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Multi Scintillation Layer–Oriented Seeing Monitor

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Abstract. The feasibility of Multi Conjugated Adaptive Optics (hereafter MCAO) is actually the subject of a great number of studies. The three-dimensional reconstruction of the atmospheric turbulence is one of the main goals to achieve optimum correction with MCAO. To obtain the optimal correction it is necessary to properly choose the layer to which conjugate the deformable mirrors (DM). In the framework of dividing the turbulence strength into a small number of layer, but containing most of the turbulence power, we have conceived a seeing monitor based on scintillation measurements, able to optically-separate the turbulence induced by two or more conjugated layers. Using a single star it is shown how one can derive the residual aberrations for an optimum MCAO system with two, three or more DMs conjugated to a specific layer. This is accomplished by conjugating some stop-down to the specific ranges and by means of numerical correlation between the various scintillation measurements. In this way one can estimate the goodness of the MCAO correction for a fixed or variable DMs configuration using a single small telescope observing a single bright star.

1. Introduction

Multi Conjugated Adaptive Optics (MCAO) is progressively turning from basic conceptual ideas (Beckers 1989) to more detailed simulations (Ellerbroek 1994) and, while the related concept of tomography (Tallon & Foy 1990; Ragazzoni, Marchetti, & Rigaut 1999) left the realm of the pure numerical simulation to allow for on–sky verifications in an open–loop fashion (Ragazzoni, Marchetti, & Valente 2000), a closed–loop system on the sky, although in progress (Ellerbroek & Rigaut 2000) is still waiting to become a reality. In such a boiling framework several authors recognize that simple seeing monitoring as devised for non– or conventional–AO based systems is rather insufficent, and in fact other systems to have a 3–dimensional mapping of the turbulence are now being considered as for the SCIDAR (Avila, Vernin, & Masciadri 1997) or for numerical atmospheric models (Masciadri, Vernin, & Bougeault 1999). The general answer to this problem is given by a *profilometer* able to sense the $C_n^2(h)$ profile, within a specified time range and with a certain accuracy, being this the result of a certain complexity both in the construction and in the operation. From the latter point of view, for instance, it is clear that the need for a bright double star is a too much limiting factor, because in practice only a few of such targets are available and heavy restrictions are imposed to the seeing monitoring campaign.

In this paper we propose a different approach, which we are going to describe in the next sections, along with further technical details in the following of the paper. It is to be noted here that the underlying approach adopted for the MCAO case is not strictly the so–called *layer–oriented* (Ragazzoni, Farinato, & Marchetti 2000). We just show which is a possible seeing–monitoring in the framework of an *ideal* MCAO under a given condition (namely the FoV). We just incidentally note that this is automatically accomplished by a layer–oriented MCAO, but the approach described here is definitively not restricted to such a case.

2. Drivers for the concept

From an end user's perspective, the $C_n^2(h)$ distribution is relevant if it is coupled with some further information on how such a distribution is sampled and corrected by an AO or MCAO system. A certain Field of View (FoV) however is usually assumed *a priori*, just because of the scientific requirement or simply because of the projected image on the sky of the imager used. Moreover the details of the MCAO system, at least up to a given level, can already be defined. In particular one should consider a certain number of DMs, realistically two or three, and the possibility to conjugate them in a certain altitudes range. All recent studies on the subject anyway agree that there is little deterioration of the results with even wide displacement in the conjugation of the DMs, provided some basic rules are adopted, like having a DM conjugated to the pupil, or close to the ground, and another at an altitude of the order of $\approx$ 10km. Under this perspective the only relevant figure is the uncorrected amount of turbulence over a given FoV and with a certain DMs configuration. It is easy to see that under the conditions described so far a single DM is able to correct the turbulence layer located exactly, or very close, to the DM itself while for layers at larger and larger distances there is a progressive smoothing out of their spatial features that increases linearly with the distance from such a DM (see Fig.1). Of course in this case we are assuming that the MCAO is well tuned to sample the lowest relevant spatial scale (that of the layer conjugated to the DMs, in the case the latter is also one of the strongest in the region). Furthermore at a certain distance the two DMs will compete each other and one should keep in mind what should be the smaller distance from the nearest DM. Using these assumptions we searched for an optical configuration that is able to provide a first–order signal (in order to improve the SNR of such an approach) proportional to the turbulence strength weighted by the minimum distance from a certain DM. We show now that this can be accomplished in a way not more complicated, or maybe even simpler, than a profilometer. The spirit of this work, just to stress it again, is to describe a seeing–monitor that does not provide a full and detailed $C_n^2(h)$ distribution but a quantitative measurement of the residual of an MCAO working in the most efficient way, when some FoV is selected a priori. We'll see

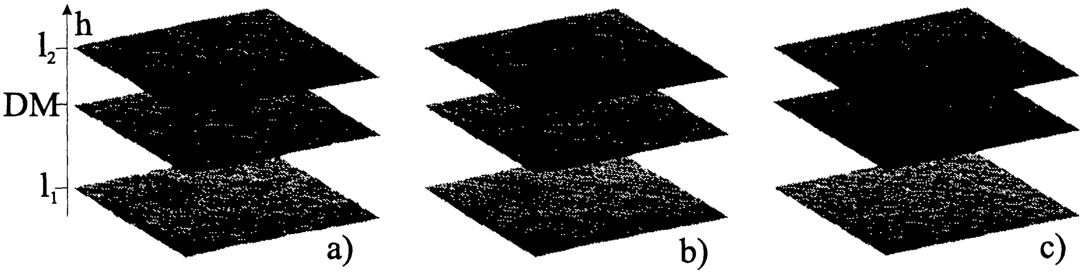

Figure 1. A DM is conjugated at a given altitude and its behaviour with respect to three layers, located exactly on such a conjugated altitude and at two different ranges l_1 and l_2 is shown for an *ideal* MCAO where a given FoV is assumed. The FoV is represented by the aperture of the double cone. **a)**: in principle the DM has the capability to correct completely all the turbulence on the layer located in the *right* place, while there is no chance to do the same for the other two. Any detailed correction for a direction inside the FoV cone would translate into poorer performances in another direction inside the same cone; **b)**: the better approach is, hence, to correct in detail the DM–conjugated layer and to correct only the lowest spatial scales of the other two layers, accordingly to their distances. In other words one has to imagine to use the footprint of the FoV to smear–out the corresponding layers; the larger the distance from the DM the stronger the smoothing; **c)**: the residual becomes a flat wavefront for the DM conjugated altitude and some high frequency residual for the other ones.

in the following that the seeing–monitor is able to generate such a number for any FoV by a simple rescaling of its output, and that a very simple hardware modification allows for the detection of the best DMs altitude conjugation. This can be of relevance not only for seeing–monitoring for site–testing but also for seeing–monitoring to assist MCAO operations at a given telescope.

3. Slicing the turbulence

We can approach the argument starting from some special or favourite cases with the help of Fig.2. We can image to have a very simple atmosphere, made of a single turbulent layer, and a telescope with a photodetector stopped down with a diaphragm (and in the following we will refer to the whole simply as a “diaphragm”). If the diaphragm is conjugated to the height of the layer it would not be able to sense any scintillation, in fact all the dispersed light coming from that layer would be collected from the diaphragm and this is valid for a layer placed on the entrance pupil (as the lowest layer) or at any height, as long as the diaphragm is conjugated at the same height.

In the same ideal situation, a diaphragm conjugated to a different height, with respect to the height of the layer, would sense a scintillation σ increasing with the distance difference Δh between the two heights (the height of the layer and the conjugated one) with $\sigma \propto \Delta h^{\frac{5}{6}}$.

Assume now to have an atmosphere of two separate turbulent layers at different heights, and a seeing monitor with two diaphragms conjugated to these heights: each of the diaphragm, for what we said before, will sense the scintillation due to the other layer, being not affected by the turbulence of its conjugated layer. The signals of the two diaphragms will be completely uncorrelated. It is clear at this point that a third turbulent layer, placed between the previous two layers, will be seen by the diaphragms as a change in the scintillation strength: a correlation will then be found between the two signals.

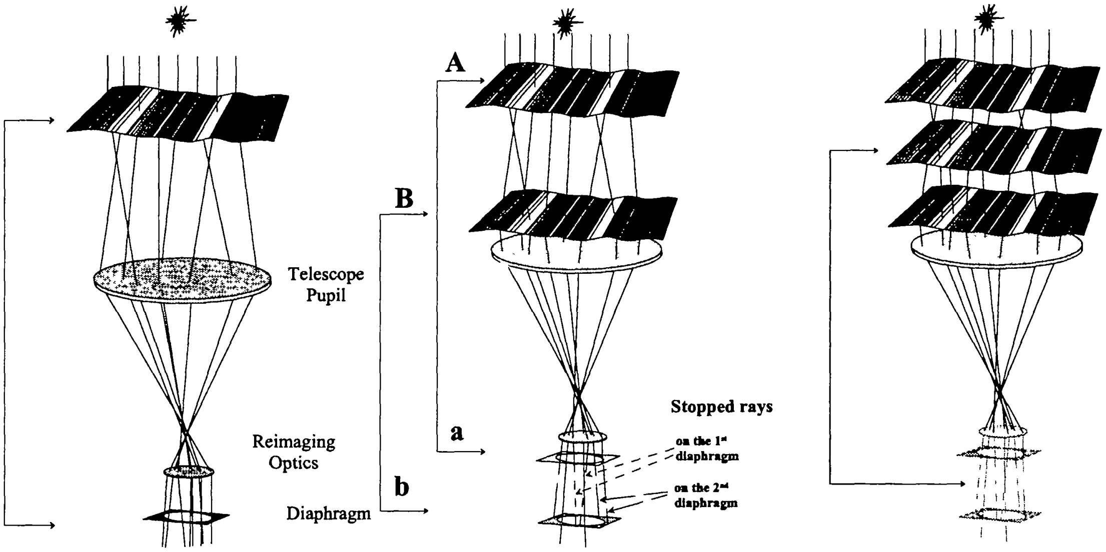

Figure 2. The ideal situations described in the text can be resumed as: no scintillation (left), no correlation (center) and correlation (right)

Obviously the atmospherical distribution of turbulence is not like this, being a continuous media. Anyway, observing a typical $C_n^2(h)$ profile it is possible to consider that most of the power of turbulence is concentrated in a discrete number of a few layers (tipycally 2 or 3). The effect of this assumption is that placing a number of DMs conjugated to compensate the most important layers will produce, as we said before, an amount of residual wavefront deformation which is directly dipendent on how the turbulence is splitted into these few layers and how good is the conjugation of the DMs with respect to the layers (see Fig.3).

4. The seeing monitor layout

A possible layout of the seeing monitor can be seen in Fig.4. The light is collectd using a small telescope, with a diameter of the order of 30cm; after the focal

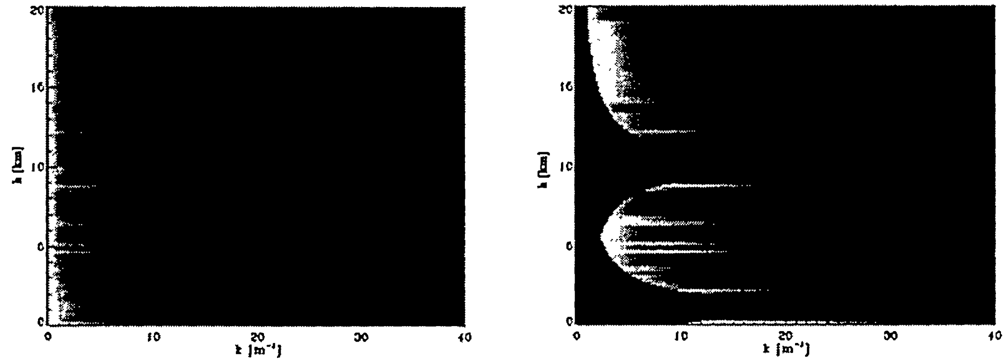

Figure 3. **Left**: in this picture a $C_n^2(h)$ distribution (Tokovinin & Viard 2001) is shown in a bi–dimensional fashion in both h and k ranges, where the latter is the spatial scale where the turbulence occours and a pure Kolmogorov law is assumed. **Right**: The presence of two DMs will allow, accordingly to the description given in the previous figure, to remove all the turbulence at a given altitude and only the larger and larger spatial scale accordingly to the distance of the related layer to the conjugated DM. This translates into the black regions that partially overlap. The seeing monitor described in the text aims to measure directly the residual turbulence

plane a lens collimates the incoming light of a single star towards one or more beam–splitters. A photon counter, stopped down with a diaphragm, can be positioned after each of the separated beams, conjugated at variable distances in order to scan the whole atmosphere.

The simplest signal that is proportional both to the strenghtness of the layer between the two altitudes identified by the conjugation of the diaphgrams and to their distance from the closer altitude is given by the correlated signal between the two photon counters. In practice the recorded signal for each sensor is averaged over a given time interval much larger than the scintillation correlation time, the average is subtracted and the remaining parts are multiplied together. In order to normalize them a root with a power equal to the number of diaphgrams simultaneously recorded is to be accomplished.

5. The simulation

In order to have an idea of how the signal should behave with such a seeing monitor we performed a numerical simulation assuming several turbulent layers and changing the conjugated height of the diaphragms. Each layer is then characterised by its own strength in the turbulence and its own speed and direction. It is to be pointed out that in such a representation it is somewhat equivalent to describe the situation in terms of wavefront instead of rays. The departure of rays from the optical axis is exactly the local tilt of the wavefront from a flat

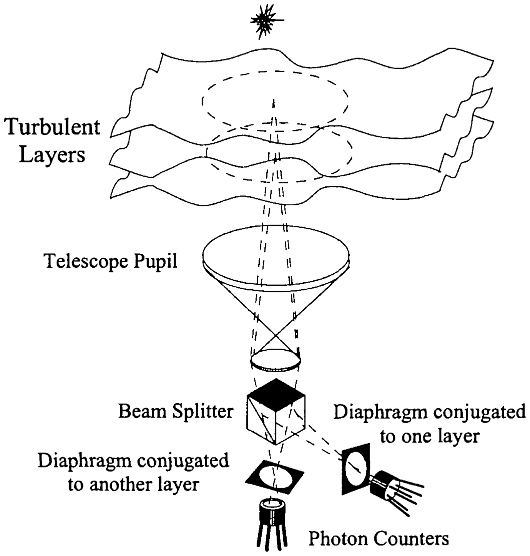

Figure 4. A schematic view of the seeing monitor

one. The larger density of rays can be deduced from the curvature or Laplacian of the wavefront. We prefer, however, to outline the concept using mathematical objects as *rays* other than the *wavefront*, keeping in mind that, at this level, they both describe the same physical reality with the same degree of accuracy imposed by the assumptions above outlined. A beam of light rays disposed on an annulus, with the diameter D of the telescope used as seeing monitor and width ΔR, is ideally sent from the star through a serie of turbulent layers placed at different heights. It is assumed that the layers have a infinitesimal width and after crossing a layer the light is sent, randomly tilted, but straight to the next layer (see Fig.5).

Consider a light ray which is propagating from the star to the seeing monitor; when it crosses a turbulent layer, which at the position X_i produces a phase difference of W_i, the effect is to introduce a tilt on the direction of propagation of $\partial W_i/\partial x$ (monodimensional for simplicity in this case). Considering that the following layer is at a distance $\Delta h_{i,i+1}$ the crossing point on this layer will be

$$X_{i+1} = X_i + \Delta h_{i,i+1} \times \frac{\partial W_i}{\partial x} \tag{1}$$

and so on until the light reaches the telescope (see Fig.5). Once at the telescope pupil the rays are back projected to the conjugated height at which the diaphragm is supposed to be. The back propagation is introduced to simulate the effect of placing a collimating system at the focus of the seeing monitor. Depending on where the diaphragm is set it will be conjugated to a layer at an height h_d, and assuming that the nearest layer to the pupil introduces a perturbation W_n, the projected ray would cross the diaphragm at the position

$$X_d = X_n - h_d \times \frac{\partial W_n}{\partial x} \tag{2}$$

From this it is easy to find, from the whole set of projected ray, the percentage of those who have a position on the diaphragm that is $\leq D/2$ and thus can be seen by the photodetector, and then obtain a measure of the variation, depending on the relative position between turbulent layers and DMs, of the power of the scintillation.

There are, however, some second–order effects that are not described by the formulation given above. In fact one relys on the idea that the diaphragms conjugated to an high altitude layer is perfectly reimaged there so that it acts as a stop at that given altitude. Generally speaking due to the lowest altitude turbulence this is no longer true. In fact the real shape (both along the diameter and in its effective istantaneous altitude) of such a diaphragm reimaged in the upper atmosphere will appear distorted and an apparent scintillation effect will be governed by such a problem. Moreover we have performed such a simulation in pure geometrical ray–tracing, without taking into account any diffraction effect. It is also clear that the relevance of both these considerations scales up when strong turbulence is occourring; a situation, perhaps, where the need for accurate MCAO performance determination is rather less interesting. Detailed simulations are ongoing to define in detail the calibration needs and the noise sensitivity of the described concept.

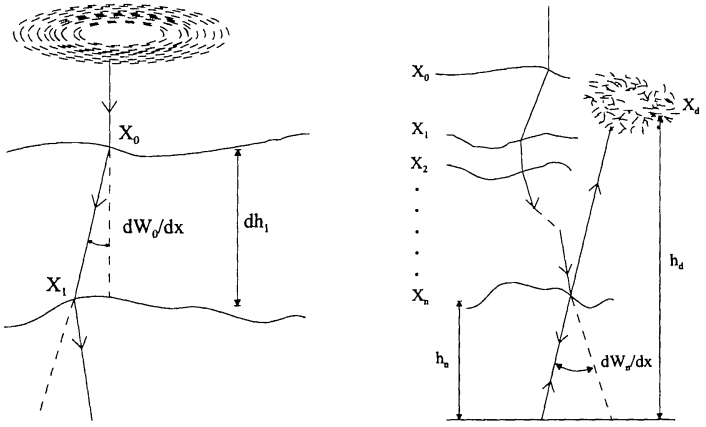

Figure 5. The simulated behaviour of a light ray through turbulent atmospheric layers. On the left figure one can see how each layer deviates the light before it gets to the seeing monitor, while on the right the back projection to the conjugated height, due to the reimaging optics, is shown.

6. Conclusions

It is hard to say, now, which is exactly the type of seeing–monitor one would like to have for next–generation Extremely Large Telescopes, or to tune–up the detailed design of the on–going and planned MCAO systems. There are some wide indication that detailed DM conjugation, variable during exposure time, could lead to only a moderate advantage at the expense of a greater opto–mechanical complexity. The seeing–monitor described here could also be seen as a very rough profilometer. In fact it deliberately introduces on the atmosphere the same type of filtering that should be applied by an optimum MCAO system. This leads to the suggestion that the described approach could be extremely useful especially as a continuous check during MCAO operation: any significant departure between the residual correlated scintillation and the residual wavefront error during science operation will be a strong indication of some potential failure during MCAO operation. In several occasions, working on conventional AO system, this is a crucial and precious information to understand if poor performances are due to improper set up of the AO system or simply due to the atmospheric conditions sometimes changing in an intriguing and hard to simplify way.

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