Exoplanet detection with the SCAO mode of MAORY-MICADO: preliminary results from end-to-end simulations

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ABSTRACT

The SCAO mode of MAORY-MICADO provides us with a very intriguing opportunity as for detection and characterization of extrasolar planets. Deep observations of the innermost regions (below 100 mas) of nearby stars will be possible thanks to the unprecedented resolution of the E-ELT. In this article, we present the results of a simulation campaign aimed at investigating the instrument performances in terms of exoplanet detectability. For this purpose, we developed an end-to-end simulator in IDL language. We simulated the AO correction as expected from the SCAO system using the end-to-end platform COMPASS. We also included the contribution of NCPA, whose dynamical evolution has been modeled on the instrument rotation. Optical aberrations are propagated through the foreseen MICADO coronagraphs, following the Fraunhofer propagation scheme. A sequence of image is generated, in order to apply post-processing algorithms to derive the corresponding detection limits. We applied this study to some benchmark exoplanetary systems and compared the expected performances with those of current 8-meter high-contrast imagers. Our goal is to investigate which kind of contribution MAORY-MICADO can offer to the science of extrasolar planets.

Keywords: MAORY-MICADO, Coronagraphy, Exoplanets, ADI

1. INTRODUCTION

MICADO[1] is one of the first-light instruments for the ELT. It is a general-purpose near-infrared imager and spectrograph working in the range 0.8 to 2.4 um and it will be primarily fed by the multi-conjugate adaptive optics (MCAO) system MAORY.[2] A complementary Single-Conjugate Adaptive Optics (SCAO) mode is also under developement as a joint effort between MICADO and MAORY consortia. The SCAO correction will allow to reach the diffraction limit of the ELT on small fields of view, opening the possibility to search for exoplanetary companions at angular separations that are not accessible to the current generation of 10-m class telescopes planet hunters. Perrot et al.[3] showed that MICADO Classical Lyot Coronagraph can provide comparable contrasts to SPHERE at the same angular separations, while hot and massive exoplanets might be detected in 1 hour at separations between 50 and 150 mas. This paper presents new simulation results for the MICADO-MAORY SCAO configuration. Section 2 describes the simulator. In Section 3 we illustrate how we tackled the problem of temporal integration in simulation. Finally, Section 4 presents the case study of a 1 hour observation of the debris-disk star AU Mic.

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2. THE SIMULATOR

The simulation of MAORY+MICADO PSFs is performed in two steps: first, we run an end-to-end simulation of the SCAO system in COMPASS[4] to compute the expected atmospheric turbolence residual in closed-loop. This residual is then propagated through a dedicated Physical Optics Propagation (POP) tool developed in IDL language. This tool implements the scheme of Soummer et al.[5] for fast numerical propagation through Lyot-style coronagraphs. The scheme is based on the Fraunhofer approximation and makes use of Matrix Fourier Transforms (MFT). Thanks to the flexibility guaranteed by MFTs, we can use different samplings between the coronagraphic focal plane and the final image plane. In the first, the sampling shall be high enough (5 to 10 pixel per resolution element) to sample the small chromatic shear of the PSF due to atmospheric refraction. In the final image plane, on the other side, the sampling is reduced to Nyquist in order to speed up the computation. Long exposures are simulated by co-adding instantaneous PSFs generated at the cadence of the adaptive optics loop (500 Hz). The computation of these PSFs runs on multiple bridges in parallel. This is mandatory in order to simulate long sequences (of the order of 30 minutes to 1 hour) in a reasonable time.

3. TEMPORAL BINNING IN CLOSED-LOOP

Temporal integration refers to the process, described in the previous section, of co-adding instantaneous PSFs. Generating PSFs at the same cadence of the AO residuals is quite expensive from the points of view of computational time and data storage, hence normally only a small number of phase screeens per second of integration is stored and used to generate the PSFs. Which is the effect of this simplification on simulated performance? To answer the question, we ran an AO loop at 500 Hz for 30 minutes and generated a datacube of instantaneous PSFs at the same cadence (i.e. one for each phase screen). These PSFs are then stacked to create 30 images of 60s integration time each. For each image, we started by stacking all the 500 PSFs per second and then we gradually decreased this number. We report the results in Figure 1. The datacubes have been processed using Angular Differential Imaging (ADI[6]), combined with single-mode Principal Component Analysis (PCA). High sampling rates provide better detection limits, with a difference as large as 1 magnitude between the extreme cases of 500 PSFs/s and 1 PSF/s. This is expected, since the higher the number of PSFs, the smoother is the speckle pattern after stacking. According to these results, a temporal binning of 10 (1 PSF every 10, corresponding to 50 PSFs per second of integration at 500Hz) seems to be a good compromise between computational effort and accuracy.

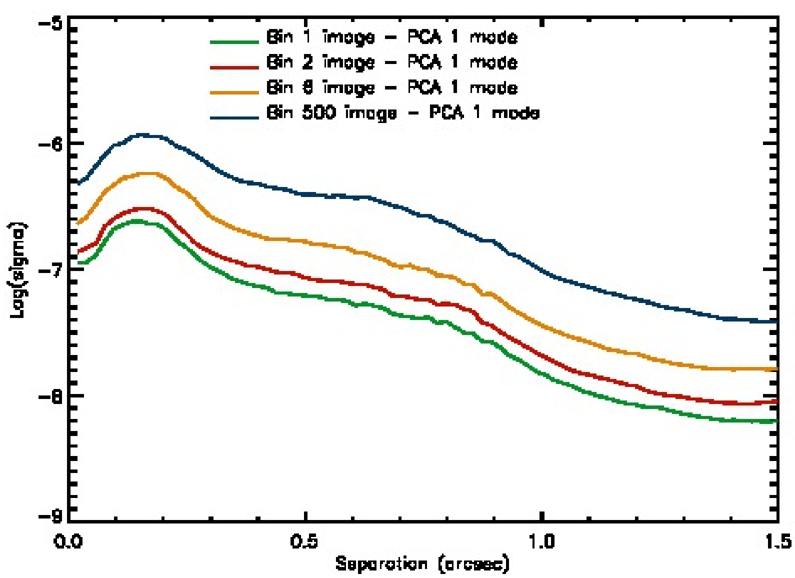


Figure 1. Detection limit as a function of the temporal binning. Bin 'n' means that 1 instantaneous PSF every n is considered in the stacking.

4. A CASE STUDY: AU MIC

4.1 Observation

We simulated an observation of 1 hour, with the star transiting at the meridian at the midpoint of the observation. At the ELT latitude, this translates into 93 degrees of overall FoV rotation (Figure 2). The observation is composed of 60-second coronagraphic images in CH4-short (central wavelength 1582 nm). We used 1 frame every 10 for the temporal integration, corresponding to 50 frames per second. The coronagraph is a classical Lyot (CLC, 25 mas occulter radius and 88% Lyot stop). The target proximity to the zenith makes the differential tip-tilt across the waveband (induced by atmospheric refraction, which is not corrected at the level of MICADO coronagrahic focal plane) as small as 1 mas peak-to-valley, which is small compared to the focal plane mask radius. Preliminary tests showed that the impact of this effect on the instrument performance is negligible. For this reason, atmospheric dispersion is not considered in the final simulation, which is is monochromatic at 1582 nm.

Instrumental aberrations, both static and time-evolving, are also implemented following the same scheme as in Perrot et al.:[3] a 6 nm RMS map rotating with the parallactic angle is superimposed on a 60 nm RMS static contribution. The main simulation parameters are summarized in Table 1.

Wavelength	1582nm
DIT[s]×NDIT	60×60
Coronagraph	Classical Lyot
Data reduction	ADI (1 mode PCA)
FoV rotation	93°

Table 1. Main parameters used in the simulation of AU Mic observation.

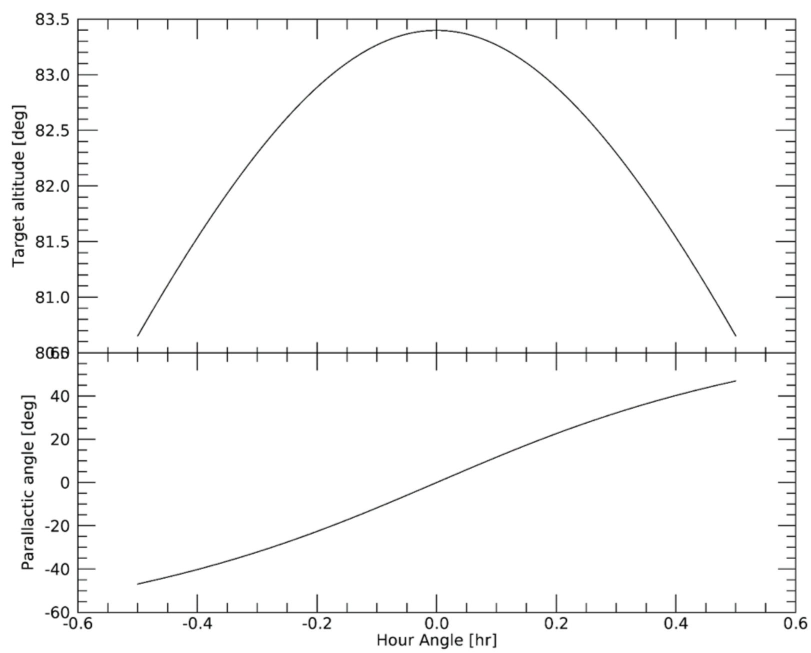


Figure 2. AU Mic altitude and parallactic angle as a function of the hour angle during the observation. The target transits at the meridian at the midpont of the observation.

4.2 Atmosphere and AO correction

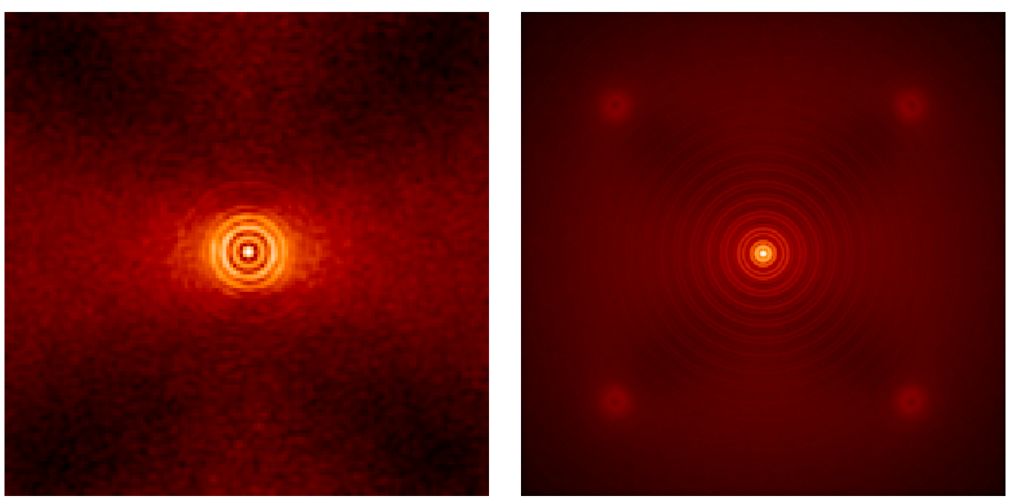
We assumed a single, zero-altitude layer atmospheric model and ELT median seeing conditions.[7] We considered a fixed zenith angle of 8° (halfway between minimum and maximum values during the observation), resulting in a Fried parameter equal to 15.9 cm (0.67” seeing).
The AO loop runs at 500 Hz. The wavefront sensor is a 78 × 78 Shack-Hartmann. Strehl Ratio (SR) delivered by the AO system is 65% at 1582 nm. The relevant parameters are summarized in Table 2.

Number of layers	1
Layer altitude	0 km
Wind speed	10 m/s
Seeing	0.67”
WFS	SHS 78 × 78
Sensing wavelength	700nm
SR (1582 nm)	65%

Table 2. Main parameters used for the atmosphere and adaptive optics.

4.3 Data reduction and detection limit

Figure 3 shows the simulated MICADO PSFs. Bright rings in correspondence of the Inner Working Angle (IWA) of the CLC represent the fundamental limitation of this technique and are clearly visible in the simulated images. Data are processed using Angular Differential Imaging.[6] The PSF model is obtained using Principal Component Analysis (PCA). Detection limit is computed as the 5-sigma noise in the final post-ADI frame as a function of the angular separation normalized to the peak of the non-coronagraphic PSF (Figure 4). According to these results, the detection limit is around 10 magnitudes at the IWA and it reaches 13.5 magnitudes at 150 mas. We found better limits at 150 mas by a factor two with respect to Perrot et al. This is consistent with the difference in temporal binning between the two simulations (50 PSFs per second against the 1 of Perrot et al.), as we discussed in Section 3.



(a) (b)

Figure 3. Simulated images of AU Mic. a) is with the classical Lyot coronagraph, while b) is the off-axis PSF used for contrast normalization.

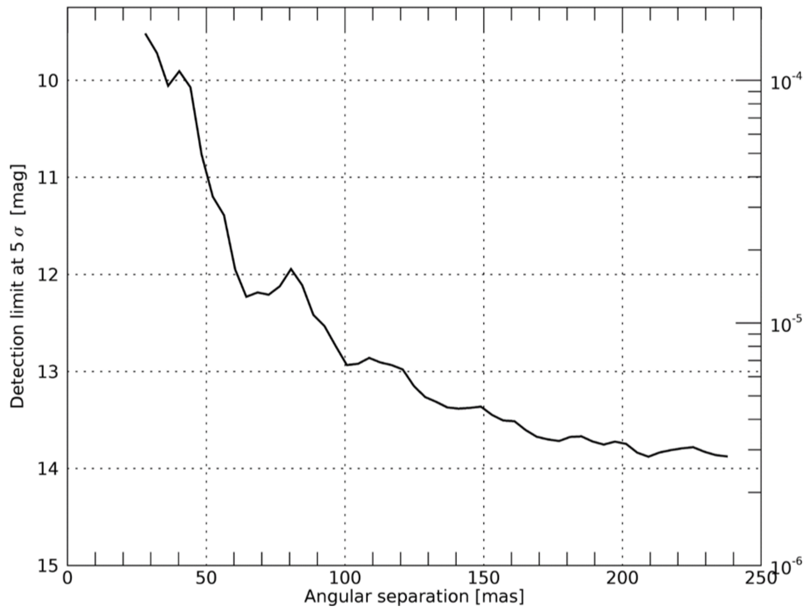


Figure 4. Simulated five-sigma detection limit using ADI+PCA for 1 hour observation of AU Mic.

5. CONCLUSIONS

The SCAO mode of MAORY-MICADO will represent an unprecedent opportunity for deep observations of the innermost regions (below 100 mas) of nearby stars, not accessible to current high-contrast imagers on 10-meters class telescopes. In this article we presented the simulator that we developed to explore the instrument capabilities and we showed preliminary results applied to the bright debris-disk star AU Mic. The simulator combines the AO platform COMPASS and a fast POP code. The problem of temporal binning is well-known for this kind of simulations: we tackled it by running an ad-hoc simulation and we found that 50 frames per second is a good compromise between computational time and accuracy. We simulated 1 hour observation of AU Mic under median seeing conditions and processed the data using Angular Differential Imaging. Detection limits range from 10 magnitude at the coronagraph IWA to 13.5 at 150mas, separations at which no other instrument can access. This confirms the enormous potential contribution of MAORY-MICADO SCAO mode to the science of exoplanets.

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