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Reconstruction of the point spread function for the ground layer adaptive optics system ARGOS

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Abstract. Present and future adaptive optics (AO) systems aim for the correction of the atmospheric turbulence over a large field of view combined with large sky coverage. Thus they use multiple laser beacons on sky. Still there will always be variations in the shape of the point spread function (PSF) with field angle. To overcome this drawback, a good knowledge of the PSF over the field is required. In the past, several algorithms of PSF retrieval have been proposed and tested. This includes on-axis PSF retrieval from wavefront sensor (WFS) data as well as a correction over the field using a reference PSF. The schemes have been set up for both an AO system using a single natural guide star as well as a system using a laser beacon. For these algorithms to work, a detailed knowledge of the atmospheric structure, i.e. Cn^2 profile, is crucial. In the context of the ARGOS system, a GLAO system proposed for the LBT with three Rayleigh laser beacons per eye of the telescope, we build a reconstruction scheme which uses the multiple guide stars to directly measure the atmospheric profile from the WFS data itself. Here we show how the conventional PSF-retrieval algorithms must be changed to make up for the difference between the multiple beacon GLAO used in ARGOS and the typical single source on-axis schemes. We present first results of PSF-reconstruction using the data from two WFS and investigate in the accuracy of this procedure.

1 Introduction

PSF-reconstruction on AO-corrected images has been subject of research more than two decades. Important work has been done by [3], [7], [8], [12], [11], and [1]. The proposed applications range from the reconstruction of the on-axis PSF from WFS data (e.g. [12]) of an AO-system using one natural guide star to the reconstruction of the off-axis PSF for the same system (e.g. [1]) or the reconstruction of the on-axis PSF for a laser based AO-system (e.g. [10]). Never the less the technique seems to be far from beeing a standard tool in the reduction of AO-based astonomical data. Therefore for the ARGOS project we aim to further investigate into the PSF-retrieval techniques especially regarding the structure of the AO system. The goal is to provide the observer with a trustworthy PSF-map directly in combination with the raw science data.
AO assisted astronomical observations produce images on which the PSf varies with the field position. Especially in the case of laser based systems there will often be no PSF reference star in the field. Of course there is the possibility to get the PSF from a star in the neighbourhood of the science field. But this method has several drawbacks: First the atmosphere evolves and as the PSF data is taken at a different time as the science target the reference PSF measured with this method will necessarily differ from the PSF at the time of the science observation. Second one needs additional observing time to gain the data of the reference star. So the idea of PSF retrieval from WFS data was born which should overcome both drawbacks the PSF reference star method has.
The standard method to retrieve the on-axis PSF [12], [4] uses the WFS data and the noise on the WFS as known input. The residual atmosphere and the aliasing on the WFS are simulated. The combination of these inputs yields the short time PSF and the averaging over the structure functions yields the long exposure PSF on-axis. To derive the off-axis PSF two algorithms have been proposed: One introduces the so-called anisoplanatic transfere function (ATF). The off-axis PSF is then the product between the on-axis PSF and the ATF. The other possibility to derive the off-axis PSF is to first project the WFS signal into the desired off-axis direction (see e.g. [13]) via correlations between the wavefront on-axis

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and off-axis and then use the standard on-axis algorithm. These approaches should be similar as the ATF is build just using these correlations (see [10]). Especially in the case of a laser based system the second approach seems favorable because within this approach it is streight foreward to include the cone effect.
ARGOS is the ground layer AO system foreseen to be used at the LBT. As guide stars it makes use of 3 green (532 nm) Rayleigh laser beacons per eye equally placed on a circle with 2' radius at a height of 12 km. The high order part of the wavefront is measured on these beacons by one 15x15 Shack-Hartmann WFS per beacon. The Tip-Tilt (TT) information is gained using one natural TT-star using a pyramid WFS. The system will run at a 1 kHz frame rate. For a ground layer AO system the requirements for the PSF reconstruction are relaxed as a large part of the residual wavefront error will be the non-corrected high atmosphere.

2 Basic concept of PSF reconstruction for ARGOS

In comparison to the classical PSF-reconstruction scheme ([12]) the reconstruction for AO systems using multiple sources, especially lasers, face a few more difficulties :

- Low order and high spatial order information has different sources
- In the case of laser systems, high layer turbulence is badly sampled if at all.

These difficulties can - at least partly - be overcome by the reconstruction scheme proposed here. The main new features are the following:

- Project the wavefronts from the different sources rather than the OTF
- Derive the (lower) atmospheric profile from the different (laser) WFS using the SLODAR [6], [9], [15], [16] technique.
- Use DIMM-MASS data to estimate the total atmospheric profile
- Use potential Truth sensor information to refine the contribution of the upper atmosphere

In Figure 1 we compare a scetch of the classical PSF reconstruction scheme with the one proposed for ARGOS. Both systems need in addition to data retrievable from the AO-system alone external data on the atmospheric profile. Note however that the reason for this requirement is different between the two approaches. The classical system needs the external input because it is not capable of retrieving the necessary information by itself. In the case of the AO system using multiple sources the DIMM-Mass data is only needed if the laser beacons are at low altitudes and thus do not sample the high atmosphere properly. In the case of a system using multiple natural guide stars or multiple sodium lasers for high order correction this external data is not needed.

The construction of the off-axis OTF as well as the projection of the wavefront on axis both require the calculation of large matrices. To speed up the application these matrices, as they are the same for any calculation, are calculated once and stored. Thus the final PSF-reconstruction algorithm contains a few matrix multiplications and the atmospheric simulation (which might be well approximated by the Zernike expression derived by [5]) only and thus be quite fast. The concerns about the disk space as expressed in [4] seems not to be applicable any more as there exist easy possibilities to extend disk space if necessary (e.g. USB-disks etc.).

3 Simulations

Simulations of a first test system were performed within the CAOS [2] environment. The choice of this environment was made because CAOS is a very intuitive module based system for AO simulations allowing the user to easily construct additional customized modules.
The simulation performed here is a first test to verify the projection scheme proposed for the ARGOS PSF reconstruction algorithm. We use very simple model of an AO-system using two different (natural) guide stars only. At the time of the writing of this paper sources at finite heights are not implemented yet in the PSF reconstruction module. Still the projection scheme is of rather universal nature, meaning

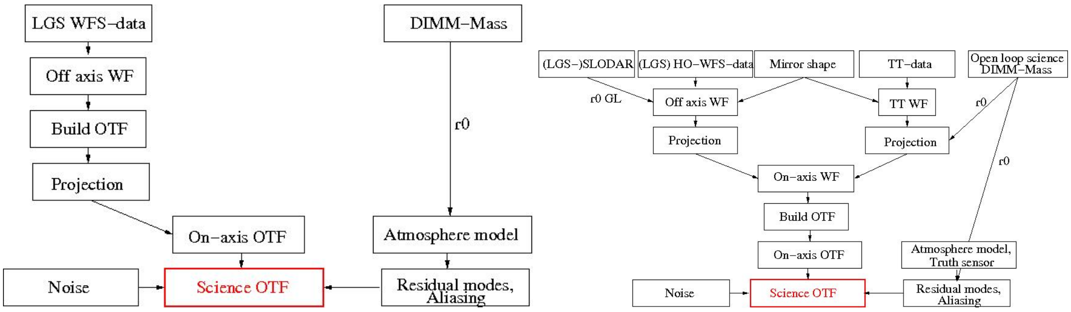

Fig. 1. Left: Conventional scheme of PSF reconstruction from an of off-axis star [1]. A single off axis PSF star is used and its optical transfere function (OTF) reconstructed. The on-axis OTF is regained via projection with the anisoplanatic transfer function (ATF). The residual atmosphere is modelled as van Karman spectrum and is scaled with the value of r_0 calculated from DIMM-Mass data. Note that the construction of the ATF also requires this DIMM-Mass data.
Right: The basic concept of the PSF-reconstruction using more than one laser guide star. The input is: (1) Laser-WFS measurements, (2) shape of the deformable mirror, (3) TT-WFS measurement, and (4) external DIMM-MASS data. The laser WFS measurements are used twofold: once for the wave front reconstruction and once to derive the Cn^2 profile of the ground layer using SLODAR. With this information and the shape of the mirror the off-axis laser measurements can be projected on-axis using inter-aperture correlation between wavefronts. The same is done for the TT-wavefront using the TT-WFS measurements and the information from the DIMM-MASS. Aliasing and residual atmospheric modes are included via simulation of the atmosphere as above.

Table 1. Simulation parameters

$r_0(500nm)$	Layer height	τ_0	λ_{obs}	guide star pos.	D	frame rate	exp.	pix. scale
0.1m	6000m	0.0062 s	2200 nm	+1’ and -1’	8m	1000 Hz	2 s	0.″1

it should work for sources at any height. So in order to best mimic the later applications one of the guide stars is used to provide TT-information the other one to provide high order information. The modal basis used are the Zernike polynomials as there exists an analytical formulation (see [13], [14]) for the projection between different directions. The later application can use any sort of mode set as the necessary matrices can be calculated numerically and then are stored (see 2) i.e. the algorithm will be executable at the same speed independently of the mode set used.

The important parameters of the simulations are the Fried parameter, r_0, measured at 500nm wavelength, the height of the atmospheric layer, the atmospheric coherence time, τ_0, the observing wavelength, λ_{obs}, the positions of the two guide stars, the telescope diameter, D, the frame rate of the AO system, the exposure time, exp., and the pixel scale on the science camera. These parameters are shown in Table1. The geometry between guide stars and science object is shown in Figure2.

As can be seen from table 1 the total exposure time is rather short. This is because the simulations require a lot of computation time. Due to the fact that the residual atmosphere is simulated via analytical expressions (Zernike polinomials [5]) the simulated PSF is rather comparable to a long exposure PSF. In order to still quantify the quality of the PSF reconstruction we tested it on an artificially produced binary star. The science image of a single on-axis source was doubled and the copy was shifted by 0.″1 and then added to the original image. The resolution of the system on-axis (for an equally bright binary) was 0.″2. This value has been measured from the width of the on-axis PSF. The brightness contrast of the binary constructed as described above is one. This binary was then compared to a model of a binary based on the reconstructed PSF. The distance and position angle between the companions was left variable and tested in steps of 0.″05 and 10 degrees respectively. With this method, using the reconstructed PSF, the existence, distance, and the position angle of the companion could be retrieved. The remaining error of the method is obviously below one step size. The image of the

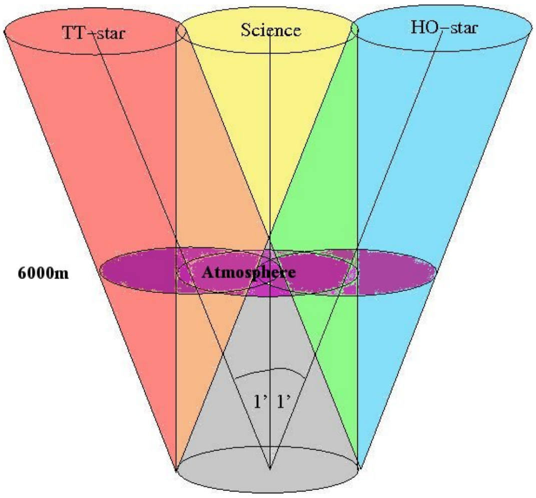

Fig. 2. Figure 2. Set up of the simulation. The science object is on-axis, the two guide stars (TT- and high order) at ±1' .

binary, the artificial binary, the residual PSF after subtraction of the artificial binary from the image, and a cut throug the PSF of the binary along the axis of the binary are shown in Figure 3.

4 Conclusion and further work

We presented a scheme of PSF reconstruction for AO systems using multiple (laser-) guide stars. The information from the multiple WFSs not only yields the wave front but can also be used to reconstruct the atmospheric turbulence profile up to a certain height given by the altitude of the lasers. The scheme is applicable for any configuration of AO-system using one or more (artificial or natural) guide stars. Note however that for MCAO systems the conjugation of the WFSs to different layers must be taken into account additionally.
In a first simulation we reconstructed the on axis PSF using one TT-star at 1' off-axis and one star for high order correction at -1' off axis. With an original system resolution of 0.″2 the PSF reconstruction enabled us to resolve a 0.″1 binary.
Remarkably the resolution achieved by the PSF-reconstruction scheme is equal to the pixel scale. So the question arises if a smaller pixel scale would enable an even better resolution. This might give implications to future instrumentation projects as a potential image improvement by post processing could have impact on the pixel scale of the science camera i.e. one would reduce the pixel scale of the science camera below the one needed for Nyquist sampling to enable a post processing with higher accuracy. This question will be adressed in future simulations.
As stated above the simple simulation yielded already promising results. To be able to fully simulate the PSF reconstruction for ARGOS future simulations will include:

- laser beacons at finite heights
- multiple lasers
- longer integration times to directly compare the science PSF with the reconstructed one
- different pixel scales on the science detector
- a large number of atmospheric layers.
- SLODAR on the laser WFS signals will be used to find the Cn^2 profile for the lower atmosphere.

ARGOS itself at first light will reconstruct the HO-wavefront by averaging over the three HO-WFS signals. An upgrade of the controller to a more sophisticated version i.e. optimization of the controller for a target at a specific position or a homogeneous PSF over the field will be added later. This upgrade however will not affect the basic PSF reconstruction scheme as this scheme only relies on the

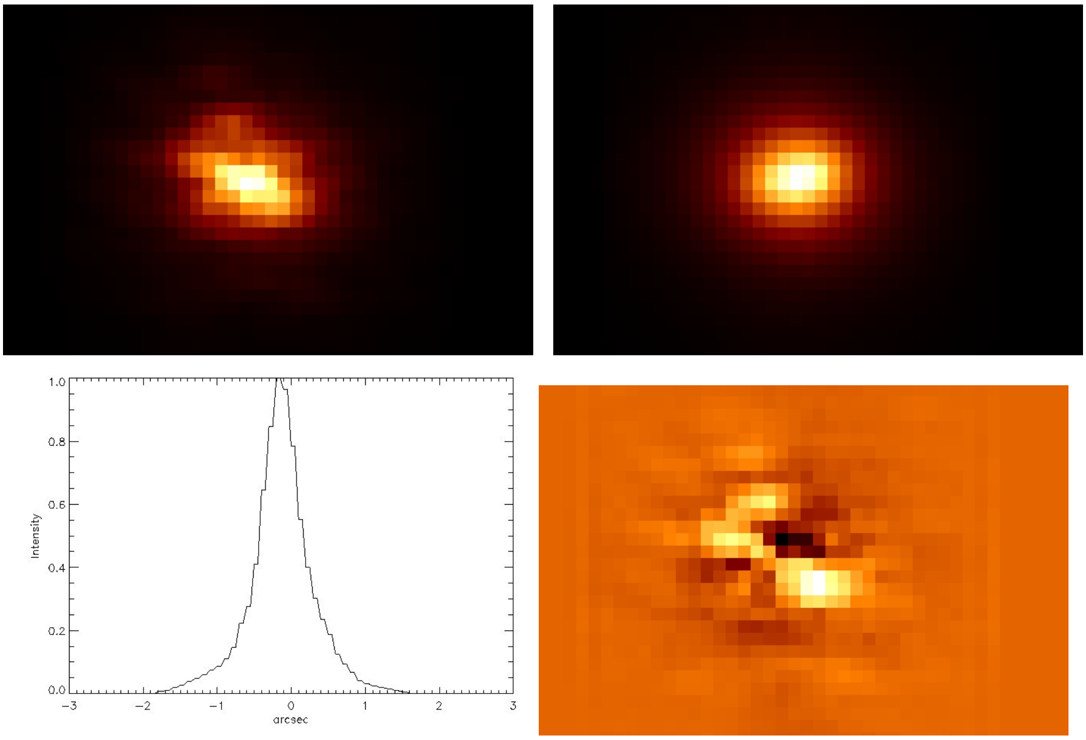

Fig. 3. Figure 3. (Upper Left.) Image of the binary star with separation 0.″1. (Upper right) Reconstructed image (Lower left) Cut through the PSF of the binary star along the axis (Lower right) Difference between both PSFs. Especially the cut through the PSF as shown on the lower left panel shows that without post processing no companion is visible.

measurements on the WFS and the mirror shape.
Altogether the simulations at the moment need a lot of computation time. So major effords will be put to speed up the computations in order to achieve the results much faster.

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