MACAO-VLTI First Light: Adaptive Optics at the Service of Interferometry

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The Multiple Application Curvature Adaptive Optics (MACAO) programme was initiated by ESO in 1998 to fulfil the high angular resolution requirements of the VLT Interferometer (Glindemann et al., 2002) and also instruments like SINFONI (Bonnet et al., 2002) and CRIRES (Moorwood et al., 2002). After a learning phase of two years with the laboratory Curvature prototype delivered by Laplacian Optics, the ESO Adaptive Optics Department set up a project team at the beginning of 2000 for the line production of seven MACAO systems (Donaldson et al., 2000): four for VLTI, one for SINFONI, one for CRIRES and one spare. Although the AO key components are similar for these seven systems, the opto-mechanical implementations are different for the VLTI, SINFONI and CRIRES. In the following we will concentrate on the VLTI implementation.

The main aim of MACAO-VLTI is to feed the VLTI with a corrected wavefront, to improve light injection efficiency in the monomode fibres. The existing Coudé mirror train M8 is replaced by the corrective optics. The MACAO-VLTI Wave Front Sensor (WFS) is located just below M9 on the Coudé platform (Figure 1). M9 is a dichroic that allows the wavefront sensing in the visible (transmits 0.45–0.9 μm) and reflects the wavelengths 1 to 13 μm to the recombination laboratory.

Simulations done for the design reviews 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″ and this has been confirmed by tests in the laboratory. Limiting magnitude is evaluated at $V \sim 18$ which would result in a Strehl ratio slightly under ~0.1. MACAO will also operate with worse seeing (1.0″) but the correction is less spectacular (expected Strehl ratio of 0.39).

The first MACAO-VLTI system was delivered to Paranal on UT2 in April 2003, and results from the first light are shown further down in this article. The other three systems will follow at 6 month intervals. By the end of 2003 the first two systems will be available and will allow wavefront corrected beam recombination at the VLTI.

Figure 1: The location of the Coudé focus where the MACAO-VLTI systems are installed. MACAO is the black box under the M9 tower (arch) shown on the photograph.

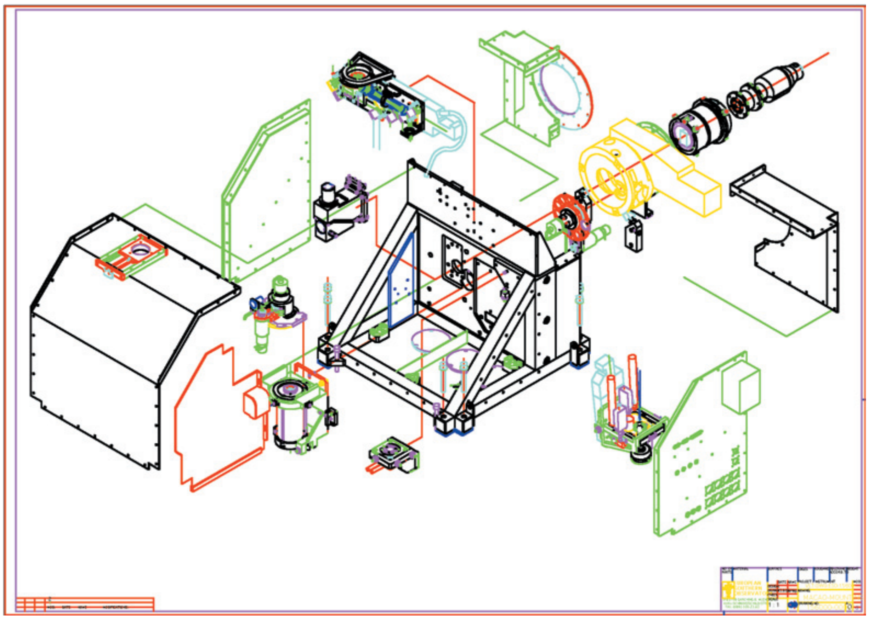


Figure 2: MACAO exploded view. The T-Mount, at the centre, is the main structure holding all components. On the front side one can see the shutter and BSD (top), the WFS optics (just below) and STRAP with its density filters wheel (at the lower-left). The TCCD (centre-bottom) and the membrane mirror on its gimball mount (lower-right) complete the equipment mounted on the front side of the T-Mount. On the back side are installed the last elements in the optical path namely: the density filter wheel, the rotating unit and the derotator prism and finally the micro-lens mount (upper right).

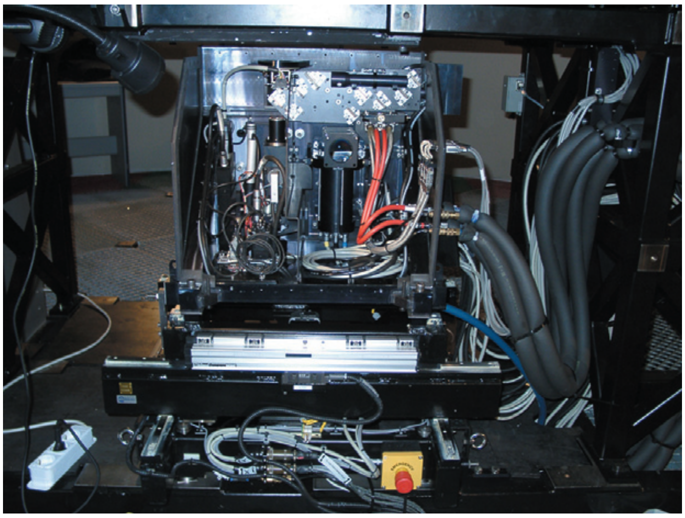


Figure 3: Opto-Mechanical setup of MACAO-VLTI on the XY table in the Coudé room during installation. The BSD can be seen in the uppermost part; the very crowded area on the left-hand side hosts the WFS optics and the membrane mirror gimball mount. Water pipes can be seen on the right side and are used for the cooling of the TCCD and STRAP units (if not helping in recognizing the components, this picture has at least the benefit of showing the complexity of the setup !).

MACAO-VLTI design

Opto-mechanical design

The existing Coudé mirror train feeds the delay lines of the VLTI before beam recombination; this constitutes the "science path" of the system. M8, which coincides with a pupil plane, is replaced by a 60 element bimorph mirror coupled with a curvature Wavefront Sensor (WFS). The WFS detectors are 60 Avalanche Photo-Diodes (APDs) from Perkin-Elmer (Canada).

The whole MACAO-VLTI assembly sits on the Coudé platform under a structure called the "M9 tower". Figure 2 shows an exploded view of all MACAO components. The whole assembly is contained in a 650 × 770 × 850 mm volume (including the XY table, not shown in this view). MACAO-VLTI provides acquisition mode with TCCD plus two main observing modes:

- Adaptive Optics image correction (curvature 60-element)
- Tip-Tilt correction (STRAP-M2 loop) on faint stars

The so-called "XY Table", based on an ESO design, fulfils the field selector function of the AO system. It positions the MACAO assembly in the 240 mm (2 arcmin) field of view of the Coudé focus. It has been proven to provide a 2 μm relative positioning accuracy. All axis motions are linear to better than 20 arcsec (pitch, roll and yaw). Figure 3 shows a picture of the inside (front) of the MACAO-VLTI "box". The XY table can be seen under the opto-mechanical assembly. Despite the small volume, one can see that space is scarce and integration/alignment definitely requires some skill.

The WFS box is composed of the following components. The Membrane Mirror, an aluminised pellicle mounted on a loudspeaker to be set in vibration at 2.1 kHz. It is located in the image plane and produces the defocus needed in the pupil plane for curvature analysis. The WaveFront Sensor Optics, a set of four diamond turned mirrors in a single mount, can be changed as a unit. A Derotator Prism is needed to compensate the rotation between the DM (rotates with azimuthal axis) and the lenslet array (at rest on the Coudé platform). Figure 4 depicts the lenslet array unit which consists of two arrays with 60 subapertures each and 60 optical fibres. The purpose of this assembly is essentially to gather the light in the individual sub-apertures and inject it into the corresponding optical fibres. The telescope pupil image is divided in 60 sub-apertures, distributed in 5 rings of varying number of lenslets: 4, 8, 12, 16 and 20. The Fibre Optic Bundle is made of the lenslets and 60 optical fibres terminated by FC connectors. It brings the light to the 60 APD WFS Detectors.

Corrective optics

The Deformable Mirror is fabricated by CILAS (France) and is of the bimorph type. Five such mirrors have been ordered (four units plus one spare) and a prototype for development and tests. The surface quality with voltage applied can reach 10 nm RMS. Less than 60 Volts are required to flatten the DM which leaves ample reserve for seeing correction (range of –400 to +400 V can be applied). The reflectivity is on average 99% in the IR ($\lambda > 1$ μm) and larger than 97% in the visible. It has been dimensioned to provide AO correction for seeing values up to 1″.

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 assembly is controlled by a dedicated electronics with its own internal 1 kHz control loop which makes tests and integration trouble-free. The bandwidth of the system has been tuned at 100 Hz for both axis and the stroke is 240 arcsec PV mechanical which corresponds to 6 arcsec on the sky.

Figure 5 shows the bimorph DM inserted into the Tip-Tilt mount. It also shows how this assembly replaces the conventional glass M8 mirror of the Coudé train.

An important property of this is the coincidence of the centre of gravity of

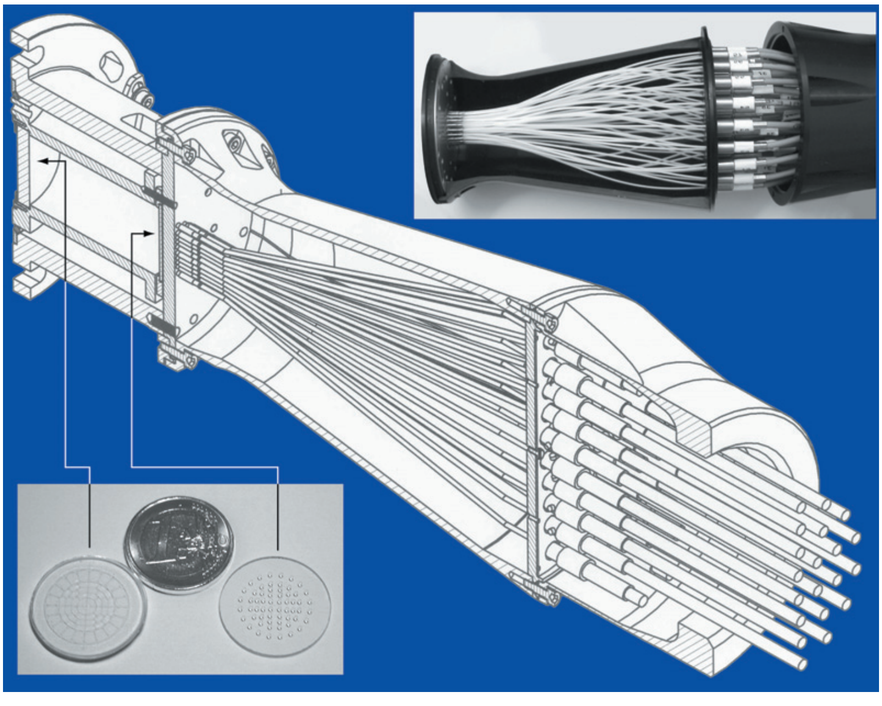


Figure 4: MACAO Lenslet array unit: The MACAO lenslet array unit is an original design and production of ESO. It uses two lenslet arrays in cascade. The first curvature lenslet array dissects the telescope pupil and focuses the light on the second ball lenslet array which concentrates and injects the light into the optical fibres connected at the other end to the 60 APDs.

the DM and its supporting ring 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 centre) in order to have no optical path difference produced when tilts are applied.

Software

MACAO-VLTI is considered a telescope system and therefore is relatively transparent to the astronomer. In the end, the AO loop will be closed as part of the interferometric source acquisition procedure. The so-called VLT-ISS (VLT Interferometer Supervisor Software) sends command to the MACAO-VLTI OS (Observing Software) which coordinates the operations of the MACAO RTC (Real-Time Computer), ICS (Instrument Control Software), STRAP and TCCD subsystems.

In addition the MACAO OS supports the following observing modes:

- Staring: a single acquisition in which the AO loop remains closed during the entire observation.
- Chopping: an observation in which 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 in which 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.

Electronics

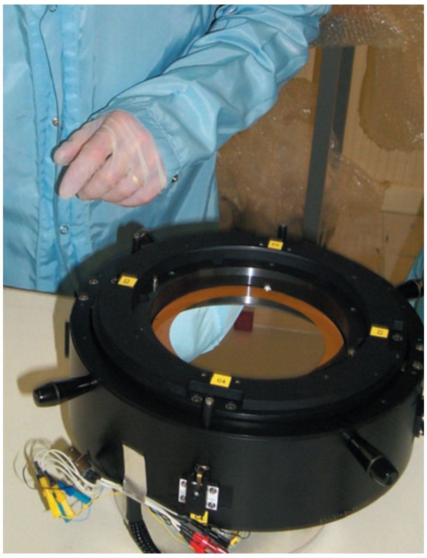
The MACAO-VLTI electronics is composed of 4 cabinets containing all the required electronics. Three of them are installed in the Coudé room: the RTC-VLTI cabinets, the IC cabinet and the APD cabinet. The fourth one is located on the VLT azimuth platform for its proximity to the corrective optics. All electronics conforms to the ESO standard.

For the RTC hardware, an effort was made to select commercially available component to insure a smooth integration into the VLT environment. Two PowerPC 2604 (400 MHz) boards are used, one as LCU controller (controls VME rack and communication with outside world) and the second totally dedicated to the RTC calculation. A custom made APD Counter board (Shaktiware, Marseille, France) is used to acquire the flux from the APD.

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's (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 VLTI LCU controls the STRAP and TCCD operation for MACAO-VLTI while the IC cabinet (Instrument Control) contains a VME rack controlling all motorized functions. The two cabinets are identical in size and covered by a wooden-insulated "coffin"-type enclosure that reduces to a minimum heat radiation in the Coudé room and acoustic noise. Each cabinet's heat exchanger is connected to the SCP (Service Connection Point) which provides the cooling fluid. No fans have been implemented for the APD cabinet and all 60 APDs are mounted on cooling "plates" in which the cooling fluid circulates. The azimuth platform cabinet contains the DM voltage amplifier and the TTM servo-unit plus the usual cooling fans and heat exchanger.

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



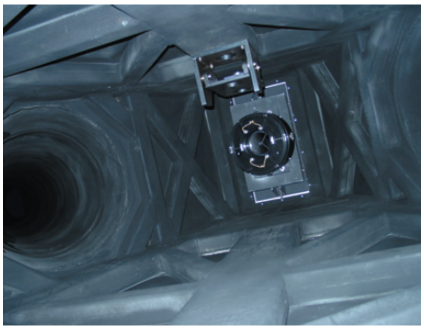


Figure 5: Bimorph deformable mirror in its tip-tilt mount. On the left one can see the protected silver coating 100 mm in diameter. The bimorph mirror is held by a spring loaded radial 3 points support in a dural ring. The assembly is inserted in the Tip-Tilt Mount (TTM) which can tilt the DM during close loop. To the right is a picture of the DM mounted at the M8 location of the VLT Coudé train. The hole on the left side leads up to M6.

Close loop & curvature

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. (Roddier, 1988)). It uses the curvature principle which is that wavefront analysis is performed by measuring the intensity in 60 different sections of the pupil (sub-apertures). Measurements are performed with the pupil defocused – so-called intra or extra-focal images. This is produced by the vibrating membrane set in vibration at 2.1 kHz and the flux is then sampled at twice this frequency. The contrast value, $(I_{in}-I_{out})/(I_{in}+I_{out})$, is proportional to the Laplacian, hence the curvature of the wavefront.

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. Besides acquiring WFS data, processing and sending commands to the correction optics (CO), the RTC also produces online diagnostic information and controls, a few electro-mechanisms (membrane mirror, neutral density filter and diaphragm). Systematic aberrations sent to the CO can be off-loaded to the Telescope Control System (tilt & focus at 0.2 Hz).

A watchdog is implemented to average the number of APD counts over a tunable number of cycles to determine whether they are over-illuminated. There are two safety levels aiming at protecting the APDs from an over-illumination. 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, the maximum voltage.

There is provision for a modal optimisation, in which sensor data can be projected in another space where variable gains can be used for the different modes. Circular buffers can be generated to post-process sensor signals or mirror commands off-line.

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. One of the main challenges of MACAO-VLTI is to insure that the corrective optics on 2 different UT's do not introduce phase delay between the recombined beams during close loop operation, which would limit fringe contrast. This is extremely critical if it occurs at high frequency, where the VLTI delay lines are no longer able to detect and correct for it. This is the reason for the strict piston specification: 25 nm RMS in 48 msec windows.

The strategy has been described by Vérinaud & Cassaing (2001) and involves defining a set of piston free influence functions. A special set-up using a commercial Shack-Hartman WFS and a capacitive sensor allows one to measure accurately (better than 1%) the optical piston averaged over the DM pupil for each electrode. 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 command the DM. The so-called tilt electrodes of the bimorph mirror (outside the pupil) contribute mostly to the production of a pure piston.

Integration & test

Test bench & facilities

A special effort was 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 five systems plus two Tip-tilt boxes (TTB) will have to be (have been) assembled and integrated in the life of this project.

For AO integration and test aspects, a complete Test bench has been designed and fabricated. This bench reproduces an f/46.7 optical beam, identical to a Coudé 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.

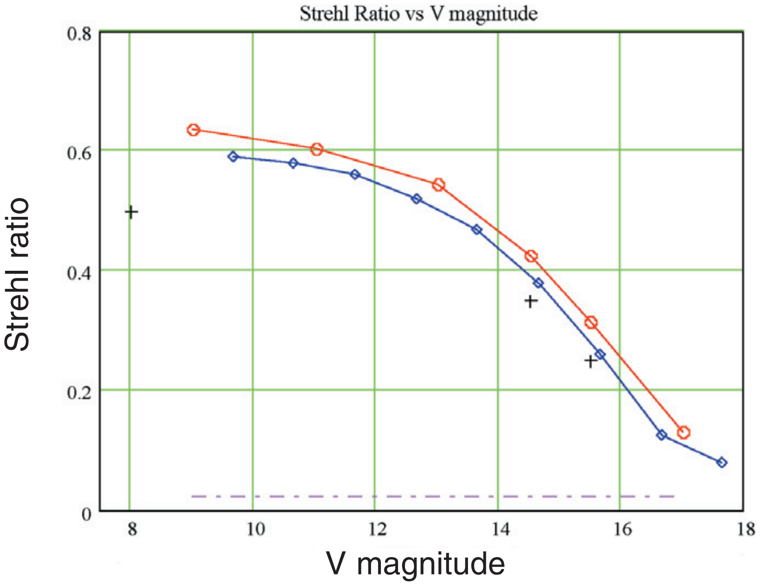


Figure 6: The blue curve shows the simulated Strehl ratio versus guide star V magnitude. The red curve shows the measured Strehl ratio in the laboratory (in K-band 2.2 μm). The simulated values include an error budget which probably explains why the laboratory curve shows better performance. The straight dashed-dot line shows the Strehl ratio in open-loop. The crosses are the specifications issued by VLTI.

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 ratio.

A second infrared test camera has been fabricated for commissioning the four MACAO-VLTI and SINFONI as well. The design is simple and uses three spherical mirrors. It uses a Hawaii 1K chip and is controlled by an IRACE system.

Simulations & test results

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 500 nm, t_0 ~ 4 ms, wind speed ~11 m/s and r_0 ~ 16 cm. We have also tested one case of worse conditions, characterized by a seeing of 1″ at 500 nm, t_0 ~ 3 ms and r_0 ~ 10 cm. Two different values 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).

The reference flux for the simulations is $4 \cdot 10^5$ detected photons/second at magnitude 15 in the overall 8.2 m aperture. We chose a value of 250 cps 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. 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.

In Figure 6 the blue curve shows the results of the simulations. The red curve shows the values measured in the laboratory in Garching with simulated turbulence. This shows a slightly higher Strehl ratio, but the most interesting feature is that a trend very similar to the simulations is seen versus star magnitude. The curve may slightly shift left if the whole system throughput (including telescope) is less efficient than what has been assumed (right if more). The plot is for a 0.65″ seeing. The crosses show the specifications issued by VLTI.

Project organisation & future

Tip-tilt boxes

The milestone "Tip-Tilt Boxes Delivery" was 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 TTB allows the observer to acquire stars, to track stars off-axis and performs a tip-tilt correction of the source (closed loop between STRAP & M2 mirror). This set-up was delivered to UT1 and UT3 in November 2001 and has been in use since then. They will ultimately be replaced by full-fledged MACAO systems. Tests carried out on an 11.7 mag star show a ~10 mas tilt residual after correction.

Project aspect

It is worth mentioning that, in addition to MACAO-VLTI, SINFONI and CRIRES 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

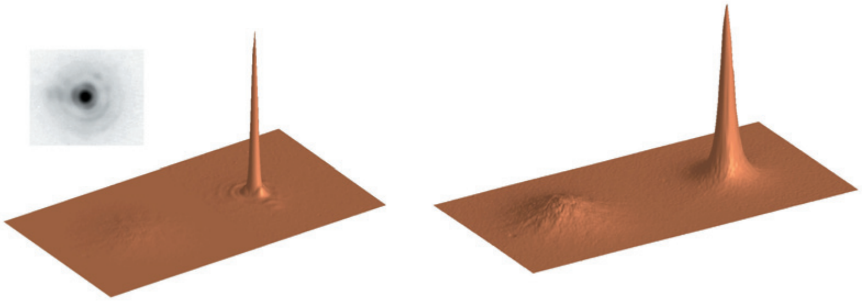


Figure 7: On the left is a K-band image of a bright star (V~10) obtained in average seeing conditions (0.8″). Three diffraction rings can clearly be seen with a Strehl ratio larger than 50% and a FWHM of 60 mas. The plot on the right demonstrates the faint guide star performance. Using a V = 16.5 star, a K-band Strehl ratio of 10% and a FWHM of 140 mas were achieved in 0.55″ seeing. The three dimensional plots also show the open loop images for comparison.

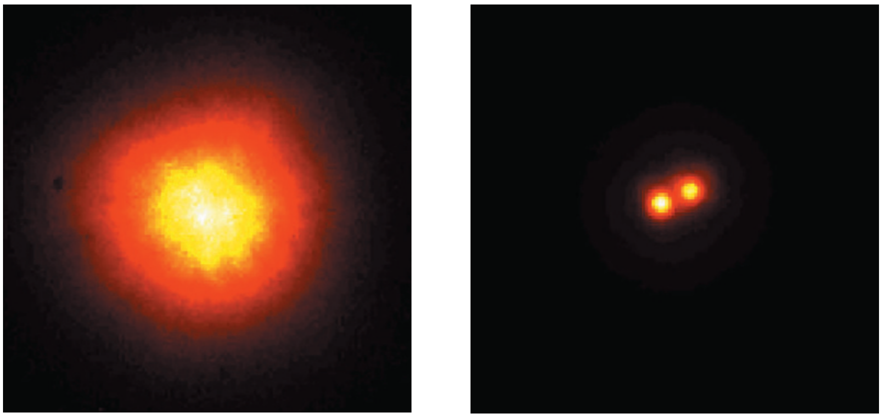


Figure 8 shows K-band images of a V=10 star obtained – before (left) and after (right) the adaptive optics was switched on. The separation of the binary is 0.12″ and the seeing at the time of observation was ~0.75″ (see the text).

substantial cost reduction but also creating some motivation in industry. Besides, work or tasks accomplished on a particular project often benefit the other which leads to a non-negligible gain in development.

Schedule

The fast-track nature of the project is illustrated by the fact that Tip-tilt boxes delivery took place in November 2001, barely 7 months after the final design review. Then the first MACAO-VLTI system was delivered last April, and the second will be delivered in August 2003. Shortly afterwards, a joint team of the AO dept. and VLTI will perform a joint commissioning to obtain fringes with two MACAO-VLTI systems. The last two MACAOs will be delivered not before spring 2004 and winter 2004.

The interval between the successive MACAO-VLTI deliveries is dictated by the manpower available to perform the integration and optimisation of the systems. However, the commissioning schedule in Paranal is extremely busy in 2004 and this may add further constraints on the actual delivery dates.

Sky observations

Goal

The main goal of the April 2003 commissioning was to test the functioning of the whole system in the telescope environment and evaluate the AO performance on the sky. These were voluntarily decoupled from any interferometric functions and aim at assessing the performance of MACAO-VLTI in stand-alone mode. Further commissioning runs will take care of the interferometric aspects.

Strehl ratio & resolution

After we were re-assured on the basic functions of the system like source acquisition, closing of the loop, and stability, the performance evaluation activities started. This constituted an important part of this run and consisted in observing a star (point source) while varying the parameters of the system in order to obtain the highest possible Strehl ratio. The parameters that can be adjusted are the closed-loop main gain and the stroke of the vibrating membrane. These are known to depend on source extend and brightness. A set of absorbing filters was used to simulate fainter stars.

Figure 7 shows a diffraction-limited *K*-band image of a bright star $V = 9.86$ (HIC 69495) obtained in April. Three diffraction rings can clearly be seen and the FWHM image resolution achieved in 0.8″ seeing was 60 mas with a Strehl ratio above 50%. Also shown is the moderate image improvement achieved using a faint ($V = 16.5$) guide star. In 0.55″ seeing, the corrected *K*-band image resolution was 140 mas with a Strehl ratio of 10%.

Figure 8 shows images of HIC 59206 ($V = 9.9$) taken in 0.75″ seeing conditions, illustrating the improvement of the image resolution when using MACAO-VLTI. The left image was taken in open-loop (seeing limited), while the adaptive optics loop was closed during the exposure shown on the right. The separation of the binary is 0.12″.

Astronomical targets

A few interesting objects, from an astronomical point of view, were selected to illustrate the performance of MACAO-VLTI. It must be pointed out that the aim of MACAO is not to produce astronomical images (the Test Camera is by no means a high performance scientific instrument) but rather to feed light to the VLTI. The following images allow comparison with other instruments. Results are impressive and compare advantageously to other AO systems with higher number of actuators.

Frosty Leo

Frosty Leo is a post-AGB star surrounded by an envelope of gas, dust, and large amounts of ice (therefore the name) displaying a bipolar morphology. It is one of the best examples of the brief transitional phase between the asymptotic giant branch (AGB) and planetary nebulae (PNe). For a three solar mass object, this transitional phase is believed to last only a few

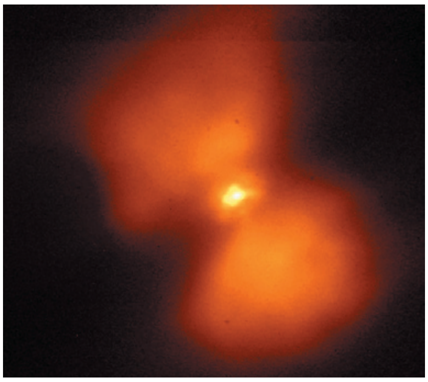


Figure 9 shows a 5″×5″ K-band image of Frosty Leo taken in 0.7″ seeing. Although Frosty Leo is rather bright (V=11), it is a difficult AO target because of its extension of about 3″ at visible wavelengths. The corrected image quality is about 0.1″ FWHM.

thousand years, just a wink in the life of the star. Hence, post-AGB objects are very rare, and Frosty Leo is one of the nearest and brightest among them (see Figure 9).

NGC 3603

Among the first objects observed was the stellar cluster NGC 3603 located in the Carina spiral arm of the Milky Way at a distance of about 20,000 light-years (see Figure 10). With its central starburst cluster, it is one of the densest and most massive star forming regions in our Galaxy. Some of the most massive stars - with masses up to 120 times the mass of our Sun - can be found in this cluster.

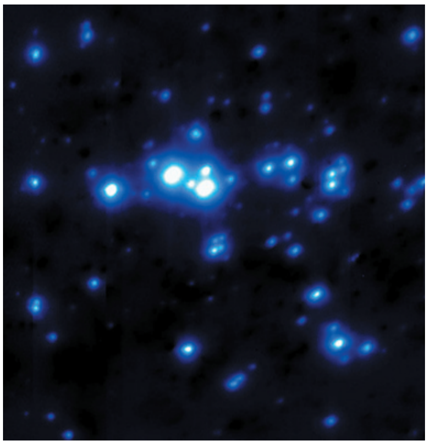


Figure 10 displays a K-band image of the starburst cluster NGC 3603. MACAO-VLTI compensated atmospheric disturbances by analyzing light from a star which was 30″ separated from the field centre. The stellar images have a Full-Width-Half-Maximum (FWHM) diameter of 0.1 arcsec. The field measures 9 × 9 arcsec.

Eta Carinae

Eta Carinae (Figure 11) is one of the most massive stars in the Universe, probably more than 100 solar masses. It is about 4 million times brighter than the Sun, making it one of the most luminous stars known. As such massive stars have a comparatively short expected lifetime of roughly 1 million years, Eta Carinae must have formed recently in the cosmic timescale. Eta Carinae is also highly unstable and prone to violent outbursts caused by the fact that its high mass causes an extremely high luminosity. This leads to a high radiation pressure at the star's “surface”, which blows significant portions of the outer layers off into space, in a slow but violent eruption. The last of these outbursts occurred between 1835 and 1855 and peaked in 1843, when, despite its distance (7,500 to 10,000 light years away), Eta Carinae briefly became the second brightest star in the sky with an apparent magnitude of –1.

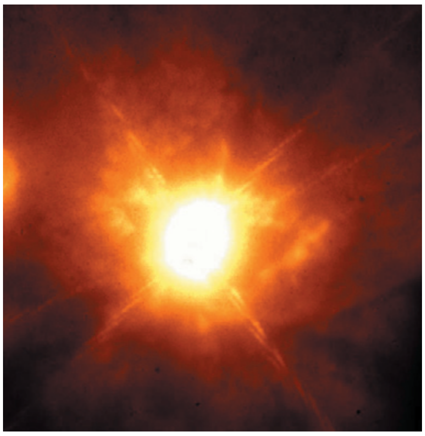


Figure 11 displays a K narrow-band image of the massive star Eta Carinae. The image quality is difficult to estimate because the central star saturated the detector, but the clear structure of the diffraction spikes and the size of the smallest features suggest a nearly diffraction limited performance. The field measures roughly 6.5 × 6.5 arcsec.

The Galactic Centre

The centre of our own galaxy (Figure 12) is located in the Sagittarius constellation at a distance of approximately 8 kpc from Earth. Recent AO observations using NACO at the VLT provide compelling evidence that a supermassive black hole with 2.6 million solar masses sits in the centre (Schödel, R., Ott, T., Genzel, R. et al., 2002; see also the March 2003 issue of *The Messenger*). This result, based on astrometric observations of a star orbiting the black hole at only 17 light hours minimum distance, could not have been obtained without imaging at diffraction limited resolution.

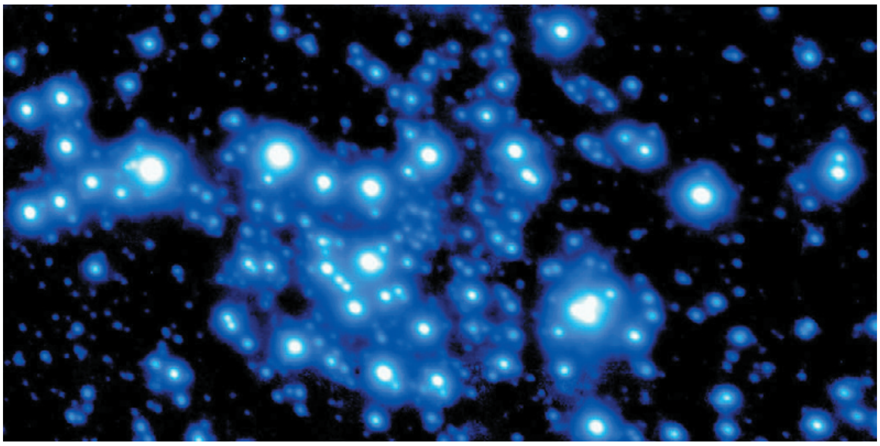


Figure 12 shows a 90 second K-band exposure of the central 6″ × 13″ around the Galactic Centre taken in 0.8″ seeing, i.e., under average atmospheric conditions. Although the V=14.6 guide star is located roughly 20″ from the field centre, leading to isoplanatic degradation of image quality, it is nearly diffraction limited with a point source FWHM of about 0.130″.

Summary

The AO department of ESO has completed the design of an adaptive AO system for the VLT Interferometer. Ordering of components, manufacturing and integration took place in 2001 and 2002. The system is built in four copies, one for each VLT. It is installed at the Coudé room and the Coudé train is used as a “science path”. Only one of the mirrors (M8, pupil conjugated) is replaced by the corrective optics. The 60 elements system should allow a Strehl ratio of ~0.6 on bright sources.

Commissioning activities started in April 2003 and the delivery of the 4th system is planned for late 2004. At the time of this writing the first commissioning of the first MACAO has been completed and results are encouraging. The integration and test phase of the 2nd system is in full swing.

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