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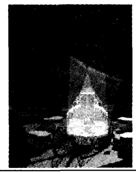
Beyond Conventional Adaptive Optics



# Specification and optical budget for layer oriented WFS for MAD

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## ABSTRACT

We trace the basic specification concerning the Wavefront Sensor (WFS) channel for the Multi Conjugated Adaptive Optics (MCAO) Demonstrator for VLT (MAD) in a Layer Oriented fashion. We perform a first opto–mechanical design including a budget covering as much as possible the various aspects related to such a design. These includes tolerancing on the optics feeding the star–light to the WFS and onto the WFS itself. A selection of commercially available products to build up such a WFS is shown along with further consideration about the implementation of such a WFS.

## 1. INTRODUCTION

In the perspective of the Extremely Large Telescopes (ELT) like OWL (the 100-m telescope proposed by the European Southern Observatory (ESO)) the concept of multi-conjugate adaptive optics (MCAO) (Beckers (1988); Ellerbroek (1994); Ellerbroek and Rigaut (2000); Ragazzoni, Marchetti & Valente (2000); Tokovinin et al (2001) for examples) need to be validated. A demonstrator called MAD (Hubin et al., this conference) is currently developed at ESO for such a purpose. Either global or layer-oriented concepts will be experimented on MAD. The global recontruction is more detailled in Hubin et al. (this conference) while the layer-oriented part is described in the following.

Layer-oriented MCAO concept is first introduced in Ragazzoni (1999) and in Ragazzoni, Farinato & Marchetti (2000). The basic idea is to sense the volume of turbulence perturbating the incoming wavefronts. A three-dimensional anamorphic copy of the turbulence is optically reproduced in the WaveFront Sensing (WFS) area. A fews detectors suitably placed in this area are coupled to specific Deformable Mirrors (DMs) in a way to obtained the best achievable correction over a defined Field of View (FoV) as shown independently by Diolaiti, Ragazzoni & Tordi (2001) and Tokovinin, Le Louarn & Sarazin (2000). Each loop of the LO WFS is a totally independent one, the three-dimensional reconstruction beeing achieved optically at the hardware level.

A number of properties makes such a system optimized for MCAO on 8-meter and 100-meter class telescopes. The system is less sensitive to the Read-Out-Noise (same number of subapertures and DM actuators). The LO WFS co-adds optically the objects in the pupil plane before to detect them. Faint objects can contribute to improve the total brightness. Spatial and temporal statistical properties of the turbulence change with altitude. Each independent loop beeing focused onto a specific altitude range can have its own spatial and temporal sampling.

In the last months novel implementations have been added to the layer-oriented approach. The LO WFS as presented in Ragazzoni, Farinato & Marchetti (2000) need a large pupil size. Star enlargers have been added in the design to change the plate scale of each star without acting on the whole FOV. A diffusive plate or a similar device is proposed to avoid any moving part in the system. The plate blurs the spot on the pyramid pin, blurring previously obtained by a dynamic modulation. This diffusing device could be also use to weigh each guide star in order to achieve a uniform signal in the sampled directions. In the following we present the LO WFS optical design for MAD and give a draft of the opto-mechanical design.

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## 2. OPTICAL DESIGN

The optical design hereafter shown assumes a telecentric, flat focal plane with F/20 focal ratio with diffraction limited performance over 2 arcmin FoV (Hubin et al., this conference). We used the wavelength range 0.6–1.0 $\mu m$ to evaluate optical designs.

Two of the three new ideas presented above are implemented in the LO WFS for MAD in order to improve the optical design feasibility. The pupil-size is reduced using star enlargers which eliminate the use of fiber taper and the need of large detectors.

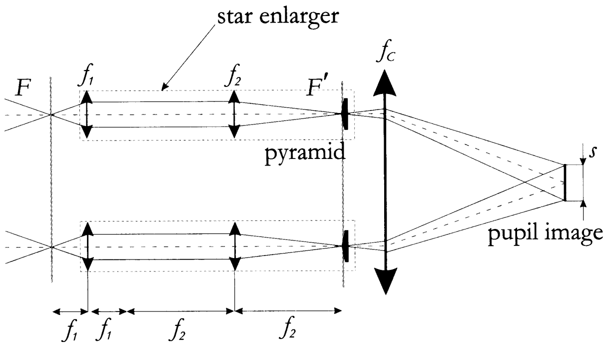


**Figure 1.** Star beams with focal ratio $F$ are focused on the telescope focal plane. Two lenses introduced before the pyramid pin increase the focal ratio to $F'$.

### 2.1. Star enlargers

The pupil-size is reduced by enlarging the F/ ratio of each star individually rather than collectively. A complete study of this concept is detailled in Ragazzoni, Diolaiti & Vernet (2002a, submitted). The pupil-space is arbitrarly reduced because it is inversely proportional to the F/ ratio while the reciprocical distance among the various stars in the focal plane remains unchanged.

A set of two lens per reference star is introduced in the optical path in front of each pyramid pin as shown in Fig. 1 in order to change the focal ratio of the beams from $F$ to $F'$. The vertical line on the left of Fig. 1 indicates the focal plane before the WFS. The telescope pupil is at infinity, the arriving beams are telecentric. For each reference star, a small image of the pupil is made up by a first lens of focal ratio $f_1$. At the same distance of the reformed pupil image a second lens of focal ratio $f_2$ is placed to obtain a new image of the reference star with a new focal ratio $F'$.

### 2.2. Diffusing device

In the previous concept (Ragazzoni, Farinato & Marchetti, 2000) a tip-tilt modulation was used to displace the spot onto the pyramid pin. Ragazzoni, Diolaiti & Vernet (2002b) propose to introduce a diffusing device in the pupil plane in order to perform the same effect of modulation with no moving part. The spot image is blurred, each incident ray being spreaded with a given probability distribution within a cone of semi-aperture $\alpha$. This angle $\alpha$ characterises the diffusing element, its value is determined by the blurring needed on the pyramid pin.

The diffusing plate is added in the optical design, positioning it at a distance $f_1$ of the first lens (Fig. 3).

### 2.3. Pyramid characteristics

With a F/ of 255 after the star enlargers, pyramids have to convey the pupil images onto two EEV 39 chips. The high layer altitude, central wavelength, the material of the pyramid and the interdistance between two opposite pupils in the CCD plane constrain the manufacturing angle of the pyramid. For MAD, the pyramids are assumed in BK7 material and the pupil interdistance is of 3.141 pupil size. Fig. 2 shows the CCD format. The pupil and the meta-pupil size are superimposed to the CCD. The physical angle of the pyramid at 800 $nm$ is 1.382°. An error on the pyramid vertex angle translates into an error on the angular separation of the beams splitted. Requiring an error of a tenth of the subaperture size one obtains a tolerance of 0.005° on the pyramid vertex angle with 9×9 subapertures.

We estimate also effects due to unprecise focal ratio and non-telecentricity angle. An error in the focal ratio of a beam produces a degradation in the re-imaged pupil. Requiring a relative error of the focal ratio smaller than a tenth of the

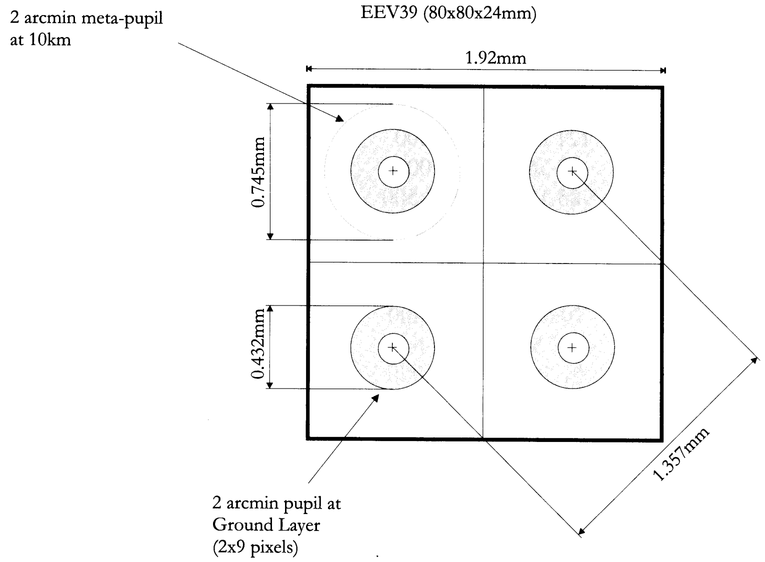


**Figure 2.** Size of the pupil and meta-pupil on the CCD for the case of $h = 0$ (ground–layer) and $h = 10$km (high altitude layer).

subaperture size, one obtains an error of 1%. The non-telecentricity angle $\delta$ is the angle between the pupil of two given beams arriving on the detector. We impose a $\delta$ angle smaller than the sampled subaperture and obtained $\delta \leq 1.9'$ for MAD. AFter the presentation of each element, the overall layout of the LO WFS for MAD can be described.

## 2.4. Optical layout

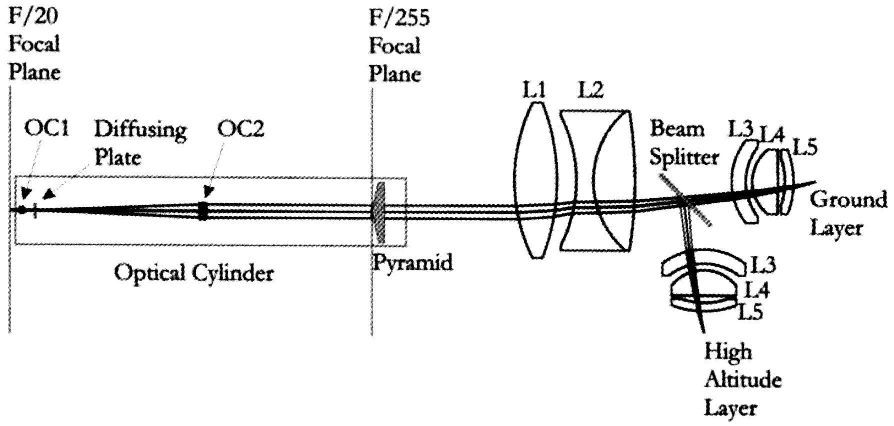


**Figure 3.** Optical layout of the WFS. Only one optical cylinder is shown including star enlarger, diffusive plate and pyramid.

The optical design of the LO is shown in Fig. 3). Each optical cylinder contains the two lens OC1 and OC2, a diffusing plate and the pyramid. The four pupil images created by the pyramid are conveyed by a relay objective up to the CCD. Relay optics have been carefully optimized in order to reach a high optical quality. The pupil reimager, composed of five lenses conveys the pupil images onto the detector. With a clear aperture of 110 $mm$ and a F/ of 1, 99 % of the Diffraction Ensquared Energy is in a single pixel. The equivalent FoV on the diagonal is 1.44 degrees. A beam-splitter divides light among the two reimaged layers. The characteristics of the optics are given in Tab. 1. Even with high optical quality of the optics, re-imaging errors could arise. This problem is more important with LO WFS than with a Shack-Hartmann due to a larger FoV and more stringent specifications. Using the Modulation Transfert Function (MTF) one obtain a measure

| | Radius | Thickness | Glass | Diameter |
|---|---|---|---|---|
| OC1 | 62.718 | 1.000 | F2 | 5 |
| | 4.500 | 2.000 | BK7 | 5 |
| | -4.621 | 10.000 | air | 5 |
| OC2 | 121.815 | 3.000 | BK7 | 13 |
| | -28.260 | 2.000 | F2 | 13 |
| | -85.189 | 127.500 | air | 13 |
| L1 | 134.548 | 33.000 | FCD1 | 120 |
| | -163.191 | 15.000 | air | 120 |
| L2 | -109.183 | 13.200 | LAFN7 | 100 |
| | 70.673 | 32.000 | LASFN31 | 108 |
| | -343.540 | 74.625 | air | 108 |
| L3 | 51.707 | 11.000 | BASF2 | 64 |
| | 43.953 | 5.000 | air | 54 |
| L4 | 32.027 | 19.800 | FCD1 | 50 |
| | -1895.081 | 5.500 | air | 50 |
| L5 | -55.308 | 6.600 | SF59 | 36 |
| | -67.758 | 16.500 | air | 50 |

**Table 1.** Optical design of all the optical elements. Lengths are in mm.

of the capability of the system to transmit a given spatial frequency. In our case, the highest spatial frequency of interest depends on the subaperture size. With 9 subapertures, a clear aperture of the objective of 110 $mm$ and a F/ of 255, the highest spatial frequency is around 21 cycles/mm. Computing the MTF of the objective by ray tracing we estimate that re-imaging errors are kept within a reasonable limit (the MTF is always higher than 0.70). The opto-mecchanical design

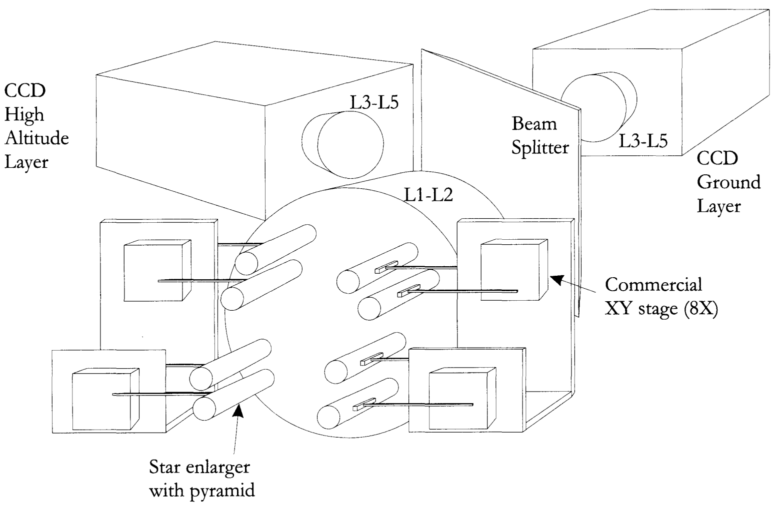


**Figure 4.** A possible opto-mecchanical arrangement. Eight XY stages allow to place the 8 cylinders. A beam-splitter divides the light for the two detectors.

is not as well defined as the optical design but a first opto-mecchanical layout is described in the following section. We especially insist on the WFS tolerances and on the requirements imposed by the WFS.

## 3. OPTO-MECHANICAL DESIGN

### 3.1. Tolerances on the WFS mechanism

Fig. 4 shows a possible opto-mecchanical layout of the LO WFS for MAD. Eight reference stars are assumed in this configuration. The 8 stars enlargers are placed in position over the optical system using XY stages. In order to have the XY stages working orthogonally to the gravity, the F/ 20 focal plane should deploy horizontally.

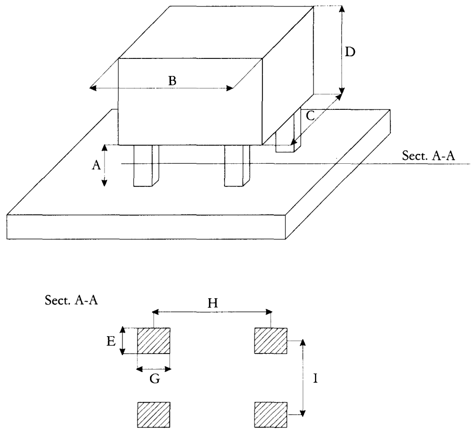


**Figure 5. Top**: 3D layout of the layer–oriented WFS respective to the demonstrator bench; the WFS volume deploys an height $A$ above the bench and has outer size of $B \times C \times D$. **Bottom**: top view of WFS supports.

Positioning of the star enlargers (including the pyramid) introduces the tightest tolerances. The cylinders should normally be positioned with an accuracy of the order of 3 $\mu m$, a precision hardly reachable as it corresponds to a knowledge of the reference star position with precision of 3.7 mas and to the knowledge of the exact plate scale on the WFS focal plane. This requirement has to be used as a repeatability specification. Such a requirement is identical with Shack-Hartmann and global reconstruction.

| Item | Requirement | Item | Requirement |
|---|---|---|---|
| $A$ | $\leq$ 250mm | $F/$ | 20.0 |
| $B, C$ | 400mm | Error on $F/$ | 0.2 |
| $D$ | 800mm | $\lambda$ | $0.6 - 1.0\mu$m |
| $E, G$ | 75mm | Strehl Ratio | $> 80\%$ |
| $H, I$ | 325mm | Non-telecentricity | $< 1.9'$ |
| $L$ | | Focal plane curvature[a] | $>$ 2000mm |
| $M, N$ | 200mm | Focal plane XY error[b] | $< 0.1''$ |
| $O$ | 100mm | Focal plane Z error[c] | $<$ 0.5mm |
| $P$ | 75mm | Optical axis direction[d] | better than $1.9'$ |
| $Q$ | 50mm | Distance FP–WFS[e] | $<$ 5mm |
| FoV | $2'$ | Fiber sources[f] | $< 0.6''$ |

[a] Absolute curvature radius of focal plane
[b] XY equivalent positioning error of focal plane
[c] Positioning error of focal plane along optical axis
[d] Error on angular direction of optical axis
[e] Distance of focal plane from WFS outer envelope
[f] Equivalent size of fiber sources on $F/15$ focal plane

**Table 2.** Mechanical and optical requirements imposed by the WFS.

A tilt of the cylinder introduces 1) the displacement of the pupil which has to be smaller than the subaperture size and 2) the deterioration of the Strehl ratio on the pyramid pin. Ray-tracing simulations show a 1:1 coupling between the pupil displacement and the cylinder tilt while the Strehl ratio degradation is marginal even if the cylinder is tilted of a few degrees.

The pupil position requires a tilt of the cylinder smaller than $9.0''$. Commercial motorized stages (MS-4M-EX-50 for example) have a repeatability of 0.5 $\mu m$ and wobbliness of $8.3''$.

### 3.2. Requirements imposed by the WFS

The LO WFS volume has to be defined in the early stages of the design in order to have the required space in the MAD instrument. We define the WFS volume in Fig. 5. The WFS volume should be placed above the demonstrator bench at a distance $A$. Some legs defined by the parameters $E, G, H, I$ support a parallelepiped of size $B \times C \times D$. The focal plane is required to be at a distance smaller than 5 $mm$ from the LO WFS volume, correponding to half the focal length $f_1$ of the first lens in each optical cylinder.

Assuming a CCD head smaller than 200 $mm$, we indicate the parameter values in Tab. 2. The optical requirements are also summarized in this table. The LO WFS is a subpart of an instrument and to avoid any interface problem, we had to defined the optical and mecchanical requirements for the conceptual design review.

## 4. CONCLUSIONS

The concept of multiconjugate adaptive optics is now extensively studied by the adaptive optics community. The demonstrator should be on the sky in 2003 at Paranal. With its two WFSs, MAD will be able to test the MCAO reconstruction using either classical WFS (Shack-Hartmann ones) or the layer-oriented WFS.

The project status is the following: the LO WFS for MAD conceptual design review has been done a few months ago. The preliminary design is scheduled before the end of the first quarter of 2002. MAD aim is to demonstrate multi-conjugate adaptive optics feasibility with a eight meter telescope and to project results for ELTs.

The LO WFS concept allows to gain in term of photon and therefore to improve the sky coverage on 8-meter class telescope. The basic properties of the LO WFS are i) the independence of each loop which eliminate the complexity of the global reconstruction ii) the possibility to optimize the temporal and the spatial sampling iii) the capability to use faint objects. A laboratory experiment is now beginning and should be pursued in the following months to test the cylinder concept and the LO WFS capabilities before to begin the building phase.

## ACKNOWLEDGMENTS

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