MICADO metrology system for spectroscopy

Garrel, V. [a], Hartl, M.[a], Hörmann, V.[a], Schubert, J.[a], Rabien, S.[a], Gendron, E.[d], and the MICADO consortium[a,b,c,d,e,f,g]

[a]MPE,Max-planck-institute für extraterrestrische physik, Gießenbachstraße 1, Garching, Germany
[b]A* group, Universities of Wien, Innsbruck and Linz Austria
[c]IfA Göttingen,Georg-August-Universität Göttingen , Germany
[d]LESIA,Lab. d'Etudes Spatiales et Instrumentations pour l'Astrophysique,France
[e]MPIA, Max-Planck-Institut für Astronomie,Germany
[f]NOVA, Nederlande Onderzoekschool voor Astronomie,Netherlands
[g]USM,Universitäts-Sternwarte München, Munich, Germany

AO4ELT6, 2019, Quebec city, Canada

ABSTRACT

MICADO, a first light instrument for the upcoming ELT, will enable diffraction limited observations in near-infrared bands. It is designed as a versatile workhorse instrument with a combination of imaging modes and a slit spectroscopy mode. The spectral resolution of the instrument is expected to reach up to R=20 000 in the case of an unresolved object, performing over wide bands (simultaneous H+K bands and simulteanous bluer bands i+z+J) while maintaining high throughput. The slit spectroscopy mode can be operated in both flavours of SCAO and MCAO modes with the assistance of the MAORY instrument. We focus here on the metrology system required to keep the slit system inside the MICADO Cryostat and the SCAO system aligned to micrometric accuracy over an extended period of observation using fine offsets commands. We describe the metrology system and its performance using tolerance simulations.

1. MICADO OVERVIEW

The Multi-AO Imaging Camera for Deep Observations, or MICADO, a first generation instrument for the 39-meter ELT, successfully completed its PDR phase in 2018. Equipped with nine HAWAII-4RG detectors ($\approx 151 \times 10^6$ pixels) arranged in a 3x3 pattern, its main modes aim to deliver diffraction-limited images in the near-infrared bands over a field of view of up to ≈ 50.5 square arcsecond with a pixel sampling of 4 milliarcsecond (mas) per pixel. A second high resolution sampling of 1.5 milliarcseconds per pixel will be able to cover a field of view of 19 square arcsecond. This second smaller pixel scale is designed to reach the diffraction limit in the bluer bands and deliver oversampled PSF in the redder bands for improved astrometric precision.

To reach the ELT diffraction limit requires to correct the blur introduced by atmospheric turbulence, MICADO will benefit from the compensation provided by one of the two flavours of AO provided by the ELT AO facility MAORY: a single conjugate natural guide star adaptive optics system (SCAO) based on a Pyramid Wavefront Sensor[1] or a multi-conjugate laser guide star assisted adaptive optics (MCAO) based on multiple Shack-Hartmann wavefront sensors.[2] The three MAORY NGS WFS (dubbed Low Order and Reference WFS - LOR[3]) and the SCAO Pyramid WFS are located in a close environment at non-cryogenic temperature dubbed the Green Donut and will be co-rotating with the MICADO cryostat. Switching between the 2 modes is possible with the insertion of a remote controlled SCAO dichroic in the optical path, in front of the MICADO cryostat entrance window. The SCAO system is currently developed along the MICADO track in order to provide a 'stand-alone' capability to MICADO in cases where the full MAORY facility cannot be available. In this 'stand-alone' mode, an extra module made of static optics provide the interface to the telescope pre-focal station.

Further author information: (Send correspondence to V.Garrel.)
V.Garrel: E-mail: vgarrel@mpe.mpg.de

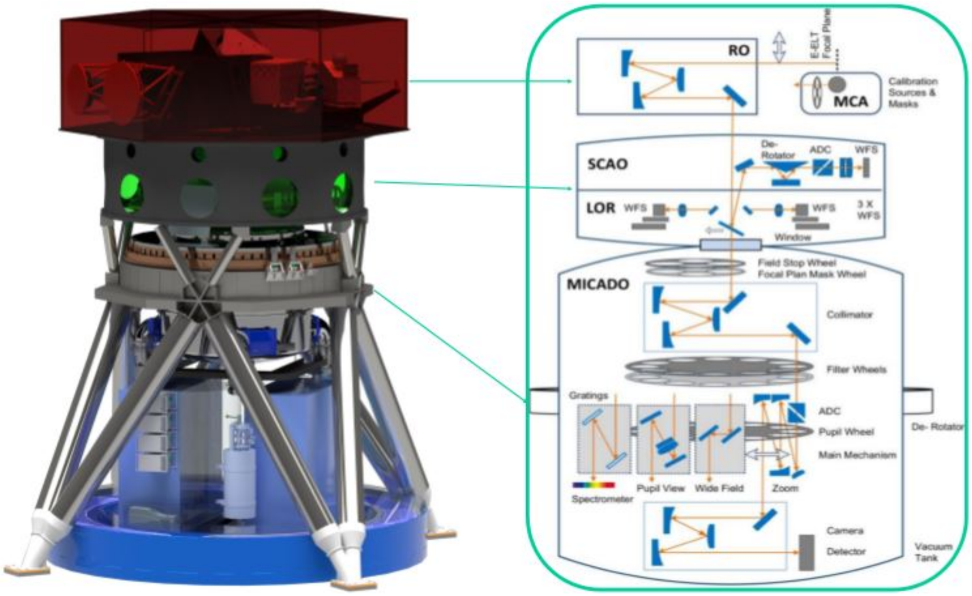

Figure 1. Left: ELT MICADO rendering in stand-alone configuration. Right: conceptual design for the MICADO instrument, including the relay optics, the Green Donut and the MICADO cryostat. Co-rotating electronic cabinets are left out of the scheme.

MICADO is designed as a versatile instrument, tackling different science cases[4] in using either SCAO or MCAO according to the science objective. Several proceedings recently presented cover most of the recent progress achieved in the MICADO[5] and MAORY projects.[6] For each AO flavour, the MICADO consortium is also aiming to deliver PSF reconstruction tools[7] to its users with an effort to save all required data since the first light of the instrument.

Next to its classic imaging modes, the astrometric mode will provide an extra level of highly precise calibrations[8] required to correct for fine focal plane distortions. MICADO will also integrate a variety of efficient coronagraphs[9] for its high contrast imaging mode. Last but not least, MICADO will integrate a spectroscopic slit mode with a variety of slit sizes. We describe the spectroscopic mode more in details in the next section.

As seen on the figure 1, the sheer size and scale of this new instrument (6+ meter high and 2.5meter diameter) can potentially make it susceptible to mechanical flexures between the AO systems and the science focal plane. For example, the optical distance between the entrance focal plane of the SCAO system and the entrance focal plane of the MICADO cryostat is $\approx 1.2\,\mathrm{m}$. Those drifts would not be caught by the AO systems and would result in performance loss. In its different imaging oriented modes (classic, astrometric, coronagraphic), the science focal plane will be analysed to keep track of reference stars and provide slow feedback offsets to the AO loop. However, the spectroscopic mode cannot benefit from such feedback, as the spatial information is lacking. In this proceeding, we describe a simple metrology system able to evaluate drifts during spectroscopic observations. The correction of the drift will achieved through a feedback offset to the AO loop, along the same mechanism as the one described for the imaging modes.

2. MICADO SPECTROSCOPIC MODE

The moderately-high resolution spectroscopy mode of MICADO has been evaluated as a secondary mode, i.e. its design shall not impact the design for the imaging modes. Nonetheless, with some clever orientation of the slits relative to the two dispersive elements and use of filters to block mixing orders, a wide spectral coverage can be achieved with minimal changes of optical elements. This mode is reminiscent of the successful X-shooter instrument on the VLT and will provide some complementarity to the spectroscopic abilities delivered by the HARMONI instrument.

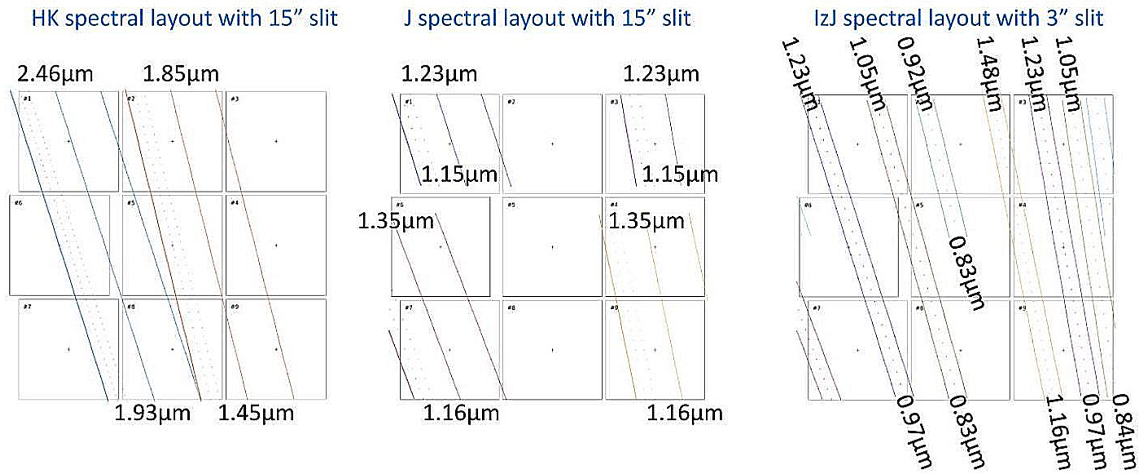

Figure 2. Spectral layout for the spectroscopic mode with the different slits.

Barring any design modification, 2 slit widths are offered, one narrow slit of 16 mas width and one wide slit of 48 mas. Slits are designed as 15″ long and will be positioned slightly off-centre. The slits are wider than the theoretical diffraction limit of the telescope and therefore are not always constraining the spectral resolution of the system. This resulted from a careful analysis and a trade-off between optical alignment tolerancing, stability and performance. For unresolved object at the diffraction limit, the theoretical design solution can provide up to R≈20k (equivalent to a precision of $15\,\mathrm{km\,s^{-1}}$) while for the 16 mas width, resolved object will be limited to a spectral resolution of R≈10k. With only 2 filters, MICADO is able to cover from J to K band (see figure 2 for reference). For a more complete coverage in bluer bands (izJ), a smaller slit of 3″ long is available in both widths. We note that the SCAO dichroic cut-off wavelength at 0.965 µm will limit the use of this particular setting for the SCAO mode. The spectral layout for the different slits is shown in figure 2. A shifted spectral layout configuration will be provided, using duplicate slits with different shifted slit positions on the MICADO focal plane. The shifted configuration allows to remove the detector gaps during the data reduction.

The MICADO instrument will include an Atmospheric Dispersion Corrector (ADC) but it will be installed close to the cold stop pupil plane to minimize astrometric distortions, hence after the MICADO entrance focal plane. It cannot consequently be used to reduce chromatic errors at at the slit level. While not impossible to implement as a future upgrade, a second pre-focal plane ADC is not deemed a project priority at the moment. This puts constraints on how the spectroscopic mode can be operated. For unresolved objects, slits will be re-aligned to the parallactic angle at the start of the exposure time but set to track the field during during the science exposure time. This mode of operation dramatically ease the operation of keeping NGS centered for the AO WFS.

The specification for stability requires to keep the static optical alignment between the SCAO WFS focal plane, the slit and the science focal plane are kept within $8\,\mu\mathrm{m}_{\mathrm{RMS}}$ per observing block of 1 hour. The goal is to keep such alignment under $4\,\mu\mathrm{m}_{\mathrm{RMS}}$ (over a ≈1.2 m optical distance). It should ensure that the spectroscopic measurements stays within a precision of $3.5\,\mathrm{km\,s^{-1}}$, currently set by the most stringent science spectroscopic cases.

3. MICADO METROLOGY FOR THE SPECTROSCOPIC MODE WITH SCAO

In the frame of the MICADO PDR, finite elements analysis (FEM) for the SCAO bench located in the MICADO Green Donut indicated the two largest potential elements of drifts were the position/tilt of the SCAO dichroic and the global tilt of the SCAO bench compared to the MICADO cryostat. As the dichroic is moving in and out of the optical path depending whether the SCAO or the MCAO mode is used, the tight weight and space constraints makes design improvements through pure mechanical means uncertain. This triggered the need for an extra way to sense such drifts between the focal plane of the cryostat and the focal plane of the SCAO WFS.

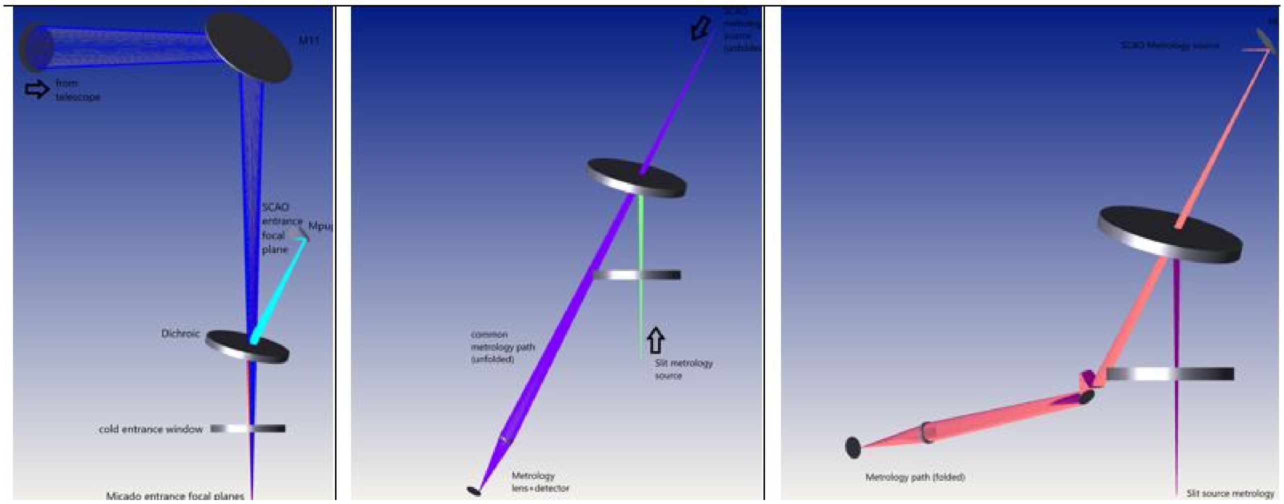

Figure 3. Zemax simplified simulation of the different paths.Left: Paths from the telescopes to SCAO and Cryostat. Middle: Unfolded path from the SCAO and Cryostat focal planes to the metrology camera. Right: Some more realistic folding to adapt to the required space constraints.

3.1 Principle of the measure

The metrology system aims to measure the drift between the MICADO entrance focal plane and the SCAO WFS entrance focal plane. It is based on the assumption, backed by the FEM analysis, that such drifts are effectively the factors contributing the most to performance loss (i.e. drifts within the cryostat, drifts within the the SCAO bench are assumed negligible). The dichroic tilt drift was evaluated for example to induce up to 4 mas per hour on the MICADO focal plane.

Two static faint sources of light can be activated through a remote control, one on the entrance WFS focal plane and one on the focal plane of the MICADO instrument, inside the cryostat. These two sources of light, used as position beacons, are observed by a common technical camera, looking at their relative distance over time, measuring the lateral drift between the 2 focal planes. A third beacon, a twin of one of the first two beacons, ensures that the metrology system is not confusing a drift originating from the main optical system with a potential rotational drift internal to the metrology system.

3.2 Opto-mechanical layout

For practical reasons, it is deemed easier to implement the twin sources on the cryostat side rather than on the SCAO WFS entrance WFS plane. The twin sources in the MICADO focal plane are projected to be scattering targets illuminated by a laser diode installed in a fixed position, located outside of the MICADO focal plane wheel, in a fixed position, for higher reliability.

To ensure a good light transmission towards this common metrology camera, the source located in the MICADO focal plane is bluer than the SCAO dichroic cut-off wavelength while the source on the SCAO WFS entrance focal plane is redder. This puts a requirement on the technical camera to be sensitive in the wavelength domain around 0.965 µm. Recent commercial back-illuminated CMOS camera with extremely low readout noise are prime targets as they are easy to integrate with their relatively small pixels.

The optical layout is conceptually extremely simple as it consists of taking images from sources in planes already optically conjugated to each other (i.e, no requirement for a telecentric objective). The beacons location can be chosen such that their images on the technical camera are close from each other (i.e. no requirement for a wild field objective). The only requirements is to be precise drift measurement which means an imaging system with a good magnification for precise centroiding and an objective relatively achromatic to focus sharply images from beacons emitting at 2 wavelengths. The actual opto-mechanical implementation is rendered difficult due to the lack of space available as the main optical elements are already in place with guaranteed volumes distributed into the different sub-systems within MICADO and MAORY consortia. A prime location was identified under the Green Donut structure, following the curve of the MICADO cryostat (See figure 4) but different alternative locations with folding mirrors were also briefly considered.

The optical layout was simulated in Zemax Studio using a multi-configuration setting in sequential mode. Up to 13 configurations were used to compare the merit of different locations for the metrology imaging camera, on both sides of the SCAO dichroic. They were referenced to each other using a Zemax "Global Reference Frame". The influence of the SCAO dichroic thickness on the different locations was compared as it introduces different amount of astigmatism depending wheter beacons are observed in reflection or transmission but this term of astigmatism can be kept small, under 20nm rms. A simulation of different perturbations was introduced and compared in both the path to measure (SCAO path+ MICADO path) and the metrology paths (from beacons to the metrology camera); the metrology system with an objective open to f/5.6 with D=40mm can effectively measure drifts with the required precision set by the specification.

Finally, we checked that a deconjugation of one of the two planes, nor the location of the beacons compared to the metrology camera, do not overly affect the precision of centroiding on the metrology camera (see Figure 5).

3.3 Operational concept

Unlike a wide field acquisition technical camera, used for a classical slit spectrograph, the metrology system will measure drifts of the system but will not help for the original slit alignment on the science target. For this purpose, we will have to rely on the MICADO imaging modes. Here is the list of actions during the operations:

- The ELT is pointing to the target, adjust itself according to the pre-focal station WFS and hand-over the telescope control to the instrument.
- At this time, a reference image of the metrology beacons is taken with the metrology camera. Once reference image is taken, beacons go dark.

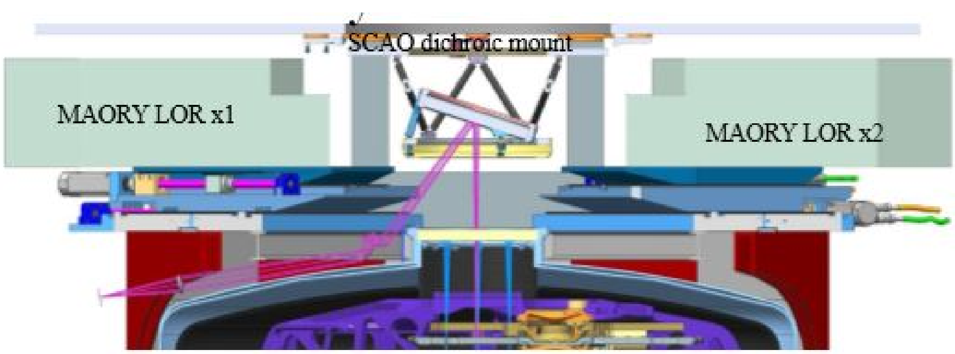

Figure 4. Prelimary Opto-Mechanical layout for the metrology system. It would slide under the Green Donut structure while staying into a room temperature environment.

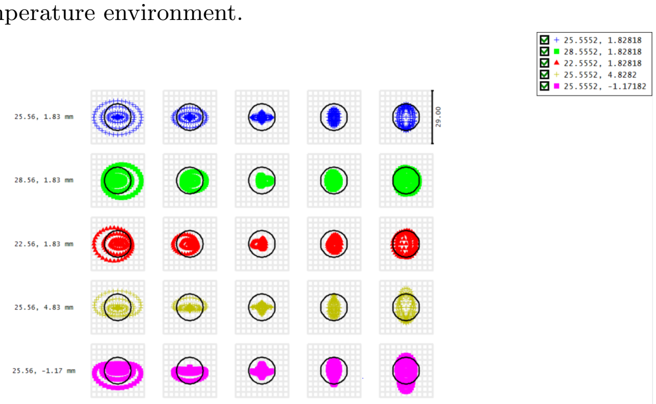

Figure 5. defocus analysis with a simple objective with different locations in the reference focal plane for the beacons.

- Once the MICADO SCAO loop is closed, the MICADO acquisition sequence will include one or several images of the science object to fine center it on the slit with offsets provided to the SCAO system.
- At intervals depending from our experience on drifts, in-between science exposures, the beacons can be activated and a measure of positions is taken with the metrology camera. A drift is measured, compared to the original image. This can be done for example when MICADO dither offsets happen. In this manner, the beacons are certainly not perturbing the SCAO loop measurements.
- In this case, the metrology system would calculate a new drift, apply some affine transformation so that it mimics offset commands issued from the imaging pipeline and send it to the MICADO SCAO INS.

4. CONCLUSION AND FUTURE WORK

Some work remains to put the concept and simulations presented here to the technological readiness level required for the MICADO FDR, which means assembling some bench demonstration for this particular subsystem. Further more detailed work will be done once the MAORY MICADO interface design is frozen.

The MAORY MCAO configuration is a work in progress and will pass its PDR during 2020. It is not yet clear which elements are expected to drift the most but most likely a specific version of the metrology system will be required. In the MCAO configuration, one of the three NGS on which the system will guide is statistically much brighter than the two others. From this star, most of the TT will be derived, the measurement of drift could be then achieved between this particular LOR WFS and the MICADO focal plane. This means the metrology has to be adjusted according to the configuration of the MAORY LORs.

REFERENCES

[1] Clénet, Y., Buey, T., Gendron, E., Hubert, Z., Vidal, F., Cohen, M., Chapron, F., Sevin, A., Fédou, P., Barbary, G., Baudoz, P., Borgo, B., Ben Nejma, S., Chambouleyron, V., Déo, V., Dupuis, O., Durand, S., Ferreira, F., Gaudemard, J., Gratadour, D., Huby, E., Huet, J.-M., Le Ruyet, B., Nguyen-Tuong, N., Perrot, C., Thijs, S., Younès, Y., Rousset, G., Feautrier, P., Zins, G., Diolaiti, E., Ciliegi, P., Esposito, S., Busoni, L., Schubert, J., Hartl, M., Hörmann, V., and Davies, R., "The MICADO first-light imager for the ELT: towards the preliminary design review of the MICADO-MAORY SCAO," in [Proc. SPIE], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10703**, 1070313 (Jul 2018).

[2] Arcidiacono, C., Schreiber, L., Bregoli, G., Foppiani, I., Oberti, S., Diolaiti, E., Agapito, G., Puglisi, A., Xompero, M., Cortecchia, F., Patti, M., Lombini, M., Busoni, L., Vérinaud, C., Felini, C., De Caprio, V., Cosentino, G., Ciliegi, P., Bellazzini, M., Feautrier, P., Esposito, S., and Ragazzoni, R., "Numerical simulations of MAORY MCAO module for the ELT," in [Proc. SPIE], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10703**, 107034I (Jul 2018).

[3] Bonaglia, M., Busoni, L., Plantet, C., Agapito, G., Giordano, C., Puglisi, A., Esposito, S., Di Rico, G., Valentini, A., Di Antonio, I., Bellazzini, M., Ciliegi, P., Diolaiti, E., Feautrier, P., and Ragazzoni, R., "Status of the preliminary design of the NGS WFS subsystem of MAORY," in [Proc. SPIE], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10703**, 107034D (Jul 2018).

[4] Davies, R., Alves, J., Clénet, Y., Lang-Bardl, F., Nicklas, H., Pott, J. U., Ragazzoni, R., Tolstoy, E., Amico, P., Anwand-Heerwart, H., Barboza, S., Barl, L., Baudoz, P., Bender, R., Bezawada, N., Bizenberger, P., Boland, W., Bonifacio, P., Borgo, B., Buey, T., Chapron, F., Chemla, F., Cohen, M., Czoske, O., Déo, V., Disseau, K., Dreizler, S., Dupuis, O., Fabricius, M., Falomo, R., Fedou, P., Förster Schreiber, N., Garrel, V., Geis, N., Gemperlein, H., Gendron, E., Genzel, R., Gillessen, S., Glück, M., Grupp, F., Hartl, M., Häuser, M., Hess, H. J., Hofferbert, R., Hopp, U., Hörmann, V., Hubert, Z., Huby, E., Huet, J. M., Hutterer, V., Ives, D., Janssen, A., Jellema, W., Kausch, W., Kerber, F., Kravcar, H., Le Ruyet, B., Leschinski, K., Mandla, C., Manhart, M., Massari, D., Mei, S., Merlin, F., Mohr, L., Monna, A., Muench, N., Müller, F., Musters, G., Navarro, R., Neumann, U., Neumayer, N., Niebsch, J., Plattner, M., Przybilla, N., Rabien, S., Ramlau, R., Ramos, J., Ramsay, S., Rhode, P., Richter, A., Richter, J., Rix, H. W., Rodeghiero, G., Rohloff, R. R., Rosensteiner, M., Rousset, G., Schlichter, J., Schubert, J., Sevin, A., Stuik, R., Sturm, E., Thomas, J., Tromp, N., Verdoes-Kleijn, G., Vidal, F., Wagner, R., Wegner, M., Zeilinger, W., Ziegleder, J., Ziegler, B., and Zins, G., "The MICADO first light imager for the ELT: overview, operation, simulation," in

[Proc. SPIE], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10702**, 107021S (Jul 2018).

[5] Schubert, J., Hartl, M., Hörmann, V., Davis, R., Sturm, E., Ageorges, N., Barl, L., Garrel, V., Geis, N., Gemperlein, H., Kampf, D., Mandla, C., Manhart, M., Rabien, S., Rüddenklau, R., and Ziegleder, J., "The MICADO first light imager for ELT: cold optics instrument," in [Proc. SPIE], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10702**, 107028W (Jul 2018).

[6] Ciliegi, P., Diolaiti, E., Bellazzini, M., Cortecchia, F., Lombini, M., Abicca, R., Esposito, S., Feautrier, P., Stadler, E., Giro, E., and Ragazzoni, R., "Organization, management and risk analysis of the MAORY project," in [Proc. SPIE], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10705**, 107051S (Jul 2018).

[7] Wagner, R., Ramlau, R., Saxenhüber, D., and Soodhalter, K., "PSF reconstruction and deconvolution forextremely large telescopes," in [*AO4ELT5*], (June 2017).

[8] Rodeghiero, G., Sawczuck, M., Pott, J. U., Glück, M., Biancalani, E., Häberle, M., Riechert, H., Pernechele, C., Naranjo, V., Moreno-Ventas, J., Bizenberger, P., Perera, S., and Lessio, L., "Development of the Warm Astrometric Mask for MICADO Astrometry Calibration," PASP **131**, 054503 (May 2019).

[9] Perrot, C., Baudoz, P., Boccaletti, A., Rousset, G., Huby, E., Clénet, Y., Durand , S., and Davies, R., "Design study and first performance simulation of the ELT/MICADO focal plane coronagraphs," *arXiv e-prints* , arXiv:1804.01371 (Apr 2018).