The ESO MCAO demonstrator MAD: a European collaboration

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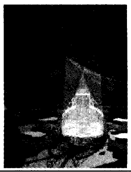
Beyond Conventional Adaptive Optics



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ABSTRACT

In the framework of the European Community Research and Training Network on Adaptive Optics for Extremely Large Telescopes, the European Southern Observatory together the RTN partners is going to build an Multi-Conjugate Adaptive Optics system to perform wide field of view adaptive optics correction. The purpose of the project is to demonstrate the feasibility of the MCAO technique and to evaluate all the critical aspects in bulding such kind of instrument both for the 2^{nd} generation VLT instrumentation and the the 100m telescope OWL. In this paper we present the conceptual design of MAD module that will be installed at one VLT unit telescope in Paranal to perform on-sky observations. MAD is based on a two deformable mirrors correction system and a multi-reference wavefront sensor capable to observe simultaneously some pre-select configurations of Natural Guide Stars. MAD is expected to correct up to 2 arcmin FoV in K band. Finally an example of selected targets together with the estimated performance will be given.

1. INTRODUCTION

Multi–Conjugate Adaptive Optics (MCAO, Beckers 1988 and 1989; Ellerbroek 1994) is working on the principle to perform wide field of view atmospheric turbulence correction using many Guide Stars (GS) located in and/or surrounding the observed target. The light coming from the GSs is analyzed through wavefront sensors whose signals are used to reconstruct the atmospheric turbulence at the different heights which some deformable mirrors are conjugated to.

Different approaches for MCAO correction have been proposed in the latest years such as the atmospheric tomography (also called Global Reconstruction) both in the zonal (Tallon and Foy, 1990) and in the modal way (Ragazzoni, Marchetti and Rigaut 1999) and the Layer Oriented (Ragazzoni 2000; Ragazzoni, Farinato and Marchetti 2000). The modal tomography has been also experimentally verified on the sky (Ragazzoni, Marchetti and Valente 2000). These two approaches, in their basic concept, need different wavefront sensors (WFSs) in order to best optimize the appropriate atmospheric reconstruction.

The European Southern Observatory in collaboration with the European Community Research and Training Network on Adaptive Optics for Extremely Large Telescopes is going to build an instrument prototype called MCAO demonstrator (MAD) to proof on the sky the feasibility of the MCAO technique using both the reconstruction approaches in the view of the future 2^{nd} generation of the VLT instrumentation and the 100–meters telescope OWL (Gilmozzi et al. 1998; Dierickx and Gilmozzi 2000).

MAD, intended as a fast track project, will be installed at the Nasmyth visitor focus of VLT and the actual timeline foresees to have the on–sky operations for mid 2003 using only natural guide stars (NGSs). In this paper we present the conceptual design of MAD, introducing the top–level requirements and the technical specs, passing through the opto-mechanical concept, the WFSs, the corrective optics, the real–time computer. The contributions of two external collaborations are

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described: the high resolution large FoV infrared camera and the atmospheric trubulence generator. Finally a brief introduction to the NGS target selection and the estimated correction performance in the case of Global Reconstruction approach will be given.

2. TOP LEVEL REQUIREMENTS AND TECHNICAL SPECIFICATIONS

2.1. Top Level Requirements

MAD is a prototype instrument with the aim to demonstrate on the sky the **feasibility of the MCAO technique** for future implementation both in **OWL** and in **the 2^{nd} generation VLT instrumentation**.

The MAD design will include the implementation of both the Global Reconstruction, also called Star Oriented, and the Layer Oriented MCAO, each one working with its dedicated WFS. **Two WFSs** will be mounted on board of the MAD bench: a **Multi Shack–Hartmann WFS** (3 SH WFSs) for Star Oriented MCAO and a **Multi Pyramid Layer Oriented WFS**, capable to observe up to 8 guide stars, for the Layer Oriented MCAO.

MAD will be built **only with the existing technology** and will be installed at the VLT Nasmyth visitor focus to first observe on the sky by **mid 2003**.

MAD is intended as a fast track project meaning that some simplifications will be taken into account. The wavefront sensing process is **based only on NGSs**, the system is kept simple with few deformable mirrors (DMs) with a small number of actuators, and the key components will be taken, whenever possible, from those available from other ESO AO projects.

The minimal correction performance to effectively proof the MCAO techniques is:

- one direction optimized Strehl ratio in K band SR(K)$\approx$ 0.50 without on–axis NGS (no FoV correction);
- high and uniform SR(K) and PSF over $2'$ on the sky: SR(K)$>$ 0.30, goal 0.35, ΔSR(K)$<$ 0.05 over $1'$, ΔSR(K)$<$ 0.16 over $2'$.

The correction performance will be estimated using an high resolution infrared camera with large FoV capabilities. As by product of the MCAO experiment, MAD will try to produce one or two outstanding astronomical results in order to convince the scientific community about the potentiality of the MCAO.

2.2. General MAD Technical Specifications

The technical specifications are directly derived from the MAD top level requirements.

- The input beam from the telescope is that of the Nasmyth VLT focus (F/15) and the FoV transferred through the MAD optics will be $2'$ in diameter efficiently transmitted from 0.45μm to 2.2μm.
- The system shall be design to achieve the best correction under the Paranal median seeing conditions: seeing $0.67''$, $\theta_0 = 2.5''$, $\tau_0 = 4$ ms and $\mathcal{L}_0$ =25 m (@ 500 nm). The maximum zenithal distance for the observations will be smaller than 45° and the maximum exposure time of the IR camera will be smaller than 3 minutes (chromatic atmospheric dispersion effects).
- The Global Reconstruction with the Star Oriented WFS will be performed observing 3 bright NGSs with $M_V = 10\ldots12$ while the Layer Oriented Reconstruction will be performed observing up to 8 bright NGSs with $M_V = 10\ldots12$. The NGSs shall be contained inside the corrected $2'$ FoV.
- The MAD opto-mechanical bench shall be compatible with both the WFSs as well as the Real–Time computer (RTC) HW and SW architecture.
- For the laboratory tests, a facility to simulate a spatially and temporally evolving multi–layered atmosphere shall be implemented.

3. OPTOMECHANICAL DESIGN CONCEPT

The optical design of MAD and the concept for the opto-mechanical bench are shown in Fig. 1 and Fig. 2. The transferred FoV is $2'$ (diameter) for visible–near infrared wavelengths (0.45–2.5μm). An optical derotator placed just after the F/15 Nasmyth VLT focus provides the field de–rotation. A 900 mm focal length collimator doublet, optimized for high transmission at IR wavelengths, collimates the optical beam to form a 60 mm pupil on the DM conjugated to the ground telescope pupil while second DM is placed before the previous one at a conjugated altitude of $\sim$ 10 Km. A dichroic transmits the IR part of the light (1–2.5μm) to the IR camera and reflects the visible part (0.45–0.95μm) to the WFS

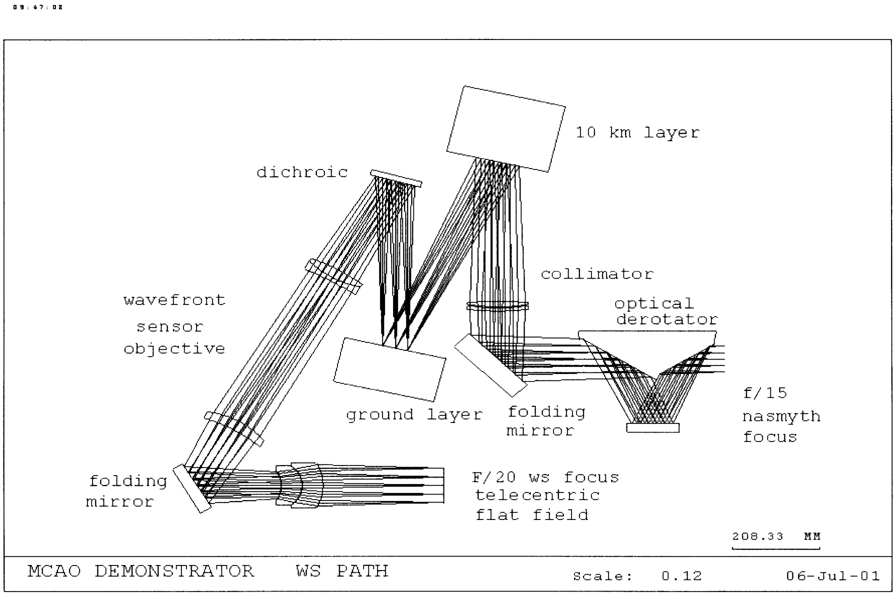

Figure 1. Optical design concept for MAD. The two boxes represent the two Deformable Mirrors conjugated at 0 and $\sim$ 10 Km. The IR camera is placed behind the dichroic.

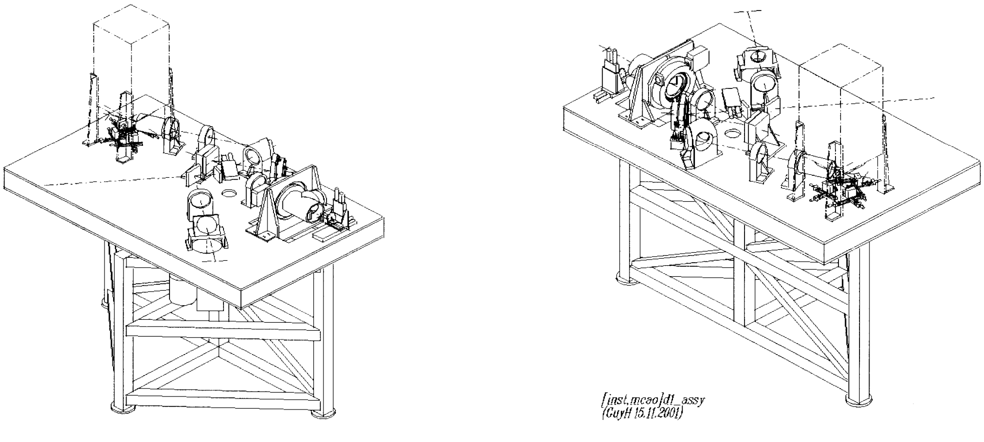

Figure 2. Mechanical design concept of the MAD bench. The elongated box above the bench represents the LOWFS volume. The Multi Shack–Hartmann WFS is located below the LOWFS.

area. The WFS path consists of three groups of lenses providing a flat and telecentric F/20 focus, with high image optical quality (Strehl > 60%), where the two WFSs are installed.

Two calibration units are foreseen. The first one is place at the F/15 focus and consists of 7 white light illuminated fibres for interaction matrix recording. The second calibration unit, similar to the first one, is placed between the ground conjugated DM and the dichroic and provides a collimated beam to be injecetd in the WFS path for estimating the non–common path aberrations given by the intermediate optics.

4. WAVEFRONT SENSORS

The two WFSs are simultaneously mounted on the bench at the F/20 focus but they are not supposed to work at the same time. The CCD cameras and the controller are the same for both the WFSs.

4.1. Multi Shack–Hartmann WFS

The Multi Shack-Hartmann WFS consists of 3 movable SH WFS capable to scan the FoV for picking up the NGSs (see Fig. 3, left). Each SH units is mounted on a high precision XY motion supporting both the optics and the fast read-out CCD. The light of one NGS is picked up by a small 45° mirror and collimated through a doublet to form a 1.6 mm pupil on a lenslet array (192μm pitch, $\sim$ 3.6 mm focal length). The lenslet images (8 x 8 subapertures) are focalized directly on the CCD camera chip and, because of the extremely short focal length, it is possible that the lenslet array will be included inside the camera head.

Additionally an acquisition camera is placed at the F/20 focus to scan the $2'$ FoV and to measure the exact position of the NGSs (see Fig. 3, left). This is important especially for the Layer Oriented WFS where the pyramid positioning accuracy is more critical.

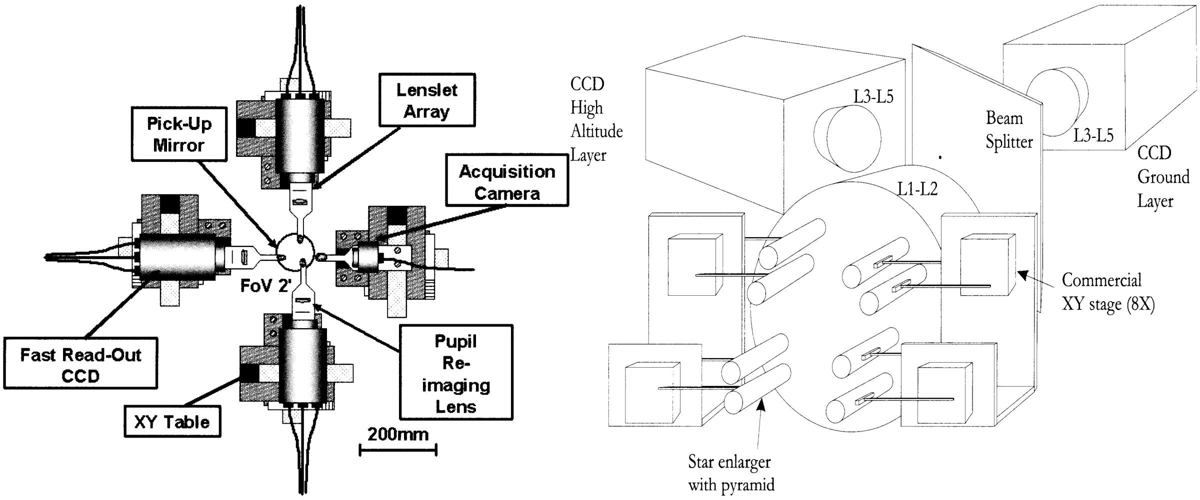

Figure 3. Left: conceptual design of the Multi Shack–Hartmann WFS and the Acquisition Camera. **Right**: conceptual design of the Multi Pyramid Layer Oriented WFS.

4.2. Multi Pyramid Layer Oriented WFS

The Multi Pyramid Layer Oriented WFS consists of 8 single movable pyramids and a single common group of optics to re–image the NGS pupils on two CCD cameras conjugated at the same altitude of the DM (0 and $\sim$ 10 Km). In front of each pyramid is placed an optical relay to enlarge the focal ratio ($\rightarrow$ F/255) at the top of the pyramid. In this way it is easier to reduce the re–imaged pupil size to an acceptable value. The 8 beams coming from the pyramids are collected by a first single objective, then splitted in two parts and finally the pupils are imaged by two other objectives (one per splitted beam). Two detectors provide the image of the pupils at different altitudes (8 $\times$ 8 subapertures). The opto–mechanical concept for Multi Pyramid Later Oriented WFS is shown in Fig. 3 (right).

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4.3. WFSs CCD cameras and controller

The detector type used for the two WFSs is the CCD50 developed especially for NAOS. This detector is a 128 × 128 pixels (24μm) with 16 outputs capable to read-out at 500 Hz frame rate with RON< $6e^-$. For the MAD purposes we have planned to use only 4 outputs in order to read–out only one quadrant of 64 × 64 pixels. The requested frame rate ranges from 50 to 500 Hz with some binning capabilities especially for the Layer Oriented WFS. In order to reduce the dark current a multiple stage Peltier cooler is coupled with the detector and a glycole water cooling system assures the heat dissipation.

A critical aspect is the overall CCD head size. Especially for the Multi SH WFS the CCD heads should have reduced dimension to fit simultaneously the maximum WFS volume. A special effort will be required to design new heads including the electronics in proximity of the CCD chip (PCB and pre–amplifiers boards).

The CCDs controller is the ESO FIERA standard controller capable to read-out simultaneously up to 16 outputs, enough for the MAD purposes (12 ouputs for the Multi SH or 8 for the Multi Pyramid). Some extra development is needed for the Layer Oriented WFS to simultaneously read–out the two CCD chips at two different frame rates.

5. CORRECTIVE OPTICS

The corrective optics of MAD consist in two deformable mirrors and one tip–tilt mount. The MAD corrective optics come from those used in other projects currently in completion at ESO in the framework to use only available key components to reduce the effort in new risky technological development.

The DMs are based on bimorph technology and they have 60 electrodes disposed in a radial geometry with almost the same patter for both the mirrors (see Fig. 4, left). The ground conjugated DM is an identical copy of that used for the VLT instrument MACAO–SINFONI where the projected pupil has 60 mm in diameter, and it is shown in Fig. 4 (right). The DM conjugated at $\sim$ 10 Km Km is an identical copy of those used for the VLTI instrument MACAO–VLTI where the projected pupil is 100 mm. Both the DMs are designed to achieve curvature radii capable to compensate atmospheric turbulence up to $1''$ seeing. The tipical first lowest resonance is around 800 Hz and the hysteresis is mantained below 10%.

The tip–tilt mount is a copy of that used for MACAO-SINFONI and it is supporting the ground conjugated DM (60 mm). The tip–tilt mount compensates the low frequency part of the atmospheric tip–tilt (bandpass of 100 Hz) while the DM compensates the higher frequencies. This particular feature reduces the stroke requirements of the DM electrodes.

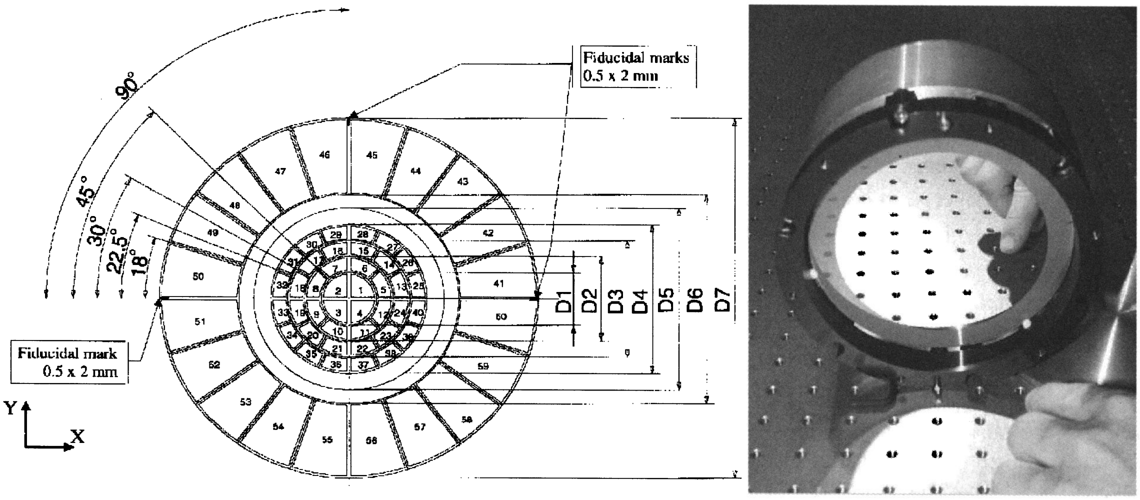

Figure 4. Left: geometrical layout of the electrodes in the bimorph deformable mirror. **Right**: an image of the MACAO–SINFONI deformable mirror.

6. REAL–TIME COMPUTER

The Real-Time Computer consists of two computational modules. One module (the Supervisory Computer or LCU) is in charge of communicating with the network to accept command from the upper level software and to provide status information and diagnostic data to tools running on remote machines. The other is the number cruncher and it implements the real time tasks: this is based on a Quad-G4 Parallel Computer.

The RTC is made of two computing modules each equipped with 2 PowerPC G4 processors, local memory and one I/O port. A third module with additional memory is used to coordinate the communication between the first two and with the VME bus.

The first computing module is used for data acquisition and preprocessing. The I/O port is equipped with a fast digital I/O acquisition card connected to a FIERA controller. Since the FIERA controller can drive up to four CCD both the Shack-Hartmann and Layer–Oriented Wavefront Sensor configurations can be accommodated with one single CCD controller. The RTC receives the pixels from all the connected CCD in the particular configuration in use from the digital I/O port. Pixels come to the RTC unordered. The first computing module has to descramble the pixels and then to equalize them and compute the slope in x and y of the wavefront as measured by the sensor. It also computes statistics on the data. Slopes are then passed to the second computational module that is in charge of generating the control values applying the control matrix and the appropriate controller.

The I/O port of the second computational module is equipped with an optical I/O card: the deformable mirrors and the tip/tilt stage are connected through a single optical connection. The intermediate module supervises the execution and sends the real-time data to the LCU. The computing power is enough to run MAD at 500 Hz.

6.1. Other Electronics

Hereafter we refer to the Multi Shack–Hartmann WFS being comprehensive of the Multi Pyramid Layer Oriented WFS (only two CCDs).

A complete FIERA controller is connected to 3 CCDs each mounted on a XY table (two linear stages). The CCDs are connected to the FIERA acquisition boards that combine the three streams into a single digital stream of pixels towards the Real Time Computer. On the other end, the RTC is connected through a single fiber connection with the High Voltage Amplifiers. The amplifiers receive from the RTC the values to be applied to the two deformable mirrors (60 electrodes each) and to the tip/tilt stage (2 values). The HVA electronics dispatches the values to the appropriate boards and then applies the voltages synchronously on all the channels.

An additional power stage is required due to the high number of high voltage channels.

6.2. Observing and Instrument Control Software

The different sofwater module consist of:

- Real-Time: in charge of the real time control of the sensors and corrective optics. It runs on the real-time computer.
- Instrument Control: in charge of controlling the position of the field selectors. In the Shack-Hartmann configuration the ICS is in charge of moving the 3 detectors (6 degrees of freedom) to pick-up the light of the chosen stars and send it to the detector. In the Layer-Oriented configuration it is in charge of moving the 8 cylinders (16 degrees of freedom) to pick up the light of the chosen stars and send it to the two detectors to obtain the overlap. It is also in charge of controlling additional devices like the calibration sources, the derotaror and the acquisition camera.
- FIERA controller: a quasi-ESO-standard CCD controller with few customizations to accommodate the special needs of MAD. Derived from the NAOS version.
- IR Camera Controller: the controller of the scientific infrared camera Observation Software: this is the piece of software that coordinates all the other components. Due to the nature of prototype of MAD, it will be kept as simple as possible with a reduced set of functionality.

7. PERFORMANCE EVALUATION FACILITIES

During the laboratory characterization and testing of MAD some facilities are required both to simulate a three–dimensional temporal evolving atmosphere and to evaluate the correction performance in K band. For this purpose two institutions are involved to build a large FoV high resolution IR camera and an atmospheric turbulence generator.

7.1. Infrared Camera CAMCAO

The IR Camera for MCAO, CAMCAO, is built by a consortium of Portugal institutions led by the Institute for Engineering and Technology (INETI) of Lisbon with the contribution of ESO.

CAMCAO is based on a 2048×2048 pixel (18 μm) Hawaii2 IR detector of Rockwell. The pixel scale is $0.028''$/px i.e. 2 pixels per Airy disk in K band and the resulting FoV is $\sim 58''$. The input beam is collimated and 3 aspheric metallic mirrors provide the field and the pupil cold stops to reduce the instrumental background. CAMCAO will use the basic J, H and K filters and a pair of narrow band filters close to K band. The CAMCAO instrument control software will be minimized limiting the number of remote controlled motions. The IR detector controller is the ESO standard IRACE. The optical design concept of CAMCAO is shown in Fig. 5.

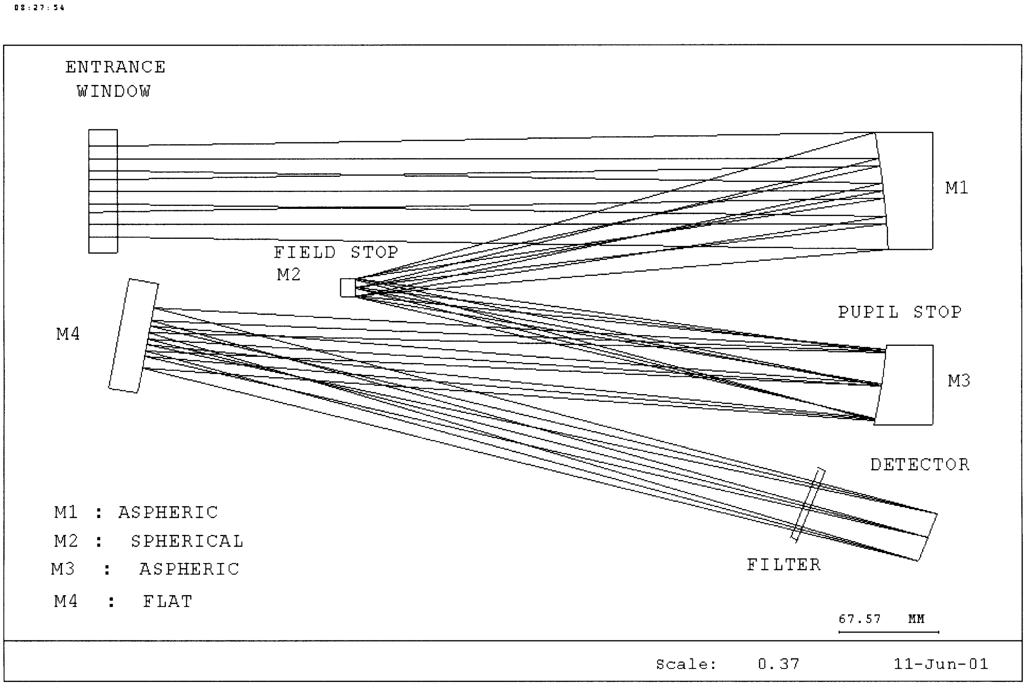

Figure 5. Optical design concept of the IR camera CAMCAO. The camera has diffraction limited imaging capabilities above 1.0μm wavelength.

7.2. Atmospheric turbulence generator MAPS

The Multi Atmospheric Phase screens and Stars, MAPS, is the atmospheric turbulence generator developed by Max-Planck Institute für Astronomie of Heidelberg (Germany) especially for MAD.

MAPS is based on transmitting phase screens simulating the main layers of the Paranal observatory atmosphere. The phase screens are based on an ion diffusing technique where the local refractive index of the glass support is changed by replacing the Sodium ions present in the substrate with Silver ions. With this technique it is possible to create transmitting plates with refractive index distribution having a Von Karman spatial spectrum.

In MAPS the guide stars are simulated by white (0.5–2.2 μm) light fibres with adjustable positions to reproduce different geometrical configurations on the sky. The guide star light beams, collimated by a proper objective, pass through 4 phase screen located at different distances to simulate different atmospheric altitudes. The phase screens have the turbulence contribution tipical of the altitude they are conjugated to. Moreover the phase screens rotate at different speeds to reproduce the different wind velocities. A second objective re–images the "aberrated" guide stars and injects the light beams into MAD with the proper focal ratio and FoV. MAPS will be used only for laboratory testing.

8. NATURAL GUIDE STAR TARGETS

A pre–selection of the possible Natural Guide Star targets has been performed (Marchetti et al. 2001) using the astrometric reference catalogue Tycho–2 (90% of completeness at $M_V \approx 11.5$).

The target identification has been implemented by cross–correlating the positions of $\sim$ 1.6 million of stars visible from the Paranal observatory at a zenithal distance smaller than 45°. All the small cluster of stars, also called asterisms, having at least 3 stars brighter than $M_V = 11.5$ contained in a circle of 2 arcmin of diameter have been selected. The final list includes more than 11,000 asterisms mainly concentrated on the galactic plane. Depending on the different criteria applied it is possible to extract sub–samples of asterisms with common characteristics. For example, considering asterisms with regular geometrical distribution of the stars, more than 454 targets have been selected and their distribution on the sky is shown in Fig. 6 (left). Depending on the galactic latitude the asterisms of this sample can be simple equilateral triangles (high galactic latitude) or crowded clusters (galactic plane) as shown in Fig. 6 (right).

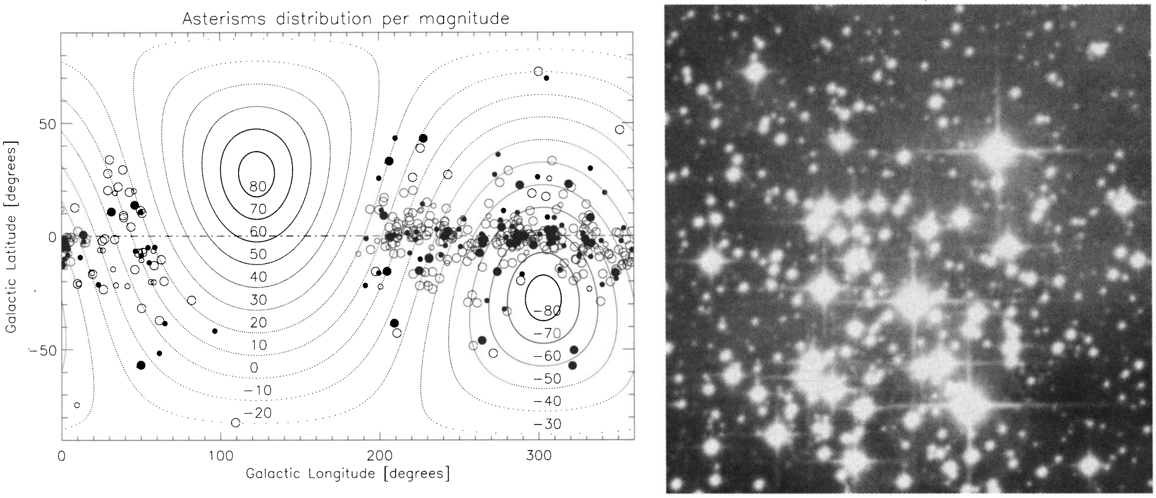

Figure 6. Left: sky distribution of the asterisms per magnitude, ● $V_T \leq 9$, • $9 < V_T \leq 10$, ○ $10 < V_T \leq 11$, ∘ $V_T > 11$. **Right**: typical crowded asterism located close to the galactic plane. The Fov of this image is $6' \times 6'$.

9. EXPECTED PERFORMANCE

The MAD correction performance has been evaluated using a Modal MCAO analytical code especially implemented for the demonstrator.

The code simulates the system in the case the Global Reconstruction is applied using the Multi SH WFS. The code computes the optimized command matrix in order to minimize the residual variance over the corrected FoV.

The system parameters include a 7 layers atmospheric model with Paranal median seeing conditions, 3 SH WFS, two 60 electrodes DMs (0 and $\sim$ 10 Km conjugations), 50 Zernike modes are used in the correction. The WFS CCD has the characteristics of the CCD50. Three NGSs of magnitude $M_V = 11$ equally distributed on a circle of 2 arcmin of diameter are used for the wavefront sensing. In Table 1 the results for J, H and K bands are given for the correction over 2 arcmin

Band	Strehl	σ_{Strehl}	50%EE	$\sigma_{50\%EE}$
K	39	6	120	7
H	19	5	153	5
J	6	3	179	5

Table 1. Strehl ratio and 50% Encircled Energy for 3 NGSs of $M_V = 11$ and Global Reconstruction. The correction performance is evaluated over 2 arcmin FoV.

10. CONCLUSIONS

The ESO MCAO demonstrator is a facility devoted to the demonstration of the MCAO technique feasibility in the framework of OWL and the 2^{nd} generation VLT instrumentation.

It is a fast track project and strategic choices are taken to simplify its contruction and speed up the on–sky observations foreseen by mid 2003. MAD is based on two 60 elements DMs correction and has two WFS, a Multi SH for global reconstruction and a Multi Pyramid for Layer Oriented reconstruction both using CCD50 detectors and a single FIERA controller. MAD will use only NGS to correct in K band up to 2 arcmin FoV.

The opto–mechanical design is already at an advanced status and some key components (DMs) are already available from other consolidated ESO AO projects. The strategy for the real–time computer architecture design has been fixed. The 1 arcmin FoV high resolution IR camera CAMCAO, to evaluate the correction performance of MAD in K band, will be built by the Portugal consortium led by INETI. The atmospheric turbulence simulator MAPS based on transmitting phase screen technology will be built by MPIA and will be used for laboratory tests and characterization.

A preliminary list of suitable NGS asterisms has been selected and the correction performance has been evaluated in the case of global reconstruction method.

MAD represents a real opportunity to strengthen the collaboration of the RTN on AO for ELTs members and to grow the basic expertize for future challanging projects.

ACKNOWLEDGMENTS

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