PARAMETERISING THE E-ELT POINT SPREAD FUNCTION FOR SCIENCE SIMULATIONS WITH HARMONI

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Abstract. With the first ELTs around the corner it is becoming ever more important to determine observational strategies and assess the prospective success of observing programs prior to making the observations. To this end, scientific simulations need to become more refined to understand the criteria required for a specific science case. We address the science simulations for HARMONI, an AO assisted first light integral field spectrograph (IFS) for the E-ELT. AO point spread functions (PSFs) vary markedly as a function of wavelength and type of AO system used, so there is need to create detailed PSFs across all IFS wavelength channels for accurate simulations. Detailed AO simulations have shown that for LTAO on the E-ELT, Strehl ratios can vary from 0.5% in V-band up to 75% in K-band. Using a single PSF for an entire datacube (especially with large instantaneous wavelength coverage) could introduce misleading features into simulated observations using HARMONI. We have developed a method to parameterise detailed PSFs using analytical models, which can then be interpolated as a function of wavelength. This allows us to create accurate, but computationally inexpensive, AO PSF datacubes for HARMONI simulations. This shall be developed to cover LTAO, SCAO and GLAO/no-AO PSFs.

1 Introduction

HARMONI (High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph) [1] is a planned first-light, image-slicer based integral field spectrograph (IFS) for the European-Extremely Large Telescope; a 39 m diameter, visible and near-IR, adaptive-optics (AO) assisted telescope, designed by the European Southern Observatory (ESO).

As astronomical instrumentation projects become ever larger and more complex, it is becoming essential to undertake detailed performance simulations during the design phase. These help define instrument capabilities as well as allow trade-offs to be made with different designs. Many instrumentation groups now perform simulations including MUSE for the VLT and EAGLE for the E-ELT [2][3]. It is also important to better quantify the instrument performance prior to construction to be able to optimise the design.

An essential component of the simulations is characterising the effects of the telescope through the spatial PSF. The E-ELT is a fully-adaptive telescope and so will always be running with AO. HARMONI is being designed to work with three AO modes: ground-layer (GLAO), single conjugate (SCAO) and laser tomographic (LTAO). The AO assisted PSF is a complex function of wavelength, seeing, zenith angle, guide star magnitude, off-axis distance and various other parameters. The PSF changes markedly over this large parameter space, and so it is imperative to incorporate detailed models of the PSF into simulations to accurately characterise the performance for any observation mode. Specifically, for an IFS with large instantaneous wavelength coverage the PSF will change markedly as AO performance improves towards the near-IR. However, detailed PSF simulations are computationally and time intensive.

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2 Method

We have developed a method to parameterise axisymmetric E-ELT PSFs using a series of analytical functions, the parameters of which can then be interpolated as a function of wavelength and seeing. Serre et al. (2010) showed that the MUSE spatial PSF could be accurately modelled by a Moffat profile, where the two parameters vary smoothly with wavelength [4]. Here we extend this analytical fitting procedure to the more complex E-ELT SCAO PSFs. We have used a set of on-axis PSFs generated using detailed adaptive optics simulation code (T. Fusco, private communication). See Table 1 for a full list of simulation parameters. These PSFs cover the full HARMONI wavelength range at 0.1 \( \mu \)m sampling, as well as zenith seeing FWHM from 0.67" to 1.10". We are currently not considering high spatial frequency phase errors from the telescope, which the AO cannot correct. Thus our PSFs represent a perfect primary mirror.

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<th>Table 1. Simulation parameters for input PSFs.</th>
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<td>AO Type</td>
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<td>Seeing FWHM</td>
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<tr>
<td>Zenith angle</td>
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<tr>
<td>NGS mag</td>
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<td>Residual tip-tilt jitter</td>
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<tr>
<td>Sampling</td>
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<td>Telescope diameter</td>
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Using the PSF fitting code elpsffit, developed by J. Liske [5], we are able to fit the radial profile of each PSF using several analytical functions, shown in equations 1, 2 and 3.

\[
A(R) = \frac{I_A}{(1 - \epsilon^2)^2} \left( \frac{2J_1(R) - 2\epsilon J_1(\epsilon R)}{R} \right)^2, \quad R(r) = \frac{\sin(r)}{w_A}, \quad (1)
\]

\[
L(r) = \frac{I_L}{\left( \frac{r - p_L}{w_L} \right)^2 + 1}, \quad (2)
\]

\[
M(r) = \frac{I_M}{\left( \frac{r}{w_M} \right)^2 + 1} \beta, \quad (3)
\]

Eq. 1 is a form of the obscured Airy function which represents the diffraction limited core, where \( I_A \) is the intensity, \( w_A = \lambda/(\pi D) \) gives the HWHM where \( D \) is the telescope diameter, and \( \epsilon = 0.3 \) is the obscuration ratio for the E-ELT. The Lorentzian function in Eq. 2 models the AO correction cutoff point where \( I_L \) is intensity, \( w_L \) is the HWHM and \( p_L \) is the radial position of the peak. The seeing halo is modelled by the Moffat function (Eq. 3) where \( I_M \) is intensity, \( w_M \) is the HWHM and \( \beta \) is the shape parameter. The full radial profile is given as:

\[
PSF(r) = A(r) + M_s(r) + L(r) + M_c(r). \quad (4)
\]

The second Moffat function \( M_c(r) \) is used only for visible PSFs to represent the non-diffraction limited core and becomes negligible in the near-IR. The analytic profile can then be sampled at any radius or wavelength by interpolating the smoothly varying model parameters (Fig. 1). This allows the generation of a PSF datacube that can be used to convolve each spectral channel of a HARMONI datacube with the correct PSF.
Fig. 1. Parameter plots for on-axis SCAO PSFs as a function of wavelength and seeing.
Fig. 2. Radial profiles of original and parameterised PSFs at $\lambda = 0.5\,\mu m$ and $\lambda = 2.2\,\mu m$. These demonstrate the different components required to accurately model the profile. Note the logarithmic y-axis.

3 Results and Discussion

Fig. 2 shows comparison radial profiles between original and parameterised PSFs for two different wavelengths. The profiles match well throughout all parts of the complex PSF shape, and at both optical and near-IR wavelengths. Fig. 3 shows two methods used to assess the quality of the parameterised PSFs. Strehl ratios and ensquared energy (EE) differences for the HARMONI spatial scales are plotted. Both of these show good agreement with the original PSFs, with negligible difference in Strehl ratios at all wavelengths and seeing. Also shown are Strehl ratios for PSFs with residual primary mirror phase errors. The EE uncertainties are less than 3.5% over the full wavelength range. The errors in EE are found to be smaller by a factor of around 1.5, compared to the difference between PSFs with a perfect primary mirror and those with residual phase errors. These demonstrate that our method does not introduce any dominant source of error through parameterisation of the PSFs.

Fig. 4 shows a qualitative demonstration of why incorporating the PSF in simulations is important. Shown is an example galaxy at $z \sim 2$ (left) alongside the same object convolved with a K-band PSF (centre) and an R-band PSF (right). The large loss of detail is clearly evident between visible and near-IR SCAO observing. Accurately determining spectral features at the observed visible wavelengths for specific regions would be hampered both by decreased resolution and signal-to-noise.

Another advantage of the parameterisation method is computational speed. As an example, using an Apple iMac desktop with a 2.66 GHz Intel Core 2 Duo and 4GB 1067 MHz RAM, the code is capable of generating a $(x, y, \lambda)$ PSF cube of size $(512, 512, 1000)$ in 213 seconds. This demonstrates the ability of running the code on any modern desktop or laptop computer,
Fig. 3. Left shows a comparison of Strehl ratios between the original, detailed simulated PSFs (solid lines) and parameterised PSFs (dashed lines). Also shown are Strehl ratios for PSFs with residual M1 phase errors (dotted-dashed lines) to give an idea of uncertainty. Right shows a plot of ensquared energy difference between original and parameterised PSFs as a percentage of total ensquared energy at each wavelength. For each spatial scale the ensquared energy is computed in a 2x2 spaxel box centered on the PSF. The lines for the 4 mas scale stop at 0.8 \( \mu \)m as this is the proposed cut between visible and near-IR wavelengths. Ensquared energies for residual M1 error PSFs are omitted for clarity on the plot.

Fig. 4. A qualitative example demonstrating the importance of the PSF. Left shows an image of a \( z \sim 2 \) galaxy at a spatial scale of 4 mas. Centre and right images show the galaxy convolved with a parameterised K-band and R-band SCAO PSFs respectively, and resampled at 10 mas. Field of view sizes of the spatial scales are not considered here.

and shows that PSF generation will not be a limiting factor when performing full instrument simulations.

While the results for the SCAO PSFs seem promising there are certain limitations with this method. It is currently only capable of parameterising on-axis PSFs of point-like reference sources. More complex PSFs formed by referencing on extended objects would be difficult to parameterise. This limits the use of these “cheap” PSFs for simulating Solar System science.
cases where the object of interest, e.g. a Jovian moon, is also used as the AO reference. An alternative method could be to use principal component analysis which has been used fairly extensively for modelling spatial variations, (e.g. Jee et al. 2007). However, for the purposes of providing general PSFs for different AO types, the above method certainly holds merit.

4 Conclusion and Further Work

We have developed a method to accurately parameterise detailed E-ELT SCAO PSFs for the purpose of enabling easy generation of PSFs to cover the HARMONI wavelength range. The radial profile of each PSF is modelled using the sum of three analytical functions, an obscured Airy function for the diffraction limited core; a Moffat profile for the seeing halo and a Lorentzian function to model the AO cutoff sub-peak. The parameters of each function smoothly vary with wavelength and seeing FWHM allowing for interpolation to any value. A circularly symmetric 2D PSF is then generated from the radial profile for a chosen wavelength and seeing.

The generated PSFs show excellent resemblance to the original, detailed PSFs, as quantified by very similar Strehl ratios and ensquared energy values. The method is able to accurately follow the large change in PSF Strehl ratios from 0.5% up to 76% between the V and K bands. The generation code is computationally efficient taking only several minutes to compute 1000 wavelength channels.

The future aims of this work are to create a parameterised database for PSFs covering a wide range of AO modes, seeing FWHM values, zenith angles, natural guide star magnitudes and further parameters. This will allow easy generation of PSFs covering an extremely useful amount of telescope parameter space, for use in detailed HARMONI simulations. A website will be developed to allow for the generation of PSFs covering the large range of observing parameters. Users will be able to download these PSFs for personal use in simulations.

References