Calibration of the static aberrations in an MCAO system

Johann Kolb [*a], Enrico Marchetti [a], Gérard Rousset [b], Thierry Fusco [b]
[a] European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching, Germany;
[b] ONERA – DOTA, BP 72 - 29, av. de la Division Leclerc, 92322 Châtillon Cedex, France

ABSTRACT

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.
In this paper we present a study to find an optimized way to correct for the static aberrations in the scientific FoV of an MCAO system. Thanks to images from the camera, the WF error in the FoV is computed, the contribution of several altitudes reconstructed, and finally projected on the deformable mirrors in order to compensate for the measured aberrations. This technique, inspired from the calibration of the static aberration of the system NAOS-CONICA, allows bringing the best quality to the scientific instrument fed by an MCAO system, by taking the most of the presence of correcting devices in the optical path.

Key words: Calibration, MCAO, VLT, Phase diversity

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 non-common path aberrations, 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). That's why the engineers building the instruments have tried to take advantage of the deformable device in the optical path to compensate for those aberrations. This was done 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 Deformable Mirror (DM) to increase the SR. This was somehow efficient to roughly correct for the low order aberrations.
In the case of the system NAOS-CONICA for the VLT [13], a high SR was required, thus a more accurate technique was set up in order to retrieve the aberrations present at the focus of the IR camera CONICA and to correct them, and this for each combination of dichroics, optics and filter possible. The idea is to use the camera as WFS (thus measuring the aberrations) and to apply static voltages to the DM that minimize the residual aberrations according to a given criterion (not in real time like an AO close loop does). Retrieving the WF from a sole focused image is not possible without indetermination, but for two images separated by a well-known amount of phase variation, a unique solution can be found, thanks to Phase Diversity (ΦD) [11]. This low-cost procedure has the drawback that it requires a complex numerical and iterative processing to restore the unknowns from the images. The easiest aberration to introduce in an optical system is defocus, by shifting the detector for instance. From the focused and defocused images and the parameters of the system (pixel scales of the camera, F ratio, central obstruction…), the ΦD software developed at ONERA [6] retrieves the aberrations present in the optical path from the calibration source to the camera detector.
This procedure has been successfully applied to NACO, achieving great performances in terms of SR on the camera [2, 3, 9]. The conclusions of this work are positive and underline the fact that for future instruments, the implementation of the technique of ΦD should be thought from a very early phase in the design.

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

2. THE MCAO CASE

An upgrade to the procedure used on NACO could have been to record the aberrations in the field of the system and apply a reference shape to the DM that gives a uniform quality in the FoV, instead of an optimized quality at the center. But for this AO system in operation with only one DM in the pupil, the main cause of degradation of the quality in the FoV is anisoplanetism [4], so it is worthless making this effort.

On the contrary, for a Multi-Conjugate Adaptive Optics (MCAO) system which aim is to provide the best uniform performance in the whole FoV, things have to be thought differently. The goal of MCAO is to perform a real-time correction of the aberrations introduced by the atmosphere in a larger FoV than what a normal AO system does. This is possible thanks to the use of several WFS aligned with different Guide Stars (GS) in the FoV and of several correcting devices conjugated with different altitudes of the atmosphere. The difficulty is increased by the large FoV and the complexity of the system, but the presence of several DMs help correcting more efficiently the aberrations in the field.

We can here also consider the camera as WFS that allows taking several WF measurements in the FoV. The optics creating the aberrations can be assimilated as atmospheric layers placed at different altitudes. In order to correct for this, it is then logic to apply a tomographic approach inspired by the atmospheric tomography approach for MCAO real-time correction [5].

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.
- Pre-process the images so that they are suited for the ΦD analysis.
- Run the ΦD algorithm with the images in order to get the estimations of the aberrations.
- Transform the aberrations vectors measured in the N_{GS} directions into the WF at the N_t layers having different altitudes that give the best estimation according to a given criterion.
- Project those vectors on the DMs and apply the correction.

In this paper we focus on the fourth point. We start from simulated images of the PSF at the scientific focus of the MCAO system, we shown briefly how the ΦD algorithm analyses them and gives the resulting aberrations projected on the Zernike polynomial. The following step consists in presenting the algorithm that we developed and that reconstructs the aberrations at the level of the aberrant optics, and projects them on the N_{DM} correcting devices. The simulated performances of this correction are finally presented and discussed.

The tomographic approach for correction of the static aberrations will be tested and implemented on the ESO MCAO Demonstrator [10] coupled with CAMCAO (CAmera for MCAO [1]) when it will be time to finalize its calibration.

3. IMPLEMENTATION OF THE PHASE DIVERSITY

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 minimizes a criterion given by a probability law, after an iterative process. In practice, the result is a list of Zernike coefficients that estimate the best the WF responsible for the measured PSFs.

To test the algorithm, we have submitted it to on-axis simulated images of a WF distorted by a known quantity of aberrations. The list of the input coefficients and of the result of the phase estimation is given in Table 1, for the case of images containing no noise. On this example the ΦD algorithm manages to estimate successfully the aberrations between 4 and 15 with a total error of 6nm rms, over a total WF of about 100nm rms.

The case of noisy images in not studied in this paper, but we can say that the accuracy of the estimation depends on the properties of the images recorded, as the size of the array used and the pixel scale. To this will be added the practical uncertainties on the process of recording of the images: defocusing distance, pixel scale error, pupil shape …

Zernike number	4	5	6	7	8	9	10	11	12	13	14	15
Input (nm)	60.5	-39.3	58.1	-16.2	-14.1	-2.5	13.7	-24.3	0.5	-3.2	2.8	-2.4
Estimated (nm)	61.2	-39.0	58.7	-16.2	-14.0	-2.5	13.5	-23.0	0.8	-2.8	8.5	-2.4

Table 1. List of coefficients used to simulate the input images for the ΦD algorithm and result of the phase estimation

4. TOMOGRAPHY ALGORITHM TO CORRECT FOR STATIC ABERRATIONS

4.1. Theoretical background

Let us suppose that the aberrations are produced in a discrete number of layers N_t. The expression of the phase measured in the N_{GS} directions is:

$$\Phi_{N_{GS}} = M_{N_{GS}}^{N_t} \varphi + n \tag{1}$$

where φ is the vector of the aberrations in the N_t layers, and n the noise on the measurement. The matrix $M_\alpha^{N_t}$ sums the contributions of the wavefronts in N_t altitudes, in the telescope pupil and for a given direction α; $M_{N_{GS}}^{N_t}$ is the concatenation of the matrices $M_\alpha^{N_t}$ for all the directions of interest.

The estimation $\hat{\varphi}$ of φ we seek has the shape:

$$\hat{\varphi} = W \times \Phi_{N_{GS}} \tag{2}$$

where the unknowns are the elements of the reconstruction matrix W.
The criterion to be minimized is the residual phase variance in a FoV of interest $\{\alpha\}_{fov}$:

$$\varepsilon = \left\langle \int_{\{\alpha\}fov} \left\| M_\alpha^{N_{DM}} \hat{\varphi} - M_\alpha^{N_t} \varphi \right\|^2 d\alpha \right\rangle_{\varphi,\text{noise}} \tag{3}$$

where $M_\alpha^{N_{DM}}$ is defined as $M_\alpha^{N_t}$ but for the N_{DM} altitudes.
The minimization of this equation gives [8]:

$$W = P_{N_{DM},N_t} \times W_{MA} \tag{4}$$

with

$$P_{N_{DM},N_t} = \left(\int_{\{\alpha\}fov} \left(M_\alpha^{N_{DM}}\right)^T \left(M_\alpha^{N_{DM}}\right) d\alpha \right)^+ \left(\int_{\{\alpha\}fov} \left(M_\alpha^{N_{DM}}\right)^T \left(M_\alpha^{N_t}\right) d\alpha \right) \tag{5}$$

and

$$W_{MA} = C_\varphi \left(M_{N_{GS}}^{N_t}\right)^T \left(M_{N_{GS}}^{N_t} C_\varphi \left(M_{N_{GS}}^{N_t}\right)^T + C_n \right)^{-1} \tag{6}$$

where C_φ and C_n are respectively the aberrations and noise covariance matrices. It is interesting to notice that C_φ is computed from statistics on the aberrations in optical systems, and not from the prior knowledge of the atmospheric turbulence like in the classical case. The matrix $M_{N_{GS}}^{N_{DM}}$ is defined the same way as $M_{N_{GS}}^{N_t}$ but for the N_{DM} altitudes of the DMs instead of the N_t altitudes of the layers. $^+$ denotes a generalized inverse.
In the case where the number of layers containing the aberrations N_t is the same as the number of DMs N_{DM}, the projector is equal to identity and then W_{MA} is the reconstruction matrix. In the realistic case where there are $N_t > N_{DM}$ equivalent layers, W_{MA} reconstructs the WF on the N_t layers and the multiplication by the projector P_{N_{DM},N_t} gives the reconstruction matrix on N_{DM} layers.
From the matrix W, one can then compute $\hat{\varphi}$ as in the equation (2). This gives the estimated correction phase on each DM that ensures a minimal residual phase variance for all the directions of the specified FoV $\{\alpha\}_{fov}$.
In addition to the directions of the GS, we can evaluate the quality of the correction in more directions in the field. The residual seen in those N_a directions of analysis is then:

$$R_a = \Phi_{N_a} - M_{N_a}^{N_{DM}} \hat{\varphi} = \Phi_{N_a} - M_{N_a}^{N_{DM}} W \Phi_{N_{GS}} \tag{7}$$

where $M_{N_a}^{N_{DM}}$ is defined the same way as $M_{N_{GS}}^{N_{DM}}$, but enlarged to the N_a directions of analysis.

R_a is the residual WF seen in the N_a directions of analysis (its calculation requires the knowledge of the aberrations in those directions). From it we can derive the SR (as in the section 6) or the decomposition into Zernike coefficients of the residual.
In this paper we will limit ourselves to the evaluation of the performances in the direction of the GS:

$$R_{GS} = \Phi_{N_{GS}} - M_{N_{GS}}^{N_{DM}} \hat{\varphi} = \left(1 - M_{N_{GS}}^{N_{DM}} W\right) \Phi_{N_{GS}} \tag{8}$$

4.2. Practical implementation

The output of the ΦD software is a list of Zernike coefficients, typically from 4 (focus) to 15 for our application. At ESO we have developed a routine in Matlab that computes the reconstruction matrix W.

The first step is to calculate the meta-matrix $M_{N_{GS}}^{N_t}$, which depends only on the position of the calibration stars in the FoV and on the position of the N_t equivalent layers. It has to be calculated only one for a given set of those parameters. The role of this matrix is to sample the Zernike polynomials in the meta-pupils at the N_t altitudes into Zernike polynomials in pupils of the appropriate size. It has been shown [12] that the number of polynomials required for such decomposition is smaller or equal to the number of polynomials used to define the meta-pupil. The analytical expression of the decomposition is demonstrated in [7]. However for the present simulations we use a numerical projection, accurate enough for our need and that shows the same behavior as the theory demonstrated (Fig. 1). We see that from a polynomial of order N over the meta-pupil, it is possible to select any pupil and describe it thanks to a number of polynomials ≤ N. The whole procedure is repeated for the calculation of $M_{N_{GS}}^{N_{DM}}$.

The second step of the routine is to calculate the reconstruction matrix W described in the equation (4) thanks to the knowledge of the matrices $M_{N_{GS}}^{N_t}$, $M_{N_{GS}}^{N_{DM}}$ and to some priors on the measurements which are included in the aberrations covariance matrix C_φ and in the noise covariance matrix C_n. W is determined for a set of positions, altitudes and measurement conditions. Finally by multiplying W to a vector of measurements we get immediately the optimal shape to give to the DMs.

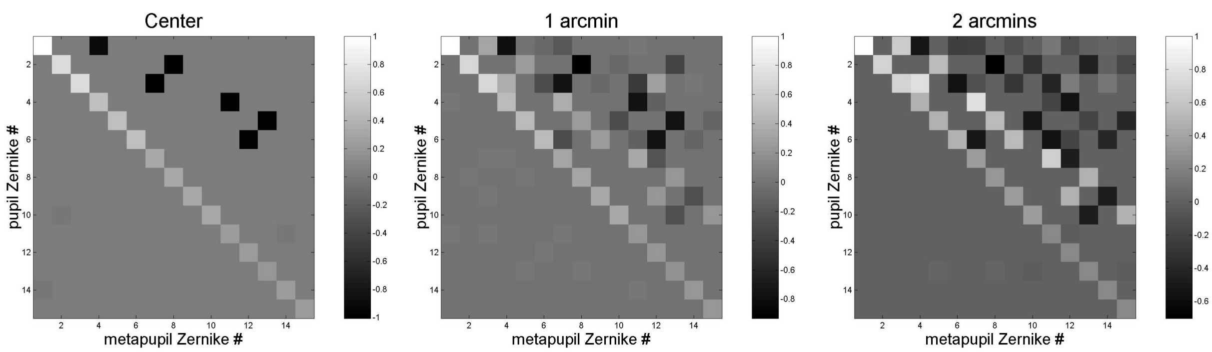


Fig. 1. Result of the projection of Zernike polynomials in a meta-pupil at 6 km altitude in a pupil, placed at the centered of the FoV (left), at 1 arcmin (middle) and 2 arcmins from the center of the FoV (right). The Zernike polynomial of order X in the meta-pupil can always be described by the polynomials of order ≤ X in the pupil.

5. FRAMEWORK OF THE SIMULATIONS

For the following simulations, we take the example of the MAD instrument to experiment the tomography algorithm. The optical scheme is shown in Fig. 2, as well as the projected altitudes of the optical element bringing aberrations. We are interested only in the common and IR camera paths for this study. It is interesting to notice that for a perfect system (particularly with the possibility to flatten perfectly the DMs in open loop), the presence of the WFS path is not even required to perform the calibration of static aberrations by ΦD.

When the derotator is active, its optics is rotating in the FoV, thus it is not possible to calibrate it. However the optics is conjugated with high altitudes (small footprints), and are constituted only of flat mirrors, so shouldn’t introduce much aberration. All the ΦD images should be recorded on the axis of the IR camera, to disentangle the field-dependant aberrations of the camera from the ones of MAD. The calibration of the aberrations in the field of the camera should be done for the achievement of extreme performances only, but in principle the ΦD approach is able to take care of it too.

The optical elements mainly responsible for the degradation of the beam quality in the IR path are:

- the two collimators situated at equivalent altitudes of 16.2 Km
- the two folding mirrors at 13 and 14 Km
- the IR/visible Dichroic at 7.5 Km
- the residual non-flatness of the two DMs at 0 and 8.5 Km

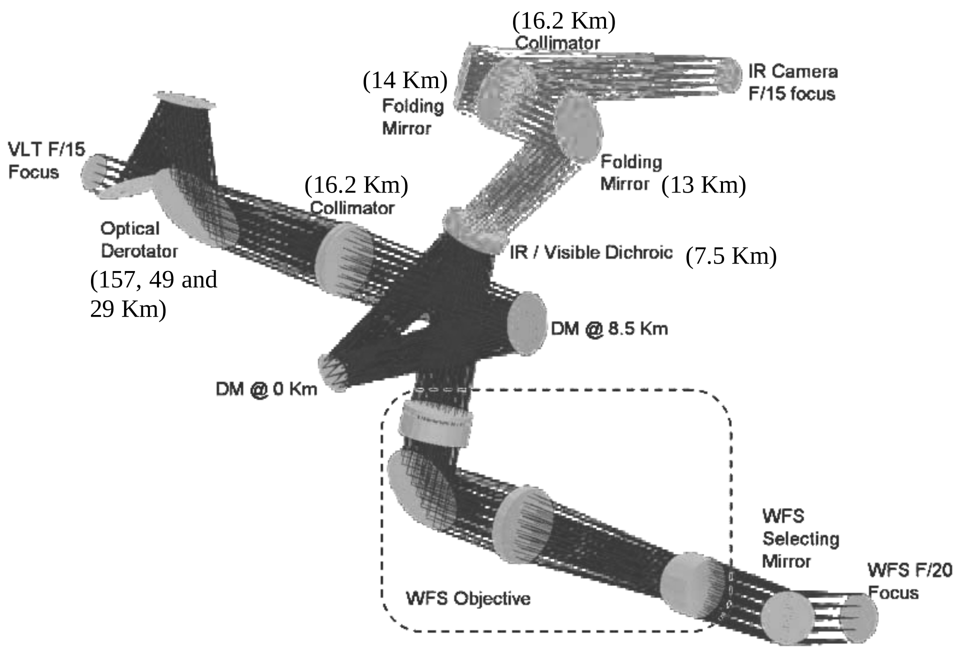


Fig. 2. MAD optical layout and equivalent altitudes of the optics. The optics in the IR camera (not represented) is conjugated with altitudes of 0, 45 and 55 Km and the filters are higher than 100 Km.

Only measurements on the bench once fully integrated and aligned will teach us the amount of aberrations to correct, but we can get an estimation of this value from the data on the separated optical pieces (Table 2) exaggerated to simulate a worst case situation. In a first estimation, we consider that only four elements bring aberrations to the system, and that distortion can be modeled by a simple WF shift when the beam passes through a plane at the position of the optical element.
Thus, in order to simulate the real system, those aberrations were added to the optical design of MAD made by a ray-tracing software. By this way we combine the design aberrations, the chromatic aberrations and the expected optics aberrations.

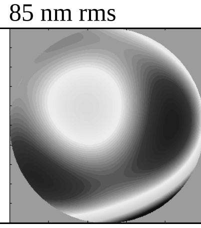
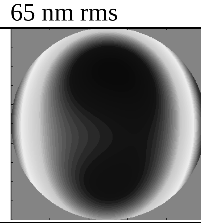
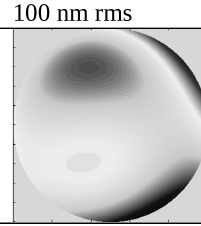
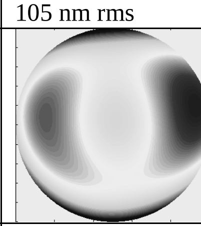
Optical element	Collimator #1	Mirror IR1	Collimator #2	Mirror IR2
Aberrations added	85 nm rms	65 nm rms	100 nm rms	105 nm rms
Aberrations map				
Useful surface (mm)	130	130	130	170
Beam footprint (mm)	60	60	60	60

Table 2. Aberrations on four optical elements of the common and IR camera path, as implemented in the simulations. The rms value given refers to the aberrations over the whole surface of the optics.

6. RESULTS

6.1. Aberrations measurement

A grid of 13 points has been defined in the FoV, following the geometry shown in Fig. 3. Those points will be the measurement points of the aberrations. But in a first time only the SR was evaluated at those positions in order to check the quality of the PSF in the FoV at the level of the IR focus. The degradation of quality is only due to the static aberrations in the optical path.
The results of the SR measurements (as calculated by the ray-tracing software) are also shown in Fig. 3 for three different wavelengths (J band: 1250 nm, H band: 1600 nm, K band: 2200 nm). In K band the SR is always greater than 90%, except some points at the border of the field where it drops down to 75%. Obviously the shorter is the wavelength, the smaller the SR.

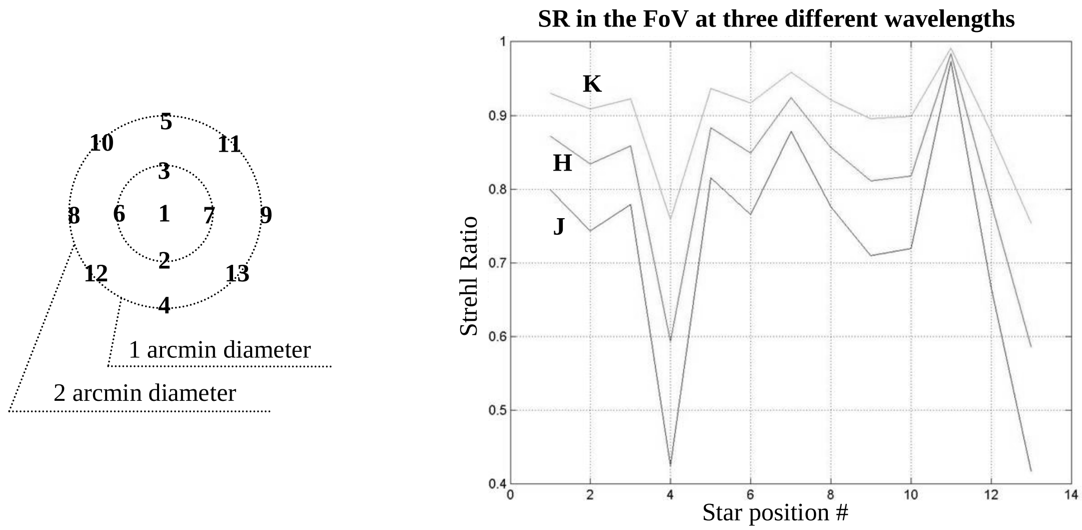


Fig. 3 Repartition of the measurement points in the field and SR associated

6.2. Reconstruction

The WFs calculated by the ray-tracing software Zemax at the stars position are transformed into focused and defocused images (Fig. 4). No noise is added to those images. They are analyzed by the ΦD algorithm that gives a table of Zernike coefficients for each position in the FoV. Those coefficients and the parameters of the system are used as input of our algorithm. As the simulated images contain no noise, the noise covariance matrix C_n is set to identity.

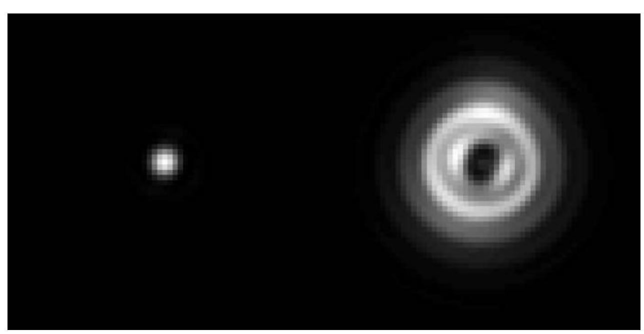


Fig. 4. Examples of simulated focused and defocused images to feed the ΦD algorithm

The meaning of the aberrations covariance matrix C_φ is not obvious: in the case of atmospheric tomography, it contains the knowledge we have of the statistical behavior of the turbulence, more exactly the variance of the Zernike coefficients. Using this knowledge leads to a regularization of the solution. In the case of the study of the optical aberrations of a system (which are static), we could fill it with an estimation of the aberrations we expect at the level of the different optics. Some tests made on simulated images show that the regularization doesn't enhance the results, due to a bad knowledge we have of the aberrations in the system. Thus for the present simulations, the matrix C_φ was also set to identity. However in the case of the real system those covariance matrices will play a crucial role for reducing the error brought by the noise of the IR images measured with the camera.

The projection is done on eight layers (at 0, 4, 7.5, 8.5, 13, 14, 16.2 and 30 Km) to take into account the position of the optics and to fill efficiently the equivalent volume occupied by the instrument. The projection is done at the levels of the two DMs (0 and 8.5 Km).

The residual aberrations in the directions of interest are calculated thanks to the equation (8). The correction achieved is plotted in Fig. 5. At the positions of the measurements, the SR in J is ranging from 42 to 97% in the FoV, with an average of 73% (90% in K band). After correction it is restricted to the range 81-96% with an average of 91.5%. It corresponds in K band to an average SR of 97%.

This result proves that the tomographic reconstruction of the aberrations of the optics in the MCAO instrument is efficient, and that the projection on the two DMs brings a great enhancement of the quality of the images in the full scientific FoV.

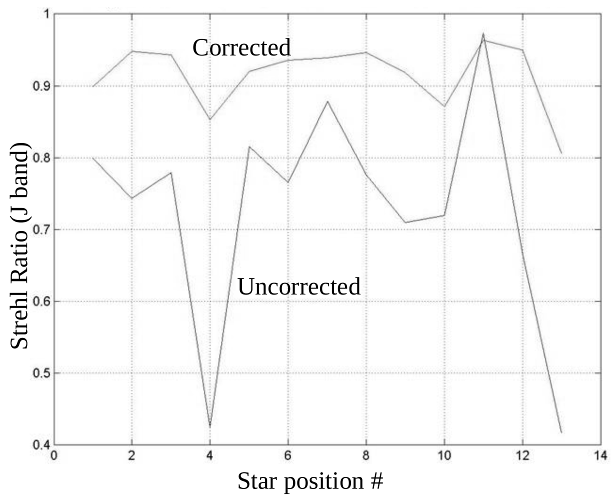


Fig. 5. Result of the correction in the case of the 8 layers tomography projected on 2 DMs. The position of the stars in the FoV is defined in Fig. 3.

6.3. Numerical optimization

Although the minimization of the criterion described previously (equation (3)) leads to the best correction in the field, maybe it would be of an interest to define another one. In the case of the correction of the static aberrations in the FoV, an interesting criterion could rather be the dispersion of the residual variances in the directions of interest. The minimization of this criterion would lead to a solution with the best uniformity of the residual aberrations in the scientific field (or at least in the directions of interest) of the MCAO instrument, even if the average SR is a bit lower than the result obtained in the previous section. A possible expression of this estimator would be:

$$\varepsilon' = \left\langle \left(\sum_i a_{\alpha,i}{}^2 \right)^2 \right\rangle_{\{\alpha\}fov} \tag{9}$$

where the $a_{\alpha,i}$ are the coefficients of the decomposition on the Zernike polynomials of the residual aberrations R_α in the direction α, and:

$$R_\alpha = \Phi_\alpha - M_\alpha^{N_{DM}} W \Phi_{N_{GS}} \tag{10}$$

The drawback of this estimator is that it focuses on the uniformity of the residual variance in the FoV, but doesn't help for increasing its average value. Thus an estimator taking both into account would be:

$$\varepsilon'_{\mathrm{G}} = \int_{\{\alpha\}\mathrm{fov}} \left\| \sum_{\mathrm{i}} \mathrm{a}_{\alpha,\mathrm{i}}{}^{2} - \mathrm{Goal} \right\|^{2} \mathrm{d}\alpha \tag{11}$$

The constant "Goal" represents an average variance (that we can also express as a SR) we try to reach in addition to the minimization of the residual variance everywhere in the FoV. More precisely, instead of calculating the variance which is the deviation around the average value, this estimator represents the deviation of the SR around a goal value.
Here again we will limit ourselves to the evaluation of the performances in the direction of the GS:

$$\varepsilon'_{\mathrm{G}} = \sum_{N_{GS}} \left\| \sum_{\mathrm{i}} \mathrm{a}_{\alpha,\mathrm{i}}{}^{2} - \mathrm{Goal} \right\|^{2} \tag{12}$$

The analytical solution to the problem would come from deriving this estimator in order to find its minimum. In a first time we choose to adopt a numerical approach for solving the problem, not optimized but much faster. Thus we considered that a way to make uniform the residuals in the FoV is to put weight on the reference stars. This can be done by filling appropriately the matrix C_n. By default this matrix is set to identity, and its dimension is equal to the number of GS multiplied by the number of Zernike coefficients used for the reconstruction. If we choose to put the same weight on all the coefficients of each GS, the number of parameters to resolve is equal to the number of GS (13 in our example). So we have kept the solution W given by the equation (4), and modified the matrix C_n in it in order to minimize the criterion ε'_G (equation (12)). Thanks to a routine that calculates the minimum of an unconstrained multivariable function, it is possible to numerically find the values of the 13 parameters that minimize ε'_G. The result of this optimization for a Goal of 90% of SR in J band is shown in Fig. 6. The average value of the SR is 89.5 % (pretty close to the goal), and the variation is successfully limited to the range 85-93 %. The use of the new criterion, even if not analytically derived, brings a certain enhancement of the uniformity of the residual aberrations as measured in the directions of the GS.
In Fig. 6 is also shown the shape of the two DMs that brings this correction. We can notice that mainly low order aberrations are present. The amplitude of the correction is of a great importance, as it uses some of the stroke of the DM that then is no more available for the MCAO real-time correction. The two deformable devices in MAD are curvature mirrors, one of 60 mm useful diameter and the other one of 100 mm (fitting respectively the two altitudes of 0 and 8.5Km for a 2 arcmin FoV), both with about 3 microns of stroke. The stroke used to perform the correction is 195 nm for the ground MD and 445 nm for the altitude DM, which is quite a consequent part of the full stroke. If the aberrations in the real system, especially at the edges, turn out to be that greedy in DM stroke, we might have to select carefully the area for the field optimization during the tomographic reconstruction.

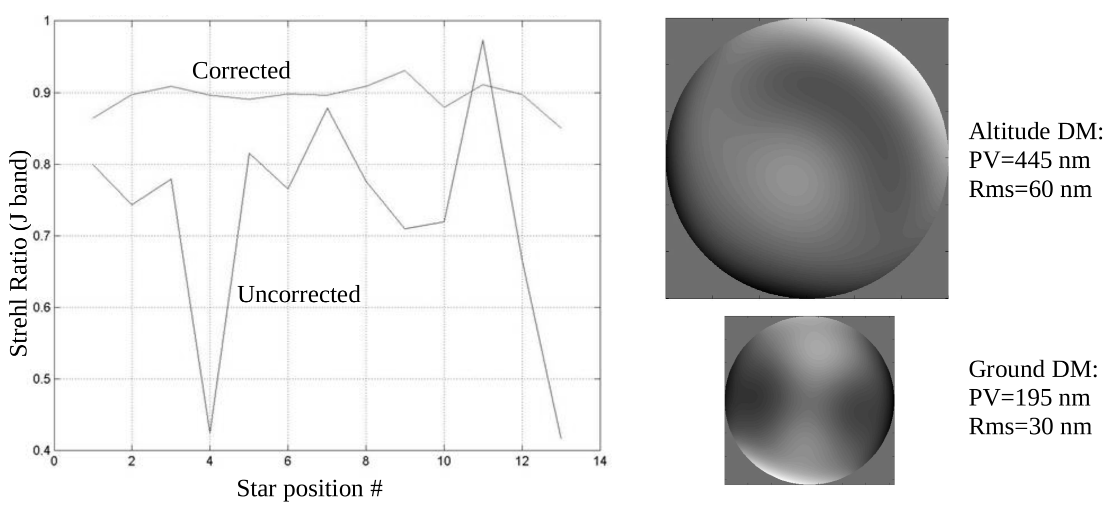


Fig. 6. Result of the correction in the case of the 8 layers tomography projected on 2 DMs, after numerical optimization. The position of the stars in the FoV is defined in Fig. 3.

7. CONCLUSION / FUTURE WORK

It has been demonstrated on the system NAOS-CONICA that it was possible to correct for the optical aberrations in the path of the camera, by the use of the ΦD algorithm to compute the WF from IR images, and by applying the proper shape to the DM. In this paper we have pushed a bit further and demonstrated that it is also possible to correct for the field-dependant static aberrations in an MCAO system, by taking the most of the presence of several correcting devices conjugated with different altitudes. This can be done by using the IR camera as WFS, analyzing its images by the ΦD in order to retrieve the WF, and then by reconstructing tomographically the WF in the layers. On the particular example of a geometry of 13 stars in the FoV of the MAD instrument, and with no noise in the images, we have showed that a very irregular FoV with 73% of SR in average in J band can be enhance to a quasi-flat FoV at 90% of SR.

Some more developments would enhance the reconstruction and/or bring the simulated system closer to the reality. First of all, in order to get an ultimate expression for the reconstruction matrix W, it would be required to derive the estimator defined in the equation (11). A more complete grid of simulated measurement points would allow at the same time optimizing the correction for some areas in the FoV, studying more GS configurations, and estimating the quality of the correction in the whole scientific field. The introduction of noise in the simulated images before their analysis by the ΦD algorithm would give us an idea of the robustness of the algorithms when faced to realistic data. Finally the practical way of recording the images and applying the proper static voltages to the DMs has to be defined accurately; this might introduce some errors in the whole procedure and decrease the quality of the correction.

AKNOWLEDGMENT

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. A. Amorim, A. Melo, J. Alves, J. Rebordão, J. Lima, J. Pinhão, G. Bonfait, R. Fernandes, R. Barros, J. Azevedo-Lucas, L. Correia, M. Carvalho, J. Santos, R. Marques, F. Duarte Santos, I. Catarino, J. Poncet "*The CAMCAO infrared camera*", Ground based instrumentation for astronomy, SPIE Proceedings, 5492, article number [5492-120], 2004
2. A. Blanc "*Identification de réponse impulsionnelle et restauration d'images : apports de la diversité de phase*" Thèse de Doctorat, Université Paris XI Orsay, July 2002
3. 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
4. D. L. Fried "*Anisoplanetism in adaptive optics*" J. Opt. Soc. Am., 72(1):pp 52-61, Jan. 1982
5. T. Fusco "*Correction partielle et anisoplanétisme en Optique Adaptative: traitements a posteriori et Optique Adaptative multiconjuguée*" Thèse de Doctorat, Université de Nice Sophia-Antipolis, October 2000
6. 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
7. T. Fusco, J.-M. Conan, V. Michau, L. M. Mugnier, G. Rousset "*Phase estimation for large field of view: application to multiconjugate adaptive optics*", Proc. SPIE 3763, 125-133 (1999)
8. T. Fusco, J.-M. Conan, G. Rousset, L. M. Mugnier, V. Michau "*Optimal wavefront reconstruction strategies for multiconjugate adaptive optics*" J. Opt. *Soc. Am. A*, (10):2527-2538, October 2001
9. 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
10. 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

11. 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)
12. R. Ragazzoni, E. Marchetti, F. Rigaut "*Modal Tomography for Adaptive Optics*" Astronomy and Astrophysics 342:L53-L56 (1999).
13. G. Rousset, F. Lacombe, P. Puget, N. Hubin, E. Gendron, T. Fusco, R. Arsenault, J. Charton, P. Feautrier, P. Gigan, P. Y. Kern, A.-M. Lagrange, P.-Y. Madec, D. Mouillet, D. Rabaud, P. Rabou, E. Stadler, G. Zins "*NAOS, the first AO system of the VLT: on-sky performance*" in Adaptive Optical System Technologies II. Edited by Wizinowich, Peter L.; Bonaccini, Domenico, vol. 4839 of Proc. SPIE, pp. 140-149, Feb. 2003.