MACAO-VLTI: An Adaptive Optics System for the ESO Interferometer

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ABSTRACT

MACAO stands for Multi Application Curvature Adaptive Optics. A similar concept is applied to fulfill the need for wavefront correction for several VLT instruments. MACAO-VLTI is one of these built in 4 copies in order to equip the Coude focii of the ESO VLT's. The optical beams will then be corrected before interferometric recombination in the VLTI (Very Large Telescope Interferometer) laboratory. MACAO-VLTI uses a 60 elements bimorph mirror and curvature wavefront sensor. A custom made board processes the signals provided by the wavefront detectors, 60 Avalanche Photo-diodes, and transfer them to a commercial Power PC CPU board for Real Time Calculation. Mirrors Commands are sent to a High Voltage amplifier unit through an optical fiber link. The tip-tilt correction is done by a dedicated Tip-tilt mount holding the deformable mirror. The whole wavefront is located at the Coude focus. Software is developed in house and is ESO compatible. Expected performance is a Strehl ratio sligthly under 60% at 2.2 micron for bright reference sources (star V<10) and a limiting magnitude of 17.5 (Strehl ~0.1). The four systems will be installed in Paranal successively, the first one being planned for June 2003 and the last one for June 2004.

Keywords: Adaptive Optics, Curvature, Bimorph, Real-Time-Computer, Piston

1. INTRODUCTION

The ESO Adaptive Optics Department (part of Instrumentation Division) decided in 1998 to undertake an active adaptive optics program aimed at feeding several ESO instruments with wavefront corrected beam[2,3,7]. In particular the VLT Coude focii needed to be equipped with low cost adaptive optics to improve beam recombination of the VLTI [2]. Four identical copies of this instrument are being built; one for each VLT.

The existing Coude mirror train feeds the delay lines of the VLTI before beam recombination; this constitutes the "science path" of the system. Therefore, no transfer optics has been built for this project as it is often the case for a "bonnette" type instrument. The 8th mirror (M8) of the Coude train, coincides with a pupil plane and will be replaced by the corrective optics. The Adaptive Optics (AO) system consists in a 60 element bimorph mirror (CILAS, France) coupled with a curvature Wavefront Sensor (WFS). The WFS detectors are 60 Avalanche Photo-Diodes (APDs). The Real Time Computer (RTC) is a commercial Power PC board in a VME rack (ESO standard) coupled to a custom made (ShaktiWare, France) counter board for the APD pulse counting.

Computer simulations show that MACAO-VLTI will reach a strehl ratio of 0.58 at 2.2 μm on bright stars (V<10) with a seeing of 0.65". Limiting magnitude is evaluated at V~18 which would result in a strehl slightly under ~0.1. The case of 1.0" seeing has also been simulated and reduces the strehl to 0.39 for a V~10 reference source.

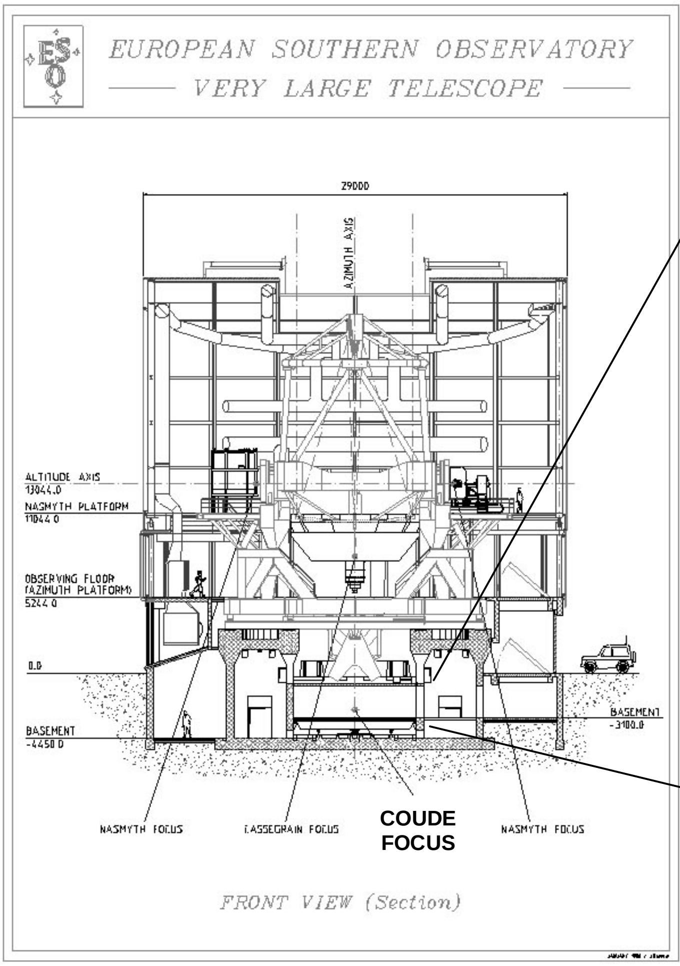
A comprehensive Test Bench has been built with a turbulence generator in order to test, characterize and tune the performance of the system in Garching (Germany). It simulates a f/46.7 input beam and uses so-called "phase screens" in order to produce a turbulent wavefront. An infrared camera (built by the Observatoire de Paris) allows to take images in K band to test the corrected image quality.

The first MACAO-VLTI system will be delivered to PARANAL VLT Unit 2 in June 2003 and the other 3 systems will follow at 6 months interval. By the beginning of 2004 the first 2 systems will be available and will allow wavefront corrected beam recombination at the VLTI.

2.MACAO-VLTI DESIGN

OPTO-MECHANICAL DESIGN

MACAO-VLTI will be located at the Coude focus, in the Coude room of each VLT's. The Coude train is composed of 8 mirrors, the 8th of which being conjugated with a pupil plane. This particular flat mirror is replaced with the corrective optics, a 150 mm (98.4mm pupil) bimorph deformable mirror (DM) in a Tip-Tilt mount. The ninth mirror of the train (M9) is a flat 45° dichroic that reflects the light from 1-13 μm to the VLTI while transmitting the visible (0.45-0.9 μm) to MACAO-VLTI for wavefront sensing.



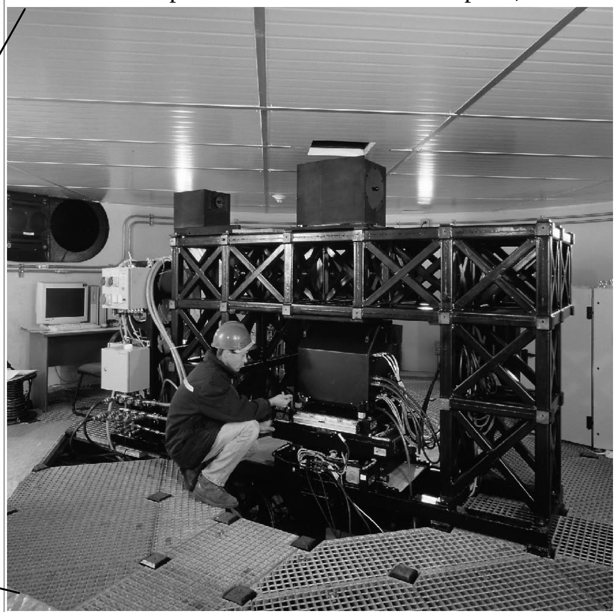


Figure 1: The location of the Coude focus where the MACAO-VLTI systems will be installed. MACAO is the black box under the M9 tower (arch) shown on the photograph (shown here a Tip-Tilt Box).

The whole MACAO-VLTI assembly is sitting on the Coude platform under a structure called the "M9 tower" supporting the dichroic and M10 which along with other mirrors is sending the beam to the delay lines and recombining laboratory of the VLTI. The beam transmitted by M9 is made telecentric by a 300mm lens and then feeds MACAO-VLTI with a f/46.7 beam (scale 1.824 mm/arcsec).

Figure 2 shows an exploded view of all MACAO components. The whole assembly is contained in a 650x770x850 mm volume (including the XY table, not shown in this view). MACAO-VLTI provides 5 main observing modes:

- Adaptive Optics image correction (curvature 60-element)
- Tip-Tilt (with dedicated STRAP sensor) correction on faint stars
- TCCD (Technical CCD) field identification (10" field of view (FOV))
- Simultaneous (with BeamSplitter (BMS)) STRAP[6] correction and TCCD field viewing (5" FOV)
- Simultaneous (with BMS) AO correction and TCCD field viewing (5" FOV)

A Beam-Switching-Device (BSD) made of 45° mirrors and BMS mounted on a translation stage allow selection of the appropriate mode.

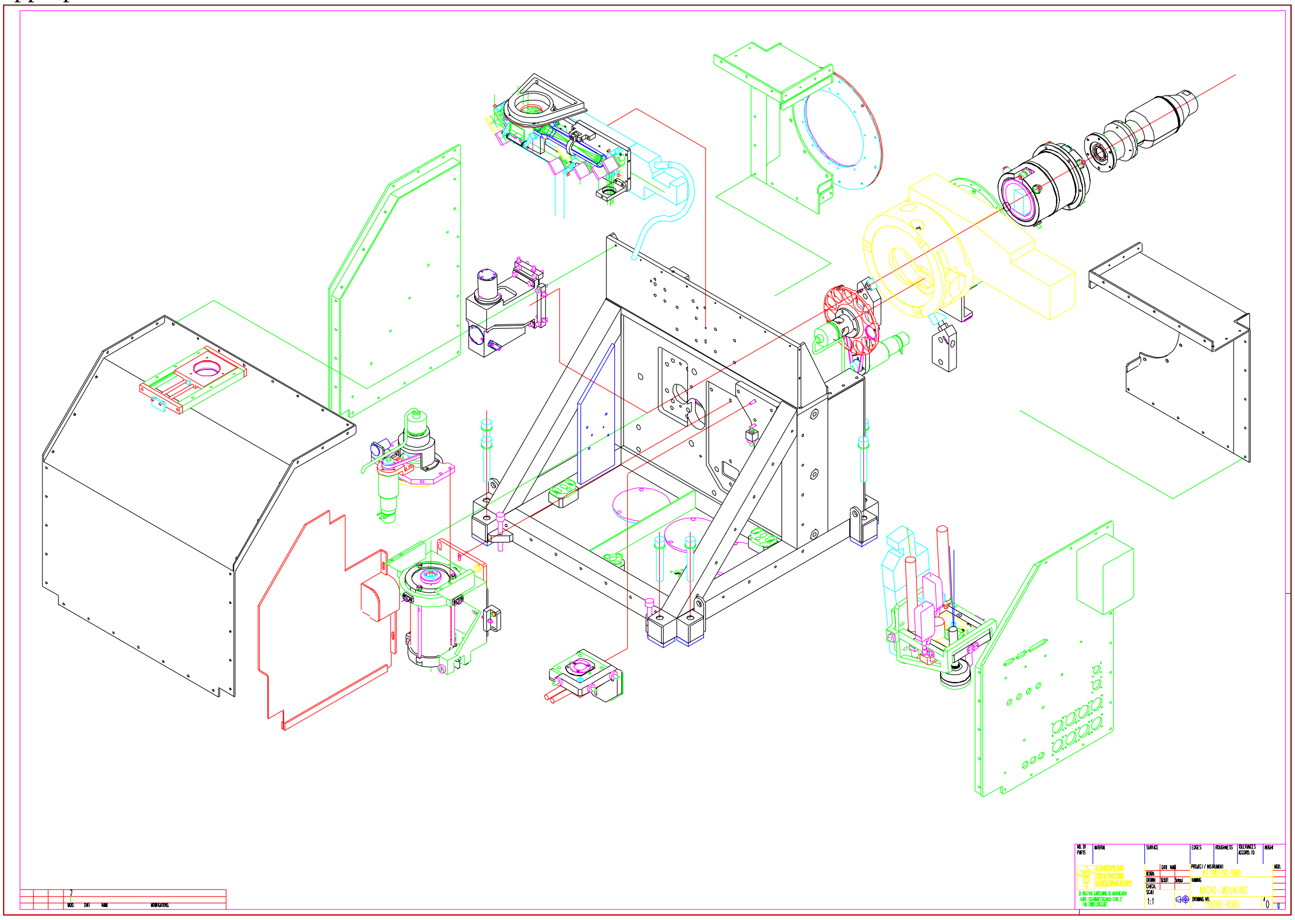


Figure 2: MACAO exploded view. The T-Mount is the main structure on which all noble components are bolted. On the front side (top) the shutter and BSD, WFS optics (below), STRAP and its density filters wheel (lower-left), the TCCD (center-bottom) and the membrane mirror on its gimball mount (lower-right). On the back side (upper right) the main density filter wheel, the rotating unit and the derotator prism and finally the micro-lens mount.

The whole MACAO-VLTI assembly is sitting on a so-called "XY Table" (not shown) which fulfills the field selector function of the AO system. This table has been custom made (ESO design, externally contracted) because of the high requirements needed. It has been proven to provide a 2 µm relative positioning accuracy, over a 240x240 mm field of view. All axis motions are linear to better than 20 arcsec (pitch, roll and yaw).

The optical train is composed of the following units from the image focal plane to the WFS detectors:

- *Membrane Mirror:* an aluminized pellicle mounted on a loudspeaker to be set in vibration at 2.1 kHz. It corresponds to an image plane and a diaphragm can be remotely controlled to minimize sky background. The whole assembly is mounted on a gimball mount; it allows the centering of the pupil on the micro-lens. All these are mounted on a translation stage for focus adjustment (or injection by the deformable mirror into the Coude train).
- *WaveFront Sensor Optics:* the function of the WFS optics is two-fold; to image the pupil onto the lenslet array and increase its size. It is composed of 4 diamond turned optics: a sphere to collimate the image from the membrane mirror, a flat folding mirror, and 2 off-axis parabola acting as a beam expander. All optics are mounted into a case, made of the same material as the mirrors and pinned in place. No adjustments are required and the whole assembly can be considered as a module that can be exchanged during maintenance.
- *Derotator Prism:* A prism is needed to compensate the rotation between the DM and the lenslet array. The DM is mounted on the telescope structure and rotates with the azimuth axis. On the other hand, the MACAO-VLTI

structure is sitting on the Coude platform, at rest with respect to the ground. This setup compensates the rotation between the DM electrodes and the lenslet sup-apertures. Rotation accuracy is not a challenge but alignment of the axis of rotation is however critical.

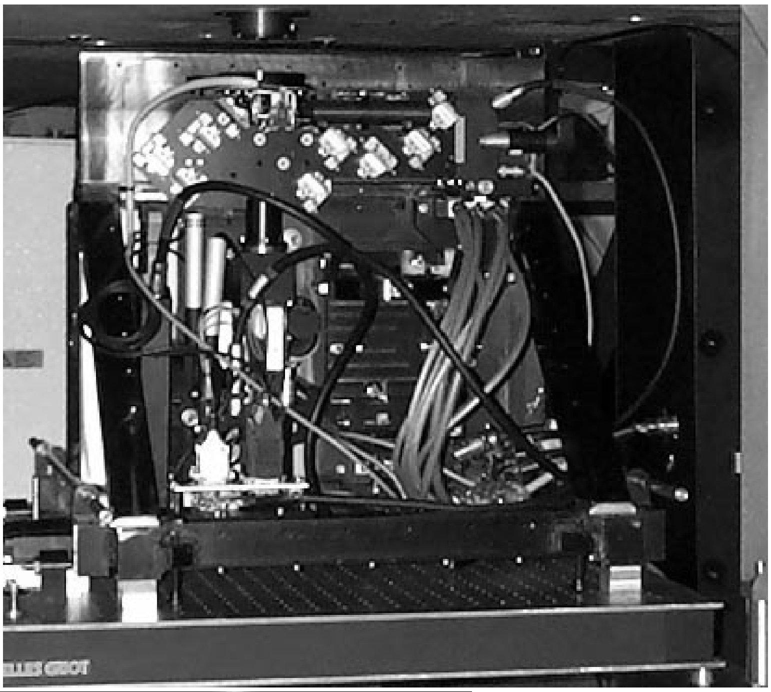


Figure 3: Opto-Mechanical setup of MACAO-VLTI. The STRAP unit is not installed. The BSD can be seen in the uppermost part; on the left-hand side a very crowded area where is located the WFS optics and the membrane mirror gimball mount. Water pipes can be seen on the right side and are used for the cooling of the TCCD and STRAP units.

- *Lenslet arrays:* The geometry of the sub-apertures, the sag of the lenslet, encircled energy and accuracy of the lenslet vertex altogether constituted a very demanding design. The 60 apertures keystone geometry is distributed in 5 rings of varying number of lenslets: 4, 8, 12, 16 and 20. In order to reduce the required sag, 2 lenslets are used: a first one made of 2 keystones shape apertures back to back; this allows to realize the 45mm focal length needed with less sag on each lenslet. The second one is made of 60, 800 μm circular lenses deposited on a substrate and located at the vertex of the first lenslets. It is used to inject the light into the optical fibers.
- *Fiber Bundle:* This component includes the 2 lenslets pre-aligned in a high precision mechanical mount, the centering piece for the fibers including stress relief, 3m of fibers ended by the FC connectors to be plugged into the Avalanche Photo-Diodes.
- *WFS Detectors:* 60 Avalanche Photo-Diodes are used as WFS detector (see Electronics section).

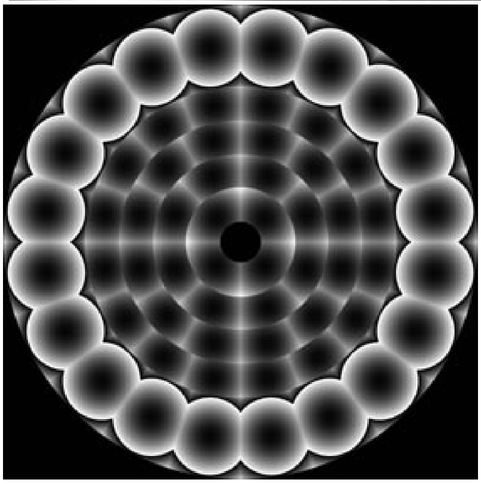


Figure 4: Two such arrays are glued back to back in order to produce the first lenslet. The gray level indicates the sag of each lenslet; the external ring is made of fresnel lenses in order to reduce the sag needed. A master is fabricated with a laser writing technique and replicated to produce the deliverable units (Heptagon, Zurich, Switzerland).

Fig. 5 shows the optical layout of MACAO-VLTI or WFS optics. SBM1 is a 13mm diameter sphere with R=440mm; SBM2 13mm flat; SBM3 a 7mm diameter off-axis paraboloid R=50mm and SBM4 a 22mm diameter off axis paraboloid R=150mm. The pupil imaged on the lenslet is 14 mm in diameter.

CORRECTIVE OPTICS

The Deformable Mirror is fabricated by CILAS (France) and is of the bimorph type. The single piezo layers are 1mm thick. Two 0.2 mm glass plates sandwich the piezo bi-layers to provide a symmetric ensemble. The top glass plate is polished and coated to become the phase plate. The back of the mirror is used for electrode connections.

Five such mirrors have been ordered (4 units plus one spare) and a prototype for development tests. The performances of the mirrors are listed in the following table.

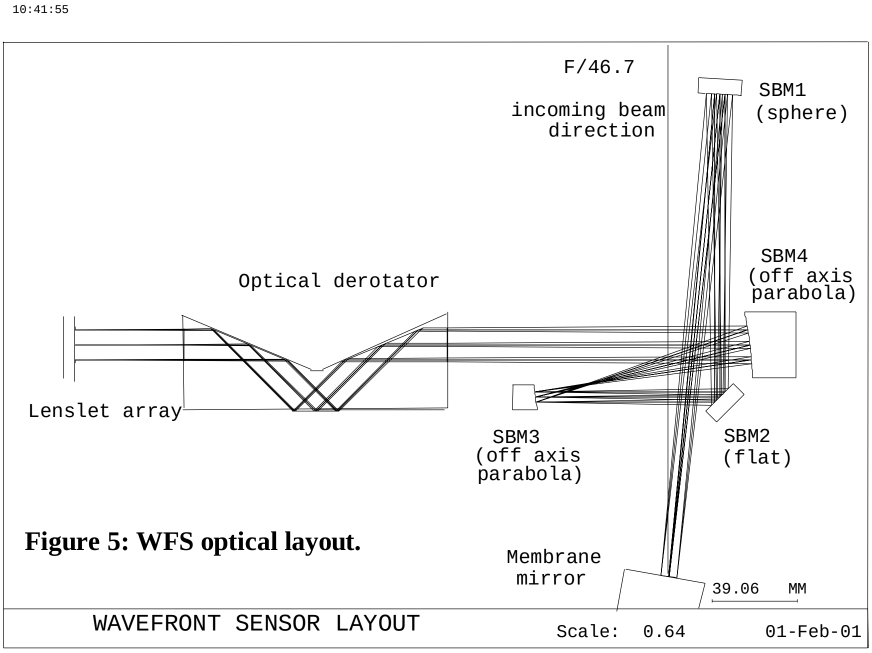


Figure 5: WFS optical layout.

The Tip-Tilt Mount is a custom design from the Observatoire de Paris (LESIA). It is based on a gimball mount in which the DM is inserted. The 2 gimball axis are powered by 2 pairs of voice coil motors working in push-pull and located near the edge of the mount. The actual tilt applied is measured by a pair of capacitive position sensors located near the motors. The assembly is controlled by a dedicated electronics with its own internal 1 kHz control loop.

DM Specification	**As Built Performance**	**Comment**
Surface quality flattened (voltages applied)	~10 nm RMS	Over 100mm pupil
Amplitude of flattening voltages < 10% of 400 Volt	20 Volt RMS	7 electrodes out of 60 with 40<V<50
Surface Roughness < 3 nm RMS	0.73 nm RMS	
Printtrough < 5nm RMS over any 5mm	Undetectable	
Reflectivity: R> 97% 450-1000 nm R> 98% 1-13 µm	Ravg >99%	R< 97% for λ<470nm and Dips @ 800nm, 3µm, 10.5 µm
Electrode Stroke RoC < 32m	RoC 27.3 m	48 µm PV over 100 mm pupil
Tilt stroke	±18.5” mech. (37.1” PV)	Corresponds to 0.46 arcsec (0.93” PV)
First Resonnance @ f> 500Hz	Main Resonance @ 730 Hz	Secondary peak @ 230 Hz (trefoil mode)

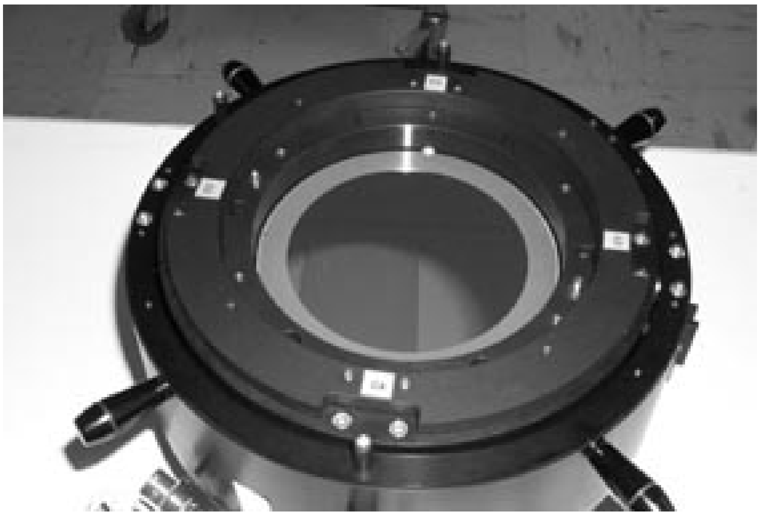


Figure 6: Bimorph Deformable mirror in its tip-tilt mount. One can see the protected silver coating 100mm in diameter. The bimorph mirror is held by a spring loaded radial 3 points support in a dural ring. The assembly is inserted in the Tip-Tilt Mount (TTM) which can tilt the DM during close loop. The TTM is used mainly to offload tilt angles from the DM which itself corrects for atmospheric tilt.

This system can then be developed, integrated and tested completely independently from the AO system.

The mount exhibits excellent performance mainly limited by the weight and moment of inertia of the tilted mass (DM and supporting ring ~813g). The bandwidth of the system has been tuned at 100 Hz for both axis (phase lag 12.5° X-axis and 17° Y-axis). Stroke is 400 arcsec PV mechanical which corresponds to 10 arcsec on the sky. Crosstalk between axis is below 0.5% for frequencies below 15 Hz.

The system has been designed so that the center of gravity of the DM+supporting ring is coincident with the intersection of the X and Y tilt axis. This insures a better close-loop performance of the TTM. Furthermore, the surface of the DM is made coincident with the tilt axis (at center) in order to minimize (ultimately not to have) piston when tilts are applied.

SOFTWARE

MACAO-VLTI is considered as a telescope system and therefore is relatively transparent to the astronomer. In the end, the AO loop will be closed when appropriate as part of the interferometric source acquisition procedure. The so-called VLT-ISS (VLT Interferometer Supervisor Software) sends command to MACAO-VLTI OS (Observing Software) which coordinates the operations of the MACAO RTC (Real-Time Computer), ICS (Instrument Control Software), STRAP and TCCD subsystems implementing the guide star acquisition procedure. The OS manages the various operation modes of MACAO-VLTI already alluded to in previous sections: AO curvature control, AO curvature control and TCCD viewing, STRAP tip-tilt control, STRAP tip-tilt control and TCCD viewing, and TCCD viewing alone. Another important function is the tracking of a source off-axis; the MACAO ICS calculates the XY coordinates required for the XY table to follow sources in the 1 arcmin radius field updating the table position at ~20Hz.

In addition the MACAO OS supports the following observing modes:

- *Staring*: a single acquisition where the AO loop remains closed during the entire observation.
- *Chopping:* an observation where M2 is used to shift the field from object to sky and back again. The AO loop is synchronized (using the TIM board) with the frequency of M2 and the loop is opened during the chop on sky cycles.
- *Nodding:* an observation where the telescope is used to shift from object to sky and back again. The ISS informs the MACAO OS of the nod to sky and nod to object cycles, the AO loop is opened during the nod to sky cycles.

An engineering interface of the OS has been designed and allows full control of the functions during integration and tests.
All of the MACAO subsystems have been written conforming to the normal VLT S/W standards, reusing the standards VLT packages for OS (boss), ICS (icb), and LCU applications (lsf).

ELECTRONICS

The MACAO-VLTI electronics is composed of 4 cabinets containing all the required electronics. Three of them are installed in the Coude room: the RTC-VLTI cabinets, the IC cabinet and the APD cabinet. The fourth one is located on the VLT azimuth platform for its proximity to the corrective optics. All electronics is conform to the ESO standard using PowerPC CPU boards, VME architecture, TIM board and heat exchanger to expel heat produced by the electronics. Motorized functions are realized with MACCON boards (MAC4SA and corresponding amplifier boards) while digital and/or analog I/O done through ACROMAG I/O boards.

The RTC-VLTI Cabinet contains a heat exchanger unit (fed with glycoled-water), two 1U fan units and the VLTI and RTC LCU.

For the RTC hardware, an effort was made to select commercially available component to insure a smooth integration into the VLT environment. The RTC main components are:

- Power PC2604 (400 MHz) LCU controller (controls VME rack and communication with outside world)
- Power PC2604 (400 MHz) RTC calculation
- APD Counter board (Shaktiware, Marseille, France)

Other boards like a TIM board allows synchronization with other VLT systems. A MAC4 board controls some of the WFS motorized functions; a VME4SA is the associated amplifier board. These control the functions that are close to the real-time calculation or require a feed back from the RTC: neutral density filter wheel and diaphragm control. The RTC also controls the main instrument shutter through the ACRO9481 board. A VMIVME 5576 board is a reflective memory component allowing fast communication; it is used to notify the instruments in the VLTI lab of the current performance of the AO correction.

The membrane mirror is set in vibration at 2.1 kHz; this function is managed by the APD counter board, a solution chosen because a single board manages the counter read rate and membrane driving signal which need to be well synchronized. The counts from the APD (intra-focal and extra-focal) transit on the VME bus and are acquired by the RTC. They are processed (contrast calculation and multiplication by control matrix) and commands to the corrective optics are sent at a frequency of 350 Hz, hence 6 membrane mirror cycles. The time delay of the calculation has been measured to 310 μsec. The number of electro-mechanical functions controlled by the RTC LCU (Local Control Unit) has been kept to a minimum in order to leave the VME bus free for data transfer between the PowerPC board and the APD counter board.

The VLTI LCU controls the STRAP and TCCD operation for MACAO-VLTI and some functions of the VLTI mirror train located in the Coude room. The IC cabinet (Instrument Control) contains a VME rack controlling all motorized functions: BSD mode selection, the membrane mirror orientation and focus, the derotator angular position and the XY table position. Note that a dedicated XY table controller has been developed and constitutes a separate rack in the IC cabinet for the position and velocity loop control of the XY table. The 2 cabinets are identical in size and covered by a wooden-insulated "sarcophage" that reduces to a minimum heat radiation in the Coude room and also allows acoustic noise insulation. Each cabinet's heat exchanger is connected to the SCP (Service Connection Point) which provide the cooling fluid and an extra distribution unit allows a separate setting of the fluid flow, well adapted to the heat dissipation of each cabinet.

The APD cabinet is smaller and slightly different in construction. No fans have been implemented and all 60 APD's are mounted on cooling "plates" in which the cooling fluid circulates. The FC connectors at the end of the FOB are connected to each individual APDs. The cabinet provides power to the APD's and a driver board transforms the BNC output of the APD's into two 38 pins SCSI type connectors. These are connected to the RTC APD counter board through a 3m long cable.

Figure 7: On the left-hand side the APD cabinet without its panels. It contains 4 plates with 8 APD's mounted on each side (60 total for 64 positions). Cooling fluid is circulating inside these plates. On the rack back side the power supply and the driver board BNC-SCSI. Individual APD's can be seen on the right view.

The azimuth platform cabinet contains the DM voltage amplifier and the TTM servo-unit plus the usual cooling fans and heat exchanger. The DM and TTM are located at M8 under the telescope structure between the Coude room and the azimuth floor. This location for the cabinet was chosen because it offers the shortest path to these components. In order to allow this, a solution had to be found for the "transport" of the low voltage signals from the RTC rack (Coude room) to the DM voltage amplifer and TTM servo-units. Instead of using analog voltages through copper cables, a fiber optic link has been implemented. The fiber optic controllers are located in the RTC rack and the HV amplifier rack.

The HV amplifier has been designed and built by 4D Engineering and uses a VME architecture. This rack is controlled by a PowerPC CPU and signals are sent via a fast optical fiber communication link. A RS232 utility link allow various maintenance actions. The rack contains 4 boards which provide each 16 HV channels for a total of 64. It is upgradable up to 15 boards (240 channels). The 10V signals to be sent to the TTM servo-unit also transit through the fast optical fiber link.

3.AO CONTROL & PERFORMANCE

A curvature system was chosen because it offers a good performance for relatively low degrees of freedom, allowing lower costs for components (DM, RTC, lenslet, etc.[4])

SIMULATIONS

A whole set of simulations has been carried out in order to predict the performance of the system. The various assumptions were a model of the atmosphere with three main layers, matching what is agreed to be the standard average atmosphere in Paranal. The three layers are chosen to match a seeing condition of 0.65" at 500nm, τ_0~4ms, wind speed~11m/s and r_0~16cm, and they are characterised by the following parameters:

Layer	Wind speed	Direction	Weight
Upper Layer (10000m)	33m/s	Horizontal	0.2
Medium Layer (1000m)	5.7m/s	Vertical	0.6
Low Layer (10m)	5.7m/s	Horizontal	0.2

We have also tested one case of worse conditions, characterised by a seeing of 1" at 500nm, τ_0~3ms and r_0~10cm. Two different values (based on measurement made in La Silla and Paranal) for the sky background have been considered: m_V=20.7 mag/arcsec^2 (average dark sky) and m_V=19 mag/arcsec^2 (bright sky).

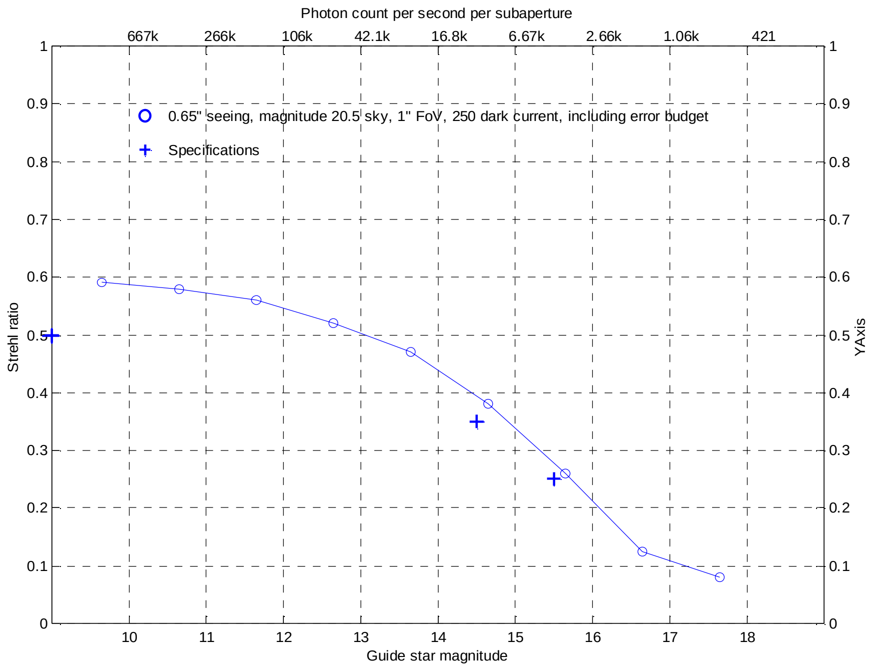


Figure 8: Resulting Strehl ratio in K-band (2.2 µm).

The reference flux for the simulations is $4{\cdot}10^5$ detected photons/second at magnitude 15th in the overall 8.2m aperture. This flux is computed by integrating the photons detected from the telescope aperture, including the transmission curves concerning the telescope and the quantum efficiency of the APDs; everything has been integrated in the entire range of sensitivity of the diodes. We have considered a peak of sensitivity for the WFS of 700nm corresponding to the sensitivity peak of the APDs.

We choose a value of 250cps

for the APDs' dark current, from the Perkin Elmer commercial list. The membrane stroke used is 0.25 m minimum (focal length) and a 500 μsec computing delay was assumed.

Figure 8 shows the results of the simulations. This plot includes the full optical budget, that is the strehl loss due to optical aberrations in the non-common parts of the beam. The plot is for a relatively good seeing but MACAO-VLTI corrective optics stroke has been calculated to correct also for worse seeing up to 1". The crosses show the specifications issued by VLTI.

Different configurations of sub-apertures and electrodes geometry have been envisioned. The one adopted minimizes the total noise variance and the variance of noise on the tilt correction.

CLOSE LOOP CONTROL

The commands are applied to the corrective optics at a frequency of 350 Hz. The APD counter board provides the RTC with one set of intra/extra-focal counts every 0.48 msec. These counts are integrated by the RTC for 6 cycles and then multiplied by the command matrix to produce a command vector to be sent to the corrective optics. The basic functions of the RTC algorithm are:

- Data acquisition from the WFS,
- Data processing in real-time (calculate command vector to be sent to corrective optics (CO)
- Send a command vector to the CO
- Producing on-line diagnostic information
- Controlling the membrane mirror, neutral density filter and diaprhagm (WFS image plane)
- Producing offsets (tip-tilt for centering and focussing)

In order to avoid saturation of the DM with quasi-static aberrations three nested loops are implemented:

1. WFS measurements to bimorph mirror at 350 Hz (main loop)
2. A fraction of the til-tilt component is sent to the tip-tilt mount at each cycle to decrease a systematic tilt applied to the bimorph mirror (equivalent update rate of 5 Hz)
3. Systematic tilt and focus will be offloaded to the telescope; this will be done through the MACAO OS to the VLTI ISS and finally to the VLT control system. It will be done on demand (0.2 Hz)

A watchdog has been implemented to monitor the count rate on the APD. It averages the number of APD counts over a tunable number of cycle to determine whether they are over-illuminated. There are 2 safety levels; in a given interval a warning is sent. If an upper-limit is exceeded it triggers the switching off of the APD power, close the instrument main shutter, open the loop and raise an alarm. Note that 2 conditions must be fulfilled in each case i.e. a certain level of counts maintained during a specified time interval. We are aware that this procedure has its limitation and offers a limited protection in case of a sudden increase in light level.

The routine which sends commands to the DM is also responsible for monitoring the voltages sent to the electrodes. It clips values in excess of + or – 400 Volts back to acceptable values. If, for a given time, the voltage sent to a number of electrodes exceed the maximum, it triggers an alarm. Only if the condition persists for a longer time is the loop opened.

The heart of the RTC software is the "control loop" routine. In open loop it takes the data from the sensor, computes the Zernike coefficients and sends everything to the LCU. In closed loop it takes the data form the sensor, applies the control matrix and sends the results to the DM. It computes the values to offload and send them to the LCU to be stored in the database. It also computes the Zernike coefficients and sends them to the LCU as well. In calibration mode it applies a set of mode to the DM and measure the WFS signals building up the interaction matrix.

A "Command Server" has also been developed to exchange commands and data with the LCU.

There is provision for a modal optimization. The algorithm can be implemented on the LCU CPU and change can be made to the control loop parameters in close loop on the fly. This includes also a change of the control matrix. A circular buffer is also implemented to post-process sensor signals or mirror commands off-line. A background subtraction algorithm is possible in case a very faint reference source is used with high sky background. Modal filtering projects the sensor data in another space where variable gains can be used for the different modes.

PISTON FREE AO SYSTEM

For imaging purpose the piston produced by the deformable mirror in an AO system is not critical and the main concern is usually to avoid an accumulation of piston applied on the DM which would cause saturation of the electrodes. A filter is usually applied in the close loop algorithm to this purpose.

One of the main challenges of MACAO-VLTI is to insure that the corrective optics of 2 different MACAO-VLTI on 2 different UT's does not introduce any phase delay between the recombined beams during close loop operation[5]. The associated specification is extremely tight and applies to other close loop systems in the VLTI (delay lines for instance).

Since MACAO-VLTI feeds an interferometer, differential pistons or a variable optical path difference (OPD) between 2 recombined AO beams would limit, if not destroy, fringe contrast. This is extremely critical if it occurs at high frequency, where the VLTI delay lines are no more able to detect and correct for it. This is the reason for the strict piston specification listed in the following table.

The strategy has been described in Verinaud & Cassaing (2000) and involves defining a set of piston free influence functions. A special setup using a commercial Shack-Hartman WFS and a capacitive sensor allows to measure accurately (better than 1%) the optical piston averaged over the DM pupil for each electrodes. The WFS is a HASO type with 64 sub-apertures and provides the global shape, while the capacitive sensor gives the phase lag at one position of the wavefront. We expect to reach a accuracy of $\lambda/100$ with the SH sensor and the capacitive sensor provides a 2nm RMS measurement error. First a pure piston mode must be defined. The piston-free influence functions are built by adding a pure piston to the original influence function equal but opposite in sign. These are used to measure the interaction matrix and command the DM. The so-called tilt electrodes of the bimorph mirror (outside the pupil) contribute mostly to the production of a pure piston.

Piston Error Source	Piston r.m.s (48ms)	Piston r.m.s (290ms)	Piston PTV (10 min)
Imperfect Removal	18 nm	26 nm	76 nm
Hysteresis	1nm	8nm	<700nm
Tip/Tilt misalignment	5.6nm	<5.6nm	<34nm
Mirror resonance	<<1nm	<<1nm	<<1nm
Total Piston Error	**19nm**	**28 nm**	**<810 nm**
VLTI Specification	**25 nm**	**125nm**	**2000nm**

4.INTEGRATION & TEST

A special effort has been made to develop all necessary tools for a straightforward assembly and integration of the MACAO systems. This has turned out to be justified since all together 5 systems plus 2 TTB will have to be (have been) assembled and integrated in the life of this project. By the same token, conception errors or fabrication errors have a big impact since they involve 5 times the same corrective action. Furthermore, a well defined set of handling tools has been designed and fabricated for manipulation of the components or sub-systems heavier than 50 kg.

For AO integration and test aspects, a complete Test bench has been designed and fabricated. This bench reproduces a f/46.7 optical beam, identical to a Coude focus. The source module provides alignment sources (laser) and various set of target for the alignment of MACAO-VLTI with respect to the bench. A turbulence generator using phase screens produces a turbulent wavefront. This concept already used for the NAOS experiment consists in setting in rotation a 50mm circular disk, lit on a 5mm aperture on the circumference. The surface of this disk is covered with a varying thickness coat of resin conform with a kolmogoroff phase spectrum. It is aluminized and used in reflection. A given disk provides a given coherence length (r_o) and the rotation velocity, which can be set, reproduces a given coherence time (τ_o). In the Test Bench two such disks are used in series allowing different combinations of seeing condition from 0.2" to 1.0".

The setup will allow a complete integration and performance evaluation of the system in the laboratory plus optimization of the close loop algorithm. This will reduce time spent on the telescope during commissioning activities since only those that requires the telescope environment or astronomical sources will be performed in Paranal.

A dedicated infrared camera working in K band is installed permanently on the Test bench for characterization of the resulting image quality and evaluation of the Strehl.

A separate infrared test camera is in fabrication. The design is simple and uses 3 spherical mirrors. The optical components and mount have been received and aligned. The cryogenics are being completed and the read-out electronics is available (IRACE system). This camera will be used for tests in Paranal of the MACAO-VLTI systems. The necessity to have 2 cameras is stressed by the need to have parallel activities in Garching (tests of the next in the line MACAO-VLTI system) while a previously integrated system is being commissioned in Paranal.

5.TIP-TILT BOXES

The milestone "Tip-Tilt Boxes Delivery" is a partial delivery of the MACAO systems to accommodate the VLTI planning. These are composed of the MACAO-VLTI opto-mechanical structure, including the XY tables, but without high order wavefront sensing and wavefront correction capability. The MACAO-VLTI structure includes a TCCD (Technical CCD) and a STRAP unit for tip-tilt sensing. The TTB allows thus the observer to acquire stars, to track stars off-axis and perfoms a tip-tilt sensing of the source. These tilt signals are fed to the VLT M2 (secondary mirror) for tip-tilt correction. This setup has been delivered to UT1 and UT3 in November 2001, only 7 months after final design review. It shall allow VINCI to reach a better fringe contrast. It has been in use since December '01. Tests carried out on a 11.7 mag start shows a ~10 mas tilt residual after correction. This excellent result is partly due to a sub-arcsec seeing (~0.45") and the use of a bright reference source. The STRAP unit delivers tilt contrast values at a frequency of 200 Hz and time averaged values were fed to the M2 unit at a frequency of up to 80 Hz.

6.STATUS AND PROJECT DESCRIPTION

PROJECT ORGANISATION

MACAO-VLTI is stricly an ESO driven project. The VLTI is the customer and has issued the high level requirements for the production of MACAO-VLTI by the Instrumentation division (AO department). The AO department is responsible for the complete design. All procurement is made outside ESO, with acceptance tests defined and carried out by ESO staff. The final assembly and integration of the complete systems is being carried out by the ESO Integration Department (part of Instrumentation Division).

It is worth mentioning that SINFONI and CRIRES (other ESO instruments) besides MACAO-VLTI also use similar AO components. The implications are that several components can be ordered in several copies (usually 7 up to 10) leading to a substantial cost reduction but also creating some motivation in industry. Besides, work or tasks accomplished on a particular project often benefit the other which lead to a non-negligible gain in development.

The project has followed the usual steps for a project development at ESO Instrumentation Division. Several reviews were organised for project auditing covering management to technical design aspects.

SCHEDULE

The important milestones for the project are listed in the table below:

MILESTONE	DATE
Critical Design Review	Spring '00
Preliminary Design Review	October '00
Final Design Review	March '01
Tip-Tilt Boxes Delivery	November '01
MACAO #1 PAE*	December '02
MACAO #1 Commissioning	June '03
MACAO #2 PAE	May '03

MACAO #2 Commissioning	July ‘03
MACAO #3 PAE	January ‘04
MACAO #3 Commissioning	March ‘04
MACAO #4 PAE	June ‘04

*Provisional Acceptance Europe

The interval between the successive MACAO-VLTI systems is dictated by the manpower available to perform the integration and optimization of the systems.

To this day all mechanical components have been fabricated, all commercial positioning devices received and all optical components accepted. One complete MACAO system has been integrated and installed (aligned) on the Test Bench. The basic test program of the AO system has started and the first closing of the loop should happen in a matter of a few weeks. The RTC currently sends commands to the corrective optics and at this time tests are carried out to insure that the WFS can reliably measure a wavefront aberrations. Once ascertained, the first interaction matrix could be measured.

Also in a matter of weeks the integration of the second MACAO system will start.

7.SUMMARY

The AO department of ESO has completed the design of an adaptive AO system for the VLT Interferometer. Ordering of components and manufacturing took place during the summer 2001. At the time of this writing all components have been received and the Integration and Test phase is in full swing.
The system is built in 4 copies one for each VLT. It is installed at the Coude room and the Coude train is used as a “science path”. Only one of the mirror (M8, pupil conjugated) is replaced by the corrective optics. The 60 elements system should allow strehl ratio of ~0.6 on bright sources.
The first system should be commissioned in Paranal in June 2003 and the delivery of the 4th system is planned for June 2004.

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