The Layer-Oriented Wavefront Sensor for MAD

Elise Vernet\textsuperscript{a,e}, Carmelo Arcidiacono\textsuperscript{b}, Andrea Baruffolo\textsuperscript{c}, Emiliano Diolaiti\textsuperscript{d}, Jacopo Farinato\textsuperscript{a}, Matteo Lombini\textsuperscript{d}, Roberto Ragazzoni\textsuperscript{a}

\textsuperscript{a} INAF - Astrophysical Observatory of Arcetri – Largo E. Fermi, 5 – I-50125 Firenze – Italy – Phone:+39 055 2752273 Fax:+39 055 220039

\textsuperscript{b} Department of Astronomy and Space Science – University of Firenze – Italy

\textsuperscript{c} INAF - Astronomical Observatory of Padova – Padova – Italy

\textsuperscript{d} INAF-Osservatorio Astronomico di Bologna – Bologna – Italy

\textsuperscript{e} European Southern Observatory – Karl Schwarzschild Strasse 2 – D-85748 Munich – Germany – Phone:+498932006322 Fax:+49893202362

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\textsuperscript{1}For more information, contact Elise Vernet, evernet@eso.org
ABSTRACT

Diffraction limit imaging from the ground on 2 arcmin field of view is about to be real with the demonstrator of new generation of multi conjugate adaptive optics which should be installed at Paranal in 2006. The layer oriented part of the Multiconjugate Adaptive optics Demonstrator (MAD) selects up to eight natural guide stars over the Field of View allowing a uniform correction. Using the layer-oriented concept and two deformable mirrors conjugated to the ground and 8.5 km we will determine MCAO performance on 8m class telescope. We describe initially the optical constraints, the adopted solutions and several opto-mechanical approaches used to build such a system. Alignment procedures are indicated with some useful details in the last section.

1. Introduction

Since the launch of the Hubble space telescope a particular effort has been made to develop Adaptive Optics (AO) systems in the main astronomical observatories. AO goal is to reach diffraction limit images from the ground. Classical AO systems (Roddier (1999); Tyson (1998)) are limited by several constraints: only science objects located at less than a few arcseconds from a bright enough reference guide star can be observed at the diffraction limit. Hence high angular resolution from the ground is only achieved for a small number of interesting sources.

To overcome such a limitation Beckers (1987, 1993) proposed at the end of the 80s the Multi-Conjugate Adaptive Optics (MCAO) concept. The basic idea is to use several reference stars to sense the atmosphere in several directions and correct it in three dimensions using several correctors. By the mid 90s, extensive theoretical studies on MCAO appeared in the litterature (Tallon et al. (1992); Ellerbroek (1994); Johnston & Welsh (1994)). An MCAO system is usually composed of several Wave Front Sensors (WFSs) each one sensing a specific reference guide star and several interconnected real time computers to retrieve the correction to be applied to each deformable mirror. This technique called Star-Oriented (SO) applies the tomography method to measure the wavefront. In 2000, a new technique of sensing called Layer-Oriented (LO) has been proposed (Ragazzoni (2000); Ragazzoni et al.
Each WFS conjugated to a specific atmospheric layer measures the wavefront and drives a specific Deformable Mirror (DM) conjugated to the same altitude. This MCAO method is particularly suited when using pupil plane WFSs: the guide stars light is optically combined by the instrument to reproduce an anamorphic copy of the 3D atmosphere close to the pupil plane.

The most important astronomical observatories (Bauman et al. (2002); Rigaut et al. (2004); Marchetti et al. (2004); Ragazzoni et al. (2003a)) are now all building their own MCAO system in order to improve the image quality on a substantial Field of View (FoV). The goal of MCAO systems is to procure a wider uniform corrected FOV in order to increase the number of scientific target to be observed with limited diffraction from the ground allowing both high resolution imaging or spectroscopy on faint objects. MCAO is also a key point for the Extremely Large Telescopes (ELTs) which are currently in their conceptual phase. There is a general consensus that such ELT projects will be pursued only if limited diffraction images are achievable on a reasonable sky coverage allowed by enlarging the equivalent isoplanatic patch or solving the conical LGS problem. Both approaches require some sort of MCAO.

2. MAD Overview

The ESO Multi conjugate Adaptive optics Demonstrator (MAD, for more informations Viard et al. (2000); Hubin et al. (2002); Marchetti et al. (2004)) has been developed to demonstrate MCAO feasibility and to determine the achievable gain using both Shack-Hartmann WFSs in SO configuration or LO-WFS. The system will be first test in laboratory during one year before to be installed at Paranal for test on sky. The scientific instrument is a 1×1 arcmin FoV near-InfraRed (IR) camera scanning a diameter of 2’ FOV. The entire system is placed on a bench which will be mounted directly on the Nasmyth platform of one of the Very Large Telescope units (VLT) at Paranal in Chile.

The mechanical design of the overall system is outlined in Fig. 1a. The 2 arcmin FoV is de-rotated at the entrance of MAD. The F/15 input beam is collimated to reimage the telescope pupil on 60 mm diameter. The larger DM with a 100 mm pupil is conjugated to 8.5 km altitude while the smaller DM with a 60 mm pupil is conjugated to the reimaged telescope pupil. The IR light is transmitted by the
Fig. 1.— (a) Mechanical design concept of the complete MAD bench. (b) Mechanical design of the LO-WFS. Description: (a) The beam arrives on the de-rotator, passes through the collimator and is successively reflected by the two DMs. Then the IR light is transmitted to the camera while the visible light is reflected by the dichroic toward the WFS objectives. The Multi Shack-Hartmann WFS is located below the LO-WFS. The volume of the LO-WFS is represented on the left side drawing by the elongated box placed above the bench. (b) On the right side drawing the LO-WFS is represented. The entrance focus plane is at the bottom of the instrument. Each star enlarger selects one reference star. The reference star beam is splitted into four beams which are re-imaged on the two CCDs.

dichroic to the IR camera while the visible light is reflected toward the WFS path. The WFS input beam is a flat telecentric $F/20$ beam. The correction is optimized at $2.2 \, \mu m$ (K band) to give the best correction to the $2k \times 2k$ IR detector. A calibration unit with multiple reference stars is also available. The two WFSs cannot be used simultaneously: a WFS selector folds the light either to the LO-WFS located above the bench or to the SO WFS which is on the bench.

In the LO case each detector is conjugated to a given altitude while in the SO case each detector measures the light coming from a given reference star. In the LO-WFS, the two loops can work inde-
pendently each DM being driven with the WFS conjugated to the same altitude with specific optimized spatial and temporal samplings directly defined from the statistical properties of the layer. Pyramid WFSs (PWFSs) have been selected among various pupil plane WFSs for their ability to co-add the pupil images of all the reference guide stars. The PWFS (Ragazzoni (1996); Esposito et al. (2000); Ragazzoni et al. (2000b); Bello et al. (2003)) is a 2D Foucault-like WFS: the light is splitted into 4 beams whose illumination distribution depends on the wavefront aberrations. The four pupil images are then re-imaged on the detector. It has been demonstrated theoretically (Ragazzoni & Farinato (1999); Costa et al. (2003)), numerically (Esposito & Riccardi (2001); Vérinaud (2004); Vérinaud et al. (2004)) and experimentally (Ghedina et al. (2003)) that the PWFS has a gain in sensitivity respectively to other WFSs. We describe more extensively the pyramid features for this instrument and the required quality in section 3.4.

In the LO-WFS for MAD up to eight pyramids can be positioned over the two arcmin FoV to catch the light from eight reference guide stars (Fig. 1b). The maximum number of guide stars is a trade-off between the system complexity and the achievable sky coverage. Marchetti et al. (2002) have shown that more than 400 asterisms are accessible from Paranal with such a number of guide stars.

The various misalignment errors are listed in the following sections and the induced alignment specifications are discussed. We have studied numerically the translation of the sub-aperture blurring in term of Wave Front Error (WFE) (Arcidiacono et al. (2003, 2004)). We have selected a reasonable blur of 1/10 of subaperture as tolerance requirement for most of the sub-systems, which corresponds for instance, under normal seeing conditions, to a WFE of 24 nm.

3. Optical Design

The optical design has been optimized to reproduce an anamorphic copy of the atmosphere inside the instrument without reducing the pupil images sharpness. In its original approach the layer-oriented concept imposes a practical limit on the minimum size of the re-imaged pupils. Ragazzoni et al. (2003b) propose several techniques to overcome it; the star enlarger technique has been implemented in this
instrument. With this technique, two lenses are introduced on each reference guide star path to enlarge their focal ratio individually rather than collectively. As a result, the pupil size, which is inversely proportional to the focal ratio, can be arbitrarily shrunk, while the distance between the various stars across the covered FoV remains unchanged. The layout is shown in Fig. 2. The focal plane before the

Fig. 2.— Star Enlarger concept: increasing separately the focal ratio for each star, one can reduce the pupil image for each star without changing the distance between the various stars across the covered FoV remains unchanged.

LO-WFS is indicated by the vertical gray line. Rays are arriving from a certain FoV in telecentric mode at a focal ratio $F$. The beam of each reference star is collimated by a lens of focal length $f_1$, producing a small pupil image for each sensed star. A second lens of focal length $f_2$, placed at a distance $f_2$ after the intermediate pupil (the exit pupil remains at infinity), forms an enlarged image of the reference star with an equivalent focal ratio $F' = kF$, where the enlarging factor is given by $k = f_2 / f_1$. In this position a pyramid can be placed in order to split the light in four beams, which are focused by an objective of focal length $f_l$ onto four pupil images. The re-imaged pupils corresponding to different reference stars are collected by the objective, which optically co-adds the light of the stars. It is easy to show that using the small angles approximation the size of each re-imaged pupil can be equal to $s \approx \frac{F \theta D}{k}$, $\theta$ being the FoV and $D$ the telescope diameter.
3.1. The CCD size: a limitation

The detector size is one crucial parameter to determine the optics characteristics. The detector is a EEV39 with 80×80 pixels. Because of practical reason and limited controllers capabilities only the 64×64 pixels central zone is used to re-image the four meta-pupils. To avoid light contamination among the four different meta-pupils in the high-altitude channel only a 28×28 pixels array near each corner has been considered to map one pupil image (Fig. 3) allowing a 8 pixel band between two different meta-pupils. The central part of the DM (including the inner 40 actuators) has to be mapped onto this 28×28 region. The meta-pupil in the high altitude layer is slightly smaller than the diameter of the inner region of the DM; this fixes the diameter of the meta-pupil on the detector and hence the diameter of each single re-imaged pupil, which results to be $s \approx 0.388$ mm. In order to achieve this figure, several combinations of enlarging factor $k$ versus objective focal length $f_l$ are possible. Focal lengths $f_1$ and $f_2$ are indicated in section 3.2 while the objective details are given in section 3.3.

Fig. 3.— The pupil and meta-pupil sizes are superimposed to the CCD format. The CCD has 80×80 pixels but only the 64×64 pixels central zone of the detector is considered. Every meta-pupil is mapped onto a 28×28 pixels region, leaving 8 pixels between each couple of meta-pupils.
3.2. Star Enlargers optics

We have adopted focal lengths equal to $f_1 = 10$ mm and $f_2 = 150$ mm for the two achromat lenses to obtain a new focal plane equal to F/300. The second lens diameter fixes the minimum separation between two reference guide stars. The two lenses used for each star enlarger are custom ones, optimized to reduce chromatic effects. The pyramid quality is actually essential for the output pupil image. Specifications are indicated in section 3.4.

3.3. Re-imaging Objective

With $k = 15$ the re-imager must have a focal length equal to $f_l = 115.7$ mm to fit the CCD. The equivalent FoV has been adjusted in order to match the CCD diagonal. The re-imaging objective composed of two groups of 8 lenses is shown in Fig. 4. It has a clear aperture of $d = 110$ mm. The design has been optimized in the full wavelength range 0.45 - 0.95 µm with uniform weighting. The back-focal distance has been kept to the comfortable value of 20 mm. Furthermore the last lens is made of SILICA glass and the last surface is flat: this allows to account for the CCD window by a simple modification of the thickness of this lens. Only standard Schott glasses (except SILICA) with high transmission in the wavelength range of interest have been selected. All the surfaces are spherical or plane; no cemented doublet or multiplet is present, in order to ensure high alignment precision. The objective is composed of two groups of lenses: the first is a beam compressor, which reduces the beam cross section while collimating it; the second group focuses the beam at $F/1.05$ ratio. A convenient space of 125 mm is left between the two lens groups, allowing the insertion of the beam splitter for the ground and high altitude channels. The beam splitter is in a substantially collimated beam, hence it does not introduce any significant aberration. The optical quality of the pupil re-imager objective is practically diffraction limit. A detailed optical tolerances analysis has been carried out in order to provide the necessary specifications for manufacturing and alignment. Mechanical adjustment systems have been included in the mechanical design. A detailed description is done in section 4.
Fig. 4.— Optical layout of the LO-WFS. In the real system 8 star enlargers are available but we represent only three star enlargers here for drawing simplification. The stars light coming from the left is caught by the star enlargers. The beams pass then through the common pass pupil reimager before to be split to the high and the ground pupil reimagers. The pupil images are sensed by the two CCDs.

3.4. A key point: Pyramid specifications and procurement

The pyramid quality is essential for the wavefront measurement. Hence, the manufacturing has been done with particular specifications on the edge sharpness, the wedge of the back surface, the vertex angle repeatability and on the orthogonality of the faces.

The pyramid can be made of any optical material, provided that the internal transmission is acceptable. In Table 1 we report the optical specifications of the pyramids. The main parameter from the optical point of view is the divergence angle between the output beams (Fig. 5b), which is related to the pyramid vertex angle and to the material refractive index $n$ according to the relation

$$\alpha = \frac{\beta}{n - 1}. \quad (1)$$

Using the small angle approximation it is easy to show that the beam divergence $\beta$ is equal to:

$$\beta = \frac{d_d}{f_l} \quad (2)$$

where the interpupil distance $d_d=1.222$ mm to avoid light contamination between the different meta-pupils and $f_l=115.7$ mm. The beam divergence is therefore $\beta = 0.605^\circ$ as reported in Table 1. Assuming BK7 glass, the vertex angle is $\alpha = 1.176^\circ$. In this computation, the refractive index at the reference
wavelength, specified in Table 1, shall be used. It should be noticed that the vertex angle is very small and this corresponds to a sag of approximately 55 µm, as defined in Fig. 6a.

Fig. 5.— Relevant angles in the pyramid prism: (a) $\alpha$ is the vertex angle defined as the angle between two opposite slopes. (b) $\beta$ is the beam divergence related to $\alpha$ by Eq. 1 in the small angle approximation.

Due to the tight specification on the transmission an anti-reflection coating optimized for the full wavelength range has been applied to each pyramid. The pin of the pyramid had to be centered with respect to the outer diameter with a precision of ±0.1 mm. The surface flatness and roughness refer to the five faces of the pyramid. Since that several samples are required and due to the particular application for which these pyramids are used, the most important aspect is their similarity. A key point is the repeatability of the divergence angle $\beta$, specified in Table 1 as $\Delta \beta = \pm 0.002^\circ$; this specification translates into a repeatability requirement for the vertex angle and for the refractive index $n$. For instance with BK7 glass, the two values will become $\Delta \alpha = \pm 0.004^\circ$ and $\Delta n = \pm 0.001$.

The edge sharpness $\eta$ (Fig. 6b) affects the light transmission efficiency of the pyramid prism. It can be shown that the fraction of lost light due to the rounded edges is given by:

$$\epsilon = \eta \frac{2}{\lambda F'} \left[ \frac{n}{D} (1 - s) + S \right]$$

where $\eta$ is the edge width, $S$ the Strehl Ratio (SR) at the wavefront sensing wavelength $\lambda$ and $F'$ the enlarged focal ratio of the incident beam. Under normal seeing conditions, assuming $S = 0.05$, the light losses range from 1% to approximately 5% for rounded edges in the range $\eta = 16 - 80$ µm. This translates into a rigid shift of the SR vs. magnitude curve, by an amount ranging from 0.01 to 0.06
Fig. 6.— Pyramid characteristics definition. (a) Wedge ($\delta$) and sag definition. (b) Pyramid turned edges ($\eta$) superimposed onto a seeing-limited spot and a diffraction-limited one. (c) non-orthogonality tolerance ($\Delta \phi$).

The requirements on the pyramid size are not critical. The diameter affects only the equivalent FoV covered by the star enlarger. The thickness tolerance is very loose: it has been verified by ray-tracing that even an error of $\pm 0.5$ mm has no relevant effect on the pupil quality. The wedge of the back surface might introduce additional chromatism in the pupil images. The effect may be analyzed modeling the wedged pyramid as the composition of a perfect pyramid prism followed by a wedged plate of angle $\delta$.

Using the thin prism approximation, the angular blurring due to chromatism is given by:

$$\sigma_\delta = \frac{\delta}{V}$$

where $V$ is the Abbe number of the material. Imposing a reasonable blurring of $1/10$ of sub-aperture (see Section 4), a maximum wedge angle $\delta = 10'$ follows. The angular separation of the four beams generated by the pyramids depends on the combined effect of the refractive index, the vertex angle $\alpha$ and the orthogonality of the faces $\Delta \phi$. Unless a single pyramid is considered, the scatter in the angular separation among the beams generated by different pyramids translates into a pupil blurring.

Concerning the repeatability of the refractive index and of the vertex angle, a pupil blurring equivalent to $1/10$ of sub-aperture can be achieved with a refractive index error $\Delta n = \pm 0.001$ and a vertex angle error $\Delta \alpha = \pm 0.005^\circ$. Concerning the orthogonality specification, according to Fig. 6c, it can be shown...
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<tr>
<td>Beam divergence</td>
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</tr>
<tr>
<td>Divergence repeatability</td>
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<tr>
<td>Reference wavelength</td>
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<tr>
<td>Working wavelength range</td>
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<tr>
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<tr>
<td>Edge sharpness η</td>
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<tr>
<td>Wedge of back surface δ</td>
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<tr>
<td>Orthogonality of faces Δφ</td>
<td>± 7′</td>
</tr>
<tr>
<td>Diameter</td>
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<td>Pyramid pin centering</td>
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</table>

Table 1: Pyramid specifications.

that a non-orthogonality angle Δφ translates into a shortening of the pyramid side (from L to L’) and then into a steepening of the corresponding pyramid face. The non-orthogonality angle is related to the vertex angle error Δα by the relation

$$\Delta \phi \sim \frac{\Delta \alpha}{\alpha}$$  \hspace{1cm} (5)

Imposing a pupil blur of 1/20 of sub-aperture related to the orthogonality specification, a requirement Δφ ± 7′ follows. This requirement has to be applied to each pyramid face separately, since each face
corresponds to a separate pupil image. The last specification considered here is the surface flatness. Ray-tracing simulations have shown that this specification is not critical. A surface accuracy of $2\lambda$ peak-to-valley, for instance, translates into a negligible pupil blurring of $1 \mu m_{RMS}$.

4. Mechanical Design

The LO-WFS being a subpart of MAD, the optomechanical design has been conceived to place it on the MAD bench. The LO-WFS is a $0.55 \times 0.55 \times 1.2$ m$^3$ box containing the optical elements for the proper re-imaging of the telescope $F/20$ focal plane into the two detectors (each of them accommodating four images of the pupil), one conjugated to the ground layer DM and another one conjugated to the high altitude one. The overall weight is about 165 kg. The mechanical structure holds the following

![Diagram of the Layer-Oriented box](image)

Fig. 7.— A side view of the Layer-Oriented box. The light is coming from the bottom part. Up to eight reference stars can be selected using the reference selection units of each star enlarger. Pyramids placed at the end of each star enlarger split the light into four beams. The pupils are re-imaged on the two CCDs by the re-imaging objectives.
components:

- a reference selection unit which displaces the eight star enlargers in the field for the selection of the reference stars. The linear stages are positioned horizontally on the structure to minimize deformations due to gravity effects.

- the common path pupil re-imager composed of the 4 first lenses of the re-imaging objective.

- the beam-splitter splits the light between the two detectors;

- the ground CCD pupil re-imager composed of 3 lenses;

- the high altitude CCD pupil re-imager

- the high altitude CCD adjusting unit

- the ground layer CCD adjusting unit.

Adjusting tools have been implemented on the mechanical structure to align the different optical elements. In order to obtain good images of the pupils we have also defined stringent specifications on particular sub-systems.

4.1. Star Enlargers

The pupil superimposition on the ground layer detector is strongly related to both the global tilt of the star enlargers and the alignment of the three optical elements mounted on the star enlarger: the two achromatic lenses and the pyramid. A global tilt of the star enlarger is translated almost linearly into an angular shift of the exit pupil. When different stars enlargers are randomly tilted, the net effect is a blur of the pupil images. To verify a maximum tilt of 1/10 of the wavefront sensing sub-aperture the stars enlargers should be co-aligned with an accuracy $\Delta \theta \approx \pm 10''$. This specification is fulfilled in the integration and alignment phase by means of a tilt adjusting mechanism on each star enlarger.
4.1.1. Lenses alignment

The two achromats alignment is also essential to avoid misalignment among different pupils: a relative decentering between the two achromats can affect the telecentricity of the system. The correct spacing between the two lenses is required otherwise the exit pupils corresponding to different stars enlargers are placed at different locations along the optical axis and the corresponding pupil images do not superimpose properly. A suitable specification on the relative positioning accuracy is of the order \( \Delta z \approx \pm 0.1 \text{ mm} \). A similar reasoning can be applied to the relative decentering between the two lenses, which translates into an angular deflection of the corresponding exit pupil. In order to keep this effect to an acceptable level (1/10 of sub-aperture blur) the relative decenter should be smaller than \( \Delta y \approx \pm 0.09 \text{ mm} \). Mechanical adjusting systems allow to achieve less than 0.01 mm decentering between the two achromats.

The same reasoning is applied to the positioning accuracy of the star enlargers on the focal plane. The folding mirror which bends the optical beam onto the LO-WFS can be moved along the optical axis, in order to shift the position of the F/20 focal plane and match it to the entrance focal plane of the stars enlargers. The accuracy requirement on this adjustment is of the order of \( \Delta z \approx \pm 0.2 \text{ mm} \), corresponding to the depth of focus at F/20 at the wavefront sensing wavelength. Of course all the stars enlargers shall be pre-aligned in a way that their respective entrance focal plane are coincident, in order to minimize the differential defocus among them.

4.1.2. Pyramid alignment

The centering of the pyramid, instead, is a real issue only as long as the astrometric accuracy is of concern, since a decentering of the pyramid translates into a tip-tilt signal which might introduce a local warping of the corrected image astrometry. As long as the astrometry is not a scientific driver, like in the case of MAD, the decentering just need to be within the FoV of each single stars enlarger, a condition easily fulfilled in our case. The axial positioning is not critical, as the pyramid works in a F/300 beam with a very large depth of focus.
The differential rotation among different pyramids might introduce mis-alignment errors among the different pupils. The requirement on this figure is accomplished by the adjustment mechanism. The pyramids mounts allow to adjust the pyramids orientation, so that the beams from different pyramids are parallel, a necessary condition to ensure a proper pupil re-imaging. A rotation of a pyramid around its optical axis translates into a rotation of the four re-imaged pupils onto the detector plane. Imposing that the corresponding pupil displacement is negligible, a tolerance of 1/10 of the sub-aperture size implies a tolerance on the pyramid rotation angle of $\Delta \theta_R \approx \pm 0.25^\circ$. A mis-positioning of the pyramid along the optical axis of the star enlarger translates into a defocus term; however, given the very large depth of focus of the $F/300$ focal plane, it is easy to achieve the required positioning accuracy.

4.1.3. Movement precision

The alignment accuracy on the stars enlargers translates into a requirement on the stability of the motorized linear stages, as they move across the focal plane for the positioning of the stars enlargers. In particular the so-called pitch and roll of the stages translate into a wobbling of the stars enlargers, therefore these random angular deflections should be smaller than $\Delta \theta_T \approx \pm 10''$.

Another issue is related to the so-called yaw angular deflection of the stages. This kind of wobbling, orthogonal to pitch and roll, translates into a lateral displacement of the star enlarger on the focal plane. The net effect is that the reference stars to be picked up might fall outside the field of view of the corresponding star enlarger. Imposing that the lateral displacement is always smaller than the typical stellar image size, let us say the diffraction limit at the wavefront sensing wavelength, it is possible to derive a requirement on the maximum acceptable yaw. This figure turns out to be in our case of the order of 1', a specification quite easy to fulfill, being much looser than the pitch and the roll.

In order to avoid misalignment errors among the pupils corresponding to different stars, we require a 50 $\mu$rad peak-to-valley repeatability for each star enlarger the various star enlargers are moved in the input focal plane to pick the reference stars. In fact the global tilt of every star enlarger is a useful degree of freedom to compensate the misalignment errors of the optical components inside. When this tilt has
been adjusted, the star enlarger should translate with no significant additional tilt. A mis-positioning of the star enlarger along the LO-WFS optical axis might introduce differential defocus errors among the various star enlargers. In this respect, the positioning accuracy should be much better than the depth of focus of the first achromat working at $F/20$, i.e. $\Delta z = \pm 0.2$ mm at the shortest wavelength ($\lambda = 0.45 \mu m$).

4.2. Pupil re-imager

The lens groups forming the pupil re-imager have to be aligned in order to avoid a blur of the re-imaged pupil. The alignment tolerances have been computed for a maximum acceptable degradation of the RMS spot size of the order of 10 %: the relative decenter between the common path pupil re-imager and the ground or high altitude layer pupil re-imager should be adjusted with an accuracy better than $\pm 0.05$ mm, while the tilt of the lens groups with respect to the common optical axis should be smaller than $\pm 0.01^\circ$ for the common path and $\pm 0.15^\circ$ for the ground and the high altitude layer pupil re-imagers. In order to perform these adjustments, the lens groups mounts have been provided with adjusting mechanisms. Tip-tilt of each group of lenses is tune by using three screws with two different fine tuning. Three screws fixed at 120 degree translate each group by pushing it.

4.3. Beam-splitter

While a tilt of the beam-splitter has no effect on the transmitted beam, except for a lateral displacement that can be recovered by adjusting the centering of the following lens group, the impact on the reflected beam is different. Basically a tilt of the beam-splitter introduces both a tilt and a decenter of the reflected beam going to the high altitude layer pupil re-imager. By comparison with the alignment tolerances reported before, we obtain a tilt tolerance on the beam-splitter of the order of $\pm 0.05^\circ$. 
4.4. CCD

The centering precision of the CCD, in principle, would be of no importance. In practice, since the four re-imaged pupils just fit the detector, a centering mechanism has been foreseen.

Given the very high speed of the pupil re-imager, the CCD has to be aligned very precisely with respect to tip and tilt. Imposing a maximum tolerable pupil blur of 1/10 of sub-aperture as usual, different portions of the chip should be out of focus by no more than approximately $\Delta z \approx 5 \mu m$. This high accuracy is achieved by adjusting the CCD box, whose fixing points are sufficiently far apart one from the other that this very tight tolerance actually translates into a much looser one.

Each CCD box is mounted onto a linear stage for proper focusing and for conjugating the detector to a specific atmospheric layer, namely at 0 and 8.5 km. Given the very high pupil re-imager speed, the full conjugation range is mapped in the image space into a travel range of $\Delta z \approx 0.3$ mm. In order to achieve a conjugation altitude accuracy of $\Delta H = 100$ m, a resolution of $\Delta z \approx 3 \mu m$ is required on the linear stage. The actual resolution is better than this in average.

5. Conclusions

Summing quadratically all the possible contributions to the sub-aperture blur we have obtained a global WFE budget of 85 nm of the LO-WFS for MAD which is equivalent to 94% Strehl.
All the mechanical adjustments for the system alignment have been tested and possible ameliorations have been considered for the construction the LO multiple field of view WFS for NIRVANA aboard the Large binocular Telescope.

The LO-WFS for MAD is currently scheduled to have its first light in the laboratory in 2005 and on the sky in 2006. System performances are promising: diffraction limited images on more than 1 arcmin FoV should be reached using 6 to 8 reference stars with a R=14 integrated magnitude; the scientific camera has a 57“ diffracted limited FoV, three broad band filters (J, H and K) and two narrow band filters at 2166 and 2144 nm. But before this the system has still to be tested completely. The whole
alignment of the LO-WFS is now almost complete and the first laboratory tests are beginning. The testing phase is foreseen to be splitted into several phases including static open loop and close loop tests after the integration onto MAD.

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