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DEVELOPMENT OF A CRYOGENIC SPOT SCAN BENCH FOR THE STUDY OF MID-INFRARED DETECTORS

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ABSTRACT:

In this article, we present a cryogenic spot scan bench dedicated to the 3-5.5 µm spectral band currently under development in the MIRCOS platform at ONERA. Initial tests have been carried out on a 30 µm pitch HgCdTe focal plane array, and improvements are underway to characterize the spatial response of detectors with smaller pixel pitches.

1. INTRODUCTION

Astrophysical requirements in terms of spatial and spectral resolution imply the development of larger format focal plane arrays (FPA), especially for quantum cooled infrared detectors. That generally leads to a reduction in pixel pitch. During the last twenty years, the pixel pitch has been reduced from 30µm to 15µm [1], 12µm [2], 10µm [3] and even 5µm [4, 5]. Precise knowledge of the spatial response of the pixel through modulation transfer function (MTF) and/or point spread function (PSF) is required but harder to determine as the pixel pitch decreases. These figures of merit reflect the ability of the detector to spatially reproduce the contrast of fine details in the scenery. Measurement of PSF/MTF is critical, on the one hand, for manufacturers in order to optimize pixel design, and on the other hand, for the astrophysics community in the context of the development and operation of scientific instruments. This work is supported by the LabEx FOCUS (FOCal plane array for Universe Sensing) gathering nine major French laboratories that bring their expertise in the detection field to contribute to the development of better detectors for astronomy and Earth observation.

PSF measurements on cooled infrared FPAs strongly depend on the packaging that usually limits access to the detector and thus the fineness of the projected patterns. These patterns are generally limited by diffraction which depends on the aperture number N of the cold shield. The diameter of the first black ring of the Airy pattern, equal to $2.44\lambda N$, is for instance around 24.4µm for $\lambda = 5\mu m$ and $N = 2$ which is a classical aperture number for cooled infrared FPAs.

To address this issue, ONERA developed in 2018 a versatile cryogenic test platform called MIRCOS (Moyen Infrarouge Refroidi pour la Caractérisation d'Optiques et de Systèmes), which can host different cooled projection system located in the same cold shield as the detector. Such a bench makes it possible to project very fine patterns while considerably reducing the ambient thermal background and then improving the signal-to-noise ratio. This bench has been previously used in [6] to evaluate the MTF of a specific HgCdTe MWIR FPA using a 2D interferometric method developed at ONERA. This paper describes the spot scan method currently in development.

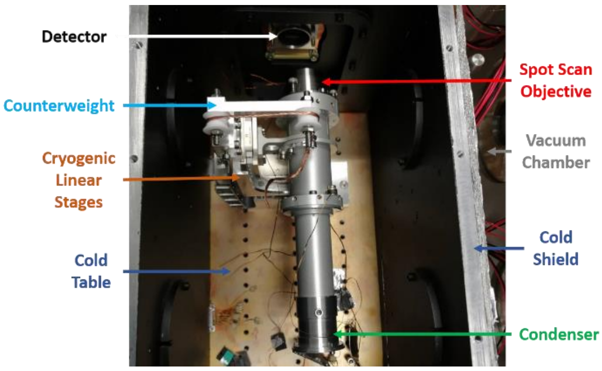

Figure 2: Picture of the PSF measurement bench. Inside view of the cold shield.

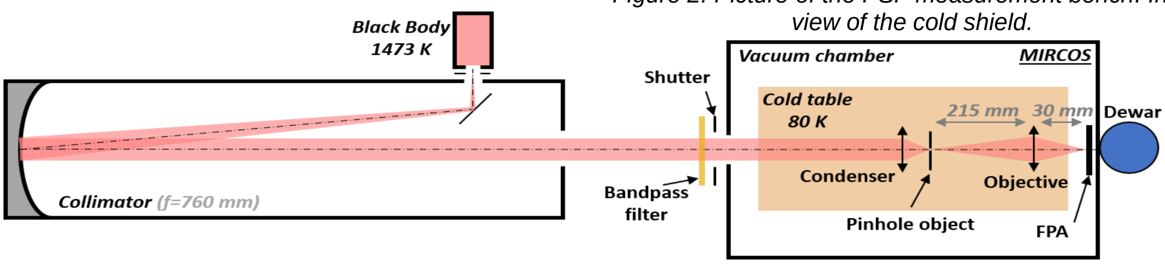

Figure 1: Drawing of the PSF measurement bench

2. DESCRIPTION OF THE SPOT SCAN BENCH

2.1. MIRCOS cryogenic chamber

An illustration and a picture of the bench are presented in Fig. 1 and Fig. 2. The light beam comes from a blackbody heated at 1473 K, which illuminates a hole placed at the focal point of the collimator. Then, the collimated beam goes through a 60mm diameter ZnSe window of the vacuum chamber (10^{-6} bar) and enters into the cryogenic chamber cooled at 80K. A narrow bandpass filter can be added in front of the window in order to limit the blackbody spectral band.

Cooling is achieved by pouring liquid nitrogen into the cold table and the final temperature is generally reached in approximatively 5 hours. The temperature is maintained at 80K by using an electrovalve (placed on a self-pressurised liquid nitrogen dewar) monitored by two temperature probes. Additional probes provide real-time monitoring of the temperature on different components (projection systems, cold shield…) inside the cryogenic chamber.

The advantage of MIRCOS is that different systems can be integrated into the same cold shield as the detector, which will allow a large optical aperture. For this purpose, the cryogenic chamber is 56cm long, 39cm large and 40cm high while the cold shield is 42cm long, 17cm large and 20cm high.

2.2. Cryogenic objective

The projection system used to measure the PSF of the detector is an objective designed and manufactured by Winlight System, as it is shown in Fig. 2. It operates in the MWIR (Mid-Wave Infrared, 3-5.5 µm) band and has a focal length of 25 mm. The aperture number N is equal to 1.2. It has been designed to operate in a finite-to-finite configuration at a working temperature of 80K. This configuration is achieved by placing a 15µm diameter pinhole object at a distance of 215mm from the principal object plane of the objective so that the magnification equals 1/3. A condenser focuses the collimated incoming light on the pinhole increasing the signal-to-noise ratio. The pinhole and the condenser are mechanically bound to the objective. This overall setup has two advantages: it allows a precise centring of the pinhole with the objective. The theoretical size of the geometric image is smaller than the first black ring of the objective Airy spot (which is about 12µm at 4µm of wavelength). The geometric image is also equivalent to the FWHM (Full Width at Half Maximum) of the objective Airy spot (which is about 4.9µm at 4µm of wavelength).

In order to perform deconvolution on the measured PSF, a fine optical characterization of the objective will be carried out.

2.3. Cryogenic linear stages

In order to scan the spot on the detector along three translation axes, cryogenic linear stages are installed inside the cold shield. Those stages have a maximum course of 20 mm, which allow covering the whole surface of the detector enough. However, the vertical stage tolerates a maximum weight of 200g, which roughly corresponds to the weight of the spot scan objective. Therefore, we chose to use a counterweight to lighten the load on the vertical stage and thus allow the system to move properly. The counterweight can be seen in Fig. 1.

3. RESULTS OF BENCH VALIDATION

Measurements presented in this section have been performed with a 30µm pixel pitch HgCdTe MWIR FPA whose MTF has been previously measured with an interferometric approach [6]. As a first step, those measurements were performed without any filter.

3.1. Simulation of optical PSF

Fig. 3 shows the theoretical monochromatic PSF of the objective simulated from the computer-aided design (CAD) provided by Winlight under ZEMAX©. In the ideal case, if the objective is diffraction limited, the FWHM will change from 3.3µm at a wavelength of 2.9µm to 6.4µm at a wavelength of 5.5µm, corresponding to a broadening of 3µm. Therefore, we planned to characterize the objective using several narrow filters in order to be able to retrieve the spectral dependency

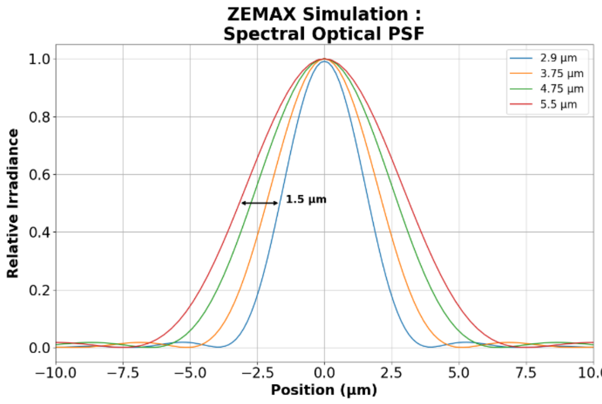

Figure 2: Spectral PSF simulation under ZEMAX© of the spot scan objective.

3.2. First spot image

Firstly, it is necessary to check the conformity of a measurement of an image focused on the detector. Fig. 4 shows the focused spot with its energy distribution.

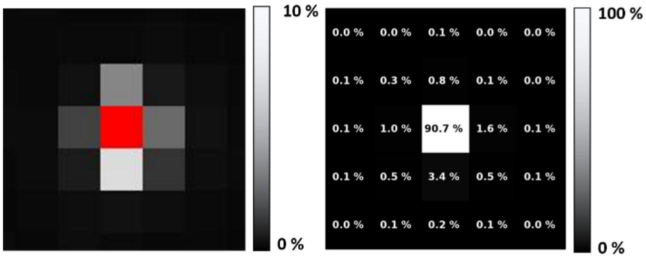

Figure 3: Picture of a focused spot and its energy distribution

New measurements will soon be carried out with narrow spectral filters and will be compared to simulated results.

3.3. Validation of the positioning of the spot

Secondly, the position of the light spot onto the detector must be in the same place for the same set point, so that the measurement is precise and repeatable.

Precise restitution of the spot position on the FPA can be obtained by defocusing the image in order to apply the barycentre method as is shown in Fig. 5.

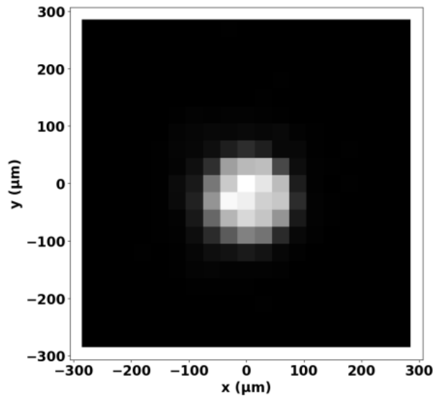

Figure 4: Defocused spot

From this defocused spot, first 2D scans were carried out in order to check the proper functioning of the linear stages (Fig. 6).

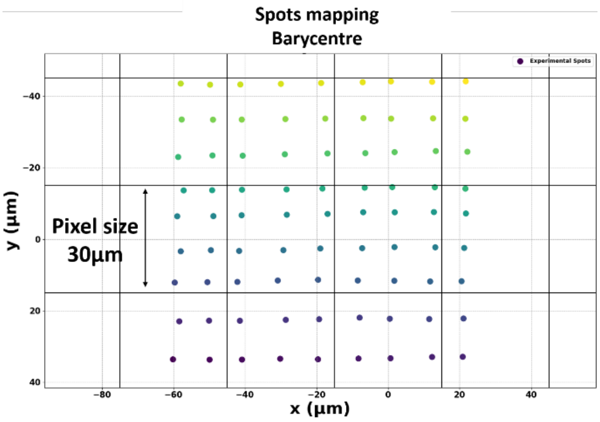

Figure 6 : Scan of a 90µmx90µm area with a step of 10µm

These first measurements allowed us to roughly validate the displacement of the spot on a 90x90µm area, which corresponds to 3x3 pixels. An analysis of the results showed that the precision of the displacements is presently limited by the accuracy of several elements of the measurement, including the reading position of linear stages. The resulting error is between 2 and 3 µm. This is not sufficient to perform accurate measurements on FPA with pixel pitch lower than 15µm. An interferometric system is currently being installed in the cryogenic bench to improve our knowledge of the position of the spot. The expected precision is lower than 200nm.

3.4. Optical alignment study

Finally, it is necessary to check that the optical bench is correctly aligned. It is important to know that 3 coordinate systems are involved into measurements: (X, Y, Z) are the orthonormal coordinate reference system where $\vec{Z}$ is the optical axis, (X_D, Y_D, Z_D) are the coordinate system linked to the detector, and (X_M, Y_M, Z_M) are the coordinate system linked to the linear stages. The latter is not necessarily an orthogonal system because each axis is linked to one different linear stage and each linear stage may not be perfectly mounted.

Nevertheless, those results do not prevent us from starting to study the optical alignment of the bench. Indeed, the Z_M-scan along the mechanical axis allows estimating residual tilts between the mechanical axis, the optical axis and the axis perpendicular to the FPA.

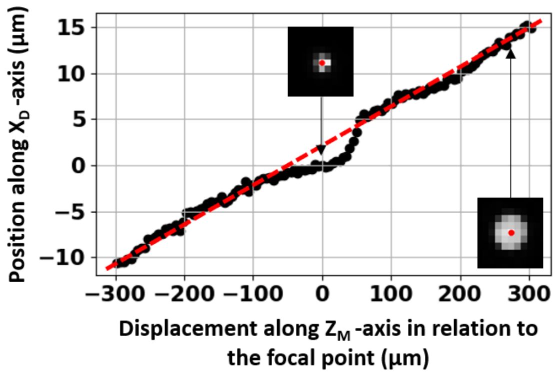

Figure 7: Evolution of the spot position along the horizontal detector X_D-axis while scanning along the mechanical Z_M-axis. The coordinates (0,0) corresponds to the focus of the image on the FPA.

Fig. 7 shows the evolution of the position of the spot along the horizontal detector axis (X_D-axis) while scanning along the mechanical axis (Z_M-axis). It is important to note that the barycentre estimation can no longer be used when the spot is focused onto one or very few pixels. (Typically, when $|\Delta Z_M| < 50\mu m$).

The apparent slope indicates the presence of a residual tilt. However, this measurement combines two tilts (in the X-Z plane) between three different axes (optical axis, mechanical axis and axis perpendicular to the detector). A drawing showing the combination of the different residual tilts is shown in Fig. 8. α is the tilt between the optical axis and the mechanical axis, and β is the tilt between the mechanical axis and the axis perpendicular to the FPA.

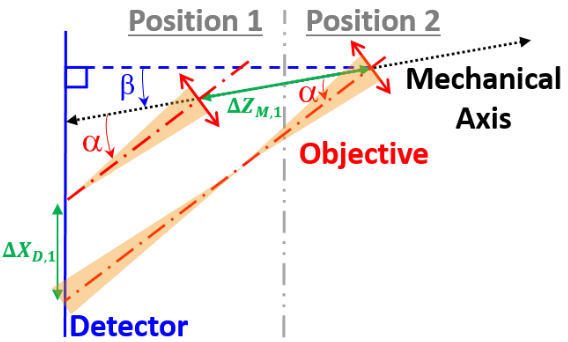

Figure 8: Illustration of residual tilts combination between optical axis, mechanical axis and axis perpendicular to the detector. The angles have been deliberately exaggerated for better readability.

The link between Fig. 7 and Fig. 8 is given by Eq. 1:

Eq.1 $$\frac{\Delta X_{D,1}}{\Delta Z_{M,1}} = \frac{\sin\alpha}{\cos(\alpha+\beta)}$$

$\Delta X_{D,1}$ and $\Delta Z_{M,1}$ respectively correspond to the displacement along the detector and along the mechanical axis,

A complementary measurement is then required in order to dissociate α and β. Fig 9 illustrates the measurement method:

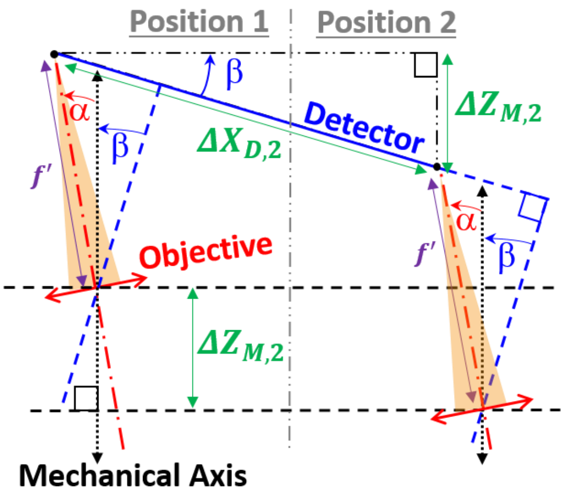

Figure 10: Second tilt measurement

It consists in successively optimizing the objective position along the mechanical axis in order to obtain a focused spot at each of the 4 corners of the FPA. Eq. 2 gives the residual tilt β in the X-Z plane:

Eq.2 $$\frac{\Delta Z_{M,2}}{\Delta X_{D,2}} = \sin\beta$$

$\Delta X_{D,2}$ and $\Delta Z_{M,2}$ respectively correspond to the displacement along the detector and the displacement along the mechanical axis.

Assessment of β can be easier considering Eq. 3:

Eq.3 $$\Delta X_{D,2} = N \times p_{pixel}$$

$\Delta X_{D,2}$ corresponds to the displacement along the detector. N is the number of pixels that separates Position 1 to Position 2. p_{pixel} is the pixel pitch.

4. FIRST ESTIMATION OF A PIXEL PSF

An initial extraction of the spatial response of the pixel during a serpentine scan (Fig. 6) allows comparison with measurements made using an interferometric technique on the same detector, as Fig. 10 shows.

The interferometric method consists in using a special grating – named CSIG for continuously self-imaging grating – to project 2D high-resolution patterns [6] that can be predicted by wave physics simulations. A specific treatment in the Fourier space of the detected pattern allows then the restitution of the 2D pixel MTF. A reverse Fourier transform is eventually computed to retrieve the 2D pixel PSF. This method was used in a global way since all pixels contributed to the pattern. Thus, the measured MTF and PSF are the ones of an equivalent average pixel.

These preliminary measurements show a good agreement between results from two different approaches. This comparison is interesting

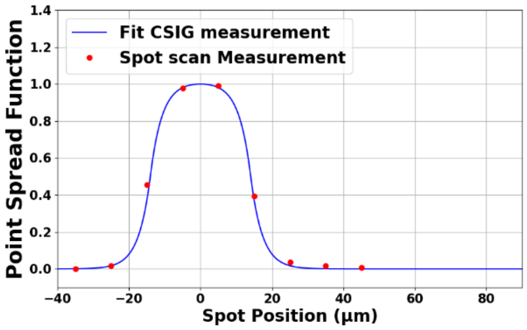

Figure 9: Measured spatial response of a pixel obtained with two different approaches

because the illumination of the detector is very different: on the one hand, the interferometric method requires an illumination over the entire FPA and, on the other hand, the spot scan method requires an illumination on a single or very few pixels of the FPA.

5. CONCLUSION AND PERSPECTIVES

The MIRCOS bench has the advantage of being a versatile cryogenic setup. It currently hosts a new cryogenic spot scan objective that will enable us to directly measure the pixel PSF with an excellent signal-to-noise ratio. A preliminary validation has been made and the first results are encouraging. A methodology has been developed in order to reach the initial goals, that is to say being able to characterize FPA with pixel pitches lower than 10um.

Interferometric sensors are currently being installed in order to manage more precisely displacements of linear stages (expected precision lower than 200 nm). Moreover, a spectral characterization of the objective is currently underway with a wavefront analyser to determine the optical PSF. This measurement will be essential for the deconvolution step in the case of pixel pitches lower than 15µm.

Once the bench is fully developed and validated, spot scan measurements will be performed on different FPA of interest for LabEx FOCUS (for instance HgCdTe FPA with smaller pitches, type-II superlattice FPA).

6. ACKNOWLEDGEMENT

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7. CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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