# Eliminating the static aberrations in an MCAO system

Johann Kolb*
European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany

## ABSTRACT

Within the last years, the Adaptive Optics (AO) systems built or designed are growing in complexity: their optics are numerous and they aim at better performances on-axis and/or in the Field of View. A limiting factor to those performances can be the Non-Common Path Aberrations (NCPA), i.e. static aberrations present in the optical path of the instrument after the dichroic, which therefore are not seen by the AO Wave Front Sensor.
Since long the Deformable Mirror of the system has been used to partially compensate for them, in a more or less efficient and complex way.
This paper will present a rapid to implement, rather simple and all-measured method of compensation for the NCPA tanks to the use of Phase Diversity and of a calibration matrix of the modes constituting the aberrations.
Moreover for systems composed of several DMs, we will present how a clever use of those can reduce significantly the aberrations in the whole FoV.
All those techniques will be illustrated by their application to ESO'S MCAO Demonstrator (MAD).

Keywords: multi-conjugate adaptive optics, phase diversity, non-common path aberrations, interaction matrix, field-dependant aberrations.

## 1. INTRODUCTION

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 NCPA, ones that lay in the camera path after the dichroic of the system. The residual is generally not important, but enough to decrease the quality of the images of some percents of Strehl Ratio (SR).
In an AO system the calibration source placed in the common path (and used to record the Interaction Matrix of the AO system) can be used to simulate a perfect diffraction limited object, and we can take advantage of the Deformable Mirror (DM) present in the optical path to compensate for the NCPA. However this procedure requires two operations which are not part of the AO loop:

- Being able to estimate the aberrations where we want them to be corrected, i.e. in the scientific focal plane. This can be done in a first approximation by using an empiric method: checking "by eye" the quality of the PSFs at the scientific focus and guessing which modes to apply to the DM to increase the SR. This is somehow efficient to roughly correct for the low order aberrations. The estimation of the aberrations can be done in a much more accurate way by inserting a Wavefront Sensor (WFS), of Shack-Hartmann type for instance, just before the scientific focal plane to measure the aberrations there, but it adds complexity to the system and maybe some optical elements which make the calibration less accurate. Another solution is the use of Phase Diversity (ΦD) [1], a phase retrieving technique already used to evaluate the NCPA in the system NAOS-CONICA for the VLT[2,3].
- Once the aberrations estimated, one has to find a way to relate them to a DM shape. This operation was formerly done by using a theoretical model of the system DM-Mirror-camera [4] with good results but linked to the quality of the model. In the present paper we propose an all-measured method of determination of the best DM shape to apply to compensate for estimated static aberrations. It is completely independent from any theoretical model, which makes it easily applicable to any AO system.

* jkolb@eso.org, phone +49.89.32006331; fax +49.89.3202362; http://www.eso.org

## 2. ESTIMATION OF THE ABERRATIONS BY PHASE DIVERSITY

Retrieving the WF from a sole focused image is not possible without indetermination. From two images (at least Nyquist-sampled) separated by a well-known amount of phase variation and using a Generalized Maximum Likelihood (GML) approach, the ΦD algorithm developed at ONERA [5] minimizes a criterion given by a probability law, after an iterative process. The output is the aberrated WF responsible for the measured PSFs, projected on the basis of the Zernike polynomials.

The application of the ΦD measurements requires from the system:

- An imaging camera placed at the scientific focus, giving at least Nyquist-sampled images with a good SNR.
- The possibility to introduce an accurate defocus of about 1 λ, by shifting an optical element in the path for example.
- The possibility to control modally the DM.

The vector of the estimated aberrations is shown in the equation (1). Its size is equal to **[NZ-3]**, as the first aberration estimated is the focus (N=4).

$$Ab = \begin{bmatrix} Z_4 \\ Z_5 \\ Z_6 \\ \dots \\ Z_{NZ} \end{bmatrix} \tag{1}$$

## 3. CORRECTION OF THE ABERRATIONS

The solution we propose to compensate for the NCPA, once known the aberrations in the scientific focal plane, is to build a Control Matrix (CM) from a measured Interaction Matrix (IM) between the camera and the DM. In this aim, we apply modes to the DM (voltages $V_1$, $V_2$, $V_3$, …, $V_{NM}$) in addition to its reference shape (voltages $V_{REF}$), and for each mode we estimate the aberrations in the focal plane by ΦD (2). The reference aberrations are also estimated. The IM is then built by concatenation of the aberrations vectors, subtracted from the reference values, in order to keep only the contribution of the modes (3).

$$M_1 = \begin{bmatrix} M_{1,4} \\ M_{1,5} \\ M_{1,6} \\ \dots \\ M_{1,NZ} \end{bmatrix} \quad M_2 = \begin{bmatrix} M_{2,4} \\ M_{2,5} \\ M_{2,6} \\ \dots \\ M_{2,NZ} \end{bmatrix} \quad \dots \quad M_{NM} = \begin{bmatrix} M_{NM,4} \\ M_{NM,5} \\ M_{NM,6} \\ \dots \\ M_{NM,NZ} \end{bmatrix} \quad ; \quad M_{REF} = \begin{bmatrix} M_{REF,4} \\ M_{REF,5} \\ M_{REF,6} \\ \dots \\ M_{REF,NZ} \end{bmatrix} \tag{2}$$

$$IM = \left[ \left[ M_1 - M_{REF} \right] \left[ M_2 - M_{REF} \right] \left[ M_3 - M_{REF} \right] \dots \left[ M_{NM} - M_{REF} \right] \right] \tag{3}$$

The size of the IM is **[(NZ – 3) , NM]**, and it contains to response of our process of aberrations estimations to the excitation of modes of the DM. The CM, containing linear combination of modes of the DM reconstructed from the estimation of aberrations, is obtained by generalized inversion of the IM (4). Badly seen modes can eventually be filtered during the inversion.

$$CM = IM^{+} \quad \text{, where } ^{+} \text{ denotes the generalized inverse.} \tag{4}$$

The correction vector (in the space of the modes applied to the DM) is obtained by application of the CM to the vector of aberrations measured (5). This vector contains the coefficients of the linear combination of DM modes to apply to compensate for the estimated aberrations.

$$\text{Corr} = - \text{CM} \times \text{Ab} \quad (5)$$

The correction vector is converted to voltages thanks to the matrix of voltages to modes, and applied to the DM in addition to its reference voltages, to produce the expected shape. The process can be repeated iteratively to correct for the residual aberrations. However we noticed [6] that if several iterations help correcting for defaults of a model when it is used, the present method using a measured IM requires less iterations (1 or 2) to reach the same performance.

## 4. APPLICATION TO THE CORRECTION OF ON-AXIS NON-COMMON PATH ABERRATIONS

The technique of compensation of the NCPA described in the previous section has been successfully applied to two AO test benches using different cameras configuration. The first one is the BOA test bench that lies in the optical laboratory of ONERA in Châtillon close to Paris (France). The tests usually performed on this bench are dealing with optimization of the reconstruction in AO, prediction of the turbulence in the command, off-axis optimization, and correction of the NCPA. There have been validated for the first time the ΦD technique before being implemented on NACO. The bench is equipped with a visible camera (sampling = 4.1) with which are taken the images for the ΦD estimation.
The second bench is ESO's MCAO Demonstrator MAD [7,8]. The FoV transmitted by this instrument is of 2 arc minutes and the MCAO is intended to be performed in this FoV by the use of 2 DMs conjugated to altitudes of 0 and 8.5 km in the atmosphere. The WF sensing is done either by 3 Shack-Hartmann WFS in a Star-Oriented mode or by 8 Pyramid WFS in a Layer-Oriented mode. To perform the lab tests of this instrument, it has been equipped successively with 3 different cameras:
a) a commercial SBIG visible camera,
b) the Infrared Test Camera (ITC), cooled at 100K, to take small field images in K,
c) the CAmera for MCAO (CAMCAO) [9], a 1 arc minute FoV IR camera cooled at 80K and taking Nyquist-sampled images at 2166 μm.
This last one is the final camera that will be used for the performance evaluation of MAD in the laboratory and at the telescope. The Figure 1 shows the modes we have applied to the Ground DM of MAD as seen by the ITC. We have chosen modes close to the Zernike modes so that the high values in the IM are close to its diagonal.

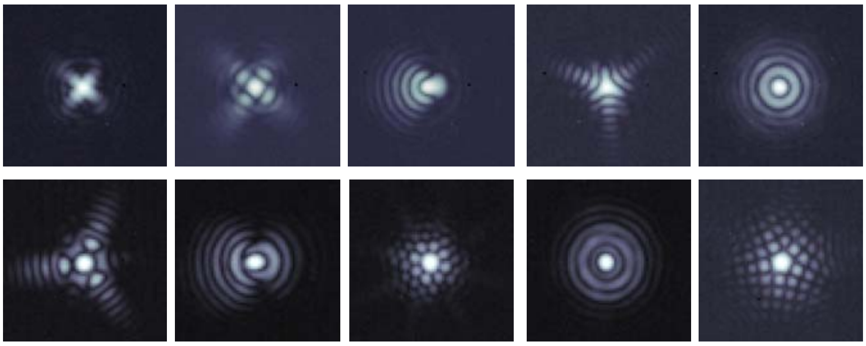


**Figure 1: Example of modes applied to the Ground DM of MAD as seen by the Infrared Test Camera at 2188nm. To produce those images the modes have been applied with an amplitude of 250nm, while only 25 nm is applied for the recording of the IM.**

The Table 1 summarizes the correction of the NCPA obtained in the 4 cases:

**MAD bench + SBIG camera:** the small-FoV CCD camera is used with relay optics allowing a sampling on the detector of 3.3, and a narrow-band filter at the input of the bench light source to obtain images at 1064 nm. The high noise on the detector (used far outside of its usual spectral wavelength range) and the low SR at the starting point didn't allow recording a lot of modes for the building of the IM. We were limited to 14, but this was however sufficient to remove the low order aberrations from the image and reach a reasonable SR in the visible.

**MAD bench + ITC:** The ITC has been used intensively to perform tests on MAD before the completion of CAMCAO. Its 1k x 1k IR detector, cooled at 100 K, provides images in K band with a sampling of 3.2. The recording of images for building the IM was thus easier and we could use more than 25 modes for the correction. One can notice that the high values are not exactly on the diagonal of the CM. This is due to that fact that the orientation and sign of the modes applied to the DM were not the same as the ones used by the ΦD algorithm. Those modes were changed when the bench was used with CAMCAO as one can see on the corresponding CM.

**MAD bench + CAMCAO:** The FoV of CAMCAO is rather large (almost 1 arc minutes square), which will be useful to record wide field images of astronomical objects corrected by MCAO. However, the drawback is that the images are not Nyquist-sampled in the J and H bands of the camera, and just Nyquist-sampled in K band at 2166 nm. This poorer sampling makes the estimation of aberrations by ΦD less accurate. We managed however to build an IM using 37 modes, and to apply it to the correction of on-axis NCPA in MAD (Figure 2), reaching a SR of more than 91 %.

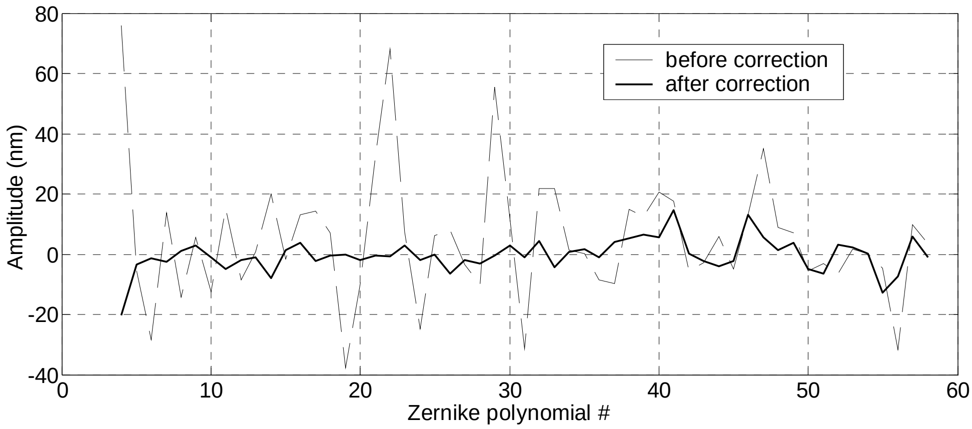



**Figure 2: Aberrations estimated by Phase Diversity before and after correction of the NCPA on-axis of MAD equipped with CAMCAO**

**BOA bench:** The goal of applying the method presented here to another bench than MAD was to prove that it can easily exported to another AO system, provided that it fulfills the requirements detailed in the section 2. Thus the same procedure has been applied to the BOA bench with success: an IM was recorded using 45 modes and the correction was brought to 96% of SR at 633 nm. This result is a slight improvement to the method previously applied to correct the NCPA on this bench, which uses a very well-tuned model of the system instead of the measured IM. Two other points help getting a great correction: the alignment of the bench's optics which was optimized to get the best performance on-axis and to have the WFS lenslet array matching the DM electrodes pattern, and the application of the modes and correction in closed loop. Indeed the DM modes are not set by applying static voltages, but rather by changing the reference slopes of the WFS in closed loop. This is possible thanks to the good sampling of the Shack-Hartmann spots on the WFS detector.

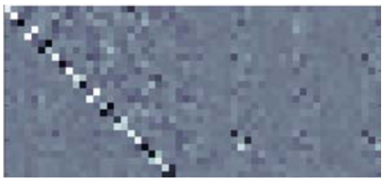
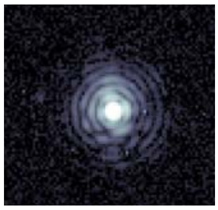
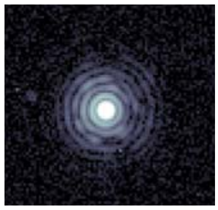
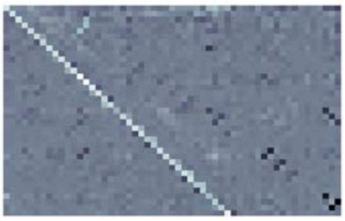
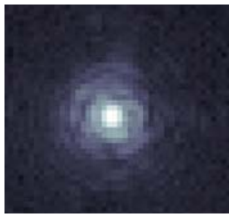
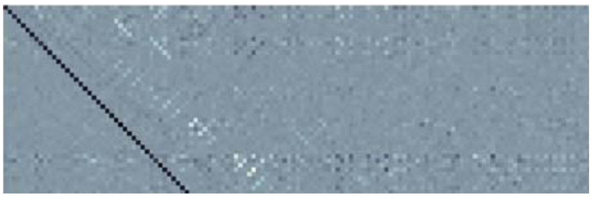
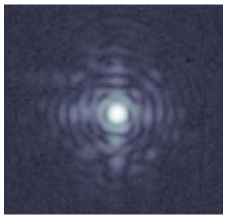
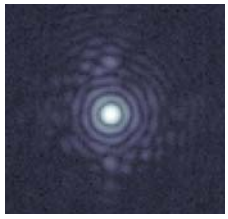
| System description | Control Matrix / Images and performance before and after correction | | |
|---|---|---|---|
| **MAD bench + SBIG camera**<br><br>λ = 1064 nm<br>Sampling = 3.3<br>14 modes | <br><br>*equivalent at 2200 nm to:* | <br>SR = 14.2 %<br>*SR = 63.5 %* | <br>SR = 43.6 %<br>*SR = 82.5 %* |
| **MAD bench + ITC**<br><br>λ = 2188 nm<br>Sampling = 3.2<br>25 modes |  | <br>SR = 83.2 % | <br>SR = 93.4 % |
| **MAD bench + CAMCAO**<br><br>λ = 2166 nm<br>Sampling = 2.0<br>37 modes |  | <br>SR =73.5 % | <br>SR = 91.3 % |
| **BOA bench**<br><br>λ = 633 nm<br>Sampling = 4.1<br>42 modes |  | <br>SR = 76.2 % | <br>SR = 96.1 % |

**Table 1: Results of the application of the correction of the NCPA to 4 different systems. The principal characteristics of the systems are given, as well as the CM between the aberrations estimated and the DM modes to apply for the correction, and images of the PSF before and after correction.**

## 5. CORRECTION OF ABERRATIONS IN THE FOV WITH ONE DM

### 5.1. Field-dependant aberrations

In the previous sections we have seen how to correct the NCPA in an AO system by recording an Interaction Matrix between the camera and the DM. We can see an analogy with the correction of the atmospheric turbulence by an AO system: the camera is here used as a WFS, and the correction is given by multiplication with a Control Matrix.

We can push the analogy further and extend the correction of the NCPA to the FoV. Indeed what is called Ground Layer Adaptive Optics (GLAO) is an extension of conventional AO, limited by anisoplanatism, and that allows the correction of the turbulence located in the ground layer of the atmosphere. The idea behind it is to sense the WF in several

direction of a rather large FoV (1-2 arc minutes), and to average the correction given by all the independent measurements, which corresponds to the portion of the turbulence seen identically by all of them, i.e. the one conjugated to the pupil of the telescope. The averaged correction is applied to a unique DM conjugated to the ground.
The FoV transmitted by an AO instrument is not uniformly degraded by static aberrations, as one can see measured on MAD in the Figure 3.a. The optical elements in the path show field-dependant static aberrations. The consequence of this is that the technique detailed in the previous section might be efficient to correct for the aberrations on-axis, its effect in the FoV is limited to the common contribution of the field-independent aberrations (Figure 3.b). By analogy the performance of a classical AO system is limited in the FoV by the anisoplanatism, equivalent to differential aberrations in the FoV.

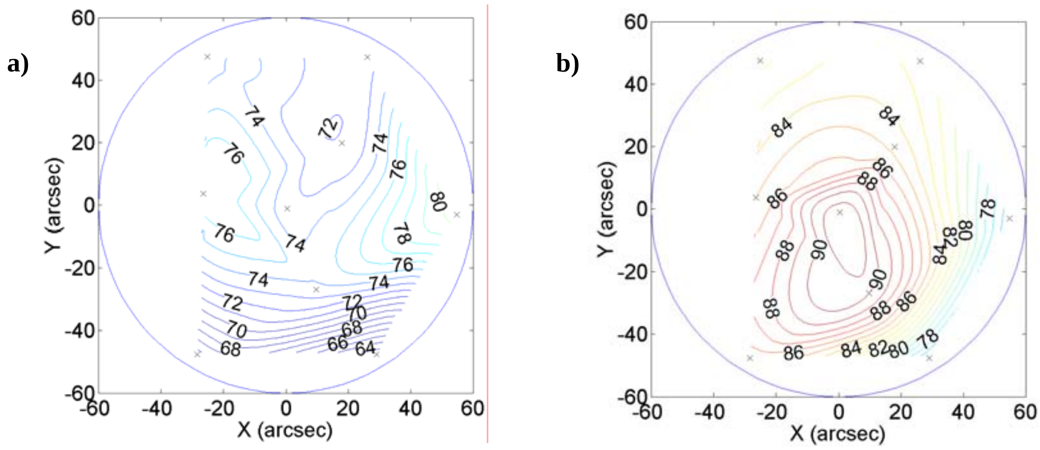



**Figure 3: Strehl Ratio maps of the static aberrations in the FoV of MAD before (a) and after (b) the on-axis correction. The measurement points (9) are represented by crosses, and the iso-strehl lines are obtained by interpolation of the measurements to the whole FoV.**

To apply this idea to the correction of the NCPA in the FoV of an instrument, as the WF sensing doesn't need to be done in real time, we can either use several portions of the camera detector to observe several sources, or move the camera in the FoV (if this one is mounted on translation stages). The number of "Guide Stars" is then not limited to hardware considerations, but by the time available to record the IM for each of them.

### 5.2. Correction in the FoV

For each direction in the FoV, an IM is built as described by the equations (2) and (3) of the section 3. Then the meta-IM is the concatenation of the measured IMs (6). The size of this matrix is **[(NZ – 3).NGS , NM]**. It contains the response of the aberrations estimations for all the directions of interest to the application of a list of NM modes to the Ground DM. The meta-CM of the system is computed, as the single source case, by generalized inversion (4). Its size is **[NM , (NZ – 3).NGS]**.

$$\text{metaIM} = \begin{bmatrix} \begin{bmatrix} IM_1 \end{bmatrix} \\ \begin{bmatrix} IM_2 \end{bmatrix} \\ \begin{bmatrix} IM_3 \end{bmatrix} \\ \dots \\ \begin{bmatrix} IM_{NGS} \end{bmatrix} \end{bmatrix} \quad (6)$$

Performing the correction in the FoV requires to measure the aberrations in the FoV. Phase Diversity is thus applied to images taken in all the directions of interest, which allows us to build the meta-matrix of aberrations (7). The "GLAO" correction of the static aberrations is obtained by multiplying the aberrations matrix by the CM (8), operation which gives as in the single-source case, a vector containing the coefficients of the linear combination of DM modes to apply to compensate for the estimated aberrations.

$$Ab = \begin{bmatrix} \begin{bmatrix} Ab_1 \end{bmatrix} \\ \begin{bmatrix} Ab_2 \end{bmatrix} \\ \begin{bmatrix} Ab_3 \end{bmatrix} \\ \ldots \\ \begin{bmatrix} Ab_{NGS} \end{bmatrix} \end{bmatrix} \quad (7)$$

where the measurement of the aberrations vectors is detailed in the section 2 and equation (1).

$$Corr = - metaCM \times Ab \quad (8)$$

### 5.3. Application to MAD

We can see on the Figure 4 an example of the IMs recorded for 2 directions in the FoV of MAD. They are very similar, as expected, as the actuated DM is located in the pupil plane and thus the footprint on it is the same for any direction of the FoV. However it is important to record the IM for each direction to take into account the particularities of the system as field distortion for instance. 37 modes are applied to the DM to build the IMs, with an amplitude of 25 nm rms, and the aberrations estimated by ΦD are projected on the first 55 Zernike polynomials. The meta-IM is obtained by concatenation of the 9 measured IM, the meta-CM by inversion of the meta-IM.

The Figure 5 shows the performance obtained after the correction of the aberrations in the FoV with one DM. The average aberrations in the 9 directions are reduced as shows the ΦD estimation, the average SR in the FoV is increased compared to before the correction (81.7 % vs. 73.6 %). We see that although the correction is now not only concentrated on the central star, the uniformity of the SR is not better than in the no-axis correction case (3.4 % rms vs. 3.1%) seen on the Figure 3. This discrepancy between the aberrations estimated in 9 directions by ΦD (improved) and the SR extrapolated to the whole FoV (not improved) could tend to show that 9 directions are not enough to sample efficiently the 2 arc minutes FoV, at least for the SR estimation.

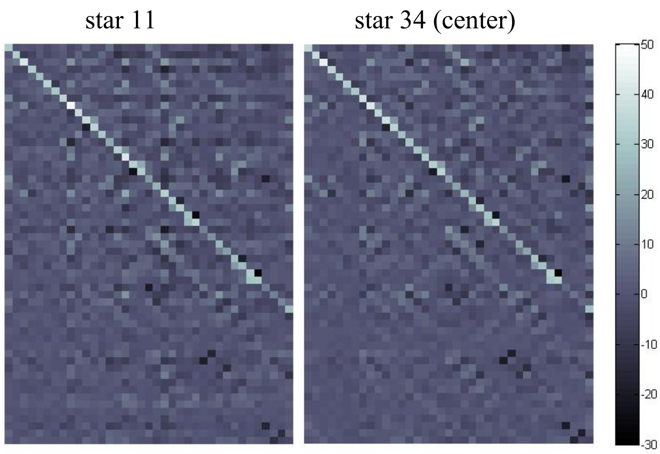



**Figure 4 Interaction Matrices recorded by actuation of the Ground DM and estimation of the aberrations (in nm) in two different directions of the FoV.**

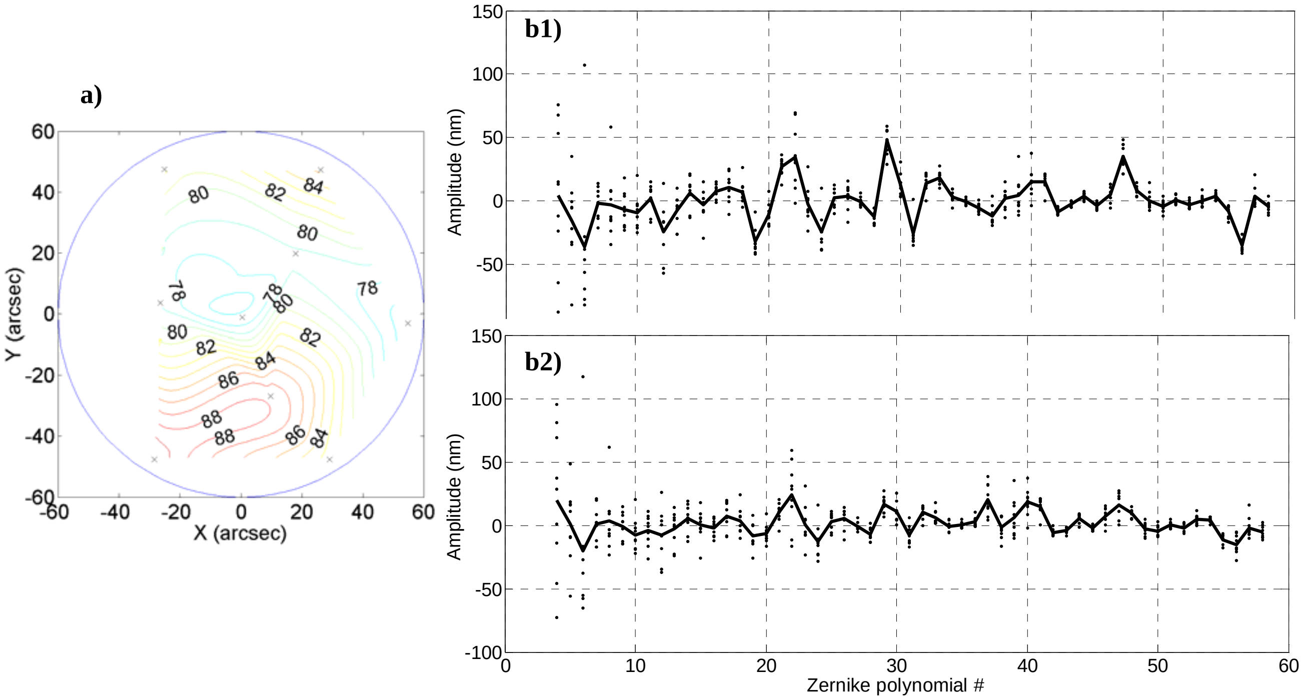



**Figure 5: a) Strehl Ratio map of the static aberrations in the FoV of MAD after the "GLAO"-like correction. b) Aberrations estimated in the 9 directions of interest (dots) and their average (solid line) projected on the Zernike polynomials before (b1) and after (b2) correction.**

## 6. CORRECTION OF ABERRATIONS IN THE FOV WITH TWO DM

### 6.1. Construction of the meta-IM and correction

Pushing even further the analogy with the AO correction of the atmospheric turbulence, we can think of applying an "MCAO" correction of the field-dependant aberrations in an MCAO system, by the use of the several DMs in the optical path, conjugated to different altitudes. Indeed an MCAO system is composed of several DMs which are supposed to correct, from the WF measured in different directions in the FoV, for the aberrations at the altitude at which they are created by the atmospheric turbulence. Such a system requires the recording of a meta-IM between all the sensors and all the Deformable devices [10]. The same applies to the correction of the static aberrations. The meta-IM measured is an extension of the "GLAO" IM to the several DMs, and is given in the equation (9). Its size is **[NM.NDM, (NZ – 3).NGS]**. The aberrations are described by the same vector as given by the equation (7), and now the vector resulting of the multiplication contains the coefficients of the linear combination of DM modes to apply to compensate for the estimated aberrations, for each DM. Its size is **[NM.NDM]**.

$$\mathrm{metaIM} = \begin{bmatrix} \left[\mathrm{IM}_{1,1}\right] & \cdots & \left[\mathrm{IM}_{1,\,\mathrm{NDM}}\right] \\ \left[\mathrm{IM}_{2,1}\right] & \cdots & \left[\mathrm{IM}_{2,\,\mathrm{NDM}}\right] \\ \left[\mathrm{IM}_{3,1}\right] & & \left[\mathrm{IM}_{3,\,\mathrm{NDM}}\right] \\ \cdots & & \cdots \\ \left[\mathrm{IM}_{\mathrm{NGS},1}\right] & \cdots & \left[\mathrm{IM}_{\mathrm{NGS},\,\mathrm{NDM}}\right] \end{bmatrix} \tag{9}$$

### 6.2. Application to MAD

The instrument MAD contains 2 DMs conjugated at 0 and 8.5 km (corresponding to 1.67 pupils in the meta-pupil on the altitude DM for two stars separated by 2 arc minutes). The meta-IM is a concatenation of the one measured for the correction of the aberrations with one DM (section 5) and of the IMs between the camera and the altitude DM for all the directions of interest. We decided to apply only 20 modes to the altitude DM, but with an amplitude higher (100 nm rms) required by the smaller relative size of the beam on the DM. The footprint of the beam on the altitude DM changing in the FoV, it is predictable that the 9 IMs will be different one from each other.

Two example of those are shown on the Figure 6.a. We see that for a polynomial N applied to the DM, the aberrations seen off-axis (over a smaller section of the DM) are projected on the polynomials up to N, as demonstrated in [11]. For the star 11 (located at the border of the FoV), all the modes from 4 to N are populated when the mode N is applied. For the star 34 (at the center of the field), we observe that an spherical aberration of the DM is seen as a defocus, and the secondary astigmatisms are seen as astigmatisms for example.

We can use this property to evaluate the quality of the IM recorded. One can see for instance that the modes 4 and 8 applied to the DM (arrows on the Figure 6) have unexpected components on high order modes as estimated by ΦD. There can be several possible causes for this:

- an error in the computation of the modes to apply to the DM
- an error of the DM when applying the modes
- a wrong subtraction of the reference DM shape (see section 3)
- an error during the ΦD estimation of those modes

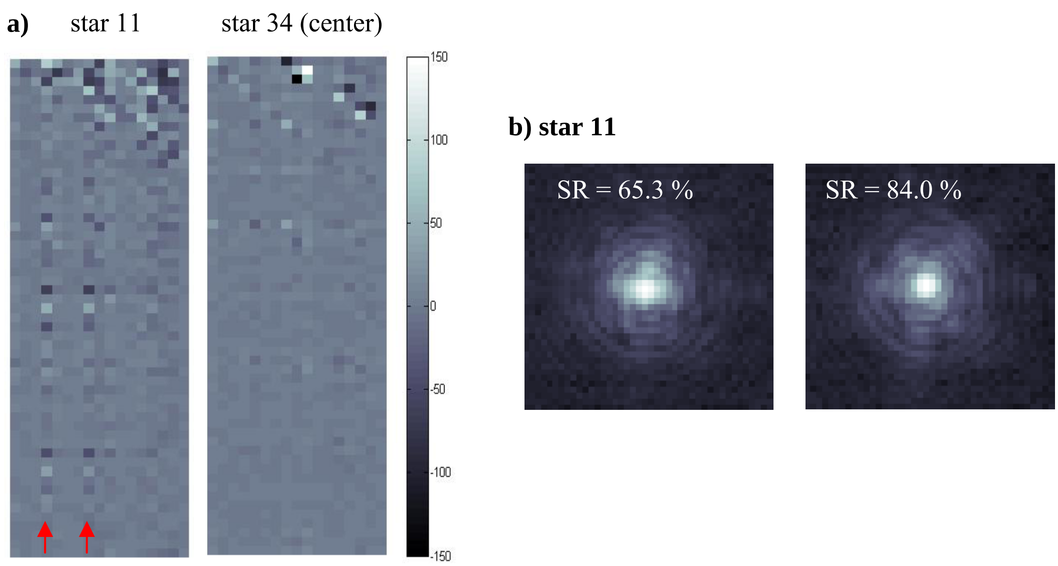



**Figure 6: a) Interaction Matrices recorded by actuation of the Altitude DM and estimation of the aberrations (in nm) in two different directions of the FoV. The arrows show modes that we estimate to have been badly measured. b) Correction of the static aberrations in one direction thanks to the altitude DM only ; Example of the star 11 before (left) and after (right) the first iteration of the correction.**

Another way to evaluate the quality of the measurements is to use the IM in a direction to build a CM in order to correct for the aberration in this direction with the altitude DM only. We have done this test after each IM measurement to ensure its validity. The Figure 6.b shows the correction obtained after the first iteration in the case of the star 11. The correction is significant, although limited by the low number of modes in the IM and the low number of actuators across the pupil.

Once the measurements validated experimentally by this method, the meta-IM is built and inverted. As long as we were using only the ground DM, no mode had to be filtered during the inversion. It is not anymore the case, as some modes applied to the altitude DM are badly seen. The Figure 7 shows the CM obtained without filtering and with filtering 8 modes. We see that the filtered modes are ones of the altitude DM. After several tries we choose to filter 2 modes in the following of the experiment.

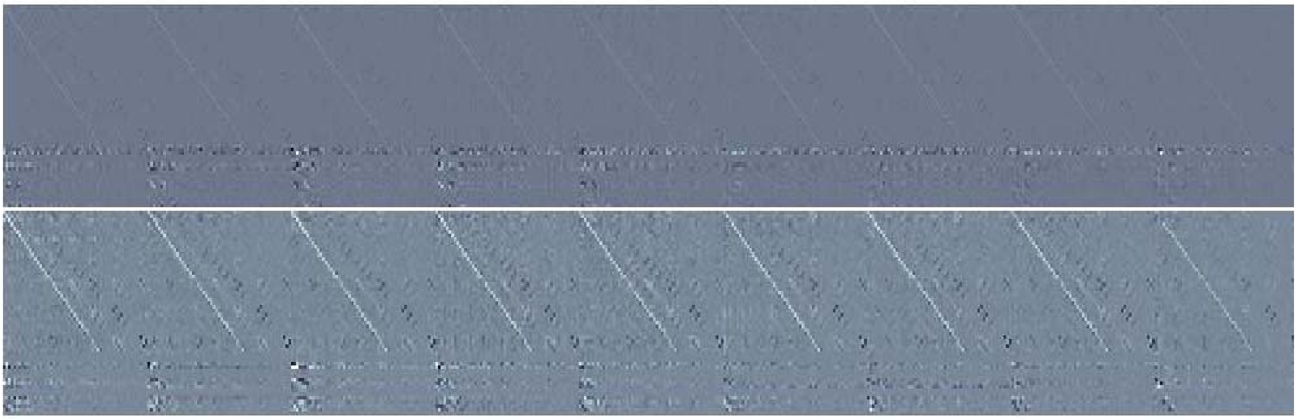


**Figure 7: Control Matrices for the correction of the field-dependant static aberrations with two DMs (different gray scales). Zero (top) and 8 (bottom) modes were filtered during the inversion.**

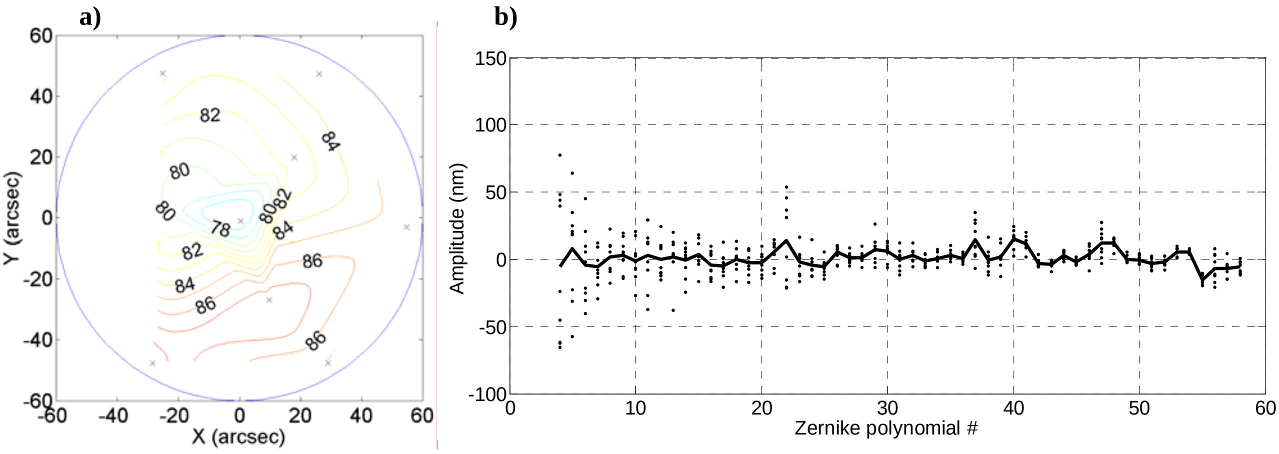



**Figure 8: a) Strehl Ratio map of the static aberrations in the FoV of MAD after the "MCAO"-like correction. b) Aberrations estimated in the 9 directions of interest (dots) and their average (solid line) projected on the Zernike polynomials after correction.**

The Figure 8 shows the performance obtained after the correction of the aberrations in the FoV with two DMs. The average aberrations in the 9 directions is reduced as shows the ΦD estimation (to compare with the Figure 5). The average SR in the FoV is increased compared to before the correction and to the correction with one DM, and the uniformity in the FoV is better, as summarized in the Table 2.

| | Average SR (%) | Standart deviation (% absolute) |
|---|---|---|
| No correction | 73.6 | 2.8 |
| Correction on-axis ("SCAO") | 84.8 | 3.1 |
| Correction in the FoV with one DM ("GLAO") | 81.7 | 3.4 |
| Correction in the FoV with two DMs ("MCAO") | 83.7 | 2.5 |

**Table 2: Comparison of the average performance and uniformity in the FoV for the different corrections of the aberrations.**

## 7. CONCLUSION AND FUTURE WORK

We have seen several different approaches to correct for the Non-Common Path Aberrations in an (MC)AO system, all based on the idea of recording an Interaction Matrix between the detector of the camera where we want the aberrations corrected and the DM(s) making the correction. We often recall the analogy with the different AO approaches for correcting the effect of the atmospheric turbulence (SCAO, GLAO and MCAO). We faced similar limitations, namely the SNR of the measurement, the modal base to use and the filtering during the inversion of the IM, and different limitations linked to the nature of the WFS we consider (a camera in a focal plane) and to the nature of the aberrations we want to correct (static), namely the exposure time or the number of measurement points.
The correction of the average of the aberrations in the FoV with one DM is somehow efficient, but the most promising technique is to use also the other DM(s) of an MCAO system for the correction.
All the proposed techniques have been tested on the MCAO Demonstrator in the laboratories of ESO in Garching (Germany) before the installation of the instrument on the VLT where the calibrations will take their real importance.
Possible improvements to the results described in this paper could be brought by the following future work:

- Using more modes for building the meta-IM, and then filtering more efficiently the badly seen modes
- Apply a tomographic approach [12] to identify the altitude of the source of the static aberrations
- Use more points of measurements in the field
- Apply the modes to the DMs in closed loop and not only statically, in order to increase the stability of the system during the measurement of the IM.


## AKNOWLEDGEMENT

This work has been partially funded by the European Research and Training Network *Adaptive Optics for Extremely Large Telescopes* with Contract HPRN-CT-2000-00147.


## REFERENCES


1. R.G. Paxman, T.J. Schulz, J.R. Fienup "*Joint Estimation of Object and Aberrations Using Phase Diversity*", J. Opt. Soc. Am. A 7, 1072-85 (1992)
2. M. Hartung, A. Blanc, T. Fusco, F. Lacombe, L. M. Mugnier, G. Rousset, R. Lenzen "*Calibration of NAOS and CONICA static aberrations. Experimental results*" Astron. Astrophys., 399:385-394, 2003
3. T. Fusco , A. Blanc, L. M. Mugnier, G. Rousset "*Development of a Phase Diversity approach to calibrate NAOS and CONICA static aberrations*" ONERA technical report
4. Sauvage J.-F., Fusco T., Rousset G., Petit C., Neichel B., Blanc A., Beuzit J.-L. "*Fine calibration and pre-compensation of non-common path aberrations for high performance AO system*" Astronomical Adaptive Optics Systems and Applications II. Edited by Tyson, Robert K.; Lloyd-Hart, Michael. Proceedings of the SPIE, Volume 5903, pp. 100-107 (2005).
5. A. Blanc, T. Fusco, M. Hartung, L. M. Mugnier, G. Rousset "*Calibration of NAOS and CONICA static aberrations. Application of the phase diversity technique*" Astron. Astrophys., 399:373-383, 2003
6. J. Kolb "*Calibration and test tools for MCAO systems : Application to the ESO Demonstrator MAD*" PhD thesis, Université Paris VI, December 2005
7. E. Marchetti, R. Brast, B. Delabre, R. Donaldson, E. Fedrigo, F. Franza, N. Hubin, J. Kolb, M. Le Louarn, J. Lizon, S. Oberti, R. Reiss, J. Santos, R. Ragazzoni, C. Arcidiacono, A. Baruffolo, E. Diolaiti, J. Farinato, E. Vernet-Viard, "*MAD status report*", Advancements in Adaptive Optics, SPIE Proceedings, 5490, article number [5490-17], 2004
8. E. Marchetti, R. Brast, B. Delabre, R. Donaldson, E. Fedrigo, C. Frank, N. N. Hubin, J. Kolb, M. Le Louarn, J. Lizon, S. Oberti, F. Quiros-Pacheco, R. Reiss, J. Santos, S. Tordo, A. Baruffolo, P. Bagnara "*MAD: GLAO and*

*MCAO experimental results*", Advancements in Adaptive Optics, SPIE Proceedings, 6272, article number [6272-62], 2006

9. A. Amorim, J. Lima, J. Alves, J. Rebordao, J. Pinhao, L. Gurriana, A. Cabral, E. Marchetti, J. Kolb, S. Tordo, G. Finger, J.-L. Lizon, F. Duarte Santos, R. Marques, R. Alves, R. Barros "*The CAMCAO NIR camera: integration and first results*" Ground based instrumentation for astronomy, SPIE Proceedings, 6269, article number [6269-191], 2006
10. S. Oberti, R. Muradore, S. Esposito, R. Arsenault, H. Bonnet, E. Fedrigo, M. Kasper, J. Kolb, E. Marchetti, F. Quirós-Pacheco, A. Riccardi, C. Soenke, S. Stroebele "*Large DM AO systems: synthetic IM or calibration on sky?*", Advancements in Adaptive Optics, SPIE Proceedings, 6272, article number [6272-70], 2006
11. R.Ragazzoni, E.Marchetti, F.Rigaut "*Modal Tomography for Adaptive Optics*" Astronomy and Astrophysics 342:L53-L56, 1999
12. J. Kolb, E. Marchetti, G. Rousset, T. Fusco "*Calibration of the static aberrations in an MCAO system*", Advancements in Adaptive Optics, SPIE Proceedings, 5490, article number [5490-109], 2004