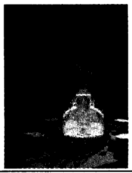
Venice 2001
Beyond
Conventional
Adaptive
Optics



Multiple Field of View Layer Oriented

R. Ragazzoni [a], E. Diolaiti [b], J. Farinato [c], E. Fedrigo [c], E. Marchetti [c], M. Tordi [a], D. Kirkman [d]

[a]Osservatorio Astronomico di Padova, vicolo dell'Osservatorio 5, I-35122 Padova, Italy
[b]Dipartimento di Astronomia, Università di Padova, vicolo dell'Osservatorio 2, I-35122 Padova, Italy
[c]European Southern Observatory, K. Schwarzschild Str. 2, D-85748 Garching, Germany
[d]Center for Astrophysics and Space Science, UCSD, MS0424, La Jolla, CA 92093-0424 (USA)

ABSTRACT

In layer oriented MCAO the same number of detectors and Deformable Mirrors are conjugated to a specific layer on the sky and collect light from a number of references, coadding them simultaneously and in an optical way. The correction achieved is perfect for the conjugated layer and it is limited to the smaller spatial frequencies for the layers within the DMs, approaching the optimum when a certain Field of View is considered. Here we introduce a further step, namely the use of different Field of View for the different DMs. In this way stars from an anulus are taken to correct for the ground layer, while stars within a certain patch are used to correct for the high altitude layers and for the residuals due to the not perfect correction on the ground volume (because of the large FoV used there). We show, along with an optomechanical design of such an approach, that in this way one can easily reach 30% of sky coverage near the Galactic Poles without using any sort of gain introduced by the use of pyramid wavefront sensor, limiting the number of stars to the 20 brightest and assuming an overall efficiency of the order of 10%. The result in term of Strehl is of the order of 0.2 at 800nm over an average continuum C_n^2 profile distribution at Paranal (as devised from literature data). Extension to 100m class telescopes and the use of pyramid WFS are briefly discussed.

1. INTRODUCTION

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 (Ragazzoni 2000 - Ragazzoni, Farinato & Marchetti 2000). Several reference stars are simultaneously sensed by a single WFS with one or more detectors that can be optically conjugated to a specific 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 which is increasing with the distance from the above mentioned DMs conjugated altitudes. Layer–oriented MCAO has been studied both with regards to stability (and it is essentially equivalent to the global reconstructor MCAO approach - Diolaiti, Ragazzoni & Tordi 2001) and with regards to the quality of the achievable correction (Ragazzoni & Ghedina 2000), which has been found to be optimum at least in the linear sense. This approach allows for extremely efficient closed loop operation, being the N–loops (where N is the number of DMs) completely independent: in fact, the spatial and temporal sampling can be tuned to match the properties of the turbulence in that specific volume, i.e. larger r_0 for the high altitude layers and lower wind speeds for the layers closer to the ground one. Another advantage is coming from the fact that the complexity of the system is scaling with the number of DMs present in the system rather than with the number of references (as it is in the global reconstructor MCAO approach - Ellerbroek 1994), which can be optically co–added on the detectors thus taking advantage also from the light coming from very faint stars. Moreover, the choice of the Pyramid, that can give significant gains in term of limiting magnitudes (Ragazzoni & Farinato, 1999) as wavefront sensor could improve even more the performance of the system.

In this article we introduce a farther evolution of the Layer–Oriented approach called Multiple Field of View Layer–Oriented. We will completely forget of all the possible advantages mentioned before related to the classical Layer–Oriented technique, but nevertheless we will show that this new approach allows for relevant sky coverages, approaching the full sky on the galactic equator. Of course all the possible advantages mentioned in this introduction, when taken into

---

Further author information: Send correspondence to R.R.: E-mail: ragazzoni@pd.astro.it account in evaluating the performance of such a system, will only improve even more the performance in term of sky coverage that we are going to find, and a section will be dedicated to the computation of the advantages of a Pyramid–based system. Finally, an example of an opto–mechanical design will be shown.

2. THE MULTIPLE FIELD OF VIEW CONCEPT

As we mention in the introduction, in the Layer–Oriented concept one very important feature is the possibility to co–add the light in a way that even the light coming from very faint references can be used for the sensing process. In a certain sense, this means that the concept of limiting magnitude, common for the classical Adaptive Optics systems, is substituted by the concept of photon density at a given layer. In fact the capability of co–adding the light gives the possibility to have the system working in SNR conditions better than the one typical of simple AO and classical MCAO systems.

There is anyway a limitation in the gain that the Layer–Oriented technique can achieve due to the increase of photons in a given layer. In fact, considering a layer at a certain altitude, the overlapping of the projection of the entrance telescope pupil at that altitude is decreasing with the increasing of the considered FoV, and of course the higher is the layer the smaller is the overlap, which is the area where the system is taking advantage of the photons co–adding. This suggests the existence of a certain limiting angle, that will be referred in the following as θ_γ. Moreover, it has to be recalled that arbitrarly increasing the FoV translates into a worse correction efficiency in the portion of atmosphere far away from the conjugated planes. In fact a non-conjugated layer can be corrected only up to a spatial frequency inversely proportional to the FoV size and to the distance from the closest DM. The larger the FoV, the worse the correction of such a layer.

At this point, the attention should immediately go to the fact that this is not a problem at all for the ground layer when conjugated to the telescope pupil (where there is perfect overlap between every reference footprint) and for all the layers which are close to the ground, where the overlap is still very high! So why not considering a bigger FoV for the detectors conjugated to the lower layers? Provided that the optical realization of the system is feasible (increasing the FoV means to take particular care in the optical design of the system), there would be a huge gain in term of photons collected on these detectors! And even if this fact cannot be used for the higher layers, for sure there the system can take advantage from the unique Layer–Oriented feature of the tuning of completely independent loops. In other words, the system can take advantage of the spatio–temporal sampling gain offered by the high altitude portions of the atmosphere, where r_0 can be significantly bigger than the typical values of layers close to the ground one. Roughly speaking, an increase of the local r_0 translates into a photon collection increase that scales with the third power of such an increase. In fact the usable portion of the pupil scales as r_0^2, while the integration time scales linearly, leading to the cubic power scaling law. The local r_0 of the ground layer is quite close to the r_0 of the overall atmosphere and this explains the limited gain achievable in this case.

To summarize, the Multiple–FoV Layer–Oriented MCAO concept, for a two DMs system, can be described as follows:

- A nearly–ground layer with a large FoV; this allows for the compensation of the lowest portion of the atmosphere. There will be a substantial gain in photon density, because of the large FoV. On the other hand the collected starlight has to be sampled essentially with the same spatio–temporal sampling of the whole atmospheric column.
- A high–altitude layer with a FoV of the order of the limiting angle θ_γ, where the gain is accomplished through a more efficient spatio–temporal sampling.

In this article we will assume an inner FoV of 1' in radius, representing the *science* field, and an anular FoV with inner and outer radius of 1' and 3' respectively. These figures are just indicative and no optimization has been performed. It is worth of note that only the small portion of the FoV is fully corrected, at least in a MCAO sense. The anular region concerning the larger FoV is corrected only for ground turbulence and, although both compensations will work in a closed loop fashion, the achieved correction will be limited on the anular and larger FoV. As the anular FoV is working in closed loop with no correction of the high altitude portion of the atmospheric turbulence, the correction of the ground layer will be, moreover, perturbated by the high altitude layers. Strictly speaking the introduced compensation should correct (at least in the high SNR regime) the ground turbulence and should apparently replace it with superimposed replicas of the high altitude layers. That means that, after the ground turbulence correction, some very low spatial frequency residual will still be introduced. Although the physical origin of these residuals is in the high altitude layers, they will appear optically, inside the MCAO system, as coming from the ground. In other words, the effect of the layer–oriented closed loop conjugated on the large FoV on the ground will replace the ground layer with a smoothed version of the high altitude turbulence.

An example of a practical implementation of the system is presented in Fig. 1 and in Fig. 2, where the system is realized with two DMs and three detectors. The two DMs are conjugated with the ground and the high altitude layer. The

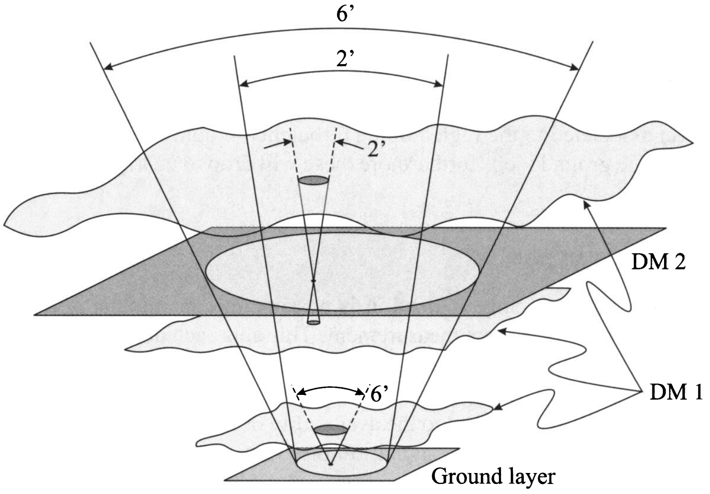


Figure 1. A MCAO system with two DMs is considered. One DM is conjugated to the ground, or very close to it, while the second is conjugated at a certain altitude. The correction for the first DM is driven by using reference stars embracing a FoV of, in the described example, 6 arcmin, while the second DM is driven by a second set of reference stars embracing a smaller FoV, in the drawing of 2 arcmin. Layers not exactly conjugated to the DMs will be corrected only at spatial frequencies lower than the ones defined by the footprints of the beams embracing the selected stars. In this way the correction performed by the DM with a larger FoV will degradate more rapidly with the distance of the layer from the altitude where the DM is conjugated. Three layers are shown with the footprint of the beam of the closer DM, just to simplify the layout.

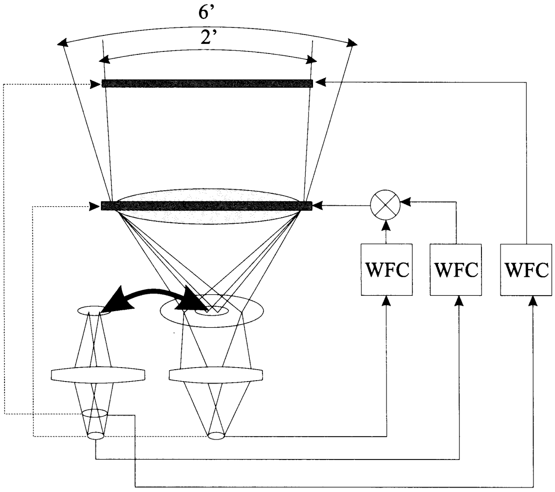


Figure 2. Schematic layout of the Multiple FoV system, with two DMs and three detectors. The signal of the two detectors conjugated to the ground is sent to the same DM.

first detector is conjugated to the ground layer, looking at a ring projected on the sky with inner radius 1' and outer radius 3', with spatial and temporal samplig typical of the lowest part of the atmosphere at the wavefront sensing wavelength, assumed to be 0.8μm. The second detector is again conjugated to the ground, looking at a circular FoV of 1' radius with spatial and temporal sampling tipical of the highest part of the atmosphere, suitably tuned in order to take into account the smoothing effect of the wavefronts, due to the superimposition of the star footprints in the anular FoV. The third detector is conjugated to the high altitude layer, looking at the same circular FoV of 1' radius of the previous detector, with spatial and temporal sampling typical of the highest part of the atmosphere. The signal of the first two detectors, conjugated to the ground, is sent to the same DM.

Even though a complete analysis of the loop stability of such a system is beyond the scope of this paper, we just note that the ground layer loop, associated to the 6′ FoV, is likely to be very robust, due to the high number of reference stars, translating into a high SNR, and to the fact that the star fooprints overlap perfectly on the telescope pupil, hence the photon density is uniform. Furthermore the major contribution to the overall turbulence is usually concentrated in the ground layer and the effect associated to the high altitude turbulence should be negligible, or at least not sufficiently strong to perturb the stability of the ground loop (furthermore these will drop to nearly zero once the whole set of loops is closed).

3. SKY COVERAGE COMPUTATION

Once the number of DMs and conjugation range is fixed, it is possible to compute the power spectrum of the residual turbulence (Fig. 3) under the hypothesis of perfect measurement. This approach defines the best achievable performance and establishes an upper limit on the Strehl Ratio (SR), which amounts to SR$\approx$ 0.2 in the case of Fig. 3. The actual performance is limited by various factors, including noise, fitting error, finite temporal bandwidth. Among these sources of performance degradation, the noise is closely related to the availability of reference sources in the FoV, which determines the photon density on the conjugated layers and the signal-to-noise ratio on the corresponding detectors. According to this discussion, we have defined the sky coverage as the fraction of sky where the average SR across the science FoV is at least 50% of the ideal SR achievable in the noise-free case.

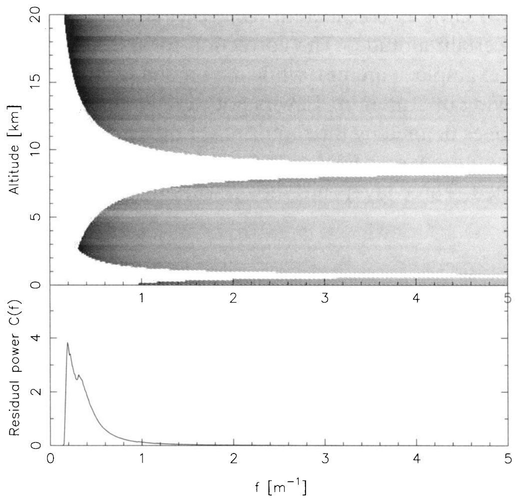


Figure 3. A plot of C_n^2 vs. both altitude h and spatial frequency k with the portion deleted from a couple of DMs, represented by the empty bands. The DMs are conjugated respectively at 800m and $\approx$ 8km. The turbulence at the conjugated altitudes is completely removed, while in the intermediate planes it is compensated only up to a given spatial frequency, because of the smoothing effect associated to the covered FoVs. The DM conjugated to the ground adopts a larger FoV and hence the degradation of the correction is faster than for the other DM, characterized by a smaller FoV. In this picture the DMs are driven by a Multiple–FoV layer oriented AO with respectively 6′ and 2′ FoV. The bottom graph shows the integral along h of the residual turbulence.

	worst	best
$r_{0,U}/r_{0,L}$	2	3
$v_{w,L}$ [m/s]	10	10
$v_{w,U}$ [m/s]	30	20

Table 1. Main features (Fried parameter r_0 and wind speed v_w) of the atmospheric turbulence profile adopted in the sky coverage computation. The terms lower (L) and upper (U) refer to portions of the atmosphere respectively below and above h = 5km. The overall r_0 corresponds to a seeing of 0.6″ in the V band.

In our calculations we have considered a turbulence distribution with an overall r_0 corresponding to a seeing of 0.6″ in the V band (0.5μm). Two cases have been considered (Tab. 1), characterized by different turbulence distribution among the lower and upper portions of the atmosphere. We have adopted a Multiple-FoV system with two DMs, conjugated at 0 and 8Km, and three detectors, each with spatial and temporal sampling approximately tuned to the corresponding atmospheric slabs. An overall photon collecting efficiency of 0.1 has been assumed. The stars distribution in the sky has been modeled according to Bahcall & Soneira (1981) at a wavefront sensing wavelength of 0.8μm; for each field of interest, at most the 20 brightest available stars have been considered. Finally we have implemented the noise propagation coefficients of the Shack-Hartmann WFS, according to Rigaut & Gendron (1992), considering the effect of both photon and read-out noise. The main result of our calculations (Tab. 2) is that, in the case of low read-out noise and good turbulence conditions, the sky coverage in regions near the Galactic plane is close to the whole sky and decreases to $\approx$ 50% at the Galactic Pole, a rather large value indeed, considering the much lower density of stars. When a higher read-out noise and worse atmosphere is considered, the above fractions decrease respectively to $\approx$ 50% and $\approx$ 10%, still rather interesting figures.

	$b = 90°$	$b = 50°$	$b = 20°$
RON = $5e^-$	0.08 ... 0.21	0.16 ... 0.42	0.46 ... 0.96
RON = $1e^-$	0.24 ... 0.47	0.38 ... 0.72	0.86 ... 0.99

Table 2. Sky coverage for different values of read-out noise, as a function of the Galactic latitude b. The range of sky coverage reported in each case refers to the worst and best turbulence conditions described in Tab. 1. We have implemented here the noise propagation coefficients of a Shack-Hartmann WFS.

4. MFOV OPTIMIZATION AND GENERALIZATION

We said at the beginning that the computation of the sky coverage performed in this article would have been done without taking into account a number of interesting feature typical of the Layer–Oriented concept. We will try in this section to identify the fundamental elements that will improve any MFoV layer-oriented based system when properly considered.

First of all, any kind of pupil–plane wavefront sensor is particularly suitable (but not the only possible) for the layer-oriented technique. Due to the advantages in term of sensitivity (Ragazzoni & Farinato 1999), the usage of a Pyramid WFS in a MFoV system improves the performance. In Tab. 3 we report the updated results in term of sky coverage due to the use of the Pyramid, obtained assuming no gain in the large FoV anulus (where only low Strehl is achieved due to the partial correction) and only a moderate gain in the central FoV (according to Esposito & Riccardi 2001).

	$b = 90°$	$b = 50°$	$b = 20°$
RON = $5e^-$	0.12 ... 0.27	0.23 ... 0.53	0.67 ... 0.99
RON = $1e^-$	0.33 ... 0.55	0.54 ... 0.79	0.97 ... 1.00

Table 3. Sky coverage values considering the limiting magnitude gain of the Pyramid WFS. Symbols and definitions are as in Tab. 2.

Another point that we want to emphasize is that the choice adopted for the references selection (the 20 brightest) might not be the optimal one. In fact, the uniformity of the field is an important criterion that could lead to different choices, since the layer-oriented technique gives more weight to the brighter stars. Moreover, in the MFoV case, a degree of freedom more is introduced from the fact that we consider different FoV, and also in this case there might be better choices than considering the same number of stars in the different FoVs.

Furthermore, the overall optimization of the system will of course play an important role in its final performance. A number of parameters has been selected doing reasonable choices, but no attempt of optimization has been performed:

- The size of the different FoV is important to maximize the compromise between overlapping of the reference footprints and number of photons collected.
- The DMs conjugation altitude is another parameter that will play a role in the achievable sky coverage and Strehl.
- The spatial and temporal sampling must be optimized depending on the Fov area considered and on the conjugation altitude of the DMs.

Finally, we just would like to mention the possibility to scale the system to more than two DMs in case of demanding requirements in term of Strehl, with an almost *natural* extension by considering of course different FoV for every detector: the lower are the conjugation altitudes of the DMs and the bigger is the related detector FoV. In Fig. 4 there is a generalization of the system to three DMs, and we just mention that studies concerning the possibility to reconstruct the signal to be applied to the additional DM without adding the related detector are on–going (Farinato et al. 2001).

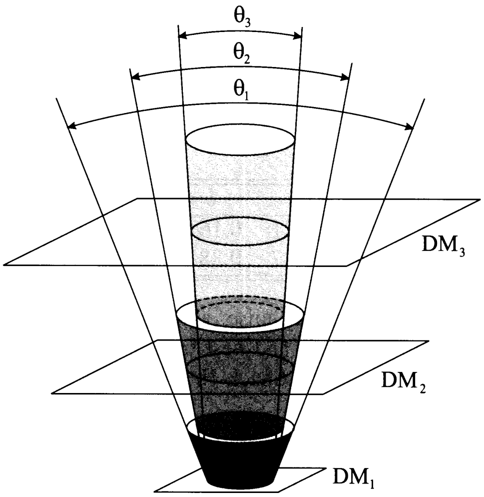


Figure 4. Generalizing the multiple–FoV concepts to more than two DMs, one can conceive different FoVs for each specific DM. Because of the different smoothing of the layers distant from the conjugated planes, the covered volumes, along the range direction, are likely to be roughly inversely proportional to the different FoVs: a smaller range for the larger FoV on the lowest DM, and progressively larger volumes for smaller FoVs at the higher DMs.

5. AN EXAMPLE OF AN OPTO-MECHANICAL DESIGN

We have also conceived a possible optomechanical layout of the Multiple FoV system, shown in Fig. 5. Assuming a typical 8m Ritchey- Chretien telescope, we have first corrected the field curvature by a simple field flattener, ensuring diffraction–limited imaging performance over a FoV of 6'. The beams produced by the pyramids placed on the two focal planes are focused onto the corresponding detectors by means of two F/2.5 optical relays; a fiber taper shrinks the image size by a further factor of 5, in order to match the size of the pupil image to the detector. The imaging performance, optimized in the wavelength range from 0.6 to 1.0 μm, is such that 80% of the total energy is ensquared in a region smaller than 1/10 of the equivalent r_0 size: this ensure that the spatial resolution of the relays is much better than the sub-aperture size for the layer oriented wavefront sensing.

6. CONCLUSIONS

An evolution of the layer-oriented MCAO approach has been described. The basic concept is to adopt a different FoV for the different portions of the atmosphere, in order to maximize the photon density on each WFS. In particular a large FoV is used for the detector conjugated to the ground portion of the turbulence, where the photon density might not always be sufficiently high and, on the other hand, the spatial and temporal sampling gain is moderate; a narrower FoV is adopted instead for the high altitude layers, where the tuning of the spatial and temporal sampling ensures a remarkable gain. The latter FoV, where the best correction is achieved, might be identified with the science field. The new approach allows for a very relevant sky coverage, close to the whole sky on the Galactic Plane and about one third of the sky at the Galactic Pole, using natural guide stars only. This result has been derived adopting conservative assumptions concerning the noise propagation. Furthermore we have not considered a number of key points that might lead to even better results. Among these, we just mention the limiting magnitude gain of the pyramid WFS in closed loop. A possible opto-mechanical layout of a Multiple FoV system with two DMs and three detectors has been shown and some extensions of the concept to more than two DMs have been discussed.

A remarkable property of the new approach is its scalability to ELTs (Gilmozzi et al. 1998; Nelson 2001). In this case, the larger footprint diameter goes in the direction of increasing the overlap in the high altitude layers, ensuring a more

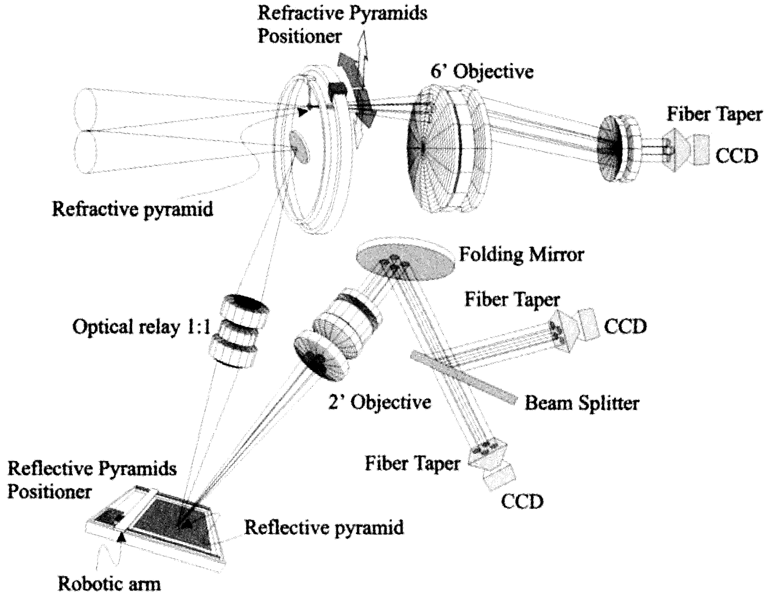


Figure 5. A possible opto–mechanical configuration. The inner, 2 arcmin wide, FoV is folded by a mirror located close to the focal plane of the telescope and sent, through a 1:1 optical relay, to a magnetic positioner of reflective pyramids, that are positioned by a robotic arm to sense the 20 brightest stars. These pyramids reflects the splitted light into an objective and, through a beam splitter, the light is fed to two CCDs conjugated to the ground and high altitude layers respectively. The anulus with external diameter of 6 arcmin interests a number of refractive pyramids positioned by a polar robotic positioner and fed, through a dedicated objective, to a CCD conjugated to the ground layer. Fiber tapers are part of the optical design to obtain reasonable sizes for the pupils to be reimaged onto the CCDs, allowing the usage of commercially available ones.

effective co-addition of the photons from the reference stars and leading to a more uniform photon density. Apparently the major problem concerning ELTs is represented by the size of the WFS optics. Scaling the components presented here for a 8m class telescope results in exceedingly large lenses. However it is possible to modify the optical design (Marchetti & Ragazzoni 2001), in order to keep the size of the lenses to a reasonable level; this can be accomplished with a longer, though straightforward, optical train. Furthermore, new optical solutions (Ragazzoni, Diolaiti & Viard, 2001) have been recently introduced in order to keep optics and especially pupil size on the detector almost arbitrarily low. We do not speculate here on the achievable sky coverage on ELTs, also because a further bunch of degrees of freedom can be introduced, making an overall optimization necessary.

ACKNOWLEDGMENTS

Thanks are due to Piero Salinari for the useful comments on the subject discussed in this paper.

REFERENCES

Bahcall J. N., Soneira R. M., “The universe at faint magnitudes. I - Models for the galaxy and the predicted star counts”, *ApJS* **44**, p. 73B, 1980.

Diolaiti E., Ragazzoni R., Tordi M., “Closed loop performance of a layer-oriented multi-conjugate adaptive optics system”, *A&A* **372**, p. 710, 2001.

Ellerbroek B. L., “First-order performance evaluation of adaptive-optics systems for atmospheric-turbulence compensation in extended-field-of-view astronomical telescopes”, *JOSA A* **11**, p. 783, 1994.

Esposito S., Riccardi A., “Pyramid Wavefront Sensor behavior in partial correction Adaptive Optic systems”, *A&A* **369**, p. L9, 2001.

Marchetti E., Ragazzoni R., “Opto-mechanical design of a layer-oriented WFS for a 100m aperture”, this conference.

Nelson J.E., *SPIE* **4004**, p. 282, 2001.

Gilmozzi R., Delabre B., Dierickx P., Hubin N., Koch F., Monnet G., Quattri M., Rigaut F., Wilson R.N., "Future of filled aperture telescopes: is a 100-m feasible?", *SPIE* **3353**, p. 129, 1998.

Ragazzoni R., Farinato J., "Sensitivity of a pyramidic Wave Front sensor in closed loop Adaptive Optics", *A&A* **350**, p. L23, 1999.

Ragazzoni R., "Adaptive optics for giant telescopes: NGS vs. LGS", in *Proceedings of the Backaskog workshop on extremely large telescopes*, T. Andersen, A. Ardeberg, R. Gilmozzi, eds., *ESO conference and workshop proceedings* **57**, p. 175, 2000.

Ragazzoni R., Farinato J., Marchetti E., "Adaptive optics for 100-m-class telescopes: new challenges require new solutions", *SPIE* **4007**, p. 1076, 2000.

Ragazzoni R., Ghedina A., in IAU technical meeting on "Astronomical Site Evaluation in the Visible and Radio Range", in press, 2001.

Ragazzoni R., Diolaiti E., Farinato J., Fedrigo E., Marchetti E., Tordi M., Kirkman D., "Multiple Field of View Layer Oriented Adaptive Optics", *A&A*, Accepted, 2001.

Ragazzoni R., Diolaiti E., Viard E., "Arbitrarily small pupils in layer-oriented adaptive optics", *PASP*, submitted, 2002.

Rigaut F., Gendron E., "Laser guide star in adaptive optics - The tilt determination problem", *A&A* **261**, p. 677, 1992.

Rigaut F., *Ground-Conjugate Wide Field Adaptive Optics for the ELTs*, this conference.