Scientific Exploitation of MICADO with Pure PSF Reconstruction

Science with MAVIS 2021 - 5-7/07/2021

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Simioni+2020 - Micado PSF-R WP description
MICADO/MAORY in a nutshell

• MICADO will be a first light instrument for the ELT
• It will work with the MAORY adaptive optics system.
• It’ll do imaging at 6-12mas resolution over a 50” field to J/H/K ~ 29 mag AB,
  R~20000 spectroscopy covering H & K simultaneously,
  (also astrometric & high contrast imaging).
• It’ll use SCAO for initial operations, &
  MCAO, providing uniform correction over the field.
• It’ll provide the user with a reconstructed PSF reference.
MICADO Science Cases

- Dynamics of dense stellar systems (3D kinematics)
- Black Hole at the center of the Milky Way (SgrA*)
- Super Massive Black Holes in local galaxies
- Resolved stellar populations of local galaxies (up to Virgo and Fornax)
- Exoplanets discovery and characterization
- Solar System
- Star Forming Clumps in high-z galaxies
- Formation and evolution of high-z galaxies in the early Universe

-> **A detailed knowledge of the PSF is required** and the PSF–R service is a deliverable of MICADO

Synergies between MICADO and MAVIS (Eline talk)
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PURE PSF–R approach is currently pursued
done without recourse to the science data, using telemetry data only:

- weather conditions: (wind, atm turbulence - Cn2 profiles etc)
- “telescope+instrument”: or non-AO components
- AO: all infos coming from the system
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<table>
<thead>
<tr>
<th>Science case</th>
<th>Observation mode</th>
<th>PSF-R type</th>
<th>Strehl ratio ΔS/S</th>
<th>FWHM ΔFWHM any axis</th>
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</thead>
<tbody>
<tr>
<td>Dynamics of Dense Stellar Systems including the Galactic Center</td>
<td>imaging</td>
<td>hybrid</td>
<td>0.002</td>
<td>0.01 mas</td>
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<tr>
<td>Resolved Stellar Populations</td>
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<td>1 mas</td>
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<tr>
<td>Galaxy Evolution: Detailed Properties of Distant galaxies</td>
<td>Imaging</td>
<td>pure</td>
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<tr>
<td>Galaxy Evolution: Detailed Properties of Distant galaxies</td>
<td>Spectroscopy</td>
<td>pure</td>
<td>0.1</td>
<td>1 mas</td>
</tr>
<tr>
<td>Planets &amp; Planet Formation</td>
<td>Imaging</td>
<td>none</td>
<td>-</td>
<td>-</td>
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<tr>
<td>The Solar System</td>
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<td>0.15</td>
<td>0.5 mas</td>
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<tr>
<td>Black Holes in Galaxies</td>
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Why Pure PSF–R?

35–40% of extragalactic target, a MICADO science frame is void of point sources suitable for standard PSF characterization

[An Astrophysical Context for PSF Reconstruction (ESO doc. Ric. Davies)]

GOODS field South ~180 sq.arcmin \([l,b= 223.6, -54.4]\)

~220 stars \((J\lesssim 23\text{mag})\) \(\rightarrow\) 1.2 star/sq. arcmin

*all stars detected in HST images

\(J<32\text{mag} \rightarrow 3.5\text{ star/sq. arcmin}\) (3x; with most of sources populating the faint end of the mass function)

*TRILEGAL simulation [http://stev.oapd.inaf.it/cgi-bin/trilegal](http://stev.oapd.inaf.it/cgi-bin/trilegal)

with no lower limit on initial stellar mass

MICADO Science Cases II

Structure of high-z Galaxies

Key science drivers at $z > 1$
- Resolving disks, bulges, clumps.
- Characterising SSSs.
- Resolving compact galaxies at $z > 1$.
- Massive E/TG progenitors in dens.
- QSO host properties.
- Structure of lensed galaxies on $< 5''$.
- The first galaxies.
- Substructure of DM halos to $\sim 10'$

SimCADO simulations
https://simcado.readthedocs.io

Based on HUDF source catalog with additional clump and cluster populations. MICADO, 10hrs each on UH bands.

SCAO for initial operations - an example

The structure of lensed Lyman-$\alpha$ absorbers/emitters at $4 < z < 5$
(courtesy of G. Caminha & K. Caputi)

Cluster CL0102 (El Gordo):
- 4 spectroscopically confirmed Lyx emitters/absorbers at $z=4.3$, within $\sim 8''$ of a star with $H_{\text{Abs}} = 15.6$ mag & Gaia $G = 15.9$ mag. (Caminha et al. 2019)
- Even with lensing magnification, HST resolution of 90mas is insufficient to resolve morphology.

ID3-b
Highest magnification of 10
Observed magnitude $H_{\text{Abs}} = 23.6$

Spatial resolution
Order of magnitude gain in resolution from 1 kpc- to 100 pc-scale at $z=1$.
6-12 mas ~ 50-100 pc matches seeing limited scale for Virgo cluster galaxies.

JWST will select samples & measure basic galaxy properties.

MICADO will trace stellar continuum & provide detailed structure.

Synergies with ALMA, HARMONI, etc.

SCAO for initial operations - an example

The structure of lensed Lyman-$\alpha$ absorbers/emitters at $4 < z < 5$
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Question: can clumpy star-forming regions be resolved in ID3-b?
- SimCADO simulations: 2-hr integration of sources based on size & total flux in ID3-b.
- MICADO can easily distinguish clumpy and smooth distributions.
- Clumps with $K_{\text{AB}} < 23.5$ can be detected for all sizes considered in range 3-600pc; small fainter clumps can also be detected.
- Lensing in ID3-b allows one to detect structures to 10-20pc scales in K-band.
Pure PSF-R is required when extended targets cover most of the FoV
PSF–R Scientific Evaluation

**Goal:** develop a work-flow (simulations and analysis) to:
- Evaluate the impact of the uncertainties of the reconstructed PSFs on the scientific output
- Given the maximum acceptable uncertainties on the scientific measurements, estimate the maximum uncertainties on the reconstructed PSFs

What is the effect of using a PSF that is not the “real” one on the scientific measurements?

**Test case:** Detailed Properties of Distant Galaxies

**Method:** Simulate pure–Sersic sources and fit Sersic profiles using different PSFs.
- Sersic profiles with size (Re) typical of early type galaxies at z~2
- High–SNR simulations [do not evaluate effects due to SNR]
PSF–R Scientific Evaluation II

Analysis scheme:

Software: GALFIT. Fit Sersic profiles convolved with an input PSF

1. GALFIT + PSF model vs inputs -> uncertainties (systematics + random noise) on the measurement process

2. GALFIT + PSF–R vs inputs -> uncertainties + systematics introduced by using a PSF different from the “real” one

By comparing the output of 1 and 2, we can isolate the effects of the PSF–R on the measured parameters
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“true” PSF model is obtained using ESO’s Octopus simulation tool; not 100% same assumptions underlying our PSF-R procedure → SR is overestimated by 8%; the outer regions of the PSF are not reconstructed with extreme accuracy
- Non-negligible systematics on the recovered values of the galaxy’s structural parameters. Re is 10 mas (50%) larger.

- Reliable values are retrieved if we exclude the outer regions of the PSF. The PSF core is OK.
LUCI+SOUL@LBT PSF–R

REAL

RECONSTRUCTED
MICADO will be a first light instrument of the EELT

Detailed PSF knowledge is required for a substantial number of MICADO science cases

PSF-R is a deliverable of MICADO and our WG is in charge of its development

A pure PSF–R approach is pursued:
- PSF is reconstructed from AO and non–AO telemetry data, with no use of science data
- a user–friendly software will be provided; it will take as input position of the object, filter, observing mode, exposure time, telemetry and calibration data; the output will likely be a FITS image with the reconstructed PSF, or a cube of reconstructed PSF at different wavelengths

We are currently at Final Design Review level, with positive feedback received from ESO

Preliminary results are extremely promising, the method has also been adapted to real data

We have also developed tools and a pipeline to evaluate how uncertainties on the reconstructed PSF translate into uncertainties on scientific measurements (and viceversa)