Focal plane scanning-system design for SAFARI on Ground Calibration

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***Abstract*—The SpicA FAR infrared Instrument (SAFARI) is the far-infrared spectrometer for the SPICA satellite. Its 34 µm to 210 µm wavelength range is divided into three bands. Each bolometer consists of a Transition Edge Sensor (TES) and a resistive absorber on a thermally-isolated silicon nitride membrane. Each detector is placed in an integrating cavity with a feed-horn in the front. The readout of the TES arrays will be performed with SQUID based current sensors in frequency domain multiplexing configuration. One of the challenges of the SAFARI instrument development is the characterization of the Focal Plane Unit (FPU) models. For this FPU characterization a dedicated cryogenic test facility is being designed. The test cryostat will be equipped with a cryogenic XYZ translation system that will allow scanning the object focal plane, created inside the cryostat by a re-imager, and to determine the image/spot quality, field curvature, and image distortion. We present the concepts and components for the intended measurements, in particular, the plate scale characterization, point spread function, and stray-light.**

***Index Terms*—Transition Edge Sensor, Focal plane characterization, Cryogenic XYZ scanner, Far-Infrared camera.**

I. Introduction

SAFARI is the Far-Infrared camera in the SPICA satellite, programmed to be launched in 2021[1]. It consists of an imaging Fourier Spectrometer with a 2'x2' Field of View (FoV) covering the 34- 210 µm wavelength region. This range is divided in three bands: Short Wavelength (SW) band between 34 and 60 µm, the medium wavelength (MW) band between 60 and 110 µm and the long wavelength (LW) band that spans from 110 to 210 µm. The detectors, TES bolometers [2], are required to exhibit a noise performance limited by the celestial background that translates into a detector NEP requirement of 2×10^{-19} W/√Hz. The total number of pixels is roughly 4000, determined by the Nyquist sampling of the FoV. Efficient readout of the high number of detectors is obtained by use of Frequency Domain Multiplexing (FDM) [3], reaching a multiplexing ratio of 160.

SAFARI will represent, with the low background bolometers, (few attoWatts per pixel), one of the most sensitive space instruments, for which a full characterization and calibration is necessary. The characterization focuses on these main aspects: radiometry (described in detail in [4]) and image quality, measuring sky position of the pixels, frequency resolution and accuracy and to calibrate the spectrometer function of the instrument. Moreover critical issue such as EMI (Electro-Magnetic Interference) or stray light and micro-phonics effects can be investigated. This study is intended to enable an early optimization and verification.

A dedicated test facility is now being designed as part of the SAFARI on ground calibration program (see Fig. 1).In order to perform the above mentioned tests the following units are required: a reimager with similar optical properties as the telescope, a pupil scanner, a calibration source in the reimaged focal plane (OFP) and a XYZ scanner with a broadband source illuminating pinhole masks. For narrower bandwidth measurements a cryogenic etalon is employed.

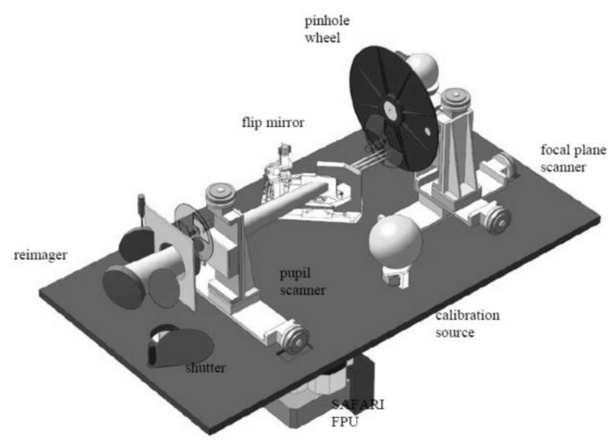

Fig. 1. OGSE (Optical Ground Support Equipment) layout within the SAFARI test cryostat. The plate is the optical bench where the test equipment is mounted. The FPU (Focal Plane Unit) is upside-down at the bottom. The FPU beam goes via the reimager and can be deflected towards the calibration source or the XYZ scanner system. The scanner moves a pinhole wheel back-illuminated by a signal source into the OFP.

In the following sections the strategy followed for focal plane (FP) characterization is described in details, in particular the requirements for the FP scanner.

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II. Optical Characterization Tests

The FP optical characterization will be performed with the following measurements: pixel spatial response (PSF), focal plane geometry study and focal position, and stray light. The characterization setup allows for XYZ motion of a pinhole or pinhole array that are back-side illuminated by a signal source. Two measurement configurations are considered: FTS in 'home' position and FTS in scan mode. With the FTS in 'home' position the source signal is directly incident on the pixel arrays and the signal modulation is generated by means of a chopper; in this measurement configuration narrow spectral band-pass filters can be inserted into the optical path. The center frequencies of these filters are chosen to be at the low and the high edge of each wavelength band. In the scanning mode the filters are not used because the spectral content of the radiation incident on the pixels is determined by the FTS itself.

The signal source concept adopted is identical to the calibration source used for radiometry characterization. The principles are similar to that of the MIRI telescope simulator [5]. For the FP characterization the signal source will provide a spectrum that is flat within the SAFARI bands. This is achieved for temperatures of the hot source between 130 and 150 K. The power incident on an individual pixel is determined by the dimensioning of the source's integrating sphere in conjunction with the pinhole size. The required power on the pixel is about 50% of the TES saturation power assumed to be 4 fW; this power level ensures a sufficiently high signal-to-noise ratio and linear response of the detector. The principle XY scanning operation will be continuous as opposed to 'stepping and integrating'. The reason for this choice is twofold. Firstly, a continuous scanning with constant speed is expected to reduce vibrations. Secondly it will reduce the scanner motor power dissipation. In order to reduce the complexity of the scanner system the scan will be performed first in X and then in Y. The constant velocity is ensured in the desired range but the total scan range will be bigger (roughly 10% in both sides) to allow deceleration of acceleration of the motors. Based on the way of the operation and dissipation the motor can give a parasitic load equivalent to a black-body at a certain temperature. The requirements on the motor background is <10K during measurements. In addition a well-defined reference position associated with a certain pixel will be approached multiple times in all scans, such a procedure is necessary to mitigate drift-induced measurement errors. A redundantly measured line (an X scan or Y around a pixel) will be used to calibrate out errors due to time synchronization between scanner and detector readout or other systematic errors.

A. Z scan

The focal plane will be curved; as a consequence the position of the pinhole is not 'in focus' for all pixels in the reimaged FP. For further characterization as PSF the focus position needs to be identified. An initial Z scan for some XY positions (grid 5x5) in the focal plane is performed. This scan generates a matrix of weighting factors that allow for correction of the incident power distribution on 'out of focus' pixels. The XY scan, for the different Z positions, will be similar to the one described for the focal plane geometry. Moreover a low resolution FTS scan will be performed to extract the spectral information.

The field amplitude in the focal region is calculated using a Gaussian beam approximation [6] (see Fig. 2). The Z scanning range is between -20 mm and 200 mm. The asymmetric shape is chosen to limit the size of the cryostat. The lowest limit is determined by the FP radius of curvature, this value ensures to hit the focus position of each pixel while measuring the near field distribution. The highest limit is given by the long wavelength distribution in the far field. A measurement of 10 equidistant Z positions is enough to map the total field distribution. For each XY pixel the field distribution as a function of Z can be fitted with a Gaussian to extract the beam waist w (see Fig. 3). An accuracy of 100 µm in focal position can be reached. This will allow the verification of the instrument-tilting alignment requirements.

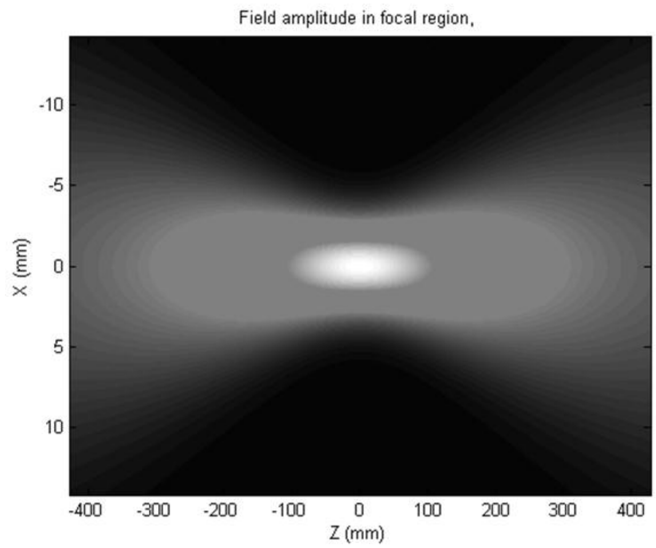

Fig. 2. Field amplitude in the focal region. The field in function of Z is calculated using a Gaussian beam approach.

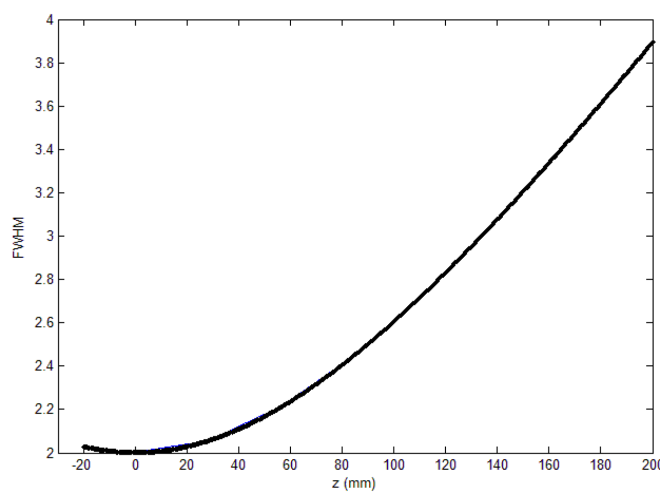

Fig. 3. Beam waist distribution in function of Z. The curve refers to the LW band array.

B. Pixel Spatial Response

The purpose of the spatial response measurement for individual pixels is to verify the image/spot quality, detector-to-detector optical cross talk and to investigate in more detail pixels considered problematic. It is planned to measure the point spread functions of 20 pixels distributed over the FP area with one pinhole mask. The requirement in the detector spatial response accuracy and optical cross talk is to be within 1% of the model prediction. In order to avoid smearing of the point spread function a sampling criterion of Nyquist/10 is applied. This translates into a scanner constant speed of 60 µm/s for the SW band and 200 µm/s for the LW band. The relative positional accuracy requirement on the scanner is 5 µm to meet the above specification of 1%. This precision can be reached only with a good calibration of the scanner system at the cold in a separate campaign before the measurements. The pinhole sizes are calculated from the convolution of the OFP Airy disk and various pinhole patterns and for an etalon bandwidth of roughly 100 GHz (see Fig. 4). The optimum pinhole sizes for the 3 wavelength bands are found to be: 120 µm for the SW band, 220 µm for the MW band, and 400 µm for the LW band.

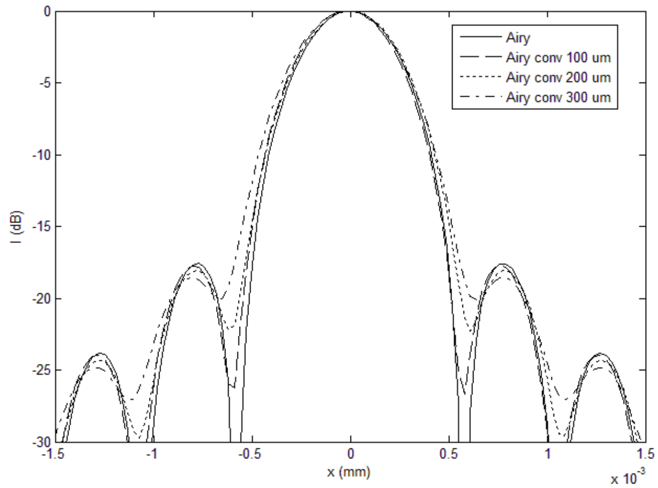

Fig. 4. Convolution of Airy disk in the OFP with various pinhole sizes for a 3% bandwidth etalon. The Airy disk calculated is for the SW band.

C. *Focal plane geometry*

The FP geometry characterization is based on scans of the full FP. The positions of all pixels of the array need to be determined so that they can be translated in position on sky. Arrays of pinholes will be used to reduce the measurement time for this investigation. The second advantage of using an array of pinholes to illuminate the reimaged focal plane is that image distortions can be directly measured. The optimum distance between the pinholes is calculated taking a figure for the distortion of the Airy pattern of both the instrument and the OGSE; this together gives an estimate of the tail of the PSF for each pixel. In order to avoid overlapping of pinhole illumination the neighboring pinhole in the mask is positioned at < 0.1 % of the PSF peak. This level is calculated assuming a Strehl ratio of 0.8 for the reimager and FPU combined [7] (see Fig. 5). The resulting distances between pinholes in the masks are 3 mm for the SW band, 5 for the MW and 7 mm for the LW band. The requirement with respect to the detector focal plane geometry accuracy is to be within 5% of the model prediction; that translates into less stringent requirements compared to the measurement of the PSF for the centroid and extension of the Airy disks.

When using a pinhole mask each sub-scan should ensure as part of the scanning strategy the overlap of first pinhole with the second one. In this way errors due to non-flat illumination of the pinhole mask can be removed.

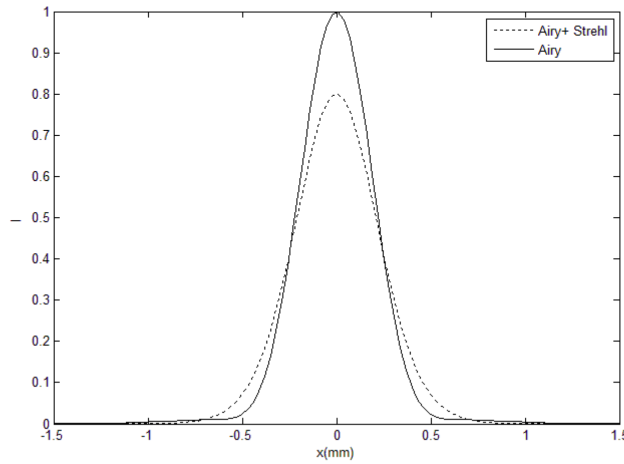

Fig. 5. Comparison between the ideal SW Airy and the Strehl version.

D. *Stray-light verification*

Stray light tests are performed both in the pupil as well as in the object focal plane. In the OFP one can discriminate two categories: ‘in-field’ and ‘out of field’ stray light. Here, in-field stray light refers to optical cross talk between illuminated pixels and nominally non-illuminated pixels. The entire FP will be mapped using a mask with a single pinhole. In contrast out of field stray light refers to parasitic illumination of pixels when the source is positioned out of the expected field of view. The test for this category of stray light is done by scanning with a single pinhole the outer perimeter of the FP, the area scanned will be extending outwards in both directions for a distance of 30% of the FP dimension. This distance is determined by the baffle positions in the cryostat. A larger illumination power compared to the in-field stray-light test has to be used. The pinhole size can be calculated assuming to have a source of 150 K in the cryostat and assuming to get a signal on the TES of a few fW for all bands (see Fig. 6). The size is set to about 1 mm.

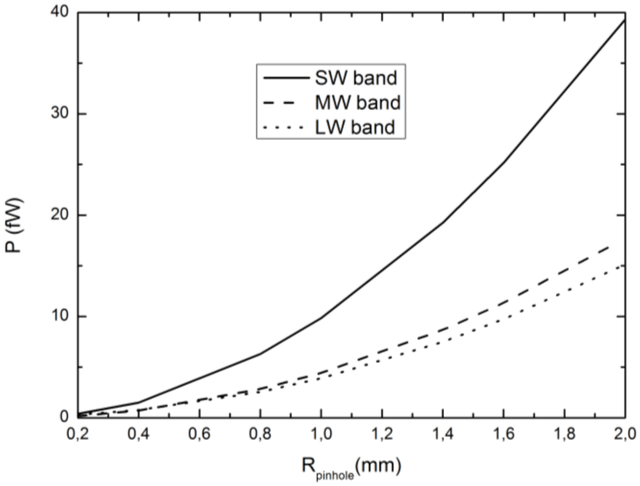

Fig. 6. Optical loading on the TES bolometers for the 3 bands in function of the pinhole sizes.

III. Conclusion

The requirements for a cryogenic FP scanner are determined as part of the SAFARI on ground calibration program. The system designed has to perform the optical characterization of .the SAFARI FPU. The hardware is now in definition phase with an accurate study of the scanner mechanisms.

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