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Preliminary design of the MICADO calibration unit

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ABSTRACT

MICADO is the Multi-AO Imaging Camera for Deep Observations, which aims to be the first light instrument of E-ELT. Thanks to its robust design with fixed mirrors and a cryogenic environment, MICADO will provide unprecedented astrometric capabilities and image stability in the range 0.8-2.4 μm. The operation of the instrument coupled with a SCAO unit provides diffraction-limited images over a field of view of 27” that will enlarge to 53” after the integration of the Multi-conjugate Adaptive Optics RelaY, MAORY. This work presents some preliminary possible concepts for the MICADO calibration unit, currently under development at MPIA. This subsystem shall provide standard flat-fielding and spectral calibration plus an astrometric calibration performed with an internal calibration mask to measure and compensate instrument distortions, discontinuities between the detectors and telescope instabilities. The goal of the instrument is to deliver an astrometric accuracy of ~50 μas over the whole field of view.

Keywords: calibration unit, flat-fielding, astrometry.

1. INTRODUCTION

The Multi-AO Imaging Camera for Deep Observations (MICADO) is targeted to be the first light instrument of the European-Extremely Large Telescope (E-ELT). The primary goal and observing mode of MICADO is imaging, with a focus on astrometry with an accuracy of ~50 μas; the instrument provides also a spectroscopic mode with a resolution R~8000. The observing window of the instrument is between 0.8-2.4 μm and its sensitivity will be comparable to that of the James Webb Space Telescope (JWST), but with six times better resolution. The instrument operations are divided in two phases. In the so-called stand-alone mode MICADO will be assisted by a Single Conjugate AO (SCAO) module that will deliver a 27” corrected Field of View (FoV). Once the Multi-conjugate Adaptive Optics RelaY (MAORY) will be integrated at E-ELT, the corrected FoV will be extended to 53”, allowing MICADO to achieve its full performance potentialities [1]. To achieve these outstanding capabilities a careful examination and calibration against all the possible statistical and systematic effects that influence the instrument observations is required. In this work we concentrate on some possible calibration schemes regarding the flat-fielding of the focal plane array and the astrometric measurements leaving the discussion on the spectral calibration to other future works. Accurate and stable (with respect to time) flat-fielding of the CCDs array is required to calibrate the observations against different quantum efficiencies and defects of the pixels that can deteriorate both the photometric and astrometric performances. In section 3, two different techniques for the flat-fielding calibration are discussed and compared in relation to some preliminary simulations results. In addition, an astrometric calibration is needed to guarantee high-resolution imaging and astrometry over the whole FoV. As discussed by Trippe [11], a total of ten different sources of error may affect the high-precision astrometry measurements with MICADO. The errors can be roughly divided into three main categories: instrumental, atmospheric and astronomical. In the current work we discuss only the calibration against the instrumental errors that are due to instrument distortions and instabilities.

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2. INSTRUMENT CONCEPT

MICADO provides both imaging and spectroscopic capabilities in the range 0.8-2.4 µm. The instrument will be installed at the Nasmyth platform of E-ELT and thanks to its robust design with fixed mirrors, gravity invariant orientation and a cryogenic environment, it will provide unprecedented astrometric capabilities (~50 µas) and image stability [1]. MICADO can be operated in four different modes (Fig. 1). The imager can be configured in a zoom mode with a pixel scale of 1.5 mas in a FoV of 20 x 20 arcsec^2 and a wider FoV of 53 x 53 arcsec^2 with a pixel scale of 4.5 mas; the camera F number is 17.48. The spectroscopic mode is optimized for compact objects with a spectral resolving power R~8000. MICADO foresees also a pupil imager configuration for alignment and commissioning phases of the instrument.

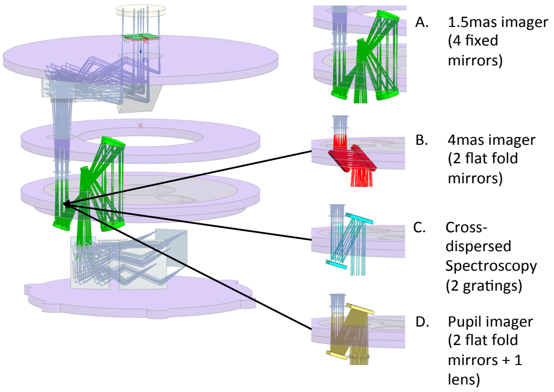


Figure 1. Insight view in the cryostat with the selection mechanism that allows switching between different observing modes: a zoom mode (A) with a pixel scale of 1.5 mas and a FoV of 20 x 20 arcsec^2 and a wider FoV of 53 x 53 arcsec^2 with a pixel scale of 4.5 mas (B); a spectroscopic mode (C) and pupil imager mode (D) for alignment operations. The selection of the instrument mode is possible through a rotating wheel.

The instrument optical design is divided into a collimation unit and a camera assembly (Fig. 2). The collimation unit collects and collimates the light from the E-ELT focal plane at the entrance of the cryostat window in a pupil plane where a cold stop is positioned. The diameter of this element is ~80 mm and at this level a filter wheel allows to chose between about 30 different filters.

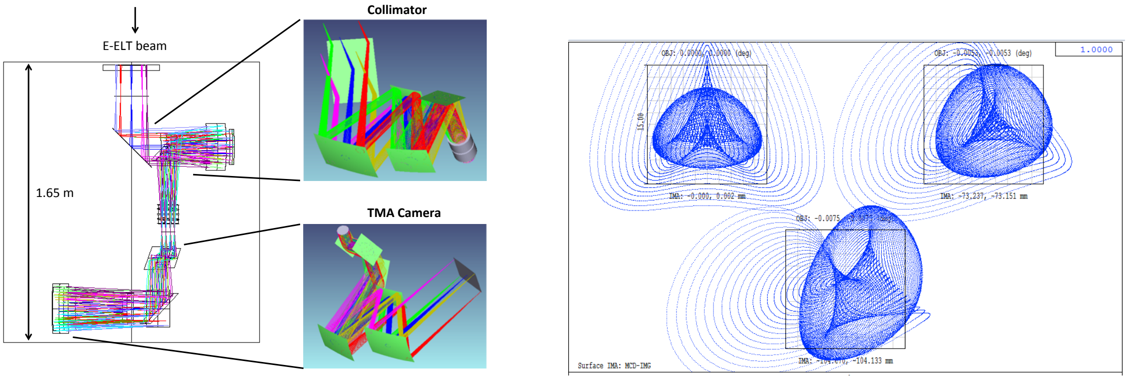


Figure 2. Left: optical path of the light inside the MICADO cryostat; the E-ELT focal plane lays inside the cryostat below the entrance window and a collimation unit creates a pupil plane 80 mm in diameter. After the pupil plane one of the possible instrument mode is selected and the light enters the Three Mirror Anastigmatic (TMA) camera and moves towards the focal plane. Right: MICADO PSFs at λ = 1 µm in different field positions: (0,0), (19”, 19”) and (27”, 27”). The box around the PSF is a pixel with 15 µm pitch.

The filtered light moves downward encountering one of the instrument modes and enters then the camera unit which is a classical Three Mirror Anastigmatic (TMA) configuration. The TMA is a design adopted by many astronomical telescopes and cameras e.g. the JWST [2] and OSIRIS-NAC [4] and it enables to minimize both spherical aberration, coma and astigmatism over a wide FoV. The size of the camera focal plane is ~196 x 190 mm and the current design baseline foresees the use of 16 HAWAII-4RG detectors (4096 x 4096 pixels, pitch 15 µm) arranged in a 3 x 3 matrix [6]. The gap between each CCD is 6 mm and 3 mm in vertical and horizontal direction respectively.

MICADO is designed to enable the use of AO at a level of sophistication that increases as more complex AO systems are commissioned. In the first *stand-alone* phase the instrument will be assisted by a SCAO with a field of 25" and later, with the introduction of MAORY the corrected FoV will enlarge to 53". With its breakthrough capabilities MICADO will address many fundamental questions of the modern astrophysics that are collected in Table 1. The instrument is expected to see its commissioning and first light in 2025.

Table 1. Different capabilities of the MICADO instrument (left column) that serve many science cases (right column) [7]. The explored astrophysical problems span from high redshift objects to extra-solar planets around nearby stars.

MICADO Capabilities	**Science Targets**
Imaging	- Cosmic star formation history: resolved stellar populations - Structure of high-z galaxies - Nuclei of nearby galaxies
Astrometry	- Stellar motion within light hours of Sgr A* - IMBHs in stellar clusters and dwarfs galaxies - Milky Way formation
Spectroscopy	- ages, metallicities, masses of elliptical galaxies at z = 2-3 - spectra of first supernovae at z = 1-6 - redshift, velocities, metallicies of SFG at z =4-6
High Contrast Imaging	- Giant/massive planets at a few AU nearby stars - Direct detection of planets discovered via RV method
High Speed Photometry	- Pulsar & magnetars - Accreting white dwarfs - Compact binaries, transits & occultations

3. MICADO CALIBRATION UNIT

The MICADO Calibration Unit (CU) has three main purposes:

- Provide a uniform illumination of the instrument focal plane
- Provide a spectral calibration
- Estimate the level of geometrical distortion affecting the instrument

To fulfil these functional requirements the MICADO CU shall include different subsystems (Fig. 3) as a series of light sources, either blackbody and spectral line lamps, an Integrating Sphere (IS) or some highly-diffusive and reflectance material that increases the spatial homogeneity of the light source. The diffuse light should be shaped and controlled by relay optics and baffling systems leading it to propagate inside the instrument along the same optical path of the starlight. The CU shall estimate the level of astrometric distortion over the whole instrument FoV by means of an astrometric calibration mask.

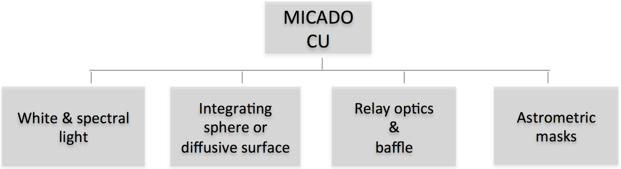


Figure 3. The MICADO Calibration Unit (CU) includes different light sources: blackbody and spectral line sources; highly diffusive and reflectance material as IS or Spectralon surfaces; a relay optics system and baffles to recreate the same F# of the telescope; one or more astrometric calibration masks.

A calibration unit is a standard concept for the current and future generation of instruments, but in the particular case of MICADO, the practical realization of this subsystem represents a challenge in relation to its tight performance requirements. In the next paragraph we discuss some preliminary design concepts related to the flat-fielding and the astrometric calibration. Exception made for the astrometric calibration mask that will be likely positioned in correspondence of the E-ELT focal plane, the CU will be located on a platform supported by an hexapod system above the MICADO cryostat (see Fig. 4).

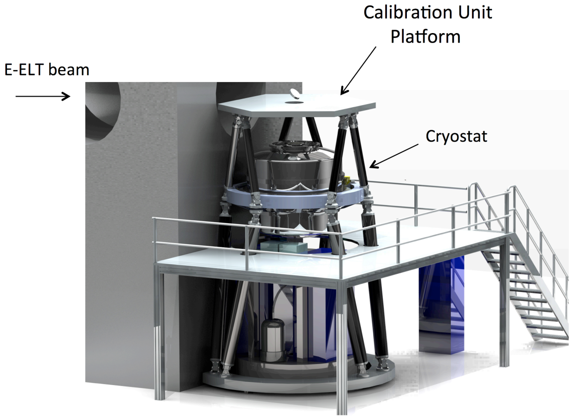


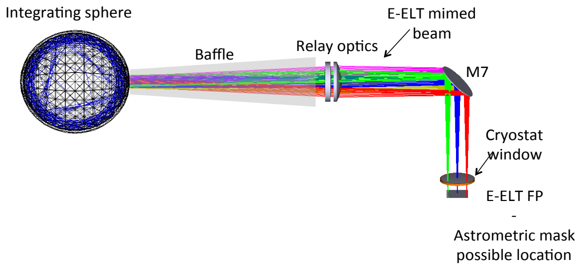
Figure 4. 3D representation of MICADO at the E-ELT Nasmyth focus. The MICADO Calibration Unit will be located on the hexagonal platform above the cryostat.

4. CU DESIGN STUDIES

Flat-field calibration

Many detector cameras of the past generation were calibrated with a procedure generally achieved by dome illumination [3]. The level of accuracy demanded for MICADO however, requires the use of an instrument internal calibration unit stable and reliable. The first baseline design explored for the flat-fielding calibration involves the use of an Integrating Sphere (IS) coupled with a relay optics. This option follows a common design adopted by many operating instruments (e.g. MUSE [9], KMOS [10]) and foresees the use of IS to spatially homogenize the light sources of calibration at its exit port and to propagate the light at the pupil plane of the instrument. If a uniform illumination of the pupil plane is realized also the light distribution transmitted to the focal plane will be characterized by a high spatial uniformity, leading to achieve a reliable flat-fielding of the camera detectors. The radiation pattern at the exit port of the sphere is conveyed to the pupil plane by a relay optics that creates a light beam with the same F# of E-ELT, mimicking the telescope beam. The scaling of this concept to MICADO is challenging in relation to the wide focal plane array to be illuminated ~190 x 196 mm.

A first concept design is based on a relay optics assembly made of two even asphere lenses as shown in Figure 5. A large IS (~50 cm diameter) coupled with a baffle to control the stray light feeds the relay optics positioned in front of M7 that redirects the beam towards the cryostat window and the instrument (Fig. 5). The illumination pattern at the IS exit port is focused by the relay optics at the E-ELT focal plane, just below the entrance window of the cryostat, and then reimaged at the instrument pupil plane. The specifications of the lenses (one doublet and one singlet) are collected in Table 2 below.



Units are mm	Doublet Lens 1	 Lens 2	Lens3
RoC*	R_1=3770 R_2 = -4500	R_1=-4500 R_2 = -3927	R_1=-459 R_2 = -459
C. Thick	30	30	29
Diameter	400	400	400
# Asphericał terms	3	2	3
Glass	CAF_2	ZnSe	ZnSe

Figure 5. Optical scheme of a possible CU design based on an IS coupled with an objective lens system. The light exiting the exit port of the IS is refracted by two aspherical lenses that mimic the E-ELT beam inside the instrument and create a uniform illumination of the pupil plane. Table 2. Main optical specifications of the objective lens components. *Radius of Curvature.

Achieving a uniform and suitable illumination over the whole instrument focal plane with this concept design requires the use of ~350-400 mm diameter lenses. Large aspherical lenses can be challenging to manufacture and expensive. For this reason also an alternative design (not reported here), based on reflecting elements, is under study. The mirrors have comparable size to the lenses, but they represent easier solution in terms of manufacturing complexity and costs. Preliminary results, still under optimization, indicate an illumination pattern smoothly decreasing (ΔI~10%) in the outer regions of the focal plane as shown in the Fig. 6. Local spatial gradients in the pattern could be acceptable provided that they are stable and constant over time. Another factor still to be modelled accurately is the uniformity of the illumination pattern at the exit port of the IS: this is affected by the area and position of the non-reflecting bodies inside the IS (i.e. the light sources) and by the ratio diameters of the IS and its exit port.

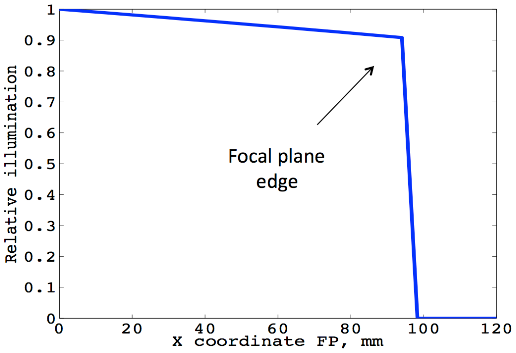


Figure 6. Simulated normalized relative illumination along a slice of the MICADO focal plane. This flat field pattern is achieved with the CU design based on two aspherical lenses. The illumination pattern smoothly decreases (ΔI~10%) in the outer regions of the focal plane, but further optimizations should improve the flatness of the profile at a few percentage non-uniformities.

A second option for the flat-fielding calibration is envisaged here and it radically differs from the standard IS + relay optics design. This approach is inspired to the design proposed for the Euclid calibration source [8] and it tries to avoid the use of large optics and IS that are expensive and could be difficult to integrate in the limited spaces available. Considering the instrument layout of Fig. 4, a panel of highly-diffusive and reflectance material such as Spectralon or

Infragold [5] is positioned in front of M7, the flat mirror that redirects the E-ELT light beam downward to the cryostat. The diffusive panel is illuminated by an array of light sources arranged in space in order to maximize the illumination uniformity of the surface. The diffused light propagates within a wide range of angles from the panel towards M7 and the rays with the same incident angles of the E-ELT beam follow the same optical path of the starlight inside the instrument. This solution although in principle simpler and cheaper requires a careful modelling of a baffling system to limit the diffuse and stray light into the instrument. The stray light produced inside the instrument in fact doesn't follow the starlight path and moves with no control among the opto-mechanical components of the instrument and can cause multiple unwanted reflections and spurious signal overlapped to the flat-fielding pattern. Preliminary results indicate a flatness with a Root Mean Square (RMS) of ~10 %, and a decreasing of the illumination pattern towards the edge of the field (Fig. 7) as for the previous discussed technique. In Fig. 7 (right-side) the footprint of the light source features is clearly visible at the top of the pupil plane not completely homogenised by the single reflection onto the panel. To avoid such spatial non-uniformities, an accurate study of the light sources arrangement and beam shaping is required to achieve the highest spatial illumination uniformity.

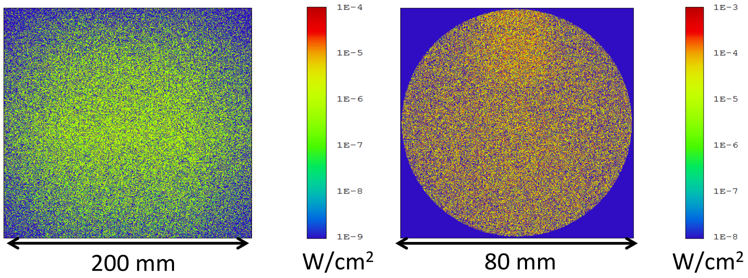


Figure 7. Left: simulation of the focal plane illumination obtained with a highly-diffusive and reflectance panel in front of M7 and one single point like source. The spatial uniformity of the pattern has a RMS~10%. Right: the illumination pattern at the pupil plane shows a spatial non-uniformity at the top due to the spatial structure of the light source not fully homogenised by the reflection on the panel.

Astrometric calibration

To calibrate the astrometric observations of MICADO a set of astrometric masks is under study. These masks are thin surfaces pierced with a grid of pinholes that will be likely positioned at the E-ELT focal plane just below the cryostat window of the instrument to create an array of perfect point-like sources. This pattern provides an absolute reference grid of PSFs to map the geometrical distortions of the instrument. The PSFs centroid position is used to retrieve an astrometric solution for correcting the observed field.

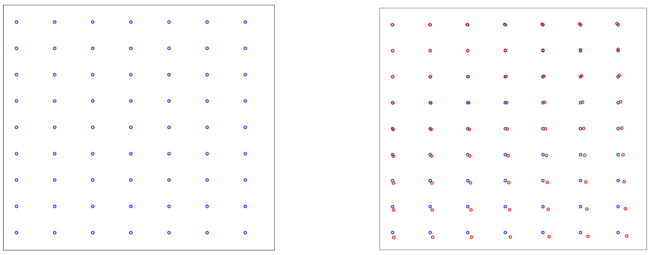


Figure 8. Left: simulation of an input grid of PSFs at the E-ELT focal plane. Right: simulation of the distorted spots pattern (red points) at the MICADO focal plane. The picture is intended only to show the working principle of the astrometric mask.

Similar masks have already been implemented in other instruments (e.g. in MUSE [10]) and their working principle is relatively easy, but the practical realization requires a careful study and design. The positions of the pinholes in the mask need be known with accuracies of about 40 nm to ensure an astrometric accuracy of ~50 μas [11] and the mask shouldn't undergo thermal variations or mechanical flexures. After the integration of the MAORY module the positioning of another mask in front of it would allow to account also for the distortions introduced by the MCAO optics, improving the overall astrometric accuracy of MICADO. In addition to the high manufacturing accuracy, the mask should be kept in a stable thermal environment to avoid deformations of the mask or of its supporting frame. A good stability will be achieved for the mask inside the cryostat, where the environment is actively controlled, but the situation is more complex for the mask in front of MAORY that is subjected to all the environmental changes. The mask inside the cryostat would be illuminated with the light from the integrating sphere and the reliability of the centroids technique for different levels of Signal to Noise Ratio (SNR) has to be studied in detail. For this reason, a lab tests campaign of the stability against thermal variations and different SNR is planned as part of the development study of the MICADO CU.

CONCLUSIONS

The MICADO CU shall provide flat-fielding, spectral and astrometric calibration of the instrument leading to fulfil at best its performance requirements. Different optical solutions are currently under development and aside the use of classical large integrating sphere and collimating optics there may be other valuable approaches exploiting radically different configurations. A trade-off between the possible designs, based both on simulations and lab prototypes, is expected in the coming years. The concept of astrometric mask for the calibration against instrument distortions is under study to assess the suitable grid density and pinholes diameter and to verify the stability of this device against different environmental conditions and illumination SNR.

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