# Status of the PSF Reconstruction Work Package for MICADO@ELT

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#### ABSTRACT

MICADO is a workhorse instrument for the ESO ELT, allowing first light capability for diffraction limited imaging and long-slit spectroscopy at near-infrared wavelengths. The PSF Reconstruction (PSF-R) Team of MICADO is currently implementing, for the first time within all ESO telescopes, a software service devoted to the blind reconstruction of the PSF. This tool will work independently of the science data, using adaptive optics telemetry data, both for Single Conjugate (SCAO) and Multi-Conjugate Adaptive Optics (MCAO) allowed by the MORFEO module. The PSF-R service will support the state-of-the-art post-processing scientific analysis of the MICADO imaging and spectroscopic data. We provide here an update of the status of the PSF-R service

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tool of MICADO, after successfully fulfilling the Final Design Review phase, and discuss recent results obtained on simulated and real data gathered on instruments similar to MICADO.

Keywords: PSF Reconstruction, MICADO, ELT, Telemetry data, WFS

#### 1. INTRODUCTION

MICADO (Multi-Adaptive Optics Imaging Camera for Deep Observations) is the first light instrument of the European Southern Observatory (ESO) Extremely Large Telescope (ELT) and it will be a workhorse facility for Adaptive Optics (AO) diffraction limited imaging and long-slit spectroscopy at near-infrared wavelengths.<sup>1</sup> We provide here an update of the status of the point spread function reconstruction (PSF-R) service tool of MICADO, after successfully fulfilling the Final Design Review (FDR) phase, and discuss recent PSF-R results obtained on simulated and real data gathered on instruments similar to MICADO.<sup>2</sup>

A first-generation ELT instrument, MICADO will take high resolution images of the Universe at near-infrared wavelengths. This makes MICADO the ideal instrument for identifying exoplanets, but also for resolving individual stars in local galaxies (up to Virgo and Fornax), the star forming clumps in high-redshift galaxies, including the dynamics of dense stellar systems, and investigating the mysterious center of the Milky Way. The optimal scientific exploitation of MICADO implies the detailed knowledge of the PSF of each acquired science image or spectrum. The PSF-R service will support the state-of-the-art post-processing scientific analysis of the MICADO imaging and spectroscopic data, but it will not be available for coronographic observations. Indeed, the knowledge of the reconstructed PSF is essential in order to evaluate the quality of the observed astronomical data. Additional to quality evaluation, the reconstructed PSF can be used for further improving the reduction of images and spectra in the post processing phase.

The structure of this paper is the following: in Section 2 we describe the methodology adopted for the PSF reconstruction of AO-assisted diffraction limited instruments, e.g. MICADO. The first results obtained by the MICADO PSF-R Team have been highlighted in Section 3. The size of telemetry data required by the PSF-R Service every day is discussed in Section 4, while conclusions are drawn in Section 5.

#### 2. METHOD

Different methods are available to obtain the PSF of AO-assisted instruments: pure PSF Reconstruction (PSF-R), Hybrid, Calibrated, Empirical, Adaptive methods. All these methods have been described in detail in.<sup>3</sup> MICADO will adopt as baseline the pure PSF Reconstruction method, relying only on telemetry data, without accessing the focal plane data (i.e. the scientific frames).

The motivations behind the choice of the Pure (or blind) PSF-R method rely on different strategic points. For 35-40% of the extragalactic targets, a MICADO science frame will be void of point sources suitable for standard PSF characterization (e.g. with empirical or semi-empirical methods). Extragalactic deep fields are selected for having as few stars as possible. In general, it is unlikely to have interesting or well studied extragalactic targets in fields with many stars per square arcmin. Extragalactic fields usually have no bright stars suitable to build reliable empirical PSF model, nor reliable empirical PSF at the position of each galaxy or rare objects (e.g. high-z/lensed targets).

In case of crowded fields, it is difficult to recover the shape of the PSF, especially on the wings, due to contamination from neighboring stars. For these reasons, the Pure PSF-R approach is required when extended targets cover most of the FoV.

The point spread function reconstruction (PSF-R) Application is a deliverable of the MICADO project. The PSF-R Team of MICADO is currently implementing, for the first time within all ESO telescopes, a software service devoted to the pure (blind) reconstruction of the PSF. This tool will work independently of the science data in the focal plane, only using adaptive optics telemetry data of the MICADO camera and spectrograph, both for Single Conjugate (SCAO) and Multi-Conjugate Adaptive Optics (MCAO) allowed by the MORFEO module, in post-processing analysis.

The PSF-R application will provide the reconstructed PSFs through an archive querying system, using the Wave Front Sensor telemetry data that MICADO will generate and save synchronously to each associated science frame. The PSF-R Application of MICADO is designed to work without accessing to the science data themselves, differently from other PSF-R techniques that instead use the science data themselves to optimize the parameters used during the reconstruction phase [4, e.g.]. This allows the pure PSF-R tool to be the most generally applicable, especially in the extra-galactic cases where empty fields, devoid of bright stars, are routinely observed.

The PSF-R Team will build up the software tools and architecture needed to develop and test the PSF-R Service for MICADO, when the instrument will be mounted on the bench, at the Preliminary Acceptance in Europe (PAE) and later on at the ELT site in Cerro Armazones for the Final Acceptance.

The pure PSF-R method has been described in detail in,<sup>2,5,6</sup> and.<sup>7</sup>

## 3. RESULTS

The pure PSF-R algorithms of MICADO have been tested using COMPASS<sup>8</sup> simulated data with a bright star (15th magnitude), a Shack-Hartmann Wave Front Sensor (SH WFS) and the ELT M4 geometry. Strehl ratio (SR), FWHM, and encircled energy (EE) of the simulated star are recovered by the pure PSF-R software at the 1-2% level (Fig. 1). Fig. 1 shows the radial profile of the simulated (blue) and reconstructed (orange) PSF.

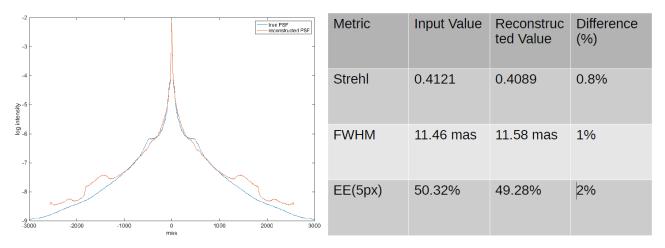


Figure 1. The radial profile of the simulated (blue) and reconstructed (orange) PSF. Accuracies of 1-2% have been reached in Strehl ratio, FWHM, and EE.

Real data from the SOUL<sup>9</sup> Adaptive Optic module of the Large Binocular Telescope (LBT) have been used in order to check that the SCAO Critical Algorithms of the MICADO PSF-R Service can successfully process also real data from other instruments. The first results show that the PSF-R algorithms are able to recover the Strehl ratio (SR), FWHM and encircled energy profiles within a few ( $\sim 1 - 7\%$ ) percent level.<sup>2</sup> Based on this tests, we can confirm that the MICADO PSF-R Application has reached at present a Technology Readiness Level (TRL) corresponding to TRL=7. Further details on the PSF reconstruction of LBT/SOUL+LUCI data can be found in this proceeding (Simioni et al. 2022).

The Final design Review (FDR) of the PSF-R software tool for MICADO has been successfully accomplished in July 2021. This review has been mainly focused on the development plan, the data flow, the telemetry data rate, the end-to-end workflow, and the development of the critical algorithms for PSF-R. No critical item has been emerged during the FDR, indicating that the maturity level reached by the MICADO PSF-R software is adequate for that milestone.

The scientific evaluation of the PSF-R tools is currently on-going for extragalactic cases (e.g. galaxy morphology, clumps), as detailed in this proceeding (Simioni et al. 2022). We have also developed tools and a pipeline to evaluate how uncertainties on the reconstructed PSF translate into uncertainties on scientific measurements (and viceversa). In the future, the scientific evaluation of the PSF-R products will be expanded to other science cases.

## 4. TELEMETRY DATA RATES

The pure PSF-R software of MICADO relies only on WFS telemetry data, saved at the highest temporal frequency, in order to better reproduce the sudden variation of the atmospheric conditions.

The telemetry data rate of MICADO WFS is 4.2 Terabyte per night, assuming 9 hours of observation, 100% of open shutter time, control, and interactive matrices saved at a frequency of 0.2 Hz. The telemetry data rate is instead 2.1Tb per night, assuming 70% open shutter time plus control and interactive matrices saved at 0.1 Hz. The expected data rate for telemetry is comparable or even less than the scientific data rate. This amount of data rate is not a problem considering the planned ESO/ELT infrastructure. Fig. 2 summarizes the expected data rates in the SCAO case for the PSF-R Service of MICADO. Preliminary calculations for the MCAO mode of MICADO indicate that the expected data rate for MCAO is slightly lower than in SCAO mode.

Data item	Array	Frame	number	bytes per	data rate
	Size per	Rate	format	number	
	Frame				
	(byte)	(Hz)			(Mbyte/s)
PUP_VIEWS_RAW	151000000	0.0031	flt32	4	1.80
M4_PHASE_DIVERSITY_SKY_RAW	151000000	0.0031	flt32	4	1.80
MICA_FOC_RAW	151000000	0.0031	flt32	4	1.80
PYR_WFS_NORMALIZED_SLOPES_TAB	24000	500	flt32	4	45.8
DM_COMMANDS_SCAO_TAB	4098	500	flt32	4	7.8
INTERACTION_MATRIX_SCAO_TAB	49152000	0.2	flt32	4	37.5
PYR_WFS_BUFFER_TAB	49152000	0.2	flt32	4	37.5
PYR_WFS_MODULATION_TAB	1	0.008	flt32	4	$3.1 \times 10^{-8}$
PYR_WFS_NCPA_OFFSET_TAB	12000	0.2	flt32	4	0.01
PYR_WFS_MODAL_OPTIMIZATION_TAB	8 4096	0.2	flt32	4	0.003
PYR_WFS_MISREGISTRATION_TAB	40000	1.0	flt32	4	0.15
ELT_TELEMETRY_TAB	40000	0.4	flt32	4	0.06
CN2_PROFILE_TAB	40000	0.4	flt32	4	0.06
AO_CONFIGURATION_TAB	100000	0.008	flt32	4	0.003
TOTAL RATE (Tbyte in 9 hr)	4.15				134.286

Summary of the SCAO Raw Data Rates for PSF-R Service

Figure 2. The expected data rates for the SCAO option of the PSF-R Service of MICADO.

# 5. CONCLUSIONS

The present status of the PSF-R software tools of MICADO has been summarised in this paper. In particular, a number of achievements have been reached by the MICADO PSF-R team:

- Accuracies of 1-7% have been reached both with simulated PSFs and with real LBT SOUL+LUCI data, as described in.<sup>7</sup>
- A TRL=7 has been reached by the MICADO PSF-R Service tools.
- There's no issue for the ESO Raw Science Archive to transfer and store all the WFS telemetry data produced by MICADO.
- No critical issue has been emerged during the FDR review, indicating that the maturity level of the PSF-R tools is adequate for that milestone.

• No showstopper for PSF-R has been currently identified, and the PSF-R Service is ready to meet the First Light of MICADO at ELT in 2027.

The PSF-R software is a data intensive tool, since it requires powerful computers and lot of disk space for storage. In the future, the development of smart and efficient algorithms is required in order to reduce the loading factor on the science users of ELT.

Further details on the PSF-R service for MICADO can be found in this proceeding (Arcidiacono et al. 2022; Simioni et al. 2022).

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