Is ESO's adaptive optics facility suited for MCAO?

Enrico Marchetti*[a], Paola Amico[a], Enrico Fedrigo[a], Andreas Glindemann[a], Norbert Hubin[a], Paolo La Penna[a], Miska Le Louarn[a], Pierre-Yves Madec[a]

[a]European Organization for Astronomical Research in the Southern Hemisphere, Karl-Schwarzschild-Str. 2, D-85748 Garching bei München, Germany

ABSTRACT

As of 2013, the ESO's VLT will be equipped with the Adaptive Optics Facility for Ground Layer and Laser Tomography adaptive optics assisted imaging and spectroscopy, using a Deformable Secondary Mirror and four Laser Guide Stars. Following the successful experience of the MAD demonstrator, we initiated a speculative study to evaluate the performance gain obtained by implementing a type of Multi-Conjugate Adaptive Optics correction that benefits from the unique features provided by the AOF. In this paper we present the basic concept and provide a first estimation of the correction performance obtained in the near infrared.

Keywords: Multi-Conjugate Adaptive Optics, Laser Guide Stars, Deformable Secondary Mirror

1. INTRODUCTION

Multi-Conjugate Adaptive Optics[1][2] (MCAO) is a powerful adaptive optics technique to enlarge the corrected FoV by means of Deformable Mirrors optically conjugated at different altitudes in the atmosphere above the telescope. The MCAO has been successfully demonstrated on sky by the MCAO Demonstrator MAD[3][4], enabling the implementation of such systems on 8-10 m class and Extremely Large telescopes.

The Adaptive Optics Facility[5] (AOF) will be located at VLT and starting on sky operations in 2013. It will perform GLAO (GRAAL and GALACSI wide field mode) and LTAO (GALACSI narrow field mode) correction by means of a Deformable Secondary Mirror (DSM), replacing the actual M2 of the telescope, and four Sodium Laser Guide Stars (LGS) as sources for wavefront sensing.

When in operation, the AOF will naturally provide all the needed infrastructures to accommodate a MCAO module for delivering wide field high level atmospheric turbulence correction. The MCAO module will also benefit from all other AOF side developments, such as wavefront sensor (WFS) detector cameras and the standard Real-Time Computer platform, which at the time of the implementation at the telescope will be fully functional.

The MCAO module speculative concept presented here has been developed exactly in the framework of maximizing the use of already existing infrastructures and critical components and minimizing the additional effort in developing its design, construction and on-sky operations.

2. HYBRID MCAO MODULE STRAW MAN CONCEPT

The Hybrid MCAO module concept (HM hereafter) is based on two decoupled atmospheric correction loops for the ground and the higher altitude turbulence.

The working principle, recalling the Layer Oriented[6][7] concept, is based on the fact that the largest part of the atmospheric turbulence is located in proximity of the ground: the correction for this layer is the most demanding in terms of spatial and temporal resolution and it requires a large number of sub-apertures for wavefront sensing, a large number of actuators for correction and high frequency loop rates to reduce the loop delay. All those constraints transfer into a need of very luminous guide stars to be seen by the wavefront sensors. On the contrary, the high altitude layers require much relaxed spatial and temporal sampling being there the contribution of the turbulence less important, and consequently less demanding in terms of guide stars flux.

*emarchet@eso.org; phone +49 89 32006458; fax +49 89 3202362; www.eso.org

In this framework we have conceived a system where the ground loop wavefront sensing is provided by GRAAL[8] (large number of sub-apertures), opportunely modified to acquire the LGS (large flux) located on a smaller FoV, and correction is provided by the DSM (large number of actuator) respectively (see Figure 1). The high altitude loop wavefront sensing and correction is assured by Natural Guide Star (NGS) visible low order Shack-Hartmann WFS and low order post focal Deformable Mirrors (DM) conjugated at a given altitudes above the telescope. The NGS WFS/science beam is not vignetted by the LGS WFS of GRAAL. The NGS WFS are positioned at the NGS by means of an acquisition camera looking at the full FoV. A coupling between the two loops can be foreseen for offloading low temporal and spatial frequency aberrations from the high altitude loop to the ground one.

The module hosting the main optical relay, the post focal DM, the NGS WFSs and the interface to the scientific instrument is supported by a fixed optical table located at the Nasmyth platform (actually occupied by the infrared wide field imager HAWK-I). The field rotation compensation is assured by an optical derotator (before the DM) which serves both the NGS WFS and the scientific instrument. A Visible/Infrared dichroic separates the optical beam in the two spectral ranges.

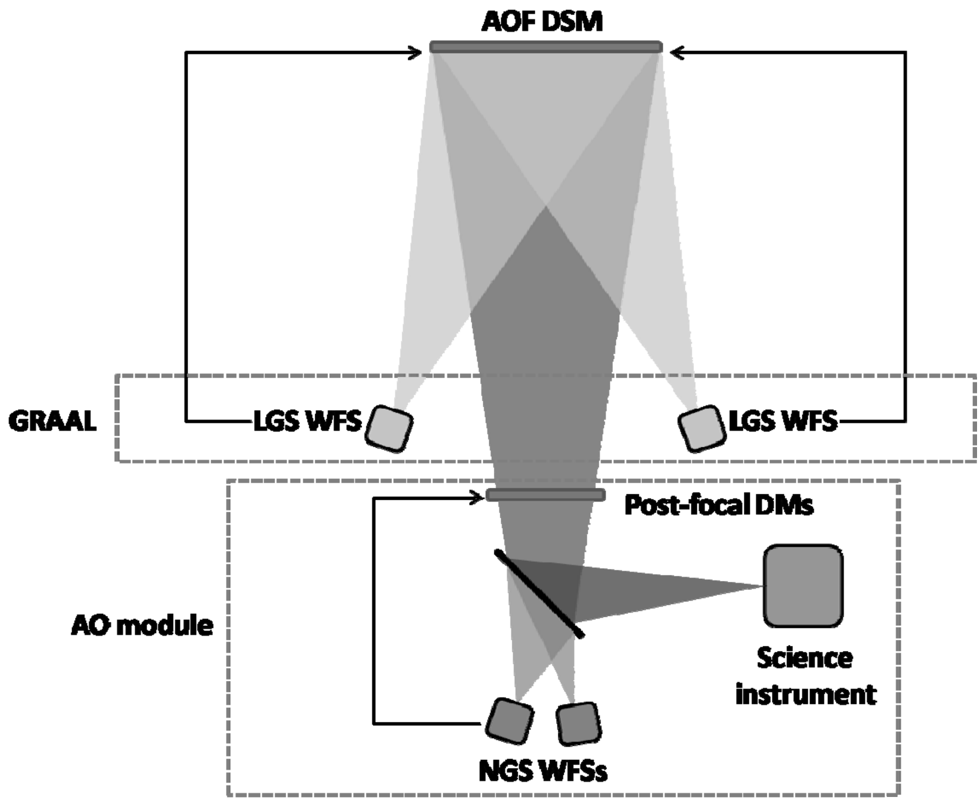

Figure 1. Concept scheme of the Hybrid MCAO module.

2.1 Ground layer loop

The ground loop is driven by the GRAAL system (see Figure 2). All the GRAAL main components are recycled: WFS cameras and controller, Real-Time Computer, Instrument Control Electronics, DSM and Control Software. Opto-mechanical modification are required to put the LGS WFS arms closer to the focal plane axis in order to acquire the LGS located on a 3 arcmin diameter FoV (originally at ~7 arcmin diameter) without vignetting the internal 2.5×2.5 arcmin FoV which has to go through without any interference (apart obviously the GLAO correction, see Figure 2). The GRAAL system is run stand alone in the foreseen GLAO mode as for the AOF.

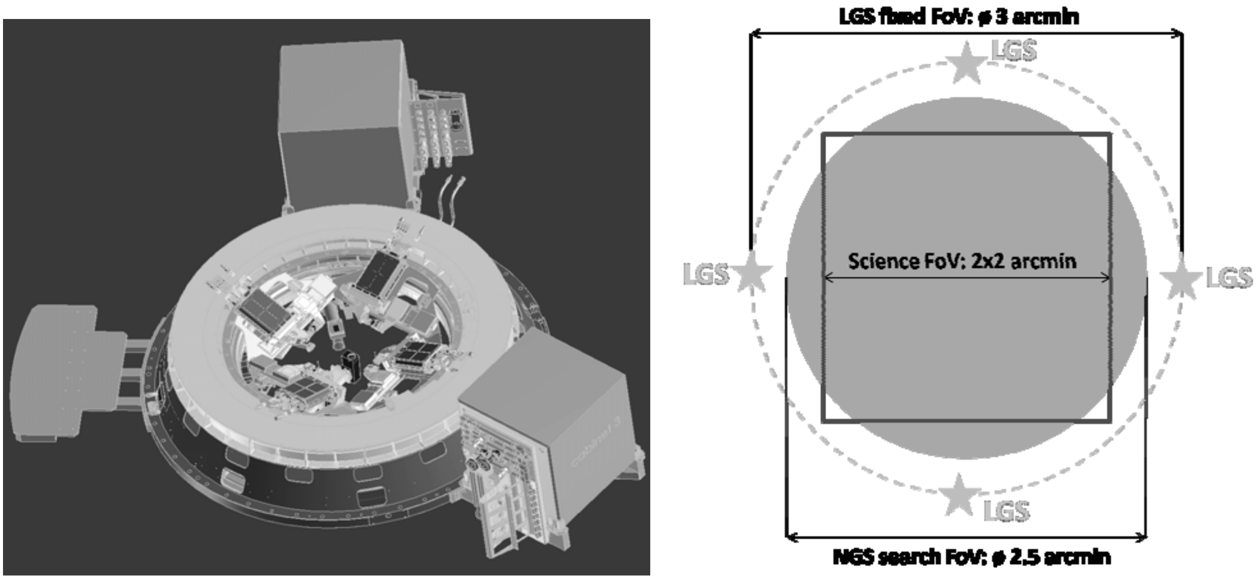

Figure 2. Left: GRAAL module for the AOF. Minor modifications are required to bring the LGS WFS probes closer to the FoV center. Right: LGS, NGS and science FoV configuration for the hybrid MCAO module.

2.2 AO module opto-mechanical bench

The bench supports the optical derotator (standard K mirror), the main relay optics, the post focal DM, the NGS WFSs, the interface to the scientific instrument and eventually the calibration unit located at of the telescope focus. The bench is supported by a dedicated structure in order to elevate the optical axis to the level of the one of the telescope. An insertable calibration unit for the HM internal calibration can be envisaged to be located in proximity of the VLT Nasmyth focus. The calibration unit is fed by illuminated fibers. A focussing mechanism to compensate for the focus mismatch between the NGS WFS and science channels can be foreseen.

2.3 NGS wavefront sensor system

It consists of three visible low order Shack-Hartmann WFS which can be freely located with high positional accuracy by two translating functions in the 2.5 arcmin diameter FoV to pick up any useful NGS. The WFS cameras are based on commercially available L3Vision EMCCD[9] based cameras. An acquisition camera enables the correct positioning on the NGS. The first order specifications for the NGS WFS system are given in Sect. 4.1.

2.4 Post-focal deformable mirrors

Two low order post-focal Deformable Mirrors conjugated at 8 and 4km altitude above the telescope assure the high atmospheric turbulence correction. Both DMs are relatively low order since the associated turbulence is weaker than the one at the ground. The stroke is also quite relaxed since the already low high turbulence is shared between the two DMs. In the innovative concept here presented the DMs can be powered optics of the optical train. The first order specifications for the post-focal DMs are given in Sect. 4.2.

2.5 Real-Time computer

It is based on SPARTA[10] light system part of the Real-Time computer platform developed at ESO in the framework of the AOF. Minor hardware/software development is required for the NGS WFS cameras interface and multiplexer.

2.6 Instrument Control electronics and software

They are based on standard ESO components/software. About 10 moving functions are foreseen. In total two standard cabinets will host all the HM module electronics: one cabinet for RTC, DMs high voltage amplifier, NGS WFS camera interface, the other is for the Instrument Control and the Acquisition Camera.

3. OPTICAL DESIGN

An example of optical layout for the HM is shown in Figure 3. No extensive optimization has been carried out for better accommodating the optical relay in order to provide the most suitable volume for the NGS WFS system and the scientific instrument.

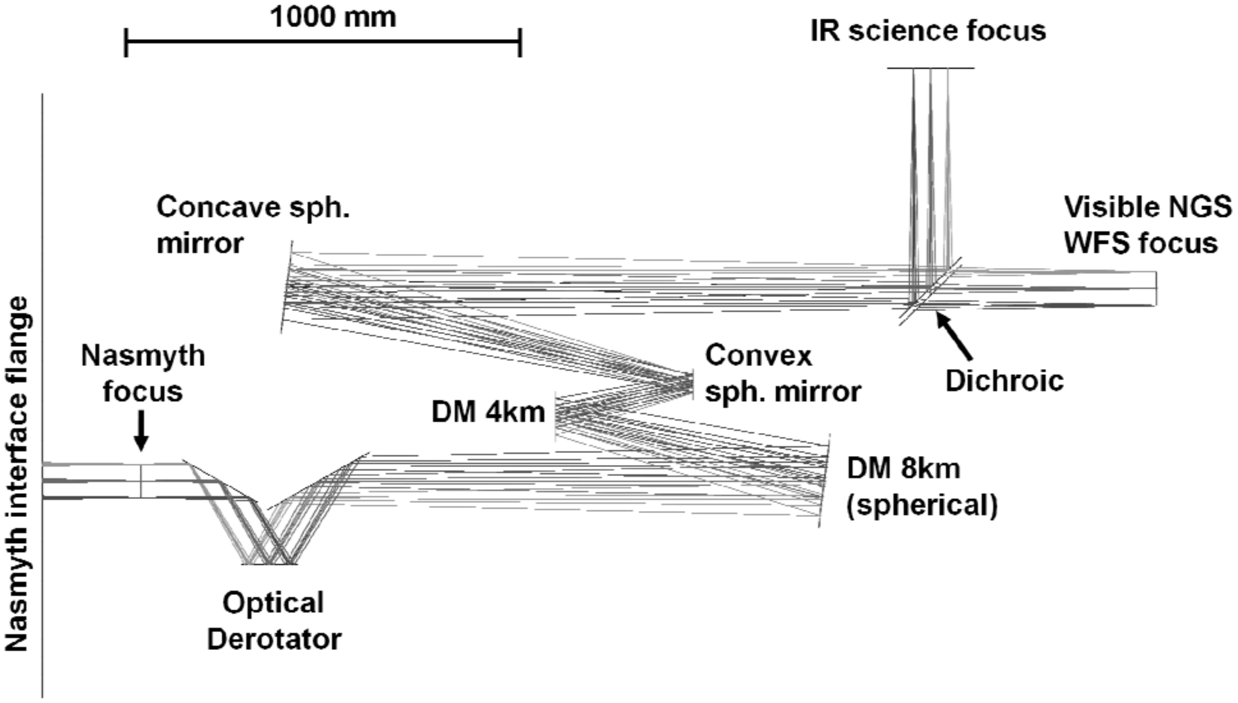

Figure 3. Proposed optical layout for the Hybrid MCAO module.

The transmitted FoV is 2.5×2.5 arcmin (un-vignetted by the GRAAL LGS WFSs). The optical derotator is located just after the Nasmyth focus. Then an Offner relay provides to re-image the VLT Nasmyth focal plane toward the NGS WFS and the scientific instrument with focal ratio F/14.4. The focal plane distortion is almost negligible (0.006%).

The first spherical mirror (concave, radius of curvature 2104 mm) is also the 8 km conjugated post-focal DM: this is a quite innovative concept which has been already successfully prototyped by CILAS for ESO (see Sect. 4.2). The second post focal DM is flat and conjugated at 4 km. The Offner relay is typically much less demanding in terms of optical misalignment relaxing the tolerances in the design of the supporting mechanics. The optical quality of the re-images layers on the DMs is within acceptable values: the blurring RMS is 1% and 3.5% of the inter-actuator pitch respectively for the 8 km and 4 km conjugated DMs.

A dichroic, with wedge of 0.7°, transmits the visible beam (wavelength < 1 μm) to the NGS WFS and reflects the IR beam (wavelength > 1 μm) to the scientific instrument.

The optical quality at the infrared and visible focal planes is shown in Figure 4 and Figure 5 respectively: in both cases the performance are diffraction limit in the whole field. The chromatic shift at visible wavelengths due to the dichroic is ~0.05 arcsec Peak to Valley (PTV) for the whole FoV the in the wavelength range between 0.5 and 0.9 μm.

The view of the optical train accommodated on the Nasmyth platform is shown in Figure 6. The total envelope of the optical train alone is not exceeding the 3×2×0.5 m and allows enough space around the supporting bench for allocating the science instruments, the electronics cabinets and the comfortable human accessibility to all components.

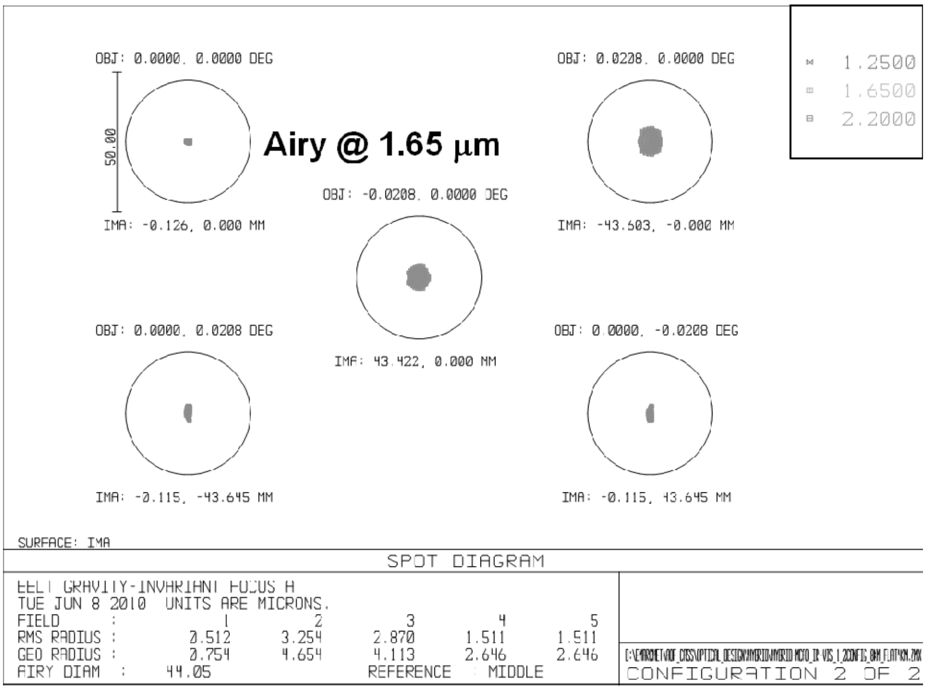

Figure 4. Spot diagrams for the infrared scientific path.

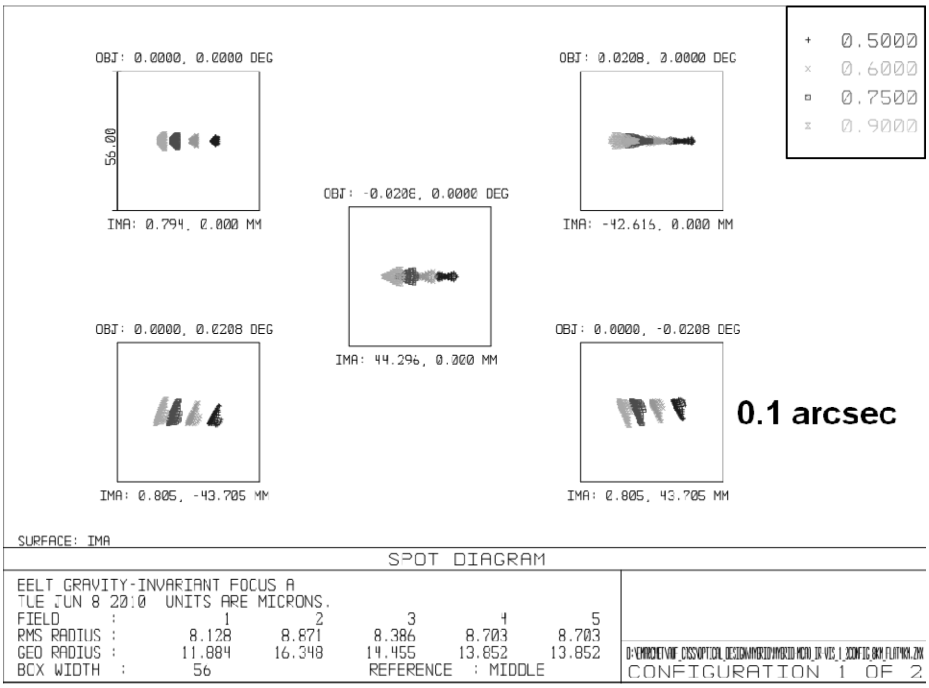

Figure 5. Spot diagrams for the visible NGS WFS path. The chromatic shift induced by the dichroic is not larger than 0.05 arcsec PTV in the whole field.

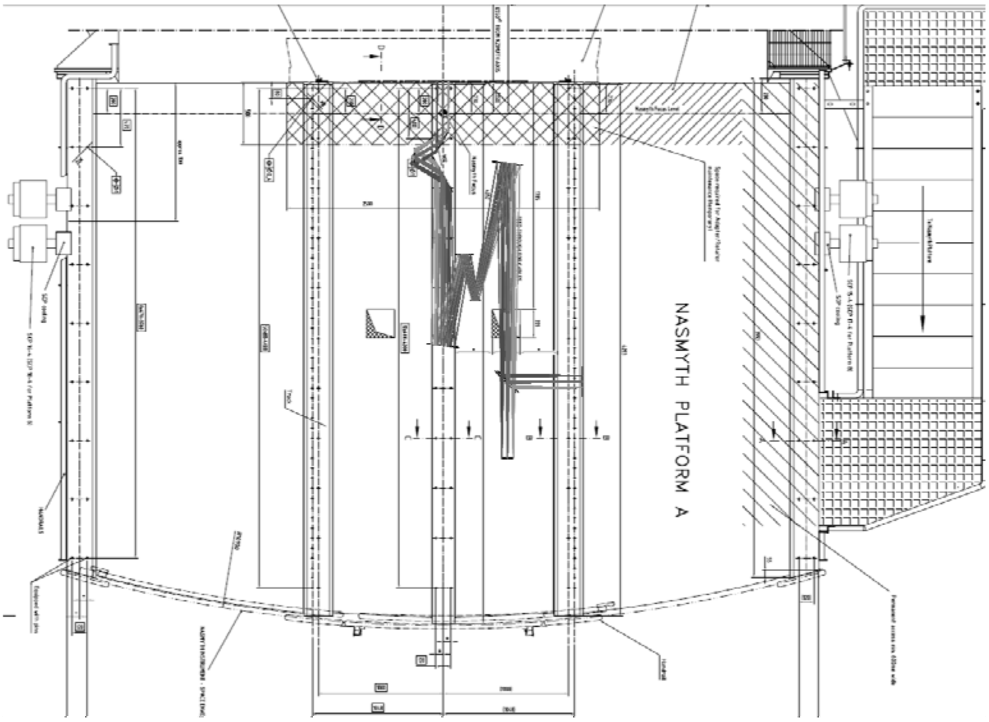

Figure 6. The optical layout for the Hybrid MCAO module accommodated on the VLT Nasmyth platform.

4. KEY COMPONENTS SPECIFICATIONS

The most critical components of the HM are the WFS NGS system and the post-focal deformable mirrors. The specifications reported here are the results of a tradeoff between simulated performance and technical feasibility in the aim of keeping the complexity, risks and costs of the system as low as possible.

4.1 NGS wavefront sensor system

As already mentioned in Sect. 2.3 the NGS WFS system consists of three visible Shack-Hartmann WFS freely positionable in the 2.5 arcmin diameter FoV. Each WFS has 5×5 sub-apertures across the re-imaged telescope's pupil with 2.4 arcsec FoV. A possible solution for the WFS cameras is based on commercially available ANDOR iXon^{EM} +860 cameras < 0.1 e^- RON and negligible dark current, with built in control electronics and cooling. The high loop should be able to run up to 1 kHz frame rate with a maximum delay of 2 loop steps. Another more complex and costly option is to use infrared detectors for wavefront sensing in order to benefit also from the NGS sharpening in close loop to increase the sensitivity of the system This potentially transfers into fainter accessible magnitudes for the NGS with consequently higher sky coverage. If infrared wavefront sensing is chosen the option of using a pyramid WFS[11] to further increase sensitivity can be considered.

The accurate positioning of the NGS WFSs is assured by an acquisition camera coupled with a dedicated objective for the direct imaging of the whole NGS search FoV. The acquisition camera detector and controller is based on standard ESO nTCCD (cooling included).

4.2 Post-focal deformable mirrors

The first post-focal DM is conjugated at 8 km altitude and it has a spherical concave shape with 2104mm curvature radius. It consists of 10×10 actuators with a pitch of 21 mm, the PTV stroke required is not larger than 5 μm. This solution has been considered in the framework of reducing the number of optical surfaces for keeping the instrumental background as low as possible. A powered surface deformable mirror demonstrator has been successfully built by CILAS under an ESO's contract to demonstrate the feasibility of such a device (see caption in Figure 7 for details).

The second post-focal DM is flat and conjugated at 4km. It consists of 10×10 actuators with a pitch of 11.5 mm, the PTV stroke required is not larger than 5 µm. Both DMs are driven by standard High Voltage Amplifier.

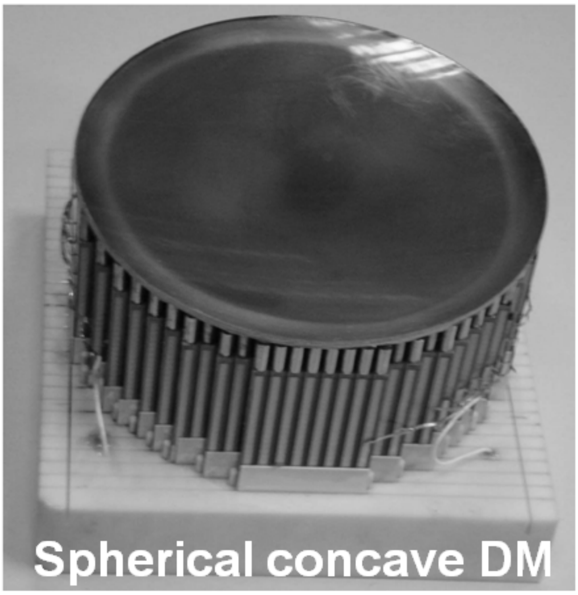

Figure 7. The spherical concave Deformable Mirror demonstrator built for ESO by CILAS. It consists of 28×28 actuators 3.5mm pitch with maximum PTV stroke of 9µm for ±400V.

5. ESTIMATED CORRECTION PERFORMANCE

The correction performance of the Hybrid MCAO system has been numerically simulated with ESO OCTOPUS[12] facility. A model of 12 layers atmosphere has been used taking the values used for GALACSI Narrow Field Mode profile with 0.6 arcsec seeing (see Table 1). The main parameters for the ground and altitude loops are given in Table 2. The WFS detectors have been considered to have negligible RON and dark current. For the numerical simulations an asterism of 4 LGS on circle of 3 arcmin diameter, and an asterisms of 3 NGS on circle of 2 arcmin diameter have been used.

Table 1. Atmospheric model used for the HM numerical simulations (GALACSI Narrow Field Mode profile).

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12
h [m]	89	204	320	346	1039	2078	5196	8198	12702	14780	16743	19052
v [m/s]	8.0	10.0	12.0	10.0	6.6	8.0	8.0	22.0	13.0	15.0	10.0	8.0
C_n^2 [%]	26.1	13.8	8.2	6.4	10.6	9.6	8.5	5.3	4.8	3.7	1.1	2.1

Table 2. Ground and high altitude loop parameters.

Parameter	Ground layer loop	High altitude loop
WFS number & type	4 x LGS	3 x NGS
Guide stars geometry	Circle: 3 arcmin diam.	Circle: 2 arcmin diam.
Sub-apertures	40×40	5×5
DM conjugation	0 km	Several combinations of 4, 8 and 12 km
Corrected modes	All DSM modes	50 Zernike
Loop frequency	1 kHz	1 kHz
Flux	Bright	Bright → 0.2 ph/sub-ap./frame
Delay	2 steps	2 steps

The Strehl ratio in K band (2.2 µm) as a function of the distance from the FoV center is plotted in Figure 8. Different post focal DMs number and altitude conjugations have been considered. The best performance with only one post-focal DM is obtained for an altitude conjugation of 8 km. Values grazing 50% Strehl are achieved up to 40 arcsec from the center slowly dropping to 30% at 80 arcsec radius. By adding a second post-focal DM the correction improves noticeably especially at larger distances and it is above 50% Strehl up to 1 arcmin radius and dropping only to 40% at 80 arcsecs from the FoV center. It is also clear that the correction performance is quite sensitive to the conjugation altitude of the highest DM: if it is elevated to 12 km the absolute Strehl loss is of 15% on the whole FoV.

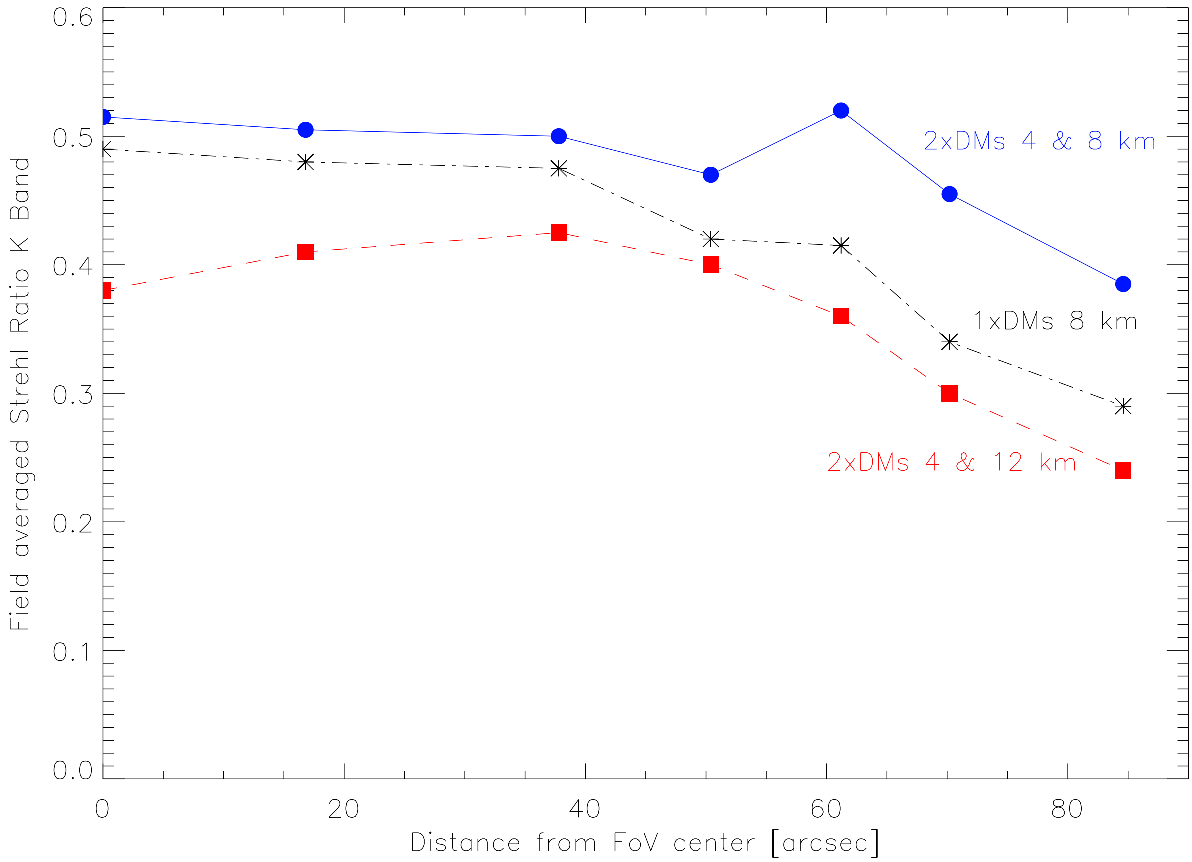

Figure 8. Estimated correction performance of the Hybrid MCAO module in the FoV vs. different numbers and altitude conjugation of post-focal DMs.

In Figure 9 is shown the K band correction performance at the FoV center for the hybrid MCAO module with two post-focal DMs conjugated at 4 and 8 km vs. the NGS flux at the WFS sub-apertures. The NGS loop frequency is maintained at 1 kHz and a dedicated control optimization is applied for each flux level in order to achieve the highest correction.

A moderately good performance is obtained even at very low fluxes and the half peak Strehl value of ~25% is achieved at ~0.3 photons/sub-ap./ms. Quite commonly the sky coverage of an AO system is computed for the lowest acceptable correction performance corresponding to half of the maximum Strehl obtained by the system when not limited by NGS brightness. A careful modelization of the system gives a total throughput for the NGS WFS of 0.35 including the telescope optics and the WFS detector quantum efficiency response (the excess noise due to the use of L3Vision EMCCD is already taken into account on the simulations): the R band magnitude equivalent to 0.3 photons/sub-ap./ms is m_R=20 corresponding to a sky coverage of 33% at the Galactic poles.

It is worth noting that if the NGSs are found on a smaller asterism the correction performance can significantly increase with a slight degradation of the uniformity across the field. This feature has positive implications for the scientific point of view: astronomical applications requiring higher Strehl typically involve the observation of starburst regions, globular clusters and nearby extragalactic stellar populations which are target much richer of NGS in the search FoV thus increasing dramatically the chances of observability and to get a sharper MCAO correction. High redshift galaxies observation targets normally are much less dense of suitable NGS, which translates into a larger distance between the NGS and lower degree of correction, but in this case the level of image sharpness required is also less demanding.

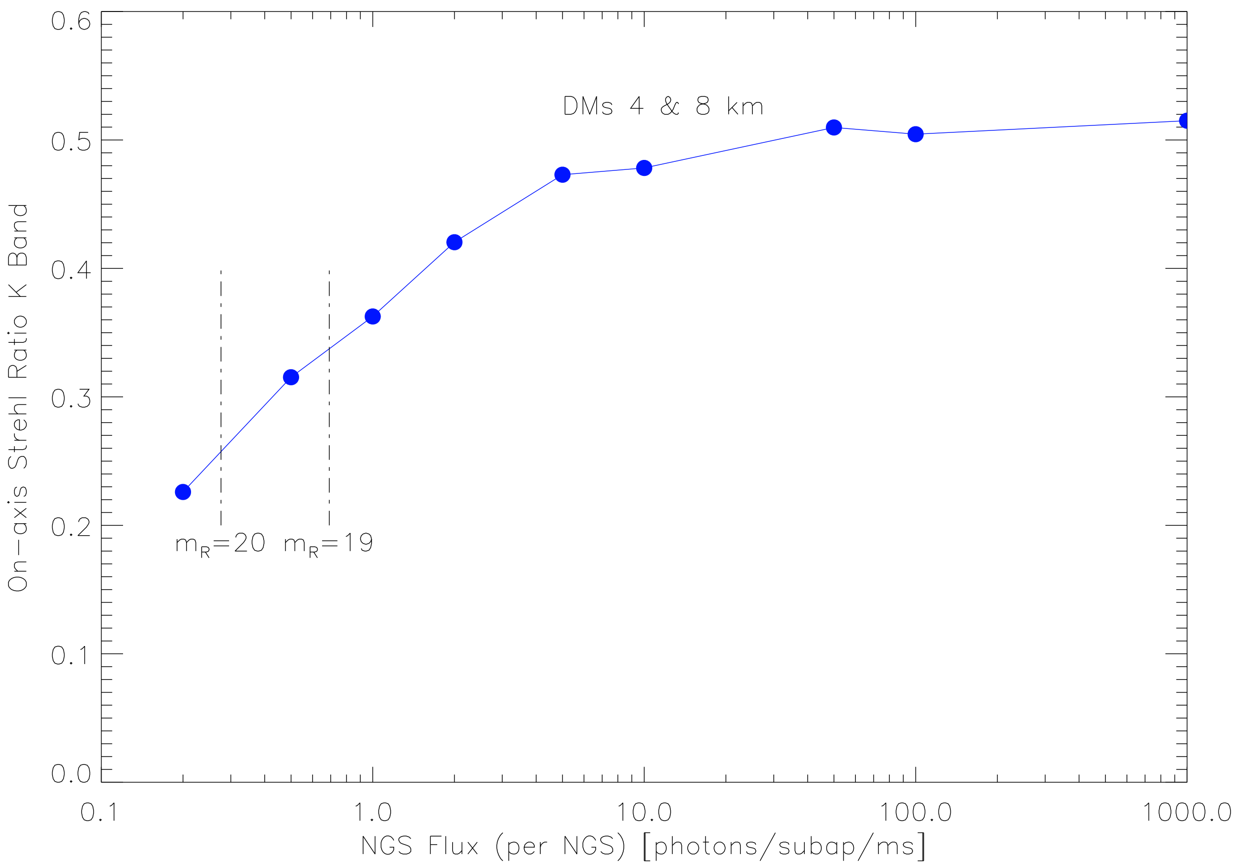

Figure 9. Estimated correction performance of the Hybrid MCAO for the selected post-focal DMs configuration (4 and 8km) vs. NGS flux

6. CONCLUSIONS

A speculative design for a hybrid MCAO module has been presented as a new system associated to the ESO Adaptive Optics facility. It is based on the concept of correcting with independent loops the ground atmospheric turbulence by means of LGS WFS GLAO and the high altitude turbulence with a low order NGS MCAO post-focal system. The module has been conceived to keep the complexity, risks and costs for its implementation as low as possible and maximize the re-use of existing systems/components developed in the framework of the AOF.

The system is making full use of GRAAL, one of the two GLAO systems of the AOF, opportunely modified in order to get the LGS WFS closer to the FoV center to correct for ground turbulence. The high altitude loop is entirely post-focal and consists of two DMs conjugated at 4 and 8km and three low order Shack-Hartmann visible WFSs.

A straightforward optical design with the innovative concept of powered surface DM has been presented and its feasibility is well within the actual technological capabilities.

Both WFS cameras and post-focal DMs are relatively simple low order components and their manufacturing implies significantly low risks and no show stopper can be envisaged on this side.

Numerically simulated performances show that the level of correction is quite uniform all across the scientific FoV and the peak correction is reasonably high for good seeing conditions. Thanks to the low order characteristic of the post-focal module the sky coverage has moderately high values taking into account the relatively simplicity of the presented concept.

In conclusion the hybrid MCAO module concept integrated in the AOF facility represents a quite cost effective, low risk and relatively short time development for providing wide FoV MCAO correction at VLT in the near infrared. Further work will include a more consolidated correction performance assessment and the option of improving the sky coverage by increasing the NGS WFS sensitivity using infrared detectors and pyramid WFS.

REFERENCES

[1] Dicke, R. H., "Phase-contrast detection of telescope seeing errors and their correction," ApJ 198, 605-615 (1975).

[2] Beckers, J. M., "Increasing the size of the isoplanatic patch size with multiconjugate adaptive optics," in ESO conference on Very Large Telescopes and their instrumentation, M.-H. Hulrich, ed., 693-703 (1988).

[3] Marchetti, E., Brast, R., Delabre, B., Donaldson, R., Fedrigo, E., Frank, C., Hubin, N., Kolb, J., Lizon, J.-L., Marchesi, M., Oberti, S., Reiss, R., Santos, J., Soenke, C., Tordo, S., Baruffolo, A., Bagnara, P., The CAMCAO Consortium "On-sky Testing of the Multi-Conjugate Adaptive Optics Demonstrator," The Messenger 129, 9-13 (2007).

[4] Marchetti, E., Brast, R., Delabre, B., Donaldson, R., Fedrigo, E., Frank, C., Hubin, N., Kolb, J., Lizon, J.-L., Marchesi, M., Oberti, S., Reiss, R., Soenke, C., Tordo, S., Baruffolo, A., Bagnara, P., Amorim, A., Lima, J., "MAD on sky results in star oriented mode," Proc. SPIE 7015, 70150F (2008).

[5] Arsenault, R., Madec, P.-Y., Hubin, N., Stroebele, S., Paufique, J., Vernet, E., Hackenberg, W. K. P., Pirard, J., Jochum, L., Glindemann, A., Jost, A., Conzelmann, R. D., Kiekebusch, M. J., Tordo, S., Lizon, J.-L., Donaldson, R., Fedrigo, E., Soenke, C., Duchateau, M., Bruton, A., Delabre, B., Downing, M. D., Reyes Moreno, J., Kolb, J., Bechet, C., Le Louarn, M., Manescau, A., Bonaccini Calia, D., Quattri, M., Guidolin, I. M., Buzzoni, B., Dupuy, C., Guzman, R., Comin, M., Silber, A., Quentin, J., Jolley, P., Heinz, V., Argomedo, J., Gallieni, D., Lazzarini, P. G., Biasi, R., Andrighettoni, M., Angerer, G., Pescoller, D., La Penna, P., Stuik, R., Deep, A., "Manufacturing of the ESO adaptive optics Facility ," Proc. SPIE 7736, 7736-20 (2010).

[6] Ragazzoni, R., "Adaptive optics for giants telescopes: NGS vs. LGS", in ESO Proceedings of the Bäckaskog Workshop on Extremely large Telescopes 57, T. Andersen, A. Ardeberg and R. Gilmozzi, eds., 175-180 (2000).

[7] Ragazzoni, R., Farinato, J., Marchetti, E., "Adaptive optics for 100-m-class telescopes: new challenges require new solutions", Proc. SPIE 4007, 1076-1087 (2000).

[8] Paufique, J., "GRAAL: a seeing enhancer for the NIR wide-field imager Hawk-I," Proc. SPIE 7736, 7736-60 (2010)

[9] Jerram, P., Pool, P. J., Bell, R., Burt, D. J., Bowring, S., Spencer, S., Hazelwood, M., Moody, I., Catlett, N, "The LLCCD: low-light imaging without the need for an intensifier," Proc. SPIE 4306, 178-186 (2001).

[10] Fedrigo, E., Donaldson, R., Suarez Valles, M., Soenke, C., Zampieri, S., Bourtembourg, R., "SPARTA for the VLT: status and plans," Proc. SPIE 7736, 7736-88 (2010).

[11] Ragazzoni, R., "Pupil plane wave front sensing with an oscillating prism", J. of Mod. Opt. 43, 289-293 (1996).

[12] Le Louarn, M., Verinaud, C., Korkiakoski, V., Fedrigo, E., "Parallel simulation tools for the AO on ELTs," Proc. SPIE 5490, 705-712 (2004).