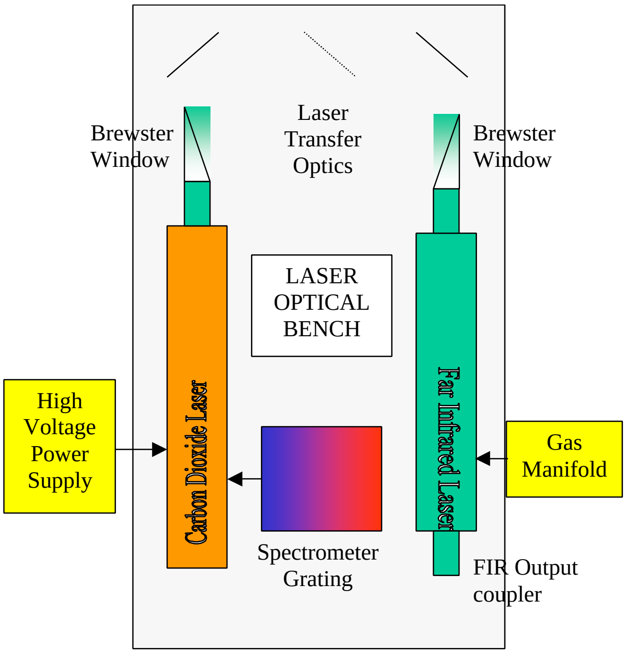

Figure 6: FIR Laser Block Diagram

The laser beam is, ideally, single moded although scattering and diffraction effects can cause transfer of energy into higher order modes. A pinhole spatial filter is utilised to eliminate any higher order Fourier components of the beam and transmit only the lowest order, Gaussian, beam mode. Longitudinal mode is selected using the FIR laser etalon in the first instance. Confirmation of the mode selected is by a broadband, FIR Fabry-perot interferometer.

CRYOGENIC BLACKBODY

When it comes to performing flat-field measurements on the detector arrays, sources coupled to SPIRE via the telescope simulator are no longer effective. The cryogenic blackbody however will be situated at the SPIRE aperture and will completely fill the instrument beam. Our cold blackbody source will be variable in temperature between 4.2 K and 40 K in order to be power-matched with sources expected in flight.

This description of the CBB conceptual design refers to the sketch in Figure 7. The structure of the CBB is mounted in the 10K section of the cryostat in such a position as the flip mirror immediately precedes SPIRE when it is in position. A position as close to SPIRE as possible is desirable in order to reduce the possibility of stray light leakage into the cryostat. The position of the flip mirror, as well as the calibration of the CBB, has become more critical recently due to the removal of the SPIRE shutter. The shutter was to be used to measure the detector array noise maps at 4.2 K. Its subsequent removal from the instrument means that some form of light-tight shroud may be required for the CBB flip mirror when in place. The orientation of the CBB is such that the flip mirror does not operate against gravity.

The heating element is a solid disc of blackened aluminium backed with a Kapton™ thin-film heating element and thermally isolated from the CBB structure using Torlon™ supports. This is housed in an aluminium "can" – a cavity which is blackened throughout with a high emissivity substance. A stepper motor, adapted for cryogenic operation, will be used to actuate the flip mirror to place the CBB in the beam when required and as a cover for the CBB when it is not required. The temperature of the device will be monitored at all times using three calibrated Cernox™ resistance thermometers read out using a Lakeshore Cryotronics® Inc. Model 218 Temperature monitor.

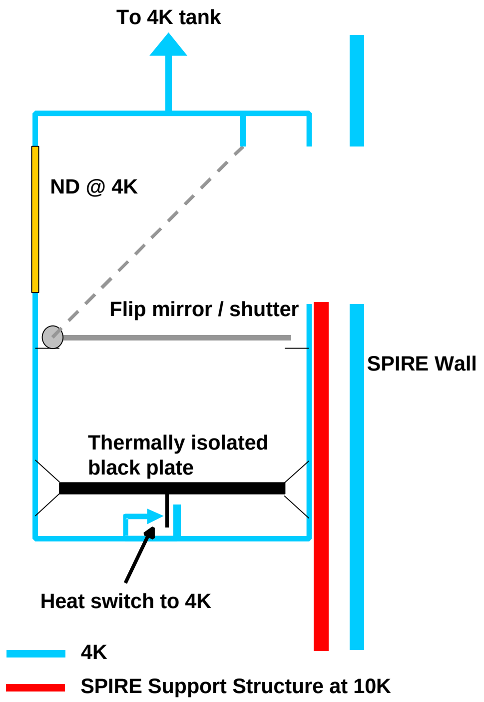

Figure 7: Cryogenic Blackbody Concept

When the CBB is no longer required, a heat switch built on to the CBB structure will latch on to a cold-finger thermally linked to the Liquid Helium bath at 4.2K to enable fast cooling of the CBB once it is no longer required.

FOURIER TRANSFORM SPECTROMETER (FTS)

The benchtop FTS is for spectral response measurements of both instruments (spectrometer and photomoter) but also is required to pick up any internal fringing within SPIRE. It will probably operate as a “step and look” device and have a resolving power of approximately 1000 at our longest wavelength. Fringing within SPIRE is expected at no more than an equivalent resolving power of 500. A Electro-optical Industries ® hot blackbody source will be the primary input device for the FTS and is variable in both temperature and source aperture.

At the time of publication no design details were available to include here.

TEST FACILITY CONTROL AND MONITORING

Total automatic control of the facility is both expensive and carries with it a relatively high risk. For these reasons and for the fact that the SPIRE AIV programme is not expected to have a duration of more than a few weeks, it is not deemed necessary here. However, certain tasks will require remote control and monitoring and this will be provided for the following:

- Calibration cryostat: Temperature monitoring and liquid cryogen level monitoring
- Control and Data acquisition of other AIV facility subsystems (Telescope simulator beam-steering system, FTS sources, …)
- Instrument control and data acquisition.

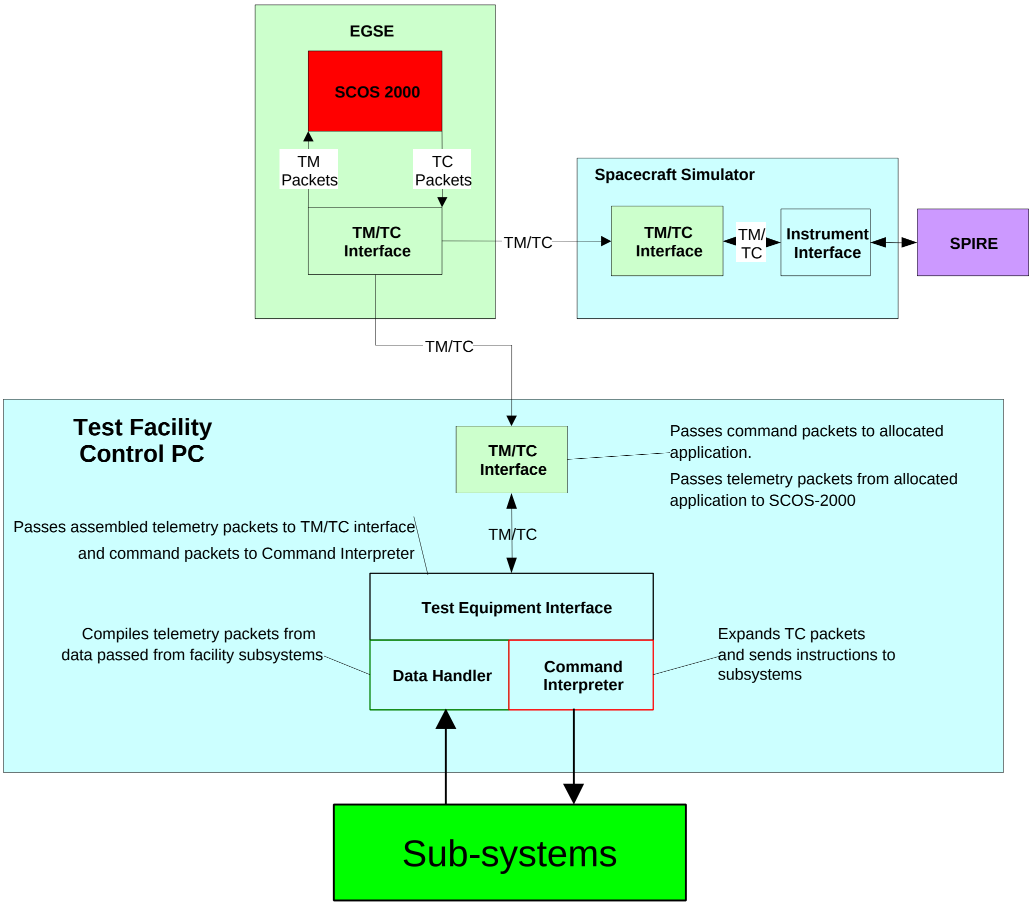

Figure 8: Test Facility Control and Monitoring System Overview

A single test facility control system (TFCS) PC will control and monitor all test equipment subsystems and each subsystem will have its own monitoring application. Other applications allow the remote control of mechanisms such as the telescope simulator, FIR FPI and cryogenic blackbody. The TFCS will form part of the overall EGSE (Electrical Ground Support Equipment) to enable synchronisation of the facility data with the instrument data. Instructions to the instrument or TFCS will be sent from SCOS-2000 as command packets via a packet router. These command packets are interpreted by the TFCS and commands are then sent to the relevant facility control applications. Data from these applications will conversely be translated into telemetry packets which are sent back to the main EGSE via the packet router and SCOS-2000 for analysis.

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