On-sky Testing of the Multi-Conjugate Adaptive Optics Demonstrator

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The aim of the Multi-Conjugate Adaptive Optics Demonstrator (MAD) is to correct for atmospheric turbulence over a field of view which is much larger than the one typically covered by the existing adaptive optics systems installed on 8-m-class telescopes. After a long period of testing at the ESO premises, MAD was installed at the VLT early in 2007 in order to evaluate its correction performance. Here we present the MAD project and the recent results obtained during the on-sky testing at the VLT UT3 telescope Melipal.

MAD (Marchetti et al. 2006) is a demonstrator instrument aimed at correcting atmospheric turbulence over a large field of view by implementing a novel adaptive optics technique called Multi-Conjugate Adaptive Optics (MCAO).

MCAO and similar atmospheric turbulence correction techniques have been recognised as strategic both for the second-generation VLT instrumentation and for the European Extremely Large Telescope (Gilmozzi and Spyromilio 2007), the 42-m telescope facility whose project is in development at ESO. In fact both the above-mentioned projects will make extensive use of wide-field-of-view adaptive optics correction systems for sharpening the astronomical images, before feeding them into the scientific instrument.

In this framework the final goal of MAD is to prove, on-sky, the feasibility of MCAO and related techniques, and to evaluate all the technical issues as well as to identify the key aspects involving the design, construction and operation of such systems.

MAD is not a fully internal ESO project as it has benefited from the collaboration of two consortia to develop some strategic components of the system. A consortium led by Universidade de Lisboa (Portugal) designed and built the Camera for MCAO (CAMCAO), which is a high spatial resolution infrared imaging camera used by MAD for evaluating the correction performance. An Italian consortium formed by the Observatories of Padova and Arcetri, both part of the Italian National Institute for Astrophysics (INAF), developed the instrument control software and a novel concept of wavefront sensor, called Layer Oriented, which will be tested separately on the sky in September 2007 (Vernet-Viard et al. 2005).

What is MCAO?

Adaptive optics corrects in real time for the atmospheric turbulence which affects the spatial resolution of the astronomical images obtained by ground based telescopes. In the existing adaptive optics systems, the field of view which benefits from the real-time atmospheric turbulence correction is very limited, typically a few arcseconds for images obtained at infrared wavelengths. This limitation arises from the fact that the distorted wavefront is estimated by the wavefront sensor only in the direction of a sufficiently bright guide star located near the observed astronomical object, and is corrected for this same direction by a deformable mirror. In this configuration, only the volume of the atmosphere probed by the beam of the observed guide star is efficiently sensed, while the atmospheric volumes probed by the light of astronomical objects far from the guide star are only partially sensed. The direct consequence of this misregistration is that the images of the astronomical objects far from the guide star are only partially corrected, with a blurring size which increases with the distance from the guide star. This phenomenon is called atmospheric anisoplanatism and a graphical representation is given in Figure 1.

MCAO tries to overcome this limitation by sensing and correcting for the whole atmospheric volume probed by the observed field of view (Beckers 1988). The process of implementing MCAO correction consists of three main steps. The first one is to measure the deformation of the wavefront due to the atmospheric turbulence along different directions in the field of view. This is performed with several wavefront sensors looking at different guide stars in the field of view. The greater the number of guide stars, the better the knowledge of the wavefront distortion in the sky field of interest. The second step is called atmospheric tomography and consists in reconstructing the vertical distribution of the atmospheric turbulence at different locations of the field, in order to obtain a three-dimensional mapping of the turbulence above the telescope. The solution to this step represents quite a complex problem, since the number of measurable quantities (the guide stars) is always smaller than the number of the unknown ones (the turbulence at several discrete altitudes above the telescope). This limitation comes from the fact that, while the vertical distribution of the atmospheric turbulence is continuous, the number of available guide stars is always limited to a few, both for natural and technical reasons.

The atmospheric tomography problem, which is quite complex and requires some a priori assumptions to achieve a simplified solution, has been already given in its theoretical form (Ragazzoni, Marchetti and Rigaut 1998) and then demonstrated in an open-loop experiment on the sky (Ragazzoni, Marchetti and Valente 2000). The third step is to apply the wavefront correction to the whole field of view and not only in a specified direction. This is achievable by using several deformable mirrors which are optically conjugated to different altitudes in the atmosphere above the telescope. The deformable mirrors intercept the light

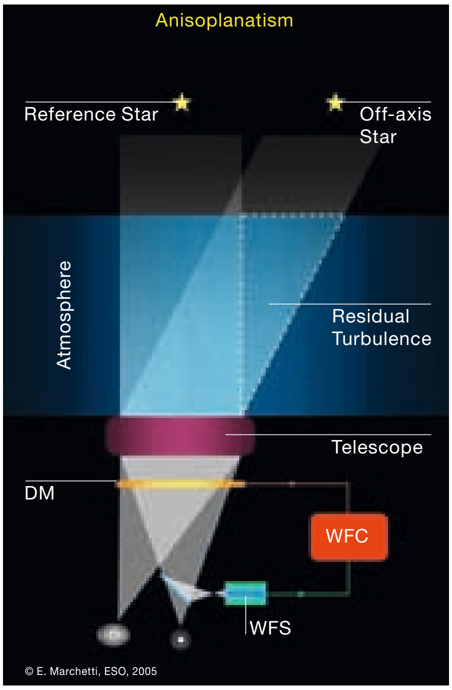


Figure 1: Graphical representation of the atmospheric anisoplanatism effect for a classical Adaptive Optics system. By means of the wavefront sensor (WFS), the wavefront computer (WFC) and the deformable mirror (DM), the system senses, computes the correction and applies it only in the direction of the guide star. The stars not in the direction of the correction see a different portion of the atmosphere, which is partially corrected, and thus appear blurred.

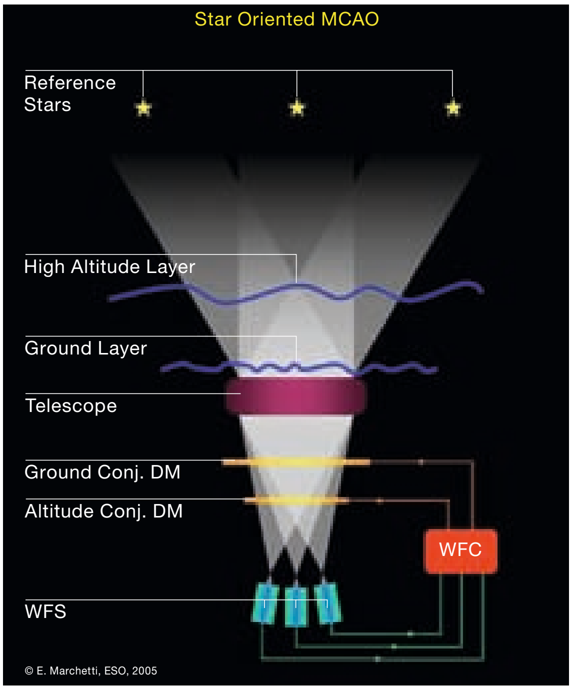


Figure 2: Graphical representation of Multi-Conjugate Adaptive Optics in Star Oriented configuration. Many guide stars are simultaneously sensed to probe the full volume of atmospheric turbulence over the field of view of interest. The signals from the wavefront sensors are recombined and applied to several deformable mirrors optically conjugated to different altitudes in the atmosphere above the telescope.

from the whole field of view and it is possible in this way to tune the correction depending on the location in the field. A graphic representation of MCAO is given in Figure 2. From this concept of multiple conjugations comes the definition of MCAO. This differs substantially from the actual adaptive optics systems which have only one deformable mirror, typically conjugated to the pupil of the telescope at the altitude of a few metres in the atmosphere.

The atmospheric turbulence has a continuous vertical structure which induces a systematic error in the wavefront correction, due to the fact that, for technical reasons, the number of conjugation altitudes at which the deformable mirrors can be placed is limited. What in practice is done for an MCAO system is to optimise the correction to be given to each deformable mirror in order to minimise the uncorrected turbulence, both along the vertical of the telescope and in the scientific field of view.

The wavefront sensing concept presented here is called Star Oriented and it is based on using as many wavefront sensors as guide stars. MAD is actually equipped with a Star Oriented wavefront sensor and it has been used to perform the first two demonstration runs of 2007. All the results presented have been obtained with the Star Oriented wavefront sensor.

As mentioned before MAD will be equipped with a second wavefront sensor, called Layer Oriented, which will have first light during the third MAD demonstration run planned for September 2007. This wavefront sensor, based on a pyramidal optical component, works with a completely new concept, which allows sensing all the guide stars simultaneously and uses as many detectors as deformable mirrors. In this way the quality of the signal from the guide stars is improved by co-adding the light on the same detector; but the complexity does not scale as the first order with the number of guide stars used. A detailed description of the Layer Oriented concept is given in Ragazzoni, Farinato and Marchetti (2000).

The MAD system

The full MAD system with the exceptions of the CAMCAO infrared imaging camera, the instrument control software and the Layer Oriented wavefront sensor has been fully designed and built by ESO in Garching. The MAD system has been optimised for providing the best correction in *K*-band (2.2 μm) and all the performance has been evaluated at this wavelength.

The main strategy we have followed has been to reuse as much as possible existing hardware and software components developed in the framework of the other ESO adaptive optics projects. We also decided to follow rigorously the ESO standards in matters of instrumentation, being fully compliant with the installation of new instruments at the VLT.

Despite the prototype nature of MAD, the full project underwent the ESO review procedure before the initiation of the procurement and construction of the main hardware components. MAD passed the Conceptual and the Final Design Reviews, as well as the Preliminary Acceptance for Europe, just before the shipment to Paranal to evaluate the compliance with VLT Paranal standards for instrument installation and operation.

The MAD optical bench consists of a static table supported by a structure which elevates the main optical axis to the level of the one from the VLT on the Nasmyth platform. The light from the 2-arcminute field of view coming from the telescope enters MAD through an optical derotator which compensates for the field rotation affecting the images at the Nasmyth focus. After a collimator lens there are the two deformable mirrors, the first one conjugated at 8.5 km above the telescope and the second at the telescope pupil (see Figure 3). Both deformable mirrors are spare units of the ones used in the MACAO family adaptive optics systems installed at the VLT (60-element bimorph mirrors). The pupil-conjugated deformable mirror is supported by a fast steering mount to assist the mirror in compensating for the largest contribution of the atmospheric tip-tilt. This mirror is also a spare unit from the MACAO systems. A dichroic allows reflection of the visible part of the light in the direction of the wavefront sensor. The infrared light is transmitted and folded down through a hole in the bench, below which is located the infrared imaging camera. CAMCAO is based on a Hawaii2 2k × 2k detector driven by an ESO IRACE control system; the pixel size projected on the sky is 0.028 arcseconds for a total field of view of ~ 57 arcseconds. A scanning table allows CAMCAO to patrol the full 2-arcminute field of view, while keeping the adaptive optics loop closed and without the need to offset the telescope or move other optical components into the light path. CAMCAO is equipped with standard *J*, *H*, *Ks* filters plus some narrowband ones.

The Star Oriented wavefront sensor is based on three Shack-Hartmann sensors of 8 × 8 sub-apertures each, which are able to scan the full 2-arcminute field of view to easily pick up the light of the guide stars. The wavefront sensor detectors are commercial E2V CCD39 units, 80 × 80 pixels, a device commonly used in existing adaptive optics systems, and driven by an ESO FIERA control system. In proximity to the wavefront sensor is located the acquisition camera, based on the standard ESO new technical CCD and its related controller; the camera images the 2-arcminute field of view in order to locate the exact position of the guide stars. During operation an interactive procedure allows correct centring of each Shack-Hartmann on the desired guide stars, using only the image from the acquisition camera. Finally two movable units, supporting illuminated fibres, can be inserted into the optical beam for instrument calibration and testing.

The MAD real-time computer provides acquisition from the wavefront sensor, wavefront reconstruction and deformable mirror actuation up to a frequency of 400 Hz with no detector binning, and up to 640 Hz in 2 × 2 binning mode. At each loop cycle 312 slopes are received and multiplied by the reconstruction matrix. In total MAD controls 122 real-time channels, 38 movable functions, and 5 detectors simultaneously through six dedicated Local Control Units located in four electronics cabinets.

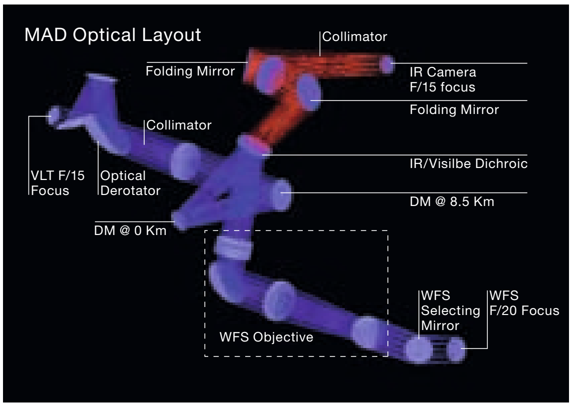


Figure 3: MAD optical layout. The input beam from the VLT is folded by the deformable mirrors and split by the dichroic. The visible light is sent to the wavefront sensor while the infrared light feeds the CAMCAO camera located below the MAD bench.

MAD installation and first light

MAD was first integrated in the optical laboratory at ESO Garching where the MAD team performed extensive system tests, lasting more than one year, before the shipment to Paranal. During the tests we characterised the performance of the system under different correction configurations, including a long phase of debugging during which we implemented the useful corrective actions to optimise both the performance and the operability of the system. A dedicated facility to emulate a three-dimensional, time-evolving atmosphere and variable configuration of guide stars, called MAPS, was placed at the MAD entrance window and used during the full testing period.

In December 2006 MAD successfully passed the Preliminary Acceptance Europe and in January 2007 it was dismounted and shipped to Paranal. The system reintegration at the VLT visitor focus located at the Nasmyth platform A of UT3 Melipal started around mid-February and lasted for about one month. In this period around 15 people, including Paranal staff, participated in the MAD installation which was completed without major problems. In the second half of March we spent about two weeks in fully characterising and calibrating the system following the procedures established the year before during the laboratory system testing.

Finally in the evening of 25 March, after concluding some software functional tests, we pointed at NGC 3293, a bright open cluster, selected three suitable guide stars and successfully closed the MCAO loop.

From the beginning we realised that the system was stable and reliable, a condition which lasted for the whole demonstration run. The run consisted of a mix of

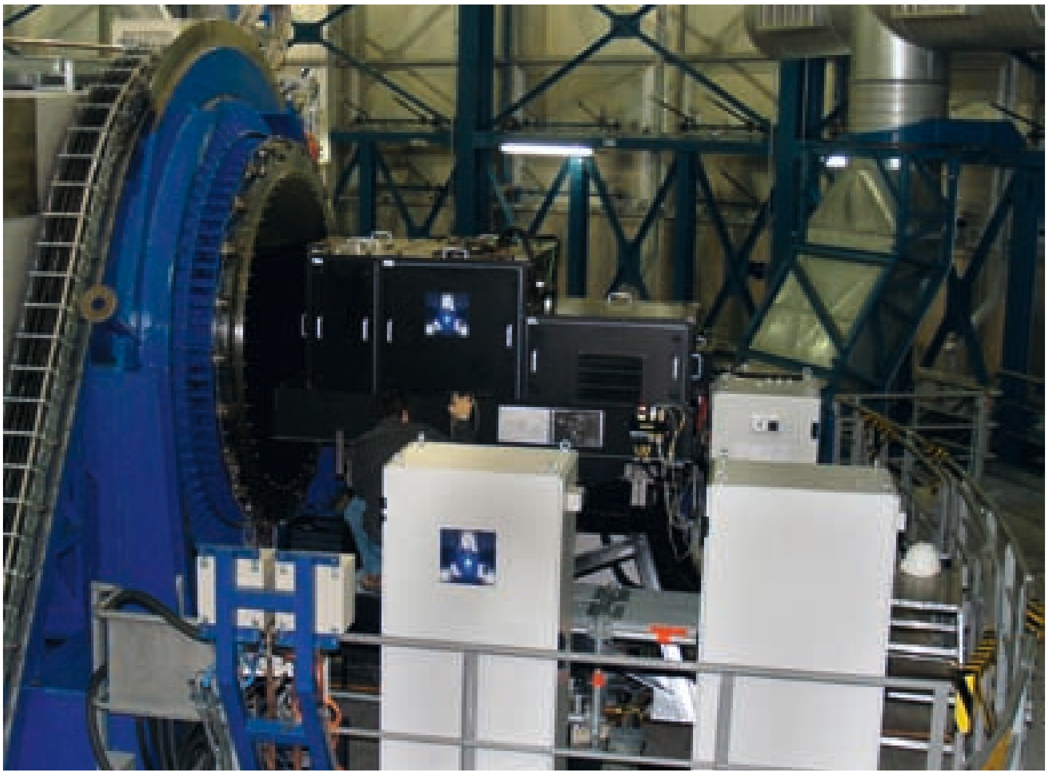


Figure 4: MAD installed at the Nasmyth visitor focus of UT3 Melipal.

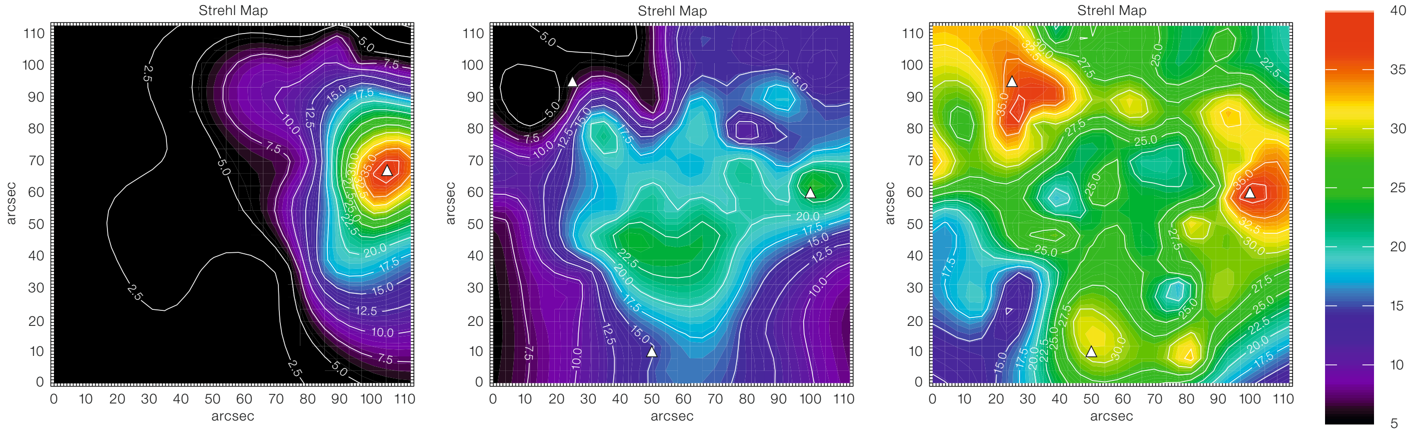
half and full nights for a total of 8.5 effective nights spread over 12 nights. This long period, originally not planned, had two positive aspects: it increased the chances of having good seeing; it permitted collection of statistics on seeing, thus allowing estimation of the MAD performance under different conditions.

On-sky results

The main target selected for the correction performance evaluation was Omega Centauri, the brightest globular cluster visible from Earth. Omega Centauri offers several relatively bright guide stars suitable for wavefront sensing and it is extremely crowded, allowing an efficient mapping of the correction quality over the whole field of view.

In Figure 5 is shown a typical example of the correction performance for a 2-arcminute field under good seeing conditions (~0.7 arcseconds as given by the DIMM monitor). Three guide stars of V magnitude ~ 11.5 were used, equally spaced and located on a circle of approximately 100 arcseconds diameter. The maps shown represent the Strehl ratio distribution in *K*-band (2.2 μm) in the field with three different correction modes: classical adaptive optics, that is, sensing and correcting for a single star in the field; Ground Layer adaptive optics; and MCAO.

Figure 5: Strehl ratio maps (in % at 2.2 μm) for classical (left), Ground Layer (middle) and Multi-Conjugate (right) Adaptive Optics. The useful corrected field of view for classical adaptive optics is reduced to 20 arcseconds. In GLAO it enlarges reaching the best performance at the centre. In MCAO the performance is much better with peaks on the guide stars and a valley at the centre of the field of view.



The Ground Layer Adaptive Optics (GLAO) is a special case of MCAO when the guide stars sensed are the same but only one deformable mirror, conjugated at the telescope pupil, is used for correction. This technique does not achieve the peak Strehl ratio of MCAO, but it can guarantee a moderate improvement in the concentration of the light for the observed objects and is a simpler technical implementation. The second-generation VLT instruments MUSE and HAWK-I will be fed by GLAO modules, which justifies its study in the framework of MAD.

The advantage of MCAO with respect to classical adaptive optics is fairly clear: for the latter the well-corrected area (Strehl ratio above 20 %) will not extend more than 20 arcseconds from the guide star; for MCAO almost the full 2-arcminute field of view benefits from such a Strehl ratio improvement. Another typical behaviour of MCAO is also evident: the correction is effective inside the polygon identified by the guide stars, with maxima located on those stars and a ‘valley’ at the centre, but it quickly drops in the outer regions of the field of view.

For GLAO the correction behaviour is the opposite: the performance peak is at the centre of the field of view and drops outwards. The absolute Strehl ratio values for GLAO are not much smaller than the ones for MCAO at the field of view centre while MCAO is clearly superior for all the rest of the field. As a comparison, GLAO had higher performance than in the laboratory testing, while MCAO performed as expected. Our explanation of this is that some obvious technical limitations, imposed by the laboratory atmospheric model (with a few discrete turbulence layers), do not match the situation on the sky (continuous turbulent structure). This difference penalised the performance estimation for GLAO.

During the observing runs, continuous real-time data have been collected from the atmospheric seeing monitors DIMM (seeing, coherence time) and MASS (atmospheric turbulence vertical profile) for cross-correlating the MAD correction performance with the instantaneous atmospheric turbulence conditions. A detailed analysis has shown that both MCAO and GLAO exhibit the expected performance, weakening with the worsening of the seeing, with MCAO dropping slower than GLAO. MCAO proved also to be much more robust when atmospheric turbulence tends to concentrate at higher altitudes. This trend is expected since GLAO corrects mainly the ground atmospheric layer and the effectiveness of the correction depends strongly on the relative strength of the ground layer. On the other hand, MCAO benefits from the deformable mirror conjugated to the upper layer and compensates more efficiently for the high-altitude atmospheric turbulence. The same trend can be observed when considering the correction uniformity across the field of view. MCAO is more uniform than GLAO in terms of the standard deviation of the Full Width at Half Maximum of image size over the field of view, while for both correction modes the uniformity improves with the seeing conditions.

A very impressive example of the gain provided by MCAO is demonstrated in Figure 6, where the open loop and the MCAO closed loop *K*-band images for the same region of 20 × 20 arcseconds near the centre of Omega Centauri are shown. The open-loop image has been obtained with ISAAC and the stars have a Full Width at Half Maximum of 0.6 arcseconds. The MCAO closed-loop image has been obtained with MAD using three guide stars of V magnitude ~ 11.5 on a circle of 2 arcminutes in diameter. The 20 × 20 arcseconds region is at the centre of this circle, that is, the closest guide star is at ~ 1 arcminute distance. The gain in angular resolution is enormous and allows very close and faint stars in the cluster to be distinguished. The MCAO image was obtained with 0.7 arcsecond seeing and the Full Width at Half Maximum of the star images ranges from 0.087 to 0.107 arcseconds, with an average of 0.098 arcseconds. The light concentration is significant since on average 56 % of the light from a star is included in 3 × 3 pixels (0.084 arcseconds). For a total integration time of 600 seconds the measured limiting magnitude is K ~ 20.5 (3σ), which makes this the deepest ever image in *K*-band of this globular cluster and permits significant increase in the observable population of the cluster’s main sequence.

Figure 7 shows a 1 × 1 arcminute MCAO corrected *K*-band image centred on the well-known Trapezium cluster, a massive star-formation region in the constellation of Orion. For this image three guide stars of V magnitude ~ 10 to 12 have been

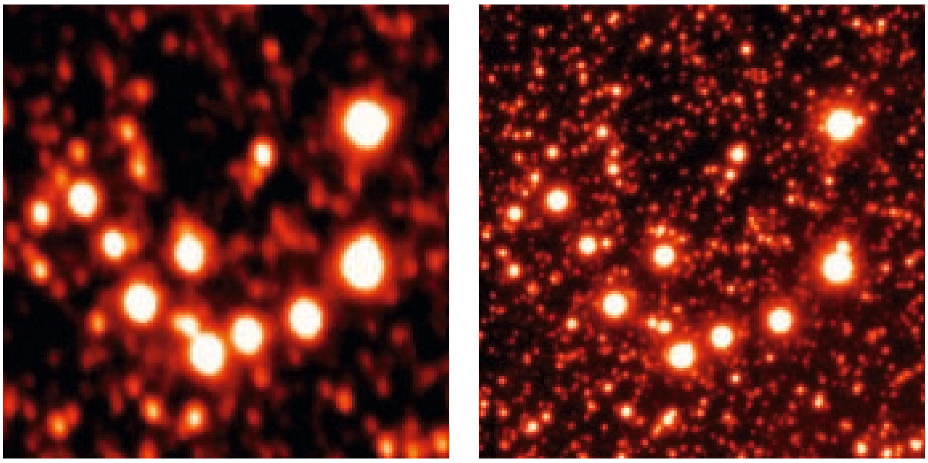


Figure 6: 20 × 20 arcseconds region nearby the centre of the globular cluster Omega Centauri. The image on the left was obtained in *K*-band by ISAAC and has an average FWHM of 0.6 arcseconds. The right-hand image was obtained at the same wavelength by MAD with MCAO correction. In the latter case the FWHM is often below 0.1 arcsecond, a remarkable value taking into accont that the closest guide star is ~ 1 arcmin away. The angular resolution improvement is dramatic and allows very close and faint stars to be distinguished. The limiting magnitude in K is ~ 20.5.

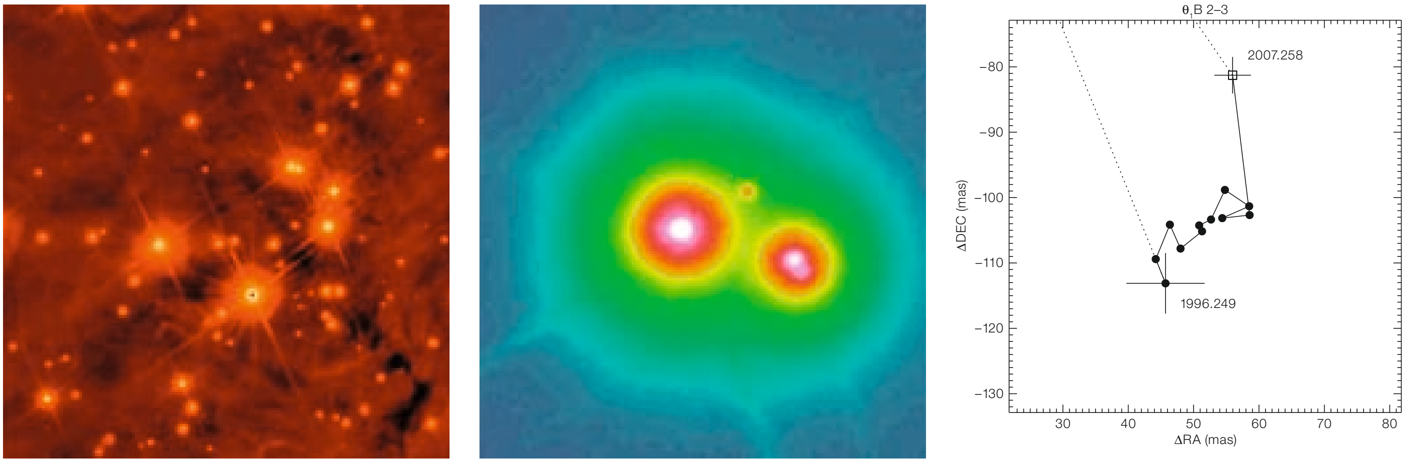


Figure 7: Left: 1 × 1 arcminute *K*-band MAD image of the region of the Orion Trapezium (north up, east left). The FWHM is ~ 0.1 arcseconds varying slightly across the field. It is possible to distinguish several protoplanetary discs as well as identify close binaries. **Centre:** Close-up view of the multiple system θ^1 Orionis B, the northernmost component of the five bright stars of the Trapezium group. The four brightest companions are clearly resolved. **Right:** Orbital evolution since 1996 for components 2 and 3 (the two rightmost ones) of θ^1 Orionis B; the latest point is the one measured from MAD images. For previous measurements see the Fourth Catalog of Intereferometric Measurements of Binary Stars (Hartkopf et al. 2001 and *http://ad.usno.navy.mil/wds/int4.html*).

selected in a quite non symmetric configuration. The seeing at the moment of the exposure was 1.2 arcseconds (DIMM monitor) and, despite the non-optimal configuration of the guide stars, the Full Width at Half Maximum of the objects in the corrected image ranges from 0.090 to 0.120 arcseconds, with an average of 0.100 arcseconds. The limiting magnitude is K ~ 19 for an exposure time of 300 seconds.

This example shows another great potential of MCAO, that is the field of view multiplexing for imaging a large portion of the sky with very high angular resolution. In the image it is possible to identify simultaneously several protoplanetary structures blown away by the stellar wind of the nearby stars. At the same time it is possible to distinguish several binary or multiple stars and measure their positions with very high accuracy. As an example, in Figure 7 is shown the orbital evolution for the components 2 and 3 of the multiple system θ^1 Orionis B, consisting of at least five stars mutually orbiting around each other. The position measured with MAD together with the ones previously obtained, both with adaptive optics and speckle interferometry, range over a total span of 11 years and show a clear trend in motion suggesting a very long-period orbit.

The scientific data obtained during the first demonstration run have been released to the community and are accessible to anybody interested in looking in more detail at the capabilities of such a technique (see *http://www.eso.org/projects/aot/mad/commdata/*).

Owing to the success of the MAD experiment, ESO decided to grant two science demonstration runs of one week each and has released a call for proposals to the scientific community to exploit the science capabilities of the prototype before the final dismounting from the VLT. The science demonstration runs will take place in November 2007 and January 2008.

After the completion of the second run MAD will be dismounted and shipped back to Garching for reintegration. The system will then be available to any research group interested in performing further and more detailed tests in view of future applications.

The future of MCAO

The scientific impact of MCAO has been recognised to be valuable both for Galactic and extragalactic astrophysics. The capability to add Laser Guide Stars as sources for wavefront sensing will improve the sky coverage for astronomical objects, enhancing the potential of this technique. The first laser guide star based MCAO instrument will have first light in 2008 at the Gemini Observatory, and quite likely its example will be followed by other large telescopes.

In the case of the E-ELT, the MCAO facility has been recognised as a primary instrument and the related Phase A design has already started in the framework of a larger study of E-ELT instrumentation.

References

Beckers J. M. 1988, in ESO conference “Very Large Telescopes and their instrumentation”, ed. M.-H. Hulrich, 693
Gilmozzi R. and Spyromilio J. 2007, The Messenger 127, 11
Hartkopf W. I., McAlister H. A. and Mason B. D. 2001, AJ 122, 3480
Marchetti E. et al. 2006, SPIE 6272, 21M
Ragazzoni R., Marchetti E. and Rigaut F. 1999, A&A 342, L53
Ragazzoni R., Marchetti E. and Valente G. 2000, Nature 403, 54
Ragazzoni R., Farinato J. and Marchetti E. 2000, SPIE 4007, 1076
Vernet-Viard E. et al. 2005, Opt. Eng. 44, 6601