Handling a highly structured and spatially variable Point Spread Function in AO images

L. Schreiber[1, 3,a], E. Diolaiti[2], M. Bellazzini[2], P. Ciliegi[2], I. Foppiani[2], L. Greggio[3], B. Lanzoni[1], M. Lombini[2]

[1]Università di Bologna, Astronomy Department, Via Ranzani 1, Bologna, Italy
[2]INAF, Astronomical Observatory of Bologna, Via Ranzani 1, Bologna, Italy
[3]INAF, Astronomical Observatory of Padova, Vicolo dell’Osservatorio 5, Padova, Italy

Abstract. Adaptive Optics (AO) has become a key technology for all the main existing 8-meter class telescopes and it is considered a kind of enabling technology for future Extremely Large Telescopes. AO systems increase the energy concentration of the Point Spread Function (PSF), but the PSF itself is also characterized by complex shape and spatial variation. Efforts in the AO PSF modelling and in the integration of suitable models in a code for image analysis are needed to improve the extraction of high-precision quantitative science from AO observations. The StarFinder code was one of the first full attempts to solve the problem of obtaining accurate photometry and astrometry from narrow field AO images with spatially constant and highly structured PSF. However it still lacks of suitable methods for handling spatially variable AO PSFs. We are developing a set of models representative of the PSF shapes and variation across the imaged field that might be obtained from different AO systems. These models are based on observed data from present telescopes. This effort is part of a project aimed at upgrading the StarFinder code and provide it with a set of tools to handle spatially variable PSFs.

1. Introduction

Efforts in the AO PSF modelling and in the integration of suitable models in a code for image analysis are needed to improve the extraction of high-precision quantitative science from AO observations. Several image analysis codes are available in the literature: Romafot ([1]), DAOPHOT ([2]), DoPHOT ([3]), HSTPhot ([4]), Sextractor ([5]). These methods have very interesting features and are extensively used by astronomers. However none of the available codes is specifically designed for AO systems: some of them have too simple analytic PSF models that are not suited to AO, some can account for spatial variations of the PSF, but following simple schemes that do not exploit the wealth of information on the PSF spatial dependency in AO. The importance of a specific and dedicated software package for the analysis of AO astronomical images has been amply demonstrated in recent years, for instance by the StarFinder code ([6]). This package was the first full attempt to solve the problem of obtaining accurate photometry and astrometry from narrow field AO images with spatially constant and highly structured PSF. Although StarFinder proved to be effective in solving the

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[a] e-mail : laura.schreiber@oapd.inaf.it

specific problem for which it was designed, it still lacks of suitable methods for handling spatially variable AO PSFs. Preliminary studies to fill this gap were made within the code, modelling the AO PSF by a convolution of the best PSF in the field with a spatially dependent blurring function ([7]) or by a fully analytic modelling of the PSF ([8]) allowing the user to give as input a cube of local PSFs defined on a regular grid. This simple method, however, requires the estimation of the local PSF from the data and considers a discrete PSF variation across the FoV. These attempts are therefore limited to single specific cases.
We are going to develop a new, free software package specifically dedicated to the analysis and restoration of AO images with complex and spatially variable PSF, based on StarFinder and designed for crowded point-like source fields.

2. The Starfinder Code

The StarFinder program ([6]) has been designed and developed for high resolution AO images taking into account the problem of reliable stars recognition in crowded fields with highly structured PSF. It recognizes the stars in the image and determines their photometry and astrometry by PSF fitting. The analysis is accomplished by using a numerical PSF template extracted from the frame and obtained as a median of a set of star images, chosen by the user, background-subtracted, centered with sub-pixel accuracy and normalized. The candidate stars are then searched in the image by selecting the sources with a peak value statistically significant above the background, they are listed by decreasing intensity and they are compared to the PSF with a correlation check. If the correlation coefficient is greater than a selected level the object is recognized as a star and its position and flux are obtained by means of a local fit. The contribution of the detected stars is recorded into an image model which is continuously updated and used as a reference to account for the contamination of the already detected sources. After a first iteration of the star detection loop with a preliminary rough photometric analysis , the contaminating sources around the stars selected for the PSF estimation have been individuated and the initial background estimation has been refined, resulting in a more accurate PSF estimation. The code has been written in IDL language and the current version, provided with a widget-based Graphical User Interface (GUI), is accurately documented and available on-line. The released version of the program with the GUI allows to handle with a constant PSF over the frame. A more recent version without GUI allows to give as input a cube of local PSFs defined on a regular grid. This represents a first attempt to handle with spatially variable PSFs that however requires the estimation of the local PSFs from the data.

3. Modelling the PSF

The PSF models may be classified in three main categories: analytical, numerical and hybrid. Modelling the variation across the image for a fully analytical PSF model implies the adaptation of the model parameters with field position. AO PSFs are often characterized by a combination of a set of components. The identification of these components and the variation model of their parameters are made easier if a priori knowledge of the AO system is considered, i.e. the GS position in the FoV or the actual seeing disk size. In the case of a fully numerical PSF template, the field variation might be achieved by partitioning the image domain into sub domains or by convolution of the “best” PSF in the field (typically the GS image in single conjugate AO) with a blurring kernel (either numerical or parametric) accounting for the variation.

We are going to implement an hybrid modelling that allows the adaptation of the parameters of the analytical part over the FoV and also takes into account for the contribution of the numerical residuals.

With the help of real AO astronomical data, presented in the next section, we considered the analytical part of the PSF as a combination of few simpler components where only the core-component can vary its parameters across the FoV. The study of the map of residual was beyond the scope of this paper and it is left for future publications.

4. The data

We collected scientific data from different existing AO instruments to develop a set of models representative of the PSF shapes and variation across the imaged field that might be obtained from different AO systems.

In particular we present here three cases:

- FLAO @ LBT;
- NACO @ VLT;
- MAD @ VLT.

The first two cases (FLAO and NACO) refer to single conjugate AO systems, featuring a deformable mirror for the atmospheric turbulence correction and a natural GS for the measurement of the turbulence. This kind of systems tend to provide a correction optimized in the direction of the GS and with a mainly radial variation of the PSF with respect to this direction. A more uniform correction may be achieved by Multi Conjugate Adaptive Optics (MCAO; [9]), a technique based on the use of two or more deformable mirrors and several GSs, demonstrated on sky by MAD on the VLT ([10]) and planned for the future E-ELT. This is the third case we consider in this paper.

4.1. FLAO@LBT

The First Light Adaptive Optics system (FLAO, [11]) of the Large Binocular Telescope (LBT) comprises an adaptive secondary mirror (672 actuators) and a pyramid wavefront sensor. The near-infrared adaptive optics images of M92 taken with the camera PISCES show the typical features of single-conjugate adaptive optics systems: a structured PSF, with a sharp core and an extended halo, and significant variations across the FoV (Fig. 1).

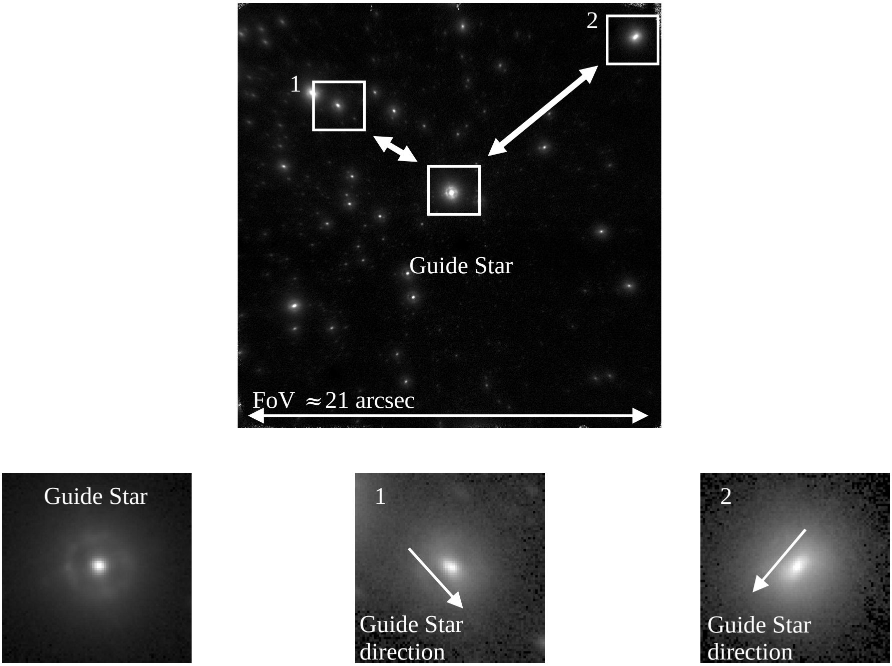

Fig. 1. Top: Image of M92 taken with the camera PISCES@LBT in J band. Bottom: sub-images of three selected stars, including the NGS, showing the radial variation of the PSF with respect to the GS position.

The simplest analytical model that better represents the PISCES M92 PSF is given by a narrow Moffat core, a broader Gaussian/Moffat halo and an external torus (see Fig. 2, left panel). The following constrains, that take into account as much as possible the knowledge a priori of the AO system, have been given to the PSF in order to reduce the number of fitting parameters leading to a more robust result:

- Core: Moffat with a radial variation with respect to the GS direction. The rotation angle respect to the pixel grid is known a priori from the GS position. The variation of the two Moffat radii with the distance from the GS is plotted Fig. 2 right panel;
- Halo: composed by 2 main components. 1) Seeing halo: round Moffat/Gaussian (no elongation). The radius of this component has been estimated on a sample of bright stars iterating the fit process and then fixed to the median of the extracted values across the FoV. The relative flux has been considered the only variable parameter across the FoV. 2) Toroidal halo: round Torus with Moffat section associated to the DM inter-actuator distance. The radius of this component has been computed by the a priori knowledge of the AO system characteristics. The radius of the Moffat section has been estimated iterating the fit process and then fixed to the median of the extracted values across the FoV. The relative flux has been bound to 1-F1-F2, where F1 and F2 are the relative fluxes estimated for the other two components.

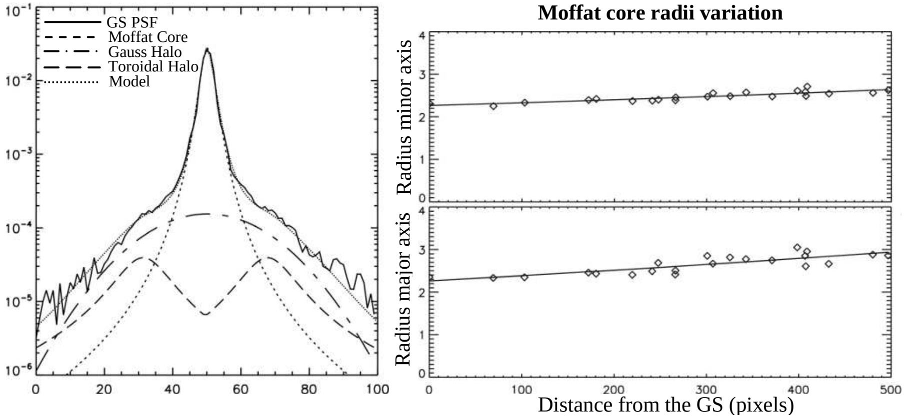

Fig. 2. Left : M92 PISCES GS PSF. In this figure the real PSF (continuous line) is well described by the Model (dotted line) that is obtained by the combination of three components: a Moffat core (small dashed line), a Gaussian halo (dashed-dotted line) and a Toroidal halo (long dashed line); Right: the Moffat core variable radii across the FoV with respect to the GS distance. These plots refer to K band images.

4.2. NACO@VLT

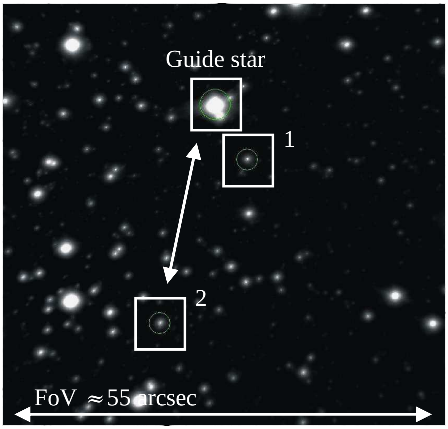

Fig. 3. The NGC 6440 globular cluster with the NACO@VLT. White squares are used to indicate the NGS and two stars at different positions in the FoV, showing increasing elongation.

The images taken with the ESO VLT NAOS CONICA adaptive optics system ([8]) of the NGC 6440 globular cluster (Fig. 3) look different from the ones previously analyzed. Even if the variation of the PSF looks again radial with elongation pointing the GS, the PSF itself looks smoother and therefore easier to model. In this case the PSF is well described by the combination of only two Moffat components:

- Core: Moffat with a radial variation with respect to the GS direction. The rotation angle is known a priori from the GS position.
- Seeing Halo: round Moffat/Gaussian (no elongation). The radius of this component has been estimated on a sample of bright stars iterating the fit process and then fixed to the median of the extracted values across the FoV. The relative flux has been bound to 1-F1, where F1 is the relative flux of the core component.

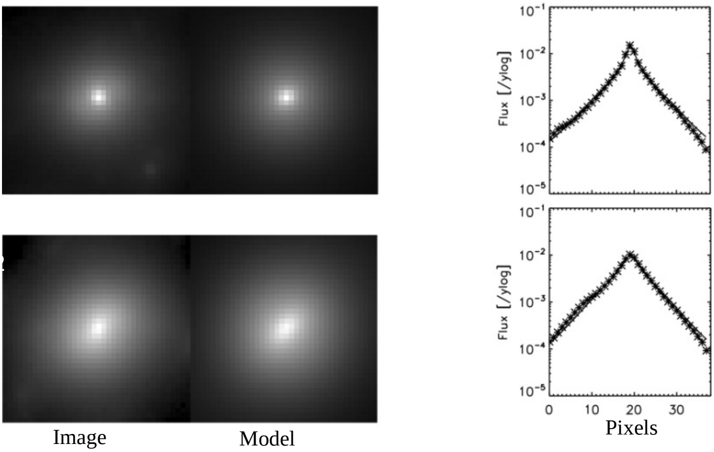

Fig. 4. Left : Sub-images of the two field stars of Fig. **3** selected for the PSF modelling and relative model built with the fitting parameters. Right: The PSF profile of the same two stars (asterisks) and modelled PSF profile (continuous line). The secondary sources were not subtracted causing the bumps in the profile.

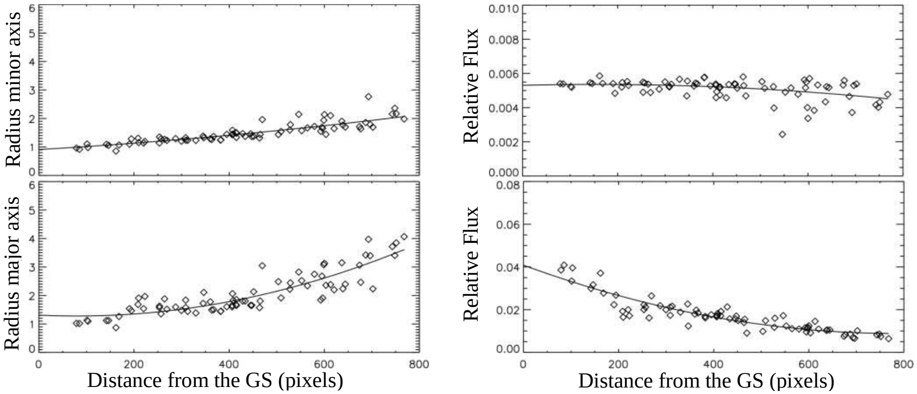

Fig. 5. Left: the Moffat core variable radii across the FoV with respect to the GS distance. The continuous lines represent the quadratic best fit. Right: the relative Flux of the two Moffat components: the halo is on the top, the core is on the bottom.

4.3. MAD@VLT

The Multi Conjugate Adaptive Optics Demonstrator (MAD) has been built by ESO to prove on sky the feasibility of MCAO. MAD is equipped with three Shack-Hartmann wavefront sensors for measuring the atmospheric turbulence from three GSs located in a FoV of 2 arcminutes. The MCAO technique strongly improves the PSF non-uniformity problem. We took a sample of isolated stars from the Omega Centauri image ([12,13]) showed in Fig. 6 to analytically model the PSF.

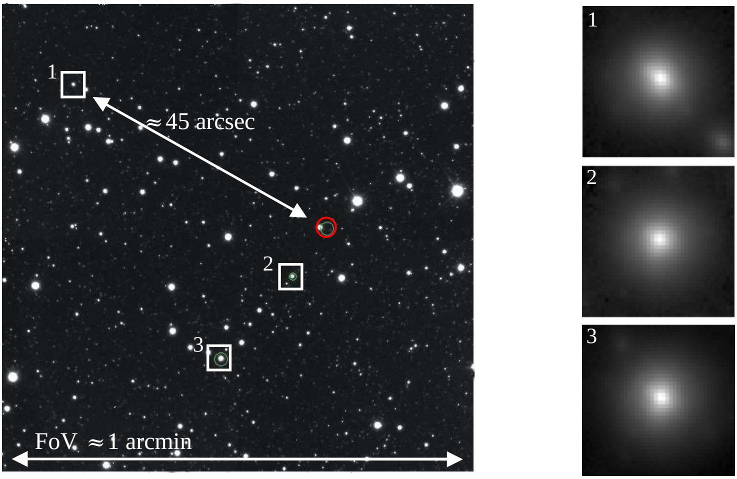

Fig. 6. The MAD Omega Centauri Globular Cluster image. The three NGSs are not in the field. The red circle indicates the position of their centre of gravity. The three stars in the white squares in the image are zoomed and showed in the right panel. In spite of their position in the FoV, the PSFs look pretty uniform.

Due to the smoothed shapes of the extracted PSFs, we adopted a simple model made by the superimposition of two Moffat functions, one for the variable core and one for the halo, as for the previous case (Section 4.2). This time we did not use the a-priori knowledge of the PSF elongation direction, due to the fact that more than one NGS has been used. Even if the PSF looks pretty constant across the FoV (see Fig. 7 to achieve a precise photometry, a detailed model of the parameters variation across the FoV would be required. This precise modelling, however, is left to a future development of this work and we present in this paper, with an illustrative purpose, in Fig. 7 the core parameters variation respect to the NGSs centre of gravity.

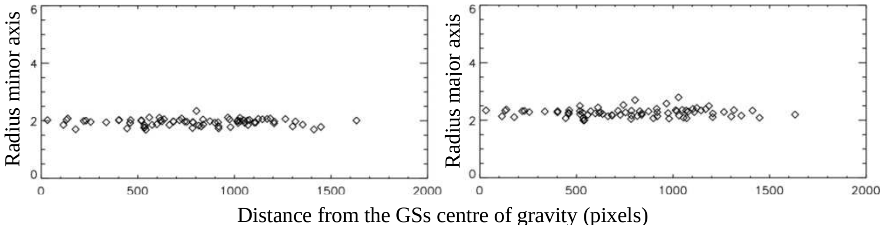

Fig. 7. MCAO: the Moffat core variable radii across the FoV with respect to the GSs centre of gravity distance.

5. Conclusion

In this paper we collected scientific data coming from existing AO facilities: FLAO@LBT, NACO@VLT and MAD@VLT. The scope of this preliminary study was to develop a set of analytical models representative of the PSF and its variation across the FoV when different AO systems are adopted. We showed that the number of components required to build an accurate PSF model increases with the complexity of the PSF shape and so with the degree of correction. This study represents the first step toward the writing of a software package based on the StarFinder code and specifically dedicated to the analysis and restoration of AO images with complex and spatially variable PSF.

6. References

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