Development of the Warm Astrometric Mask for MICADO Astrometry Calibration

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Abstract

The achievement of microarcsecond relative astrometry in the near-infrared, with ground-based extremely large telescopes (ELTs) requires an extremely careful calibration strategy. In this paper we address the removal of optical distortions originating from the ELT’s first light instrument MICADO and its adaptive optics system MAORY by means of a Warm Astrometric Calibration Mask (WAM). The results of the test campaign on small spatial scales (1.5 mm) of a prototype mask has confirmed the manufacturing precision down to ~50 nm/1 mm scale, leading to a relative precision of δσ ~ 5 · 10^{-5}. The assessed manufacturing precision indicates that an astrometric relative precision of δσ ~ 5 · 10^{-5} = \frac{50 \mu as}{mas}, corresponding to the MICADO astrometric requirement, is in principle achievable, reaching microarcsecond near-infrared astrometry on an ELT. The impact of ~20 nm, (peak to valley) error residuals on position of the pinholes of the mask is tolerable at a calibration level as confirmed by ray tracing simulations of realistic MICADO distortion patterns affected by mid spatial frequencies (MSFs) residuals. Here we demonstrate that the MICADO astrometric precision of 50 μas over 1’ field of view is also achievable in the presence of a MSFs pattern and manufacturing errors of the WAM, found by fitting the distorted WAM pattern seen through the instrument with a 10th order Legendre polynomial.

Key words: instrumentation: interferometers – techniques: high angular resolution

Online material: color figures

1. Introduction

The Multi-AO Imaging CAmera for Deep Observations (MICADO) will be one of the first light instruments of the Extremely Large Telescope (ELT) providing near-infrared (0.8–2.4 μm) high-resolution imaging with an emphasis on relative astrometry, spectroscopy and coronagraphy (Davies et al. 2018). MICADO will be assisted by a Single-Conjugate Adaptive Optics (SCAO) system and the Multi-conjugate Adaptive Optics RelaY (MAORY). The former will provide a corrected Field of View (FoV) of 19″ and the latter will enable diffraction limited observations over the whole 53 as FoV of the instrument by means of two post-focal deformable mirrors conjugated at ~5 and ~12 km height (Diolaiti et al. 2014). Reaching 50 μas relative astrometric precision requires a paramount calibration effort that must tackle the problem from multiple sides. As reported by Schöck et al. (2016) and Trippe et al. (2010), the astrometric error budget of a ground-based instrument includes instrumental, atmospheric and astronomical systematic errors. Rodeghiero et al. (2018a) studied the astrometric errors originating from the ELT telescope that require on-sky calibration. The work analyzed the distortions arising from the post-focal instruments, MAORY and MICADO, that can be calibrated by means of calibration masks deployed at their entrance focal planes (FPs).

MICADO will be equipped with a Warm Astrometric Mask (WAM) deployed at the MAORY entrance FP, and a Cold Astrometric Mask (CAM) deployed at the MICADO entrance FP inside the cryostat. This paper focuses on the manufacturing and qualification efforts for the WAM prototype. The concept of calibrating the optical distortions with a reference target mask has been proposed (Trippe et al. 2010) and already used by different instruments like GeMS/GSAOI (Riechert et al. 2018), Gemini-NICI (Hayward et al. 2014), SPHERE (Maire et al. 2016), NIRC2 (Service et al. 2016) and TMT instruments generation (Service et al. 2018). The calibration strategy relies on the accurate knowledge of the mask pinhole positions that are compared with the image of the mask taken with the instrument and affected by the optical distortions. Fitting a series of different order polynomials on the image of the pinhole pattern leads to a 2D intrinsic distortion map over the FoV of the instrument. The polynomial fitting is normally done using a different basis such as Cartesian, Chebyshev and Legendre polynomials (Riechert et al. 2018). The optical
distortion coefficient scales with the third power of the field angular coordinate $\sim \theta^3$, therefore most of the distortions are removed already with a 3rd order polynomial. The additional presence of mid spatial frequencies (MSFs) residuals at $\sim$mm scale from the optics manufacturing process requires higher order polynomial such as 5th or 9th, resulting in a need for higher number of reference sources. In this context, a calibration mask ensures a dense grid of reference points that lead to sampling the complete distortion pattern. The MICADO astrometric requirement is to perform relative astrometry with a precision of $\sigma = 50 \mu$as over 1$''$ FoV (Davies et al. 2018; Pott et al. 2018) within a single and between multiple epochs. The extension of the astrometric requirement over a larger FoV is severely limited by lower spatial modes and plate scale drifts, occurring at minute timescales, originated in the fore optics of MICADO, i.e., MAORY and ELT (Rodeghiero et al. 2018a). Given this higher level limitation, we restricted our analysis to small spatial scales errors over patches on the WAM equivalent to 1 as FoV in the instrument. To achieve the required astrometric precision, the calibration mask pattern needs to be known with a relative precision of $\delta \sigma \sim \frac{\delta}{\text{FoV}} = 5 \cdot 10^{-5}$, that for a pair of pinholes 1 mm apart translates to $\delta_{1 \text{mm}} = 50$ nm. There are two methods to tackle this extreme astrometric precision: an ultra stable and controlled manufacturing process of the calibration mask or an extremely precise metrology system for the qualification of the mask. In the case of the WAM prototype the approach chosen was a hybrid of these two methods. Significant effort was put into the identification of an adequate manufacturer due to the size of the WAM (200 mm × 200 mm). In addition, a dedicated interferometric setup was developed to measure a sample of pinhole pair separations on the mask. The paper summarizes the development process of the WAM prototype (scale 1:2, 100 mm × 100 mm) with regards to the MICADO Preliminary Design Review (PDR, 2018 November), starting from the concept of astrometric calibration with a mask (Section 2), the experimental setup built for the WAM characterization (Section 3), the results assessed in the test campaign (Section 4) and the impact of the residual manufacturing errors on the MICADO astrometric calibration (Section 5).

2. Warm Astrometric Mask Calibration Concept

The MICADO astrometric calibration concept relies on two main pillars: (i) the calibration of the telescope that is performed on on-sky observing reference star fields and self-calibration techniques and (ii) the calibration of the post-focal instruments (MAORY and MICADO) that rely on the astrometric calibration masks (Pott et al. 2018). Two astrometric calibration masks are required: Warm (WAM) and Cold (CAM). The former is placed at the entrance FP of MAORY and sees both the MAORY and MICADO distortions. The latter is placed in the MICADO cryostat and sees only the MICADO optical distortions. The astrometric calibration unit contains the WAM that can be positioned with sub-micron accuracy along its three axes with an active hexapod (Rodeghiero et al. 2018b). The translations range are used to refocus the mask against possible drift of the optomechanical interface between MAORY and MICADO and to dither the mask for increasing the distortion sampling and mapping at sub-pixel scales. The rotation degrees of freedom, tip, tilt and rotation, are used to adjust the alignment of the WAM and to assist the self-calibration techniques (Anderson & King 2003). The WAM illumination is achieved with an array of $3 \times 3$ miniaturized tungsten lamps positioned behind the WAM emitting light toward a Spectralon panel that reflects and diffuses the light in the direction of the mask as shown in Figure 1.

The diffused light is transmitted into the WAM and diffracts through the pinholes. The pinholes act as an array of artificial point-like sources that are re-imaged by the post-focal instruments (MAORY and MICADO). Knowing, with high accuracy, the position of the WAM point-like sources allows for the removal of the geometric distortion of the instruments by comparing the nominal (mask) and distorted (image) point-like source patterns. The prototype WAM contains pinholes with several different diameters, spanning between 5 and 50 $\mu$m, to verify also the absolute flux through them. From a measurement conducted with an InGaAs photodiode, we can assess whether the flux is comfortably high, above $\sim 0.2 \times 10^8$ ph s$^{-1}$ for all the pinholes with diameter $\geq 15 \mu$m as shown in Figure 2; this flux corresponds to a signal-to-noise ratio $(S/N) \sim 400$ for 1 s integration time in $H$ band at the MICADO FP. For this specific setup, of mask-to-detector separation $z$ and laser wavelength $\lambda$, we can verify that all the pinholes are diffraction-limited using the simple relation
FWHM = 0.642 \frac{2z\lambda}{a}, \quad (1)

and finding the intersection with the curve \( d = a \) at which the beam is transmitted unperturbed through the pinhole of diameter \( a \). For the WAM setup, we assessed that all the pinholes were diffraction-limited since the transition between Fraunhofer diffraction and geometric optics regimes occurs at a pinhole diameter of \( \sim 0.5 \) mm (Figure 2). In principle, if the pinholes are even only marginally resolved, the beam shape and illumination pattern on the downstream optics may be different than is viewed on-sky. This could result in incorrect distortion maps. In the case of MICADO, the WAM will be seen through the MAORY relay optics whose first optical element (Diolaiti et al. 2014) is \( \sim 4.5 \) m away from the mask boosting the Fraunhofer diffraction regime. The expected best pinhole size for the WAM, having no flux limitations, is \( 30 \) \( \mu \)m in diameter, that corresponds to the size of the ELT diffraction-limited PSF in \( H \) band.

The trade-off for the selection of the WAM substrate and production technology concentrates on two different material families and manufacturing technologies: (i) ceramic and glass substrate treated with coating photolithography and (ii) metal substrate manufactured with laser drilling. Based on the experience of the MUSE experiment (Kelz et al. 2012), there are several pros and cons for both technologies as reported in Table 1.

The main constraint for the substrate selection is the thermo-mechanical stability of the WAM in the required operational range (\( 0 \)°C to \( +20 \)°C). Any linear/volumetric expansion or contraction induced on the WAM challenges the reliability of the astrometric calibration thus requiring the use of an ultra-stable material for the substrate. The linear thermal expansion, \( \Delta l = \alpha \Delta T \), where \( \Delta T \) is the temperature variation, \( l \) is the linear size of bulk considered and \( \alpha \) is the Coefficient of Thermal Emission (CTE) of the material, estimates the linear size variations (expansion or contraction) of the substrate. As shown in Figure 3, the expected substrate length variations, over a typical pinhole separation of 2 mm, precludes all metallic substrates and soda lime glass. The most

![Figure 2. Left: absolute flux measured through different pinhole diameters in a quasi \( H \)-band filter (1450–1700 nm). The measurement is obtained moving the WAM with a motorized stage in front of a calibrated InGaAs photodiode. The WAM illumination system is based on an array of \( 3 \times 3 \) miniaturized tungsten lamps. Right: transition curve between Fraunhofer diffraction regime to geometric optics regime, for the specific WAM setup, \( z = 297 \) mm and \( \lambda = 0.632 \) \( \mu \)m, the pinholes with diameters <0.5 mm are diffraction-limited. (A color version of this figure is available in the online journal.)](image-url)

![Table 1](table-url)

| Lithography ceramic/glass | Laser drilling metallic plate |
|---------------------------|-------------------------------|
| Etching of Chrome coating | Laser drilling, micro-drilling (electro-erosion) |
| Residual background \( 10^{-3} \)–\( 10^{-4} \) | No background |
| Polished window | Flatness TBE\(^a\) |
| Low thermal expansion | High thermal expansion |
| Low thermal conductivity | High thermal conductivity |
| Higher accuracy pitch and diameter | Lower accuracy pitch and diameter |
| Lower accuracy PSF photometry | Higher accuracy PSF photometry |

\(^a\) To be estimated.
reliable material with regards to the day–night calibration, within a temperature variation range of $\Delta T \approx 20^\circ C$, is therefore Zerodur with an average relative expansion factor of $\Delta l/l \sim 0.05 \cdot 10^{-6}$. Interesting studies about the Zerodur thermal behavior and hysteresis (Jedamzik et al. 2010) indicate that a Zerodur substrate class 0–1 is the most stable material for the typical day–night temperature cycle profile at Armazones (ELT construction site) without the need of any thermalization of the WAM.

The Zerodur substrate is coated with a brown Chrome layer of $\sim 150$ nm thickness that results in an optical density of 2.8–3 at NIR wavelengths (Figure 4). The production of the pinhole pattern is carried out in a series of operations: (i) the Zerodur substrate is coated with a sputtered brown Chrome layer (ii) a layer of resistant lacquer is deposited on top of the Chrome layer (iii) the pinholes are etched with a He–Cd UV laser by a photolithography process. The WAM prototype has been produced with a series of multiple pinhole patterns of different

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Figure 3. Left: linear expansion of a 2 mm substrate for different Zerodur substrates and glass materials within a $\Delta T = 20^\circ C$. Right: the metals substrates have systematically higher CTE and expansion lengths that prevents them from being used by the WAM.

(A color version of this figure is available in the online journal.)

Figure 4. Left: picture of the WAM prototype (100 mm $\times$ 100 mm), tested at MPIA, with backside illumination showing the 16 twin quadrants (A..D $\times$ 1..4). Right: optical density of the WAM Chrome coating in five different quadrants measured with a Nicolet iS50 FTIR. The range of interest for MICADO astrometry is $H$ and $K$ band, between 1500 and 2400 nm characterized by an optical density of $\sim 2.8–2.9$.

(A color version of this figure is available in the online journal.)
diameters (from 5 to 50 μm) and separations (from 1 to 8 mm) to facilitate the test campaign.

3. Measuring at Sub-micron Scales

The measurement of the pinhole pair separation on the WAM represents a major effort in the verification of the MICADO calibration scheme. As discussed in Section 2, the current strategy relies both on the on-sky calibrations of the telescope distortions and on the calibration of the masks for the detection of distortions in the instrument. In this perspective, the WAM pinholes coordinates, as built, become the reference field points for the astrometric calibration with the polynomial fit of the instrument distortion map. A major issue in the metrology of the WAM is posed by the desired relative precision, δσ ~ 5 · 10^{-5}, that precludes standard imaging objectives or microscopes that suffer from unavoidable intrinsic optical distortions that are very difficult to disentangle from possible manufacturing errors of the mask. A first attempt with a microscope, Olympus SZX12, has led to a systematic error of ~60 μm over a pinhole pair separation of 1.5 mm (distortion ~4%). To overcome this issue imposed by the direct imaging, we decided to setup a test bench based on the Young’s double slit experiment. The test measures the separation d between two pinholes (double slit) by observing the interference fringe separation f created on a screen at distance z when the mask is illuminated with a coherent light source of wavelength λ as shown in Figure 5 and described by

\[ d = \frac{z\lambda}{f}, \]  

in the far-field approximation z ≫ d. The great advantage of this setup is the absence of any optics (and therefore distortion) between the mask and the detector.

The interference pattern at the screen is described by the Fraunhofer diffraction pattern

\[ I(\theta) = 4I_0 \left( \frac{\sin \beta}{\beta} \right)^2 \cos^2 \alpha, \]  

where the low-spatial frequency envelope originating from the diffraction of the light through the single pinhole is described by the sinc function, \( \beta = \frac{kz}{d} \) while the fast oscillating component associated with the fringes is given by the squared cosine. The coefficient of the cosine, \( \alpha = \frac{2\pi(x - c)}{f} \), contains the fringe separation f that is the main observable of the experiment. The practical implementation of the Young’s experiment is shown in Figure 6. A He-Ne laser is projected onto a pair of pinholes on the WAM and the interference pattern is recorded with CMOS1 (Prosilica GC1600H), which has a 7.13 mm × 5.37 mm sensitive area and 4.4 μm pixel pitch, located at a distance z ~ 297 mm (ARM 1 in Figure 6).

A significant effort is required for the metrology and monitoring of the relative separation z between the WAM and the detector. To measure the relative displacement between the two objects at sub-micron level, a Michelson Low Coherence Interferometer (LCI) is installed in parallel to the Young’s setup. The LCI technique has several applications and it is commonly used for measuring 3D surface morphology at
submicrometric scale, thermo-elastic expansion of structures (Wyant 2002) and optical substrate thickness measurements (Pernechele et al. 2017). This non-contact technique does not provide an absolute distance measurement of $z$, instead it measures, at a submicron scale, the variation $\Delta z$ arising from thermo-mechanical displacement of the WAM with respect to the detector. The light source for the LCI interferometer is a super-luminescent diode (SLED) (model EXS210036-01) that has a small optical coherence length (12 $\mu$m) and a narrow bandwidth (25 nm) centered at $\lambda = 820$ nm. The first arm of the LCI interferometer (ARM1) corresponds to $z$ (Figure 6), the second arm (ARM2) is placed on a carbon fiber bench with ultra low thermal expansion assumed to be length-invariant. The light from the two arms is combined in a beam splitter and projected onto a stepped mirror (LCI monitor, Figure 6) which is reimaged by the camera CMOS2 (Pixelink PL-B957U).

Given the very short SLED coherence length, the interference pattern from the LCI is localized to a small portion of a stepped mirror (example in Figure 7). A Gaussian profile can then easily be fitted on to the fringe envelope and estimating its centroid as shown in Figure 8-left. As shown in Figure 7, the stepped mirror is a polished optical ladder of 30 steps (100 $\mu$m per step) that provides a dynamic range measurement of 3 mm along the $z$ coordinate; e.g., a $\Delta z = 100$ $\mu$m of ARM1 translates to a jump of the SLED fringe from one step to another. To measure the absolute length of $z$ at a micron level we used a Zeiss ScanMax-IPX 3D Coordinate Measuring Machine (3D-CMM) by which we can also estimate the initial WAM and detector relative orientation touching the two objects with a small probe in different points. The 3D-CMM measurement also determines the zero-point on the stepped mirror, a given $z_0$ value is associated with a certain position of

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**Figure 7.** Left: stepped mirror geometry (Pernechele et al. 2017), 30 steps each corresponding to an optical path difference of 100 $\mu$m. Right: image of the stepped mirror taken with CMOS2 showing the LCI fringes (red circle). A second static fringe pattern, noteless, is visible on the top left of the stepped mirror that is the interference between a relay mirror (to reimage the stepped with CMOS2) and the stepped mirror. (A color version of this figure is available in the online journal.)

**Figure 8.** Left: Gaussian fit of the LCI fringe pattern whose centroid provides a measurement of the WAM-to-detector baseline variation $\delta z$. Right: the LCI setup allows for monitoring the optical bench diurnal cycle of thermal expansion/contraction showing a good agreement with a network of temperature sensors on the bench (color lines). (A color version of this figure is available in the online journal.)

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the LCI pattern on the stepped mirror. Any subsequent displacement or wobble of the WAM with a component along the $z$ coordinate results in the motion of the LCI fringes by $z_0 + \delta z$, which does not require the 3D-CMM to be monitored. An interesting example of the potentialities of the LCI technique is shown in Figure 8-right, where the circadian thermal expansion and contraction of the optical bench (ARM1) is tracked by the LCI fringes motion and compared to the temperature measurements of bench. The light source to study the Young’s fringes comes from an He–Ne laser ($\lambda = 632.816$ nm), spatially filtered by two orthogonal slits, used to illuminate and isolate a specific pair of pinholes on the WAM. The WAM is aligned to the LCI interferometer by means of a tip-tilt and rotation stage and different pinhole pairs are engaged in the measurement using a three axes linear stage that holds the mask. The three axes linear stage (Newport 462-XYZ-M), with <100 $\mu$rad angular deviation (wobble), has an axial run-out <2 $\mu$m Peak to Valley (PV) over 25 mm range. Two axes out of three are motorized with a stepper motor with 0.1 $\mu$m minimum incremental step. The pre-measurement sequence for a typical Young’s fringes measurement foresees: (i) aligning the WAM to the LCI interferometer and equalizing ARM1 and ARM2 within the stepped mirror dynamic range, (ii) selecting a certain quadrant and pinhole pair on the WAM, (iii) calibrating the stepped mirror using the motorized stage to move the WAM along $z$ and (iv) measuring $z$ with the 3D-CMM.

4. Test Campaign Results

The test campaign on the WAM prototype assessed a total of 14 pinhole pairs in three different quadrants of the mask, spanning a range of $\sim$80 mm on the mask surface. The analysis was restricted to a pinhole pair separation of 1.5 mm with a 50 $\mu$m diameter to maximize the S/N. Examples of Young’s fringes measured using the setup in Figure 6 are shown in Figure 9. The Fraunhofer diffraction pattern (Equation (3)) is composed of a low spatial frequency envelope associated with the diameter $a$ of the single pinhole and a high frequency fringe pattern due to the interference between the two apertures. The size of the light pool $y$ at the first minimum ($m = 1$) relates to the single pinhole as

$$y = \frac{mz\lambda}{d}. \quad (4)$$

For the current setup, i.e., $z \sim 297$ mm, $d = 1.5$ mm, the diameter of the pinhole diffraction envelope is $2y = 7.52$ mm, the fading in correspondence of the first minimum at the edge of the detector is visible both in the real image Figure 9-left and the simulated one (Figure 10). The raw frame in Figure 9 is affected by smaller rings of unknown origin likely attributable to the laser beam, but of no interest to the fringe spacing.
measurement. To improve the data quality, the raw images were bandpass filtered to isolate, within the power spectrum, the harmonic associated to the fringe spacing \( f \) (Figure 11). Since the fringe pattern is oriented vertically with respect to the image frame, a one-dimensional digital bandpass filter is designed and applied to each row using an infinite impulse response (IIR) bandpass filter. Therefore, the minimum filter order can be achieved and the transient filter effects are small. Furthermore, the transient effects are reduced by zero padding. Since a digital filter is used, the image can be filtered without a phase shift (zero-phase filtering). The filter parameters are determined by using the theory for a double slit. Thus, we obtain the spatial frequency of the fringes, which is the center frequency \( f_0 \) of the bandpass filter. The cut-off frequencies are given by \( f_0 \pm \Delta f \). An example of a filtered image is shown in Figure 9-right.

After filtering the frames, a region in the core of the image is extracted, where the fringes are sharp and the S/N is high. The columns of the image subset are stacked to obtain a 1D pixel slice combining all the counts of the region of interest which is subsequently fitted with the Fraunhofer diffraction pattern (Equation (3)) as shown in Figure 12-left. The fit retrieves an estimate of \( \alpha(f) \) that used to derive the fringe separation and the pinhole separation. To increase the data sample statistics a series of 100 frames is taken for each pinhole pair. Slow drift and amplitude variations are observed in the temporal evolution of \( \Delta d = d_{\text{meas}} - d_{\text{exp}} \) (measured–expected) as shown in Figure 12-right. The origin of these systematic errors is likely associated to the vibration state of the WAM for the fast (sub-sec) small-amplitude component and to a mechanical relaxation of the WAM support for the larger and slower (\( \sim \)sec) amplitude drifts. The selection of the pinhole pair involves a manual stage and a motorized one. A post-processing measurement with a vibrometer (Polytec OFV-505) of the unavoidable fast small-amplitude drift finds the WAM in an omni-directional vibration state with an amplitude of \( \sim 3 \mu \text{m} \). This translates to a \( \Delta d \sim 15 \text{ nm} \) (PV), in agreement with the small scale dispersion of the points in Figure 12. The slower and larger perturbations, \( \sim 30–80 \text{ nm} \) (PV), are more variable from pair to pair. This is likely due to the operator that moves the WAM with the manual linear stage and applies slightly different forces. We observed that waiting for a few minutes after the pinhole pair selection and before starting the acquisition of the frames leads to smaller systematic error on \( \Delta d \) (PV \( \sim 30 \text{ nm} \), Figure 12-right). The pinhole separation measurement was performed multiple times. In order to patrol a certain WAM quadrant, we needed to un-mount the mask from its support and change it, since the linear stage range was not sufficient to scan different quadrants. After the support replacement, the WAM had to be realigned following the steps described in Section 3 before a measurement of \( d \) could be gathered. We also repeated the measurement on the same pinhole pair within the same quadrant to assess the setup repeatability. The results were always within the PV of the distribution of points shown in Figure 13.

An overview plot of the test campaign resulting from 14 pinhole pairs distributed over a range of 80 mm on the WAM is shown in Figure 13. The plot reports the estimate of \( \Delta d \) using two different methods: the fit of the fringe pattern with the Fraunhofer diffraction law (gray points) and the Gaussian fit and centroiding of the PSD peak associated to the fringes harmonic in the Fourier space (red points).

The two techniques give comparable results and data point dispersion. The amplitude of the error bars is driven by the error on the fringe separation \( f \) (fringe distortions and fit uncertainty) and on the baseline \( z \) as given by

\[
\sigma_z = \sqrt{\Delta z_{\text{det}}^2 + \Delta z_{\text{CMM}}^2 + \Delta z_{\text{ori}}^2 + \Delta z_{\text{SCI}}^2}.
\]

The major contributors to \( \sigma_z \) are the uncertainties on the detector FP position with respect to its enclosure \( \Delta z_{\text{det}} = \pm 10 \mu \text{m} \), the error of the 3D CMM and the error of the WAM orientation \( \Delta z_{\text{CMM}} = \Delta z_{\text{ori}} = \pm 5 \mu \text{m} \). For the current setup the average uncertainty is \( \sigma_z \sim 12 \mu \text{m} \) that translates to \( \Delta d \sim 60 \text{ nm} \) giving an empirical error budget law of \( \Delta d/\sigma_z \sim 5 \text{ nm}/\mu \text{m} \) for systematic errors affecting the setup. Including the error budget from \( f \), the overall median uncertainty on the measurement of the pinhole separation is \( \Delta d \sim 75 \text{ nm} \) (PV) for the direct fit of the fringes and \( \Delta d \sim 110 \text{ nm} \) (PV) for the PSD peak fit. The systematic errors noise floor prevents achieving the expected manufacturing precision range of \( \sim 10 \text{ nm} \) for a 2 mm scale. Nevertheless 83% of the data points falls within the MICADO astrometric calibration requirement (shown by the dashed orange line in Figure 13) corresponding to an astrometric relative precision of...
The manufacturing precision $\sigma_{\text{pos}}$ for the position of the pinholes on the WAM scales linearly with size $L$ of the mask as given by Silvestri (2018)

$$\sigma_{\text{pos}} = \pm (0.5 \mu\text{m} + 5 \cdot 10^{-6}L [\text{m}]). \quad (6)$$

Equation (6) gives the absolute position error of the pinhole, while the relative position error of a pinhole with respect to an adjacent one is given by $\pm 5 \cdot 10^{-6}L [\text{m}],$ that for a 1.5 mm pair gives $\sigma_{\text{pos}} = 7.5 \text{ nm}.$

50 $\mu\text{m}$ over 1” FoV. The manufacturing precision $\sigma_{\text{pos}}$ for the position of the pinholes on the WAM scales linearly with size $L$ of the mask as given by Silvestri (2018)

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A complementary measurement of the WAM pinholes position could be derived also using the self-calibration technique as proposed by Anderson & King (2003) during the phase of assembly and integration of the instrument. The technique foresees to get multiple frames of the same grid of points with different offsets and orientations in a way that each region of the mask is imaged on different parts of the detector. The images spots centroids of the pinholes are measured and compared in all the frames to build a unique distortion model that can describe each frame exception made for translation, rotation and scale terms. In practice different WAM orientations and positions can be obtained with its hexapod that provides $\pm 22.5 \text{ mm}$ linear range and $\pm 125 \degree$ rotational degree of freedom.

5. Impact on MICADO Astrometry Calibration

The expected relative manufacturing precision in term of pinhole separation (Equation (6)) is $\sim 5 \text{ nm} / 1 \text{ mm}.$ Due to the limitations of the setup systematic errors (see Section 4) the test campaign on the WAM prototype has assessed the manufacturing precision down to $\sim 50 \text{ nm} / 1 \text{ mm}$ scale. Although the pinhole position error increases with the linear range of manufacturing, it remains very small ($\sim 2.5 \sim 5 \text{ nm}$) at the envisaged WAM pinhole pitch $\sim 0.5 \sim 1 \text{ mm}.$ The WAM is densely populated with pinholes in order to fully sample the instrument’s distortion pattern down to the MSFs scale. The MSF depends on the manufacturing technology and grinding tool size. For the MICADO optics the MSF features (PV $\sim 50 \text{ nm}$) are expected to manifest at spatial scales of $\sim 5 \text{ mm}$ given the approximate size of the manufacturing tool, and is characterized by a power law $1/f_{\text{MSF}}^2$ (Sidick 2009) as shown in Figure 14.

Figure 12. Left: stacked 1D slice (black points) of the Young’s fringes obtained from 50 $\mu\text{m}$ pinholes with separation 1.5 mm and fitted Fraunhofer diffraction pattern (orange line). The extraction of only the fringe spatial frequency removes the mean value of the signal and therefore the obtained intensity values are partially negative. Right: residual errors on the measurement of the pinhole separation for a series of 100 frames. The orange band shows the expected manufacturing precision from Equation (6).

(A color version of this figure is available in the online journal.)

Figure 13. Median value of the pinhole separation residual error $\Delta d = d_{\text{meas}} - d_{\text{exp}}$ measured in 100 frames for 14 different pinhole pairs, all with 1.5 mm separation, from three WAM quadrants. The orange band represents the expected manufacturing precision of the mask (Equation (6)), while the dashed line shows the maximum tolerable pinhole separation error corresponding to an astrometric relative precision of 50 $\mu\text{as}$ over 1” FoV. The gray dots are derived fitting the Fraunhofer diffraction pattern, the red dots are from the PSD peak fitting.

(A color version of this figure is available in the online journal.)
In relation to the MSF, all the optical surfaces close to the instrument intermediary or final FP are particularly important for the control of the distortions production. In fact, close to the FPs the optical beams from the different field points converge toward the focus and their footprints on the surface move away from each other leading to uncorrelated distortions between different fields. Since the MSF pattern is rapidly changing in space, the degree of the polynomial fit and the number of the required sampling points is large. This requirement, together with the need for a bright and dense point-like source distribution, justifies the use of astrometric masks for the calibration of the instruments. The impact on the calibration reliability of different WAM manufacturing errors, random and systematic, has been verified using a series of ray tracing simulations in Zemax. We have reproduced a calibration scenario in the presence of the nominal (from design) MICADO distortion pattern plus a series of MSF residuals on the last reflecting surface of MICADO close to the FP (Figure 15).

The distortion polynomial fit using Legendre polynomials has been performed on a grid of input points distributed over a quarter of a detector from the instrument to derive the post-fit astrometric residual errors. Additionally, to assess the impact of small manufacturing errors on the pinhole position, we simulated a few other scenarios: (i) we perturbed the nominal pinhole positions with a random error distribution with a median value of 3 nm and a PV of 20 nm; (ii) we varied the nominal pinhole positions with a linearly increasing, systematic error with the expected amplitude (Equation (6)); (iii) we simulated the distortion seen by a dithered mask position (60 μm × 35 μm offset) in presence of random pinhole position errors while performing the fit of the MICADO distortion pattern. For these three cases we run the distortion polynomial fit to derive the residual rms astrometric error (Figure 16, left-top). We also fit the input coordinates of the nominal (no error) pinhole position to the image coordinates of the pinholes affected by the errors to investigate the effect of not knowing or neglecting the manufacturing errors while assuming a perfect mask. The results of this study is shown in the residual plot of Figure 16 (left-bottom) and indicate a maximum systematic post-fit astrometric rms error of ~4 μas (PV). The distortion pattern is efficiently fitted down to an rms astrometric residual below the MICADO goal (50 μas) with a 10th order Legendre polynomial.

From the power spectrum analysis of the distortion pattern (Figure 16-right) we can infer the minimum pinhole pitch in order to sample completely the pattern in presence of MSF errors, that based on current analysis is ~0.5 mm. This number is derived by multiplying the critical sampling pinhole spacing with the instrument plate scale. The distortion pattern can be additionally over-sampled by dithering the WAM at sub-mm scale using its hexapod fine positioning system. In these simulations we did not add any photon noise or systematic errors other than the aforementioned to clearly assess the impact of the WAM manufacturing errors. Moreover the Zemax sequential ray tracing simulations do not account for quantitative flux calculations providing already the chief ray/centroid measurement that are the input data for the distortion calculation.

6. Conclusions
The paper has described a revisited, modernized Young’s experiment setup to measure at tens nanometer level the separation of 50 μm pinhole pair, 1.5 mm apart, on the prototype warm astrometric mask for MICADO. The measurement is blind to low spatial frequency modes across the whole mask (100 mm × 100 mm), and therefore only allows for a calibration of the astrometry over ~1 as FoV. Larger FoVs are anyway prevented by low spatial frequency drifts, mostly plate scale and 3rd order changes, of the MICADO fore optics (MAORY and ELT). Although unable to achieve the theoretical manufacturing precision of the mask ~5 nm/1 mm, the current setup has demonstrated the reliability of the lithographic technology within the MICADO astrometric requirement. Having assessed the precision of the experimental setup to be ~50 nm/1 mm scale, it can in be used for future characterizations of different mask prototypes and manufacturing technologies in the range of interest for the calibration of the MICADO astrometry. Using ray tracing simulations to study the MICADO intrinsic geometric distortion and MSF pattern, we found that the presence of random or linearly increasing manufacturing errors at 20 nm (PV) level on the pinhole position have a limited impact (max ~4 μas) on the post-fit astrometric residuals. These simulations have led to determine a minimum pinhole pitch of ~0.5 mm, in order to fully sample the spatial features of the pattern. We
demonstrated that the MICADO astrometric precision of 50 μas is achievable also in the presence of an MSF pattern and manufacturing errors of the WAM by employing a 10th order Legendre polynomial for the distortion fit.

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