Development of a Calibration Source for SAFARI on-ground calibration.

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***Abstract*—In a European consortium led by SRON, the Netherlands Institute for Space Research, the SpicA Far-infraRed Instrument (SAFARI) is being developed. SAFARI is an imaging Fourier Transform Spectrometer working in the 34 – 210 µm wavelength range with a Nyquist sampled instantaneous field of view of 2' x 2'. It has a selectable spectral resolution R of between 3 and 2000. It is to fly on the joint JAXA-ESA SPICA mission (SPace Infrared telescope for Cosmology and Astrophysics) which features a telescope that is actively cooled to ~5 K. SAFARI will be sky-background limited with the individual pixels having a goal NEP of 2*10-19 W/Hz1/2. The on-ground verification and calibration program will be performed in-house at SRON. For this a test facility is under development.**

To perform absolute calibration a radiometry source is needed that covers the full dynamic range of the individual detectors from atto-watts to pico-watts per pixel in the SAFARI bands. To obtain accurate knowledge of the spectral distribution of the source power a heatable cavity is chosen since this behaves as a perfect black body. The power spectrum of such a source is only determined by its temperature. To get the output in the SAFARI wavelength range and with the desired stability the temperature must be higher than ~40 K but then the output power, which goes with T^4, becomes too high. Additional attenuation of ~10-6 is needed which will be achieved by geometrical dilution.

The full concept of the calibration source will be presented here. This contains design solutions to achieve 10-6 attenuation, 3 octaves of bandwidth, while the profile of the spectral output of the source shall not deviate more than 5% from the best fit to a grey body with Planck spectral profile. Additionally, thermo-mechanical issues like thermally separating the black body cavity at maximum 300 K from the mechanism at 4 K and the integrating sphere at 1.7 K are covered.

***Index Terms*—Calibration, Radiometry, Submillimeter wave technology.**

I. INTRODUCTION

A European consortium with SRON as PI is developing an imaging Fourier Transform Spectrometer called SAFARI. This instrument is to fly on board the SPICA satellite, a joint JAXA-ESA mission that is scheduled for launch in 2021. SPICA's main characteristic is an actively cooled telescope with a goal temperature of ~5 K. This cooled telescope makes it possible to do background limited observations in the 5 to 210 µm wavelength band.

To take full advantage of this capability SAFARI will be equipped with TES-detector arrays with a goal NEP of $2*10^{-19}$ $W/Hz^{1/2}$ and operating at ~100 mK. SAFARI will cover 3 octaves from 34 µm to 210 µm divided in three bands. The goal is to have Nyquist sampled arrays with a 2'by 2'field of view leading to a total number of around 4000 pixels. Frequency Domain Multiplexing (FDM) is used to achieve 160 to 1 multiplexing to keep the thermal loading on the detector stage minimal

An important task within the SAFARI project is the development of a facility for the on-ground calibration of the instrument. The challenge here is to meet the required low background (~attoWatt per pixel) whilst operating the sources and mechanisms needed to do the characterization and calibration. For this the entire Optical Ground Segment Equipment (OGSE) will be inside a 4 K enclosure. Fig. 1 shows the OGSE layout as described in detail in [1].

The SAFARI instrument hangs below the optical table. It's main beam passes through a hole and into the first element which is a re-imager that refocuses the beam inside the OGSE bay. Two scanning mechanisms make it possible to do x-y scans both in the focal plane and in the pupil plane. The focal plane has an additional z-translator to determine the exact focus position. A flip-mirror can relay the focal plane to a focal plane calibration source which is the focus of this article.

In the next sections we describe development of the calibration source. We start with its functional and performance requirements. Next up is the conceptual design. From the conceptual design we model the expected optical performance. Then we describe the mechanical design from which we can model the thermal response. The last section gives the concept for a light pipe connection to room temperature to make possible the use of external sources for calibration.

II. FUNCTIONAL AND PERFORMANCE REQUIREMENTS

The SAFARI instrument has an internal calibrator which has

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the following functional requirements: It should be able to act as an absolute power calibration standard, a flasher and frequency calibration standard. The AIV calibration source should have at least this functionality to be able to do cross calibration between the two sources. The performance wise it should do much better. From this we came to the following functional and performance requirements:

- The calibration source will illuminate the full re-imaged focal plane
- It will operate as an absolute calibration source with:
  Known power, tunable from ~1 aW to 10 fW with a + 20 dB boost.
  Known spectrum, within 5% of a grey body from 34 to 210 µm
  Flat field: uniform distribution to within 1 % of power over the focal plane.
- The calibration source will have a flash function with:
  A flash duration between ~10 msec and 1 sec.
  A rise time as determined by the detector readout system.
  A maximum loading of typically 1 fW/pixel for all bands.
- The calibration source wil have an external port to inject signals from, single frequency LO’s, an external FTS or a gas cell

III. CONCEPTUAL DESIGN

The signal for the calibration source is generated with a cavity black body, the hot source. This hot source acts as a Planckian radiator producing a power spectrum that is only dependent on its temperature. The output of the hot source radiates over a half hemisphere. By coupling only a small solid angle to the next element geometrical dilution is created: The signal is attenuated without changing the relation between spectrum and temperature.

The next element is the Integrating Sphere. This has a small input port and a large output port. It provides additional dilution, which in the ideal case is determined by the ratio between output and input area. The inside of the integrating sphere must be low loss (emissivity > 0.99) and scattering for the SAFARI frequencies. The scattering assures that the output port is homogeneously illuminated.

The output of the integrating sphere is again in a half hemisphere from which again a small solid angle (~F/20) is coupled through the re-imager and the instrument onto the detectors. In total this geometrical dilution provides the required ~10^{-6} attenuation. Geometrical dilution is however no absorption so all unwanted radiation most be absorbed in the absorber on the baffles and housing. An absorbing material with very good absorbing properties (emissivity < 0.01) is there for needed. Potentially the coating developed for HIFI can be used [2].

In between the hot source and the input to the integrating sphere a shutter vane is mounted. This can close the hot source whilst setting a (new) temperature and it can create the flash with the required time profile.

For the external input a light pipe design is currently under investigation. In principle this will work but some design supporting tests are needed. A doodle of the conceptual design is shown in fig. 2 below.

IV. OPTICAL PERFORMANCE

In fig. 3 some Planck curves for different temperatures are plotted. The total power from a black body increases with T^4 but on the long wavelength side over the spectrum the power increases linearly with temperature which is an intrinsically much more stable regime. For temperatures over 100 K the entire SAFARI band is in this linear regime. So for stability regions the hot source temperature must be high.

High temperatures however come at a price. As can be seen in fig. 4 a hot source (diameter = 2 mm) produce 100 µW at 150 K going up to 2 mW 300 K. Looking at the in-band power levels, these range from 1 to 100 µW, still way above the fW level and again an indication of the strong requirements on the absorber material.

To get to the correct optical loading for the individual pixels is a three step optical dilution process which all dilute by approximately 2 orders of magnitude. First a set of apertures define a solid angle which is only a fraction of the half hemispheric output of the hot source containing ~1 % of the energy. Second, in the integrating sphere the ratio between input and output port together with its none-unity (but >0.99) reflectivity reduces the power with another two orders of magnitude. Finally the F-number of the instrument together with the pixel size determines the final coupling reduce the coupling with the last two orders leading to a total coupling of around 10^{-6}.

Fig. 5 shows the pixel loading versus hot source temperature for the three SAFARI bands. By varying the black body temperature between 4.5 K and 300 K we can probe the full pixel sensitivity range from noise floor to well above saturation. The long wavelength (LW) band is dominated at the low temperature end by self-emission of the instrument at 4.5 K. To prevent any contribution of the calibration source itself the integrating sphere is kept at 1.7 K which gives negligible back ground loading.

V. MECHANICAL DESIGN

The mechanical design of the calibration source starts with the hot source. This is a spherical cavity which has to be heated to 300 K in a 4.5 K environment. To keep the heat load to the environment low it has to be mounted in a low thermal conductivity suspension. For this we used a triangular stainless steel frame holding a total of 12 stainless steel wire segments created by threading a single wire through the frame and tensioning it. The twelve wires constrain all degrees of freedom of the hot source making it a very stiff suspension but with low thermal conductivity. The hot source cavity itself is made from aluminum with a rough scattering inner surface and a polished gold plated outer surface with an emissivity > 0.99 to reduce radiative heatload to the environment. A photo of the prototype of this unit can be seen in fig. 6.

The hot source and suspension are enclosed in a housing which is absorbing on the inside to remove stray radiation. The housing holds the baffles that set the coupling to the integrating sphere and the shutter mechanism. The mechanism still has to be designed but current baseline is a low dissipative resonant pivot mechanism.

Between the housing at 4.5 K and the integrating sphere at 1.7 K there is a light tight thermal break. The integrating sphere has a diameter which is 5 times the diameter of the output port to ensure a homogeneous distribution of power. Its inner surface will be high reflectivity (> 0.99) and rough for the SAFARI wavelength to create significant scattering. For this we will be using the sandblasting process from [3]. The design drawing can be found in fig 7.

The external sources will be coupled into the integrating sphere via a light pipe. Coupling to the outside world will be done with a light cone with in its throat the vacuum window. Because the throat has a small 2 mm diameter the 300 K background load can be kept low relatively low. The light-pipe will be kept at 4.5 K with a thermal break close to the vacuum feed-through. It will be aligned to the warm part by three point contacts to keep the thermal load minimal. Connection to the integrating sphere will be through a similar system as used for the hot source including apertures and a movable shutter mechanism. This is also the place where the light-pipe is mechanically fixed. The warm point-contacts form a sliding contact to allow for thermal contraction. The concept is shown in fig. 8.

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VI. THERMAL RESPONSE

An important aspect of any low load design is the thermal response time, the time required to heat up or cool down the source. It is clearly a trade is needed between acceptable load and response time. With a maximum allowable heat load of 100 mW to be reached for a hot source temperature of 300 K we need a suspension wire thickness of 2 mm. From this we can calculate for a nominal temperature of 90 K (~3 fW/pixel) a heat load of ~12 K. Typical warm up time for 100 mW input is just under 30 minutes. Cool down from nominal temperature takes just under 9 hours which is acceptable for the expected use. The warm-up and cool-down curves can be found in fig. and fig. 10.

VII. CONCLUSIONS

We have designed and modeled a calibration source that fulfills the requirements of the SAFRAI AIV program. We are currently in the process of building and testing a prototype. Although confidence in the design is high some design supporting tests are still needed in the areas of 1) the high reflectivity scattering surface on the inside of the integrating spheres and 2) the absorbing coating needed to remove excess radiation.

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[3] Manuel A. Quijada et al., Hemispherical Reflectance and Emittance Properties of Carbon Nanotubes Coatings at Infrared Wavelengths, 2011, Proc. of SPIE Vol. 8150.

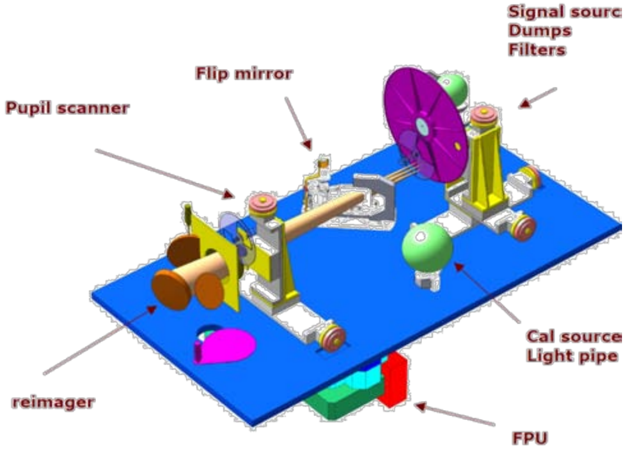

Fig. 1 Schematic layout of the Optical Ground Segment Equipment for the characterization and calibration of the SAFARI instrument.

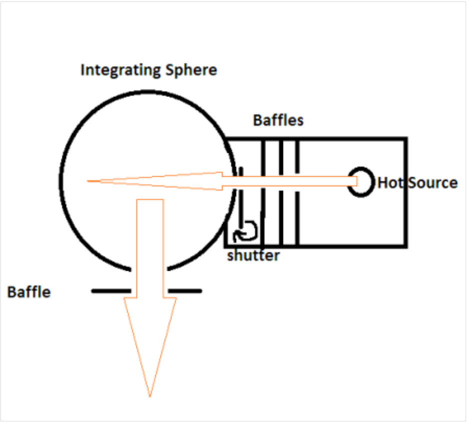

Fig. 2 Doodle of the conceptual design of the calibration source.

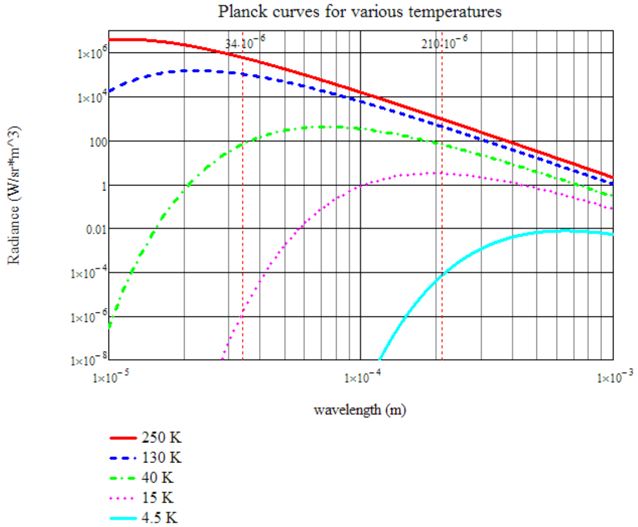

Fig. 3 Planck curves as power versus wavelength for various temperatures.

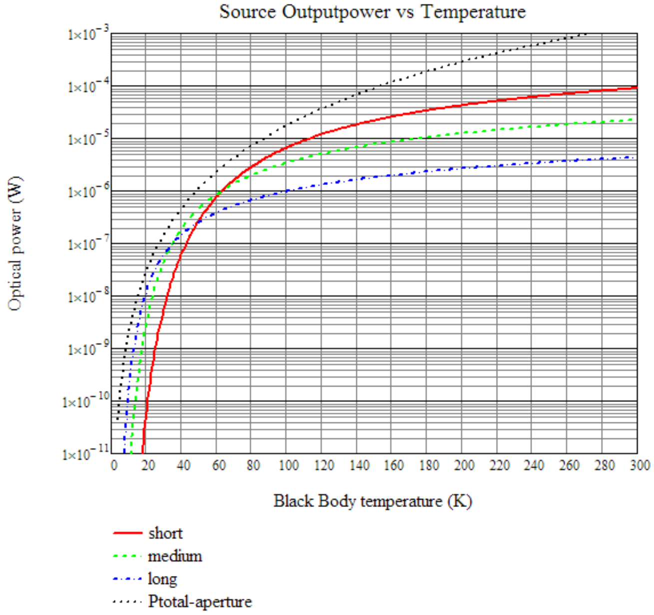

Fig.4 Output power of the hot source versus temperature for the various relevant wavelength ranges.

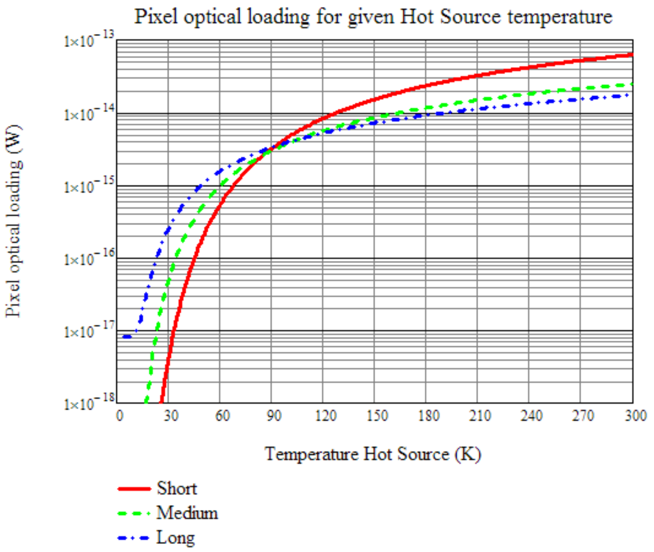

Fig.5 Pixel optical loading versus hot source temperatures for the three SAFARI bands.

Fig. 6 Prototype of the hot source and suspension.

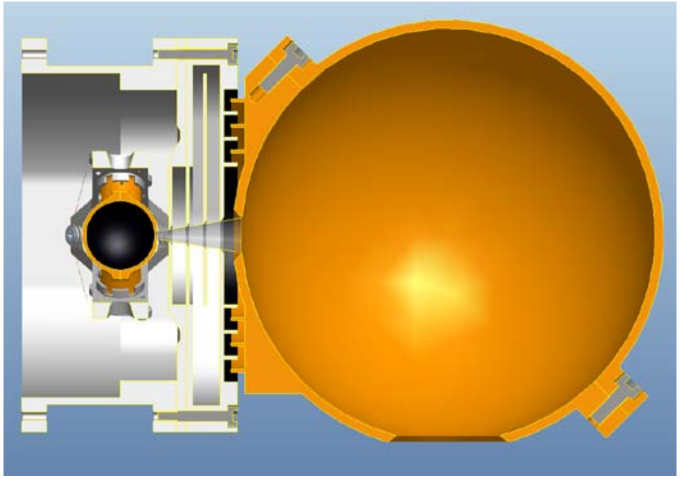

Fig 7. A cross section of the calibration source design.

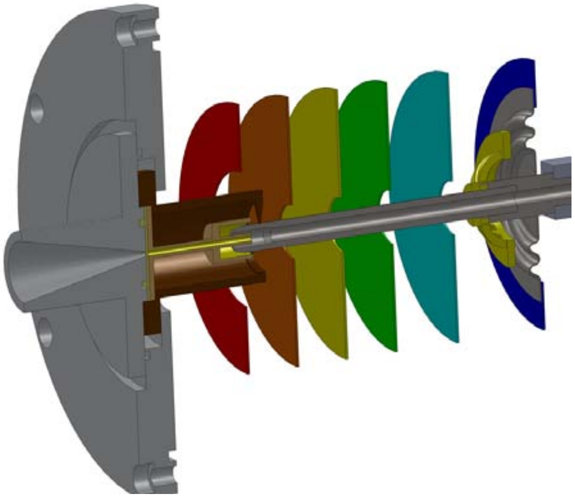

Fig. 8 Concept of the light pipe connection between the outside world and the calibration source.

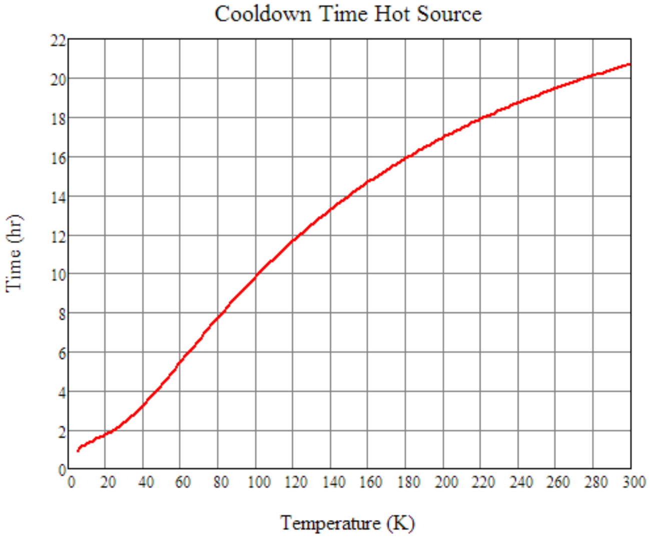

Fig. 10 Cool down curve for the hot source for passive cool down.

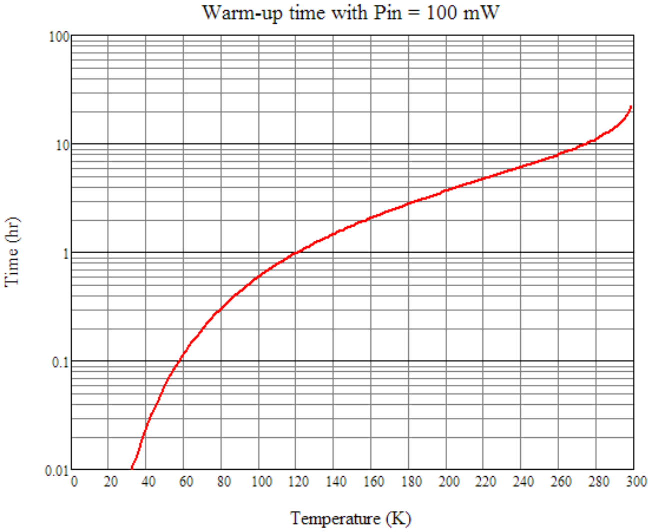

Fig. 9 Warm up curve of the hot source for 100 mW electrical input power to the heater.