Calibration of the static aberrations in an MCAO system

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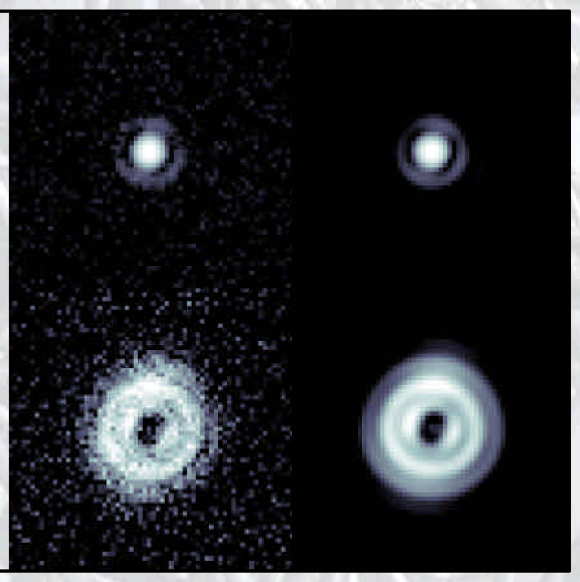
The ESO Multi-conjugate Adaptive optics Demonstrator (MAD) is a prototype intended to be tested at the VLT Nasmyth focus. With its development raises the problem of calibration of an AO system composed of several correcting devices and wave front sensors. One part of this process is the calibration of the static aberrations of the system, always present in spite of the best efforts made during the design, the manufacturing of the optics and their alignment.

PROBLEMATIC

Since the first developments of adaptive optics, it was clear that trying to get the best beam quality at the level of the Wave Front Sensor (WFS) didn't mean getting the best image at the scientific focus. Indeed the beam doesn't cross the same optics before reaching those two points, and is deformed by the non-common path aberrations, ones that lay in the camera path after the dichroic of the system.

An empiric way to compensate for that is to give to the Deformable Mirror (DM) a reference shape which, instead of minimizing the aberrations seen by the WFS, enhances the visual quality of the image on the scientific instrument. This has been somehow efficient to roughly correct for the low order aberrations.

In the framework of the calibration of the system NAOS-CONICA, a systematized technique was developed to use the IR camera as a WFS, and compensate for the aberrations thanks to the DM. Indeed from two images (separated by a well known amount of aberrations, for instance focus) of a calibration source, it is possible to retrieve the aberrations present in the path through the use of the Phase Diversity technique (ΦD).



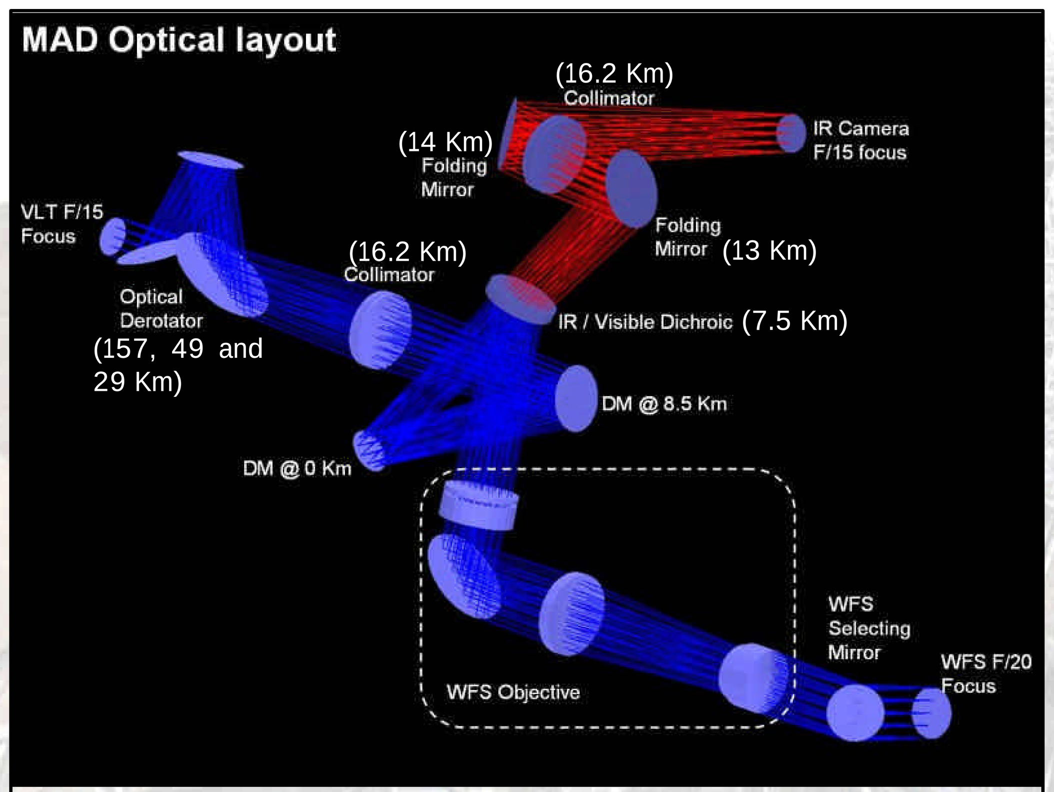
Simulation of the performances of the ΦD algorithm.

Focused (top) and defocused (bottom) images of a calibration source, as measured (left) and as reconstructed by the ΦD algorithm (right). Logarithmic scale is considered for all images.

MCAO CASE

In the case of an MCAO system such as MAD, the complexity of the task is increased by the fact that the correction of the static aberrations should be done in the whole scientific FoV of the instrument (2 arc minutes in the case of MAD). But the compensation is eased by the presence of several correcting devices in the optical path (2 DMs conjugated at altitudes of 0 and 8.5 Km for MAD).

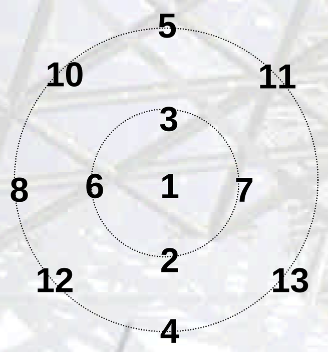
Indeed the optical elements introducing aberrations in the common and camera path are conjugated with different altitudes, and we wish to correct for them with 2 DMs. Thus it is logic to use a tomographic approach to optimize the reconstruction, as it is done in real time in the MCAO instrument to correct for the atmosphere perturbations.



MAD optical layout and equivalent altitudes of the optics in the common + camera path. The optics in the IR camera (not represented) is conjugated with altitudes of 0, 45 and 55 Km and the filters are higher than 100 Km.

The chronologic order of actions required to implement this tomographic correction of the static aberrations is the following:

- Record focused and defocused images at several positions in the FoV. The defocus is obtained either by shifting a focal plane or by displacing a collimator.



Grid of 13 positions in the FoV of MAD used to record images for the ΦD. The 1 and 2 arc minutes diameter circles are represented

- Pre-process the images and submit them to the ΦD algorithm to retrieve the aberrations as a list of Zernike coefficients
- Transform the aberrations vectors measured in the N_{GS} directions into the WF at the N_t altitudes that give the best estimation according to a given criterion.
- Project those WF on the N_{DM} correcting devices and apply the correction.

TOMOGRAPHY ALGORITHM

We seek an estimation for the aberration in N_t layers that minimizes a criterion in a given FoV:

$$\hat{\jmath} = W \times F_{N_{GS}}$$

$\Phi_{N_{GS}}$ is the phase measured in the N_{GS} directions and W is the reconstruction matrix

The criterion to be minimized is the residual phase variance in a FoV of interest:

$$e = \left\langle \int_{\{a\}\,fov} \left\| M_a^{N_{DM}} \hat{\jmath} - M_a^{N_t} j \right\|^2 da \right\rangle_{j,noise}$$

The matrices M are the projection of the direction α on either N_t or N_{DM} altitudes.

The minimization of the criterion e leads to a solution for W composed of a reconstruction matrix on N_t layers W_{MA}, multiplied by a projection matrix on N_{DM} layers P.

$$W = P_{N_{DM},N_t} \times W_{MA}$$

$$W_{MA} = C_j \left(M_{N_{GS}}^{N_t}\right)^T \left(M_{N_{GS}}^{N_t} C_j \left(M_{N_{GS}}^{N_t}\right)^T + C_n\right)^{-1}$$

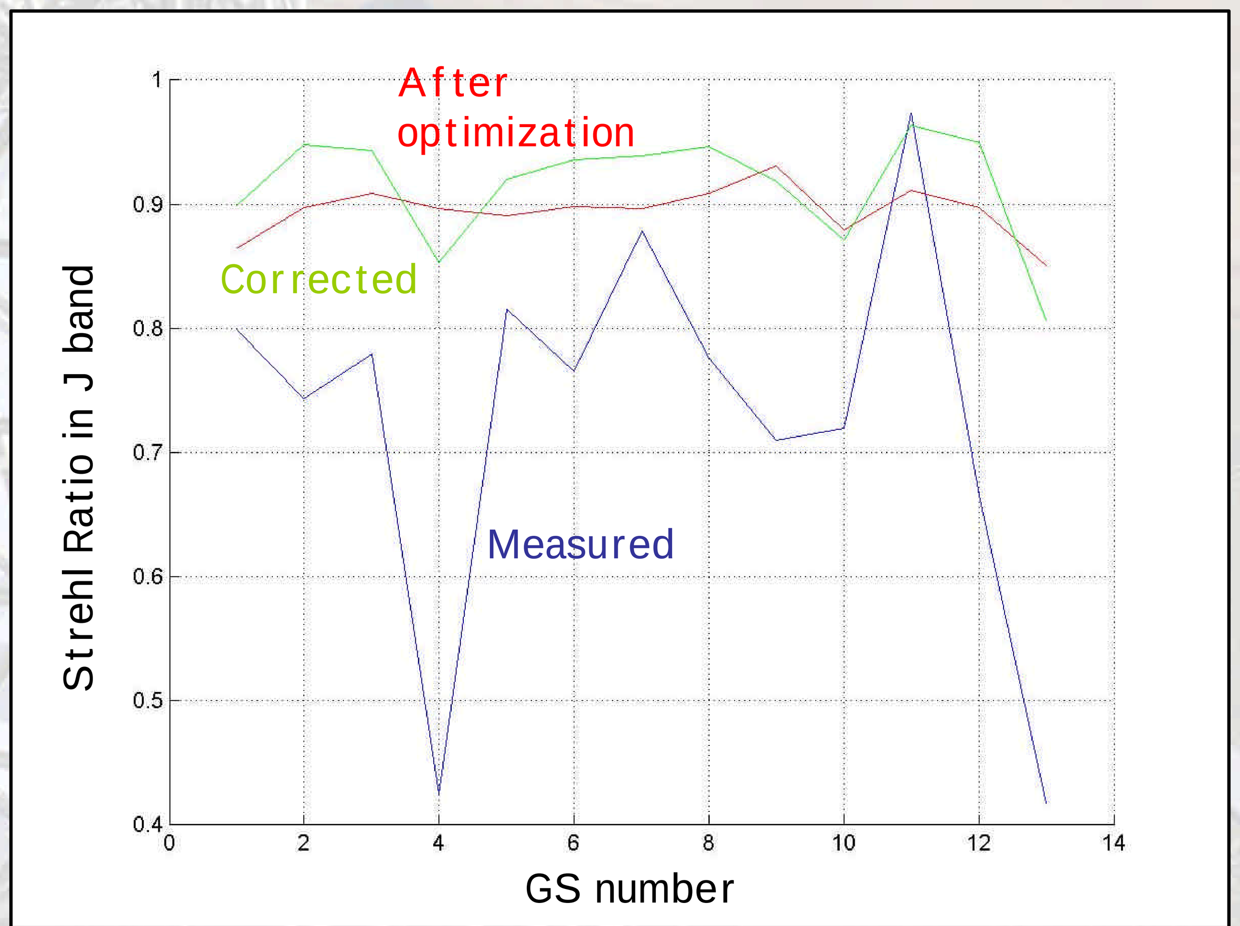
$$P_{N_{DM},N_t} = \left(\int_{\{a\}\,fov} \left(M_a^{N_{DM}}\right)^T \left(M_a^{N_{DM}}\right) da\right)^{+} \left(\int_{\{a\}\,fov} \left(M_a^{N_{DM}}\right)^T \left(M_a^{N_t}\right) da\right)$$

SIMULATIONS

In the optical design of MAD under Zemax (containing design + chromatic aberrations), we have added distortions on some optics (collimators, mirrors), and check the resulting quality in the IR FoV. The result is an average SR of 73% in J band, with minimum values of ~40% at the borders of the field.

The second step is to simulate images from those measurements, and feed the ΦD algorithm with them. The resulting list of Zernike coefficients are then introduced in the tomography algorithm for reconstruction of the aberrations at different levels and projection on the 2 DMs.

Finally the shape found for the DMs is applied and the residual aberrations measured at the same points in the FoV.



Simulated measurements of SR in 13 point in the IR FoV of MAD. The correction of the aberrations after reconstruction by tomography enhances clearly the quality of the images (91% SR in average). The use of a numerical optimization keeps almost the same average value, but with a much more uniform FoV.

Instead of the best average quality in the whole FoV, one could be interested by getting the most uniform quantity of aberrations, and this around a given value of SR. Then the criterion to minimize would be the dispersion around a Goal value of the variance of the WF in different directions α:

$$e'_G = \sum_a \left\| \sum_i \left\| a_a^i \right\|^2 - Goal \right\|^2$$

a^i_α is the residual Zernike coefficient of order i in the direction α.

For the time being, this has been implemented as an numerical optimization with N_{GS} parameters of weights on the directions of observation, and brings a good enhancement of the uniformity.