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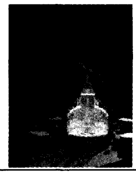
More Deformable Mirrors (and higher Strehl) in Layer-Oriented for free

Venice 2001
Beyond
Conventional
Adaptive
Optics



J. Farinato [a], E. Fedrigo [a], E. Marchetti [a], R. Ragazzoni [b]

[a] European Southern Observatory - Garching bei Muenchen - Germany
[b] Osservatorio Astronomico di Padova - Padova - Italy

ABSTRACT

Classical Layer Oriented Multi Conjugate Adaptive Optics works on the principle to couple a Wavefront Sensor with each deformable mirror, both conjugated to a certain altitude. In this way not only the layers conjugated to those altitudes will be corrected but the same will happen also for layers placed at intermediate heights with a smoothing of the high spatial frequency increasing with the distance from the above mentioned DMs conjugated altitudes. The increase of the Strehl Ratio for a given Field of View is linked to the total number of DMs. How layer-oriented scales when one switches to more than the usually considered two DMs? In the classical Layer Oriented approach, the use of an additional Deformable Mirror (for example to correct for a strong intermediate layer) would require an additional wavefront sensor conjugated to the same altitude. This will of course introduce furhter complexity to the system (nevertheless still by far smaller than any multiple star classical WFSensing) and will moreover require the distribution of the references light among several detectors, introducing a certain hampering on the achievable sky coverage. The latter is an issue when only NGSs are considered and, even in the case of multiple FoV can become a problematic issue. We show here that the information on how to drive DMs not conjugated with the detectors is already contained in the layer-oriented WFS and it can be retrieved in a numerical way (but in close loop). The insertion of an additional DM in the optical path improves significantly the Strehl Ratio with a negligible loss in term of Sky Coverage whenever the Read Out Noise of the detector is almost negligible, as it is the case when high Strehl have to be reached.

1. INTRODUCTION

The problem attacked in this paper is how to increase the Strehl Ratio achievable from a Layer Oriented based MCAO system without having a reduction in the Field of View. There is a general agreement (Rigaut (2001), Ragazzoni et al. (2001-a and 2001-b)) that the maximum achievable SR is driven by the strengthness of the turbulence present between the height to which the deformable mirrors are conjugated (Fig. 1 left side). In order to increase such a maximum SR (without being forced to shrink down the FoV to values only slightly bigger than the one obtainable with a normal AO system), the introduction of additional deformable mirrors in the system is needed (Fig. 1 right side).

In Layer–Oriented WF–sensing (both in the Classical - Ragazzoni, Farinato & Marchetti (2000) - and in the Multi–FoV concepts - Ragazzoni et al. (2001-a and 2001-b)) the normal way to add a DM goes through the insertion of a further detector conjugated with the proper altitude. This leads to the following two problems:

- The additional complexity of the optomechanics in the WF sensing area (although still by far smaller than the one of a multiple references SH sensor with a comparable number of sensed references)
- The splitting of the light in more parts, decreasing thus the amount of light used by every WFS present in the system (the situation would be better considering the MFoV concept, since one could think to choose different FoVs for the three WFSensors in a way to minimise the loss of light having an overlapping area between them).

Even if the complication of the physical implementation of a system has been in the past the killer for many AO systems, it is clear that the real problem affecting the final performance is the second one. In fact, in Fig. 2 there is an extimation of the reduction in term of Sky Coverage caused by a light reduction of 0.45 magnitude (from 50% to 33% of

Send correspondence to Jacopo Farinato: farinato@arcetri.astro.it

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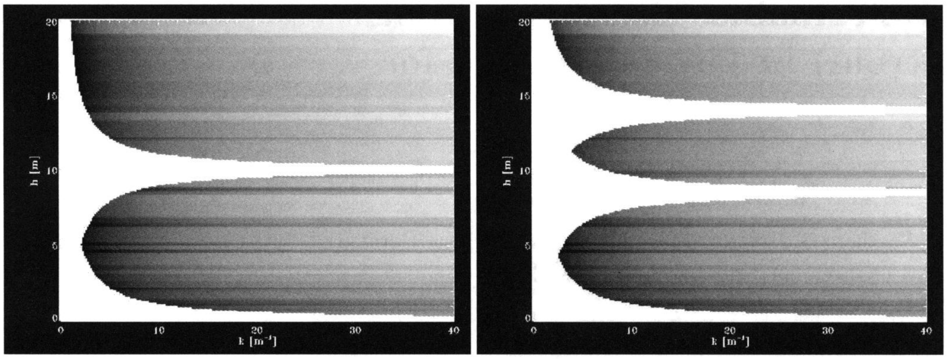

Figure 1. Residual Lack of achievable correction between two DMs (left side) and how the situation improves by using 3 dms (right side)

the total light going from 2 to 3 detectors, so no optimization due to the MFoV concept has been considered), from which it is clear that, depending on the galactic co–ordinates considered, the loss can go from few percent to more than 10%. For all these reasons, we will try to answer to the question: is there the possibility to drive additional deformable mirrors by using the informations coming from the other WFSensors? In the following, we will consider a system based on two DMs (ground one and high altitude one) and we will try to reconstruct the signal to drive a further DM (conjugated to an altitude in between the two) from the deformation measured by the WFSensor conjugated to the Ground Layer (Fig. 3).

2. BASIC CONCEPT

In the following, we will consider a Layer–Oriented system based on Pyramid WFSensor which is sensing at the scientific wavelength. Let us consider at the beginning an hypothetical system in which only a turbulent ground layer is present, being the upper part of the atmosphere not perturbated; a WFS and a DM are conjugated to this layer, that we suppose at the level of the telescope entrance pupil. Let us suppose also that we have a number of bright reference stars, in a way

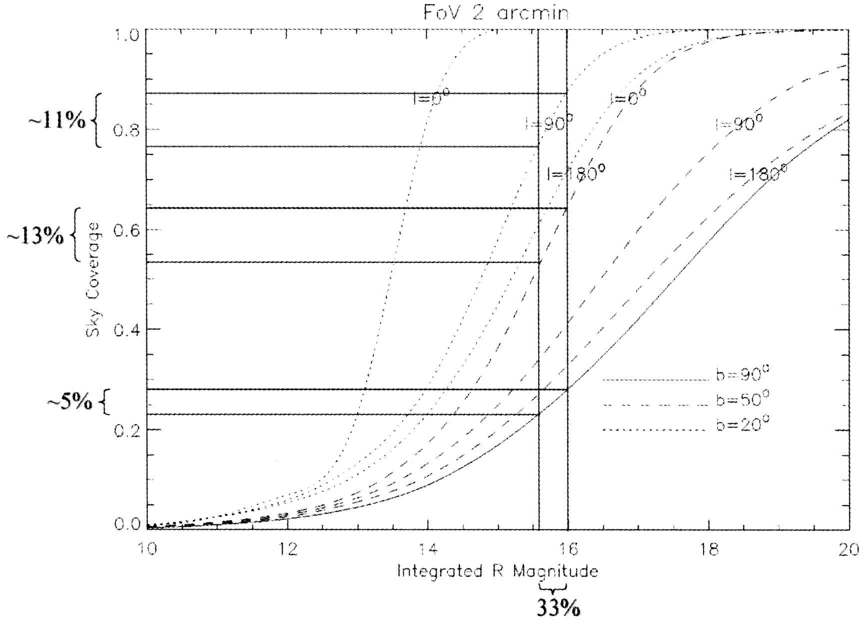

Figure 2. Reduction in term of sky coverage due to an additional light split (33% loss in term of light, equal to 0.44 magnitudes)

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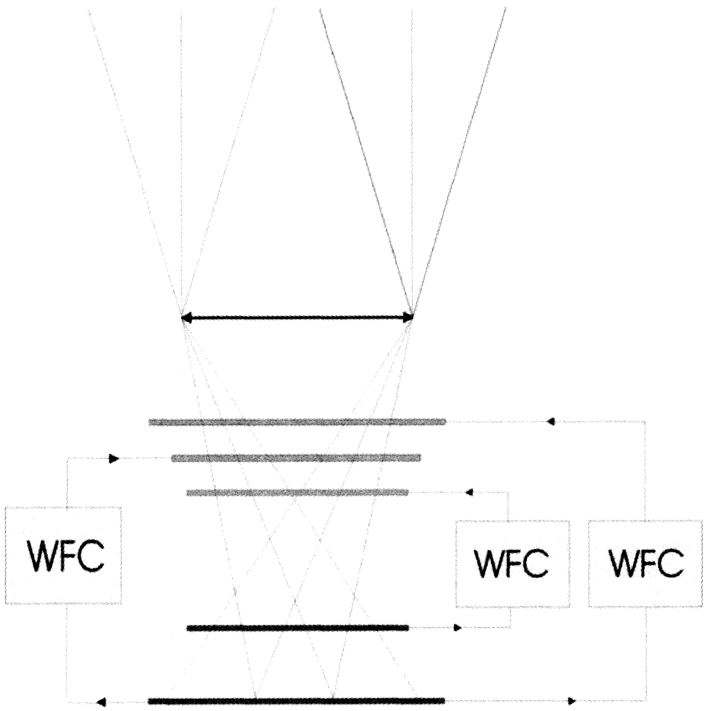

Figure 3. Reconstruction of the signal to drive a third DM from the signal coming from the WFS conjugated to the ground DM

that the SNR is quite high and the RON of the detector can be neglected. As it is sketched out in Fig. 4 left side, by closing the loop the system will correct almost perfectly the deformation which is introduced only from the ground layer since the single (in this case) ground detector is sensing perfectly (because of the high SNR) the only present turbulent layer. Thus the star images on the pyramids will be diffraction limited (since we are sensing at science wavelength) and perfectly centered. Let us now consider a second turbulent layer present in the atmosphere (Fig. 4 right side), at a certain altitude far away from the ground layer and with no DM and WFSensor conjugated.
What is happening at the level of the WFSensor conjugated to the ground layer? It will see of course the ground layer deformation with the superimposition of the high turbulent layer, being the latter smoothed in a way that is dependent from the distance between the conjugated altitude of the WFSensor (close to the pupil in this case) and the second turbulent layer (Ragazzoni (2000) - Ragazzoni, Farinato & Marchetti (2000)). This means that the ground conjugated DM will apply a correction that will cancel out almost completely the ground layer while only the low spatial frequencies of the high turbulent layer will be corrected. In this way, what is remaining is a very small residual of the ground layer and a huge residual of the high altitude layer.

What is happening at the level of the pyramids? In this case, the star images in close loop are not diffraction limited and perfectly centered because the correction is not perfect due to the presence of the high turbulent layer, but the system $WFS + DM$ will drive indeed the signal to zero in a way that apparently the deformation introduced from the second layer is somehow not retrievable. In fact, the basic principle of the Layer Oriented concept pyramid based is that the light coming from several reference stars is co–added at the level of the detector in a way that the average of the signal detected from the WFS is driven to zero.
As an example, let us consider the case of the overall tilt at the level of the ground layer (Fig. 4, right side, detector plane). The overall tilt computed on the detector is:

$$\mathrm{Tilt_y} = \frac{(P_1 + P_2) - (P_3 + P_4)}{P_1 + P_2 + P_3 + P_4} \tag{20}$$

which gives of course the average tilt in one axis of the footprint of the reference stars at the conjugated altitude (which is in this case the average tilt over the pupil, being the footprint of the reference stars at the level of the ground layer the pupil itself). Thus the applied correction is performed in a way that the centroids of the reference stars (three in

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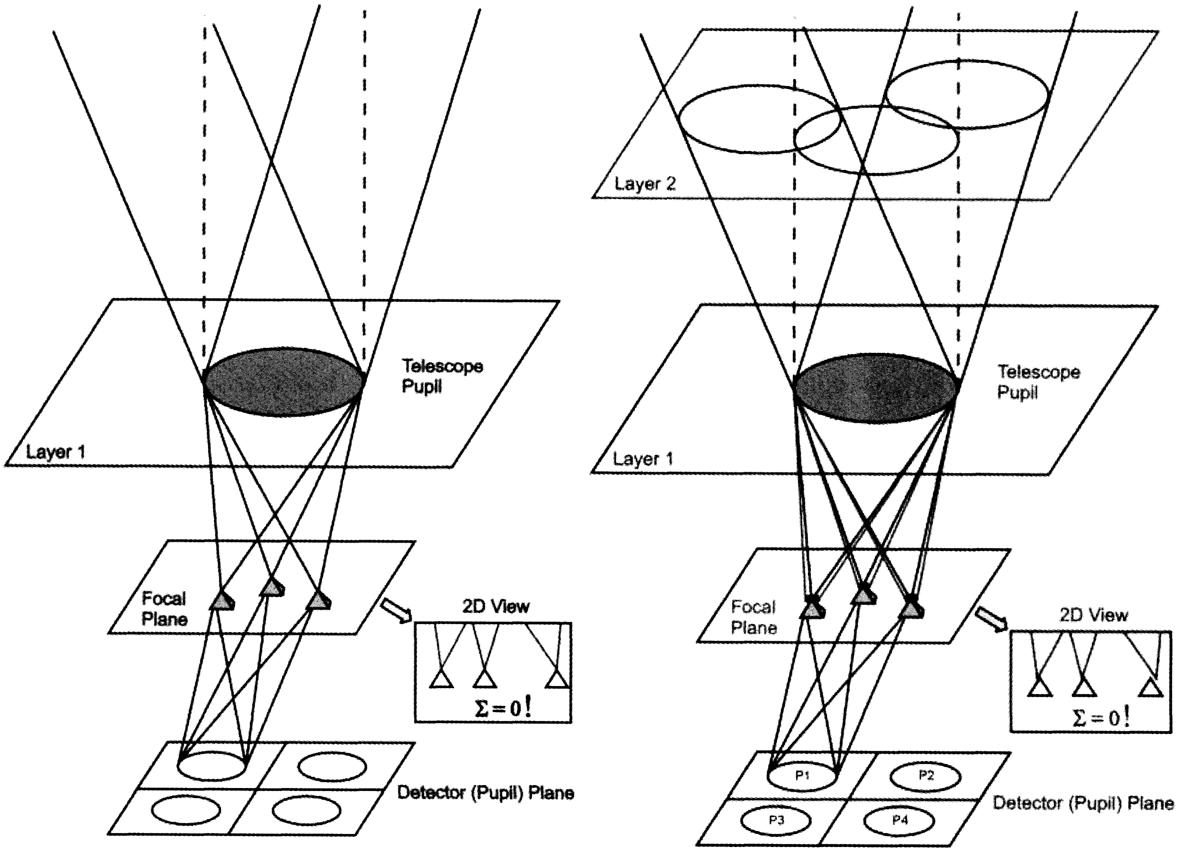

Figure 4. Perfect correction in the case of a single turbulent layer at the ground level (left side) and degradation of the correction in the case of a two layer atmosphere having only a ground DM and WFS (right side)

this case) will be displaced in a way that the average position is zero (Fig. 4, 2D view). The implication of this is that it is impossible to distinguish at the WFS level between the case of the two turbulent layers and the one of the single ground turbulent layer! Going to high order correction, exactly the same thing is happening when we consider a small area of the four pupils: only the average local tilt of the reference stars on that sub-area of the pupil is retrieved, in a way that all the considerations done for the overall tilt apply straightforward here.

In other words, Layer–Oriented is sensitive only to the wavefront departures averaged for each reference star!

3. WHICH ARE THE OBSERVABLES?

From the considerations made in section 2 it seems apparently that the reconstruction of the high spatial frequencies components of the second turbulent layer from the signal obtained by the ground conjugated WFS is not possible. But is there an observable that can give us an indication of the turbulence of the second layer?

We said in Section 2 that by considering a second turbulent layer, at the level of the focal plane (on the pyramids pins) the star images are no longer diffraction limited and perfectly centered. So it is clear that this gives an indication of the turbulence introduced by the second layer.

So the basic question at this point is if it is possible somehow to retrieve the spot size on the pyramids.

Entering in more details, one can consider a small portion of the pupil as described in Fig. 5. Considering the rays belonging to the different reference stars, due to the presence of the second turbulent layer, they will hit the pyramids in a displaced position, causing as a final effect the increase of the spots dimensions at the level of the focal plane and causing a different light distribution at the level of the pupil plane.

Therefore, the basic question becomes: can star rays displacements be reconstructed?

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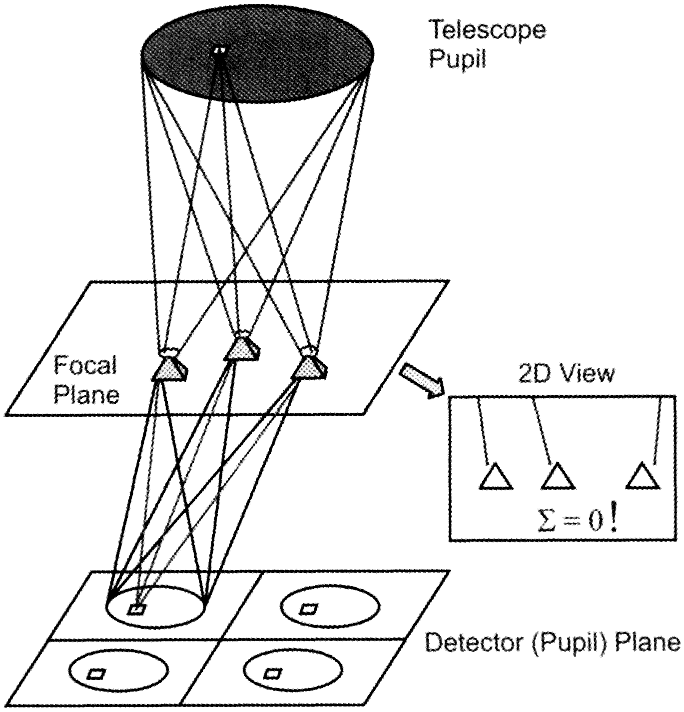

Figure 5. Observing a small portion of the pupil, one can consider the rays belonging to different stars: they will hit the piramids in a displaced position, in a way that their average displacement is 0.

4. RETRIEVING THE SPOTS SIZES WITH THE PYRAMID MODULATION

Let us assume that we are modulating the Pyramid with a frequency twice the maximum working frequency of the detector with the purpose to retrieve the spot sizes at each loop cycle to get an extimate of the deformation introduced at each integration time by the second layer.

In Fig. 6 is explained how, by modulation of the Pyramid and sampling the pupil signal at each half of the vibration loop, a signal proportional to the spot's size can be retrieved. The signal from the four pupils must be read in a way that the spot is in two different situations: in the quadrant A and B (i.e. when the modulation is imposing a movement of the spot from P1 to P3 in Fig. 6 up– left) and in the quadrant A and C (i.e. when the modulation is imposing a movement of the spot from P2 to P4 in the same figure). This must be done to compute the imposed tilt signal first in the x–axis and then in the y– axis, signal which is related with the spot size, as we are going to show. On the top-left corner, a diffraction limited spot is considered. Without modulation and in closed loop, the spot would be exactly on the pyramid pin (the cross in the drawing) and no tilt signal could be found at any moment. But if we impose a modulation in a way that, in a certain moment, we can read the tilt signal in the two axis, in the situation presented in the figure (spot in quadrant B) we would get a null signal for the x–tilt and maximum signal for the y–tilt.
On the bottom left corner, we consider a very big spot, in a way that the intensity is the same in the four quadrants of the Pyramid. Therefore, it is clear that the tilt signal that one could get imposing the modulation signal would be 0 in both axis. The logical conclusion is that, having the spot of a reasonable size (right part of Fig. 6) in between the two limit cases just discussed, one could get a tilt signal in the two axis (with values between 0 and 1) which is proportional to the size of the spot. In Fig. 7 there is a plot showing the obtained signal while the spot dimension is changing. The modulation amplitude is considered fixed, but it is obvious that it will depend on the spot dimension: the bigger the spot the higher the modulation to obtain a relevant signal.

It must be pointed out that the fact of doubling the Pyramid modulation frequency does not represent a problem if the detector Read Out Noise is negligible, which is the case in high Strehl regimes or in the case of using L3 vision technology CCDs (Craig et al. 2001).

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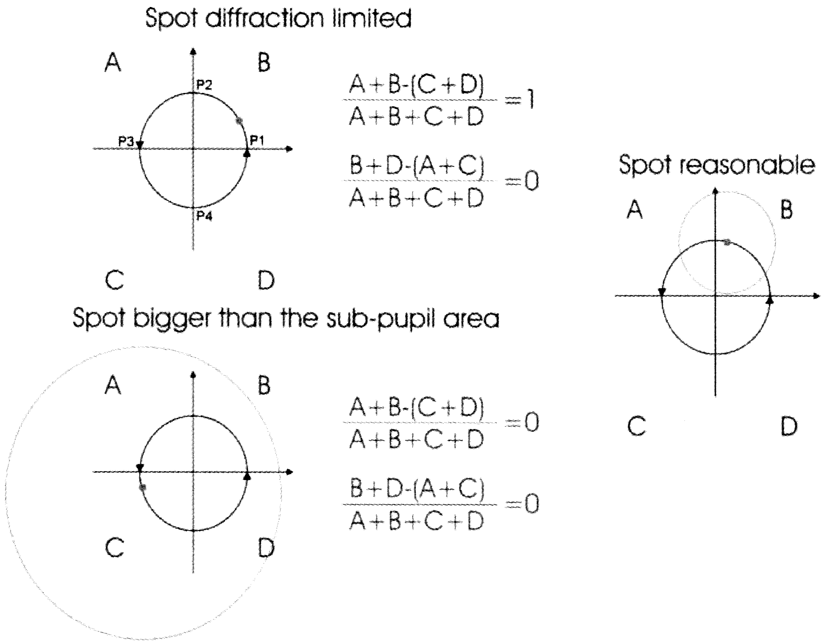

Figure 6. Retrieving the spot size by using the Piramid modulation.

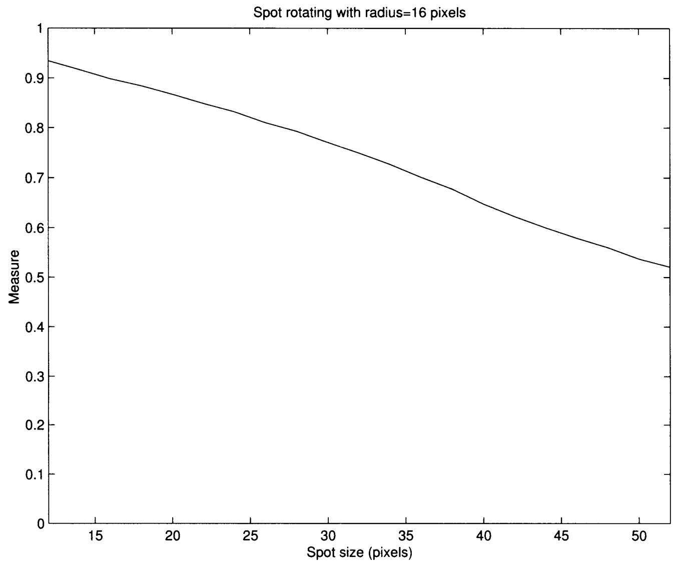

Figure 7. Plot of the result of tilt signal computation imposed by the pyramid rotation around the centre of the four-quadrant detector with a radius of 16 pixels and a spot size variable from 12 to 52 pixels. The signal heads slowly towards zero as the spot size increase and reaches zero when the spot modulated by the rotating pyramid constantly covers the detector. With a size of 32 pixels the spot rotates tangent to the center of rotation and the resulting signal is 0.75.

5. RECONSTRUCTING THE LAYER NOT CONJUGATED WITH THE WFS(S)

As it has been shown in the inset of Fig. 5 the Layer- Oriented loops, once properly closed, will make, for each subaperture on the pupil, the average of the displacement of individual rays close to zero. This will be accomplished by the proper driving of the *conventional* DMs conjugated to the repsective detectors. In principle, if all the turbulence to be corrected would be compensated by such a DM, not only the average position of the rays would be a null one, but also each individual ray coming from each individual reference star should hit precisely the pin of the respective pyramid. Uncorrected

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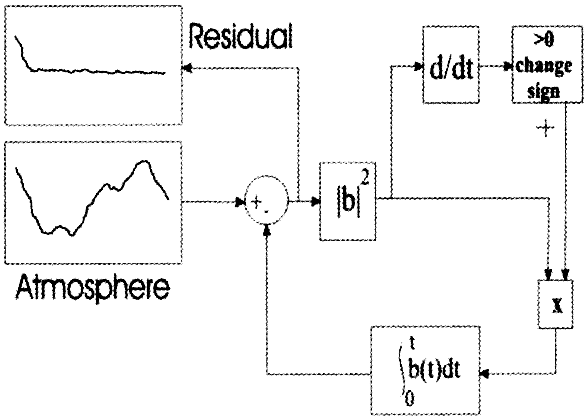

Figure 8. The simple reconstructor used for the simulations, based on an integral controller and checking the sign of the derivative of the residual, counter-acting (changing sign) in case the trend of the correction is bad (increasing residual).

perturbations, coming from the high spatial frequency turbulence located between the various heights where DMs and detectors are conjugated, will be responsible for local, specific to each reference star, misplacement of the ray on the pyramid pin. Optically speaking the whole images of the pupil as seen from the various pyramids will contribute to make the same pupil plane image. This can also be seen as that the pupil plane where the detector is located *see* a single pyramid common to all the reference stars. In this context the rays coming from each star will contribute to a *cloud* of rays whose barycenter will be driven by zero from the conventional Layer–Oriented loop while its size will be correlated to the uncompensated turbulence: the one we want to correct with the third DM not conjugated to any detector.

The size of such a cloud can be, at this point, measured with the technique described in the previous section, and gives a quadratic relation with the derivatives of the wavefront whose component is uncorrected by the conventional Layer–Oriented loop. In fact, said $\partial W/\partial x$ and $\partial W/\partial y$ such derivatives, the detailed positions will be given by multiplying such figures by the common focal length in the pyramid focal plane region. The size b of the cloud of rays will hence be given by:

$$b = f\sqrt{\sum\left(\frac{\partial W}{\partial x}+\frac{\partial W}{\partial y}\right)^2} \tag{21}$$

where the sum is extended to the whole set of reference stars.

6. SIMULATIONS

We saw in the previous section that there is a quadratic relationship between the wavefront deformation and the spot size. This means that there is an indetermination in the sign of the reconstructed signal to be applied to the additional DM. In other words, while it is matematically immediate to make an estimator able to give information on how much, in absolute sense, the correction by a third DM is far from the perfection, it is not possible to have an indication of the sign of the correction to be introduced.
It is remarkable that such an effect, being proportional to the square of the residual of the turbulence, will be missed in any linear treatment of the MCAO and specifically of Layer–Oriented theory, but nevertheless an approach to get an useful signal to drive a third DM is achievable, as we are going to show.

We implemented a very simple loop based on a reconstructor which is checking the sign of the derivative of the residual. If the trend is such that the residual is decreasing, the sign is unchanged, otherwise the controller imposes the change of sign (Fig. 8). In other words the system *tries* to perform the correction with an arbitrary sign and, in case the applied correction tends to make the system worst, the sign of the applied correction is changed. Practically speaking, it is important to establish the rate at which the change of sign is controlled in order to avoid to introduce further oscillations to the DM. We performed several numerical simulation of the described approach on a Matlab/Simulink environment. In Fig. 9 on the left side is described the simulink scheme used to simulate the system described before, while on the right side there is a normal linear reconstructor that supposes to know perfectly the input deformation with no uncetainty on

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the sign. This second system has been used only to make a comparison between our reconstructor and an ideal linear first order system based on an integrator. As it is clear (and expected) from Fig. 10, there is a loss of performance in the non-linear case, but only by roughly a factor 2 (the standard deviation is 0.017 in the linear case and 0.033 in the non-linear case). A smarter reconstructor than the very crude one we implemented here might improve the quality of the correction, which is already not far from the linear- case one.

It is remarkable that the described approach is to be considered valid in any modal form, so that one could imagine to have several b_i where the index i lies in a certain range and reppresents, for istance, actuators onto the DM in a zonal approach, or Zernike (or others more convenient) modes in a modal approach.

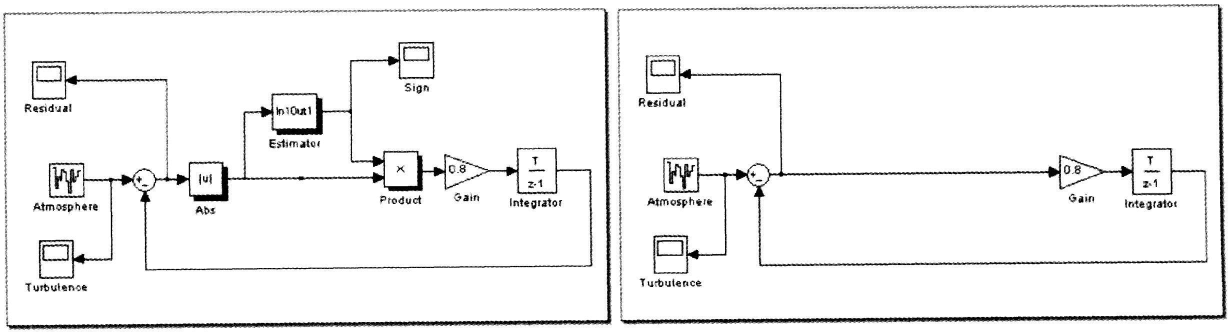

Figure 9. The non-linear reconstructor (left side) and the ideal linear first order system; both of them are based on an integral controller.

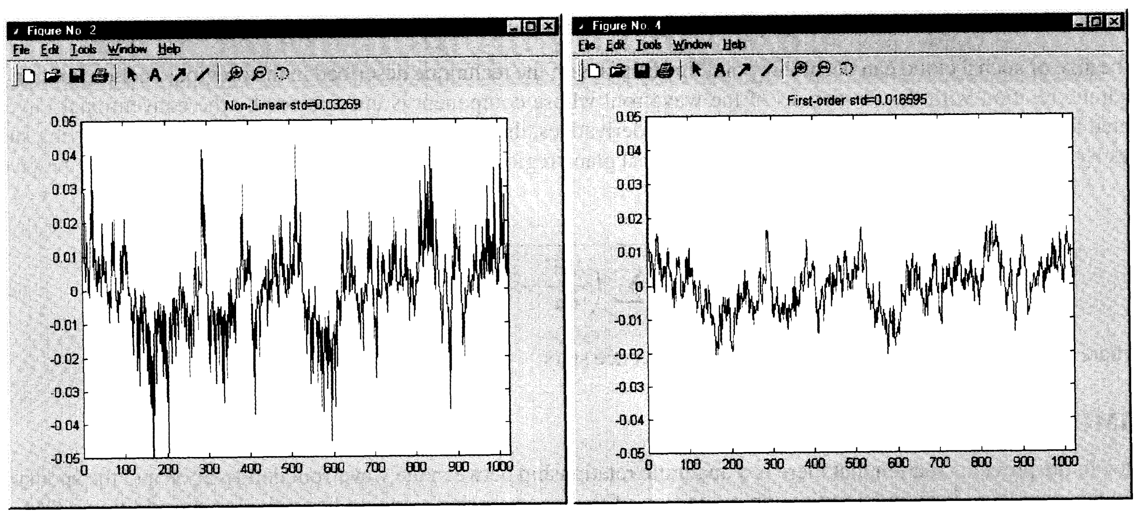

Figure 10. The residual of the correction with the non- linear reconstructor (left side) and with the ideal linear first order system (right side).

7. CONCLUSIONS

We have shown in this article that is possible to introduce an additional Deformable Mirror without a conjugated detector, driven from Layer Oriented informations. A second order measurement of the wavefront is performed without any loss if the RON of the detector is negligible (exactly the cases we are aiming to since we specified from the beginning high Strehl regimes). A good loop performance with quadratic measurement is possible by implementing a crude sign estimator based upon the derivatives of the residual; more sophisticated approaches, for sure possible, will improve the situation. We did not use at all the signal coming from the second detector, thing that will for sure improve the SNR of the reconstructed wavefront. Since that essentially no losses are introduced, a net Sthrel enhancement is obtained basically for free!

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