Status of the European Research and Training Network on Adaptive Optics for Extremely Large Telescopes
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ABSTRACT
We will report on the 4-year activities performed by the European Research and Training Network dedicated to Adaptive Optics for Extremely Large Telescopes. This Research Network, funded by the European Commission, has contributed to the development of MCAO techniques which are being evaluated with the so-called MCAO demonstrator (MAD) as well as to several original on-sky wavefront sensing methods for the cophasing of large aperture telescope. We will present an overview of the results obtained in the frame of this project.

1. OVERVIEW
The European Research and Training Network on Adaptive Optics for Extremely Large Telescope (RTN AO-ELT) was initiated mid 2000 for an initial duration of four years. An extension of one year has been granted recently to permit the completion of the work programme (until May 2005). The AO-ELT RTN has been funded by the European Commission (EC) in the context of the 5th Framework programme (FP-5) at the level of 1.4 M€. It involves eight European institutes:

- European Southern Observatory (Coordinator) (ESO) in Germany
- Istituto Nazionale di Astrofisica, Osservatorio Astrofisico di Arcetri (INAF-OAA) in Italy
- Istituto Nazionale di Astrofisica, Osservatorio Astrofisico di Padova (INAF-OAPD) in Italy
- Office National d’Etudes et de Recherches Aérospatiales (ONERA) in France
- Max Planck Institut für Astronomie in Heidelberg (MPIA) in Germany
- Laboratoire d’Astrophysique de Marseille (LAM) in France
- Gran Telescopio Canarias S.A. (GTC) in Spain
- Lund (associate partner)

The primary objective of the Research Training Networks funded by the EC is to promote training-through-research, especially of young researchers, both pre- and post-doctoral level, within the frame of high quality international collaborative research projects, including those in emerging fields of research. Networks from a wide range of disciplines are supported and normally consist of at least five participants established in at least three Member or Associated states. Funding is provided primarily for the appointment of young researchers with modest support for networking, overheads and certain direct costs. Our RTN has funded 386 Post/Pre-doc-months. In addition, internal research effort from the Participants was about 500 person-months.

The primary objective of this Research Network was to investigate Natural Guide Star (NGS) and Laser Guide Star (LGS) tomography methods coupled with Multi-Conjugate AO (MCAO) making use of the third dimension of atmospheric turbulence information to increase the corrected Field of View (FoV). Multi source NGS-LGS tomography reconstruction requires specific 3D multi-source wavefront sensor (WFS) designs to be developed together with the improvement of WFS sensitivities. The development of new 3D multi-source WFSs was also part of the RTN key objectives. Qualification of these was planned to be performed on an atmospheric test bench before being evaluated on-sky on an 8-m telescope.

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The last topic was the study of cophasing techniques and procedures for ELT large segmented mirrors with accuracy compatible with AO in the visible. Although slightly outside the Adaptive Optics field as such, it was thought that on-
AO WFS techniques and methods could advantageously be extended to the problem of large mirror cophasing. The work was divided in five work packages as shown in Figure 1.

![Figure 1: Overview of the AO-ELT activities and work packages](image)

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Since the start of this Network, the RTN participants have published about 100 papers related to the subjects described above.

## 2. SYSTEM ASPECTS

An optical design of a 100-m telescope was developed Figure 2 taking into account the requirements of the Adaptive Optics [1]. In particular the design includes the possibility to install two large deformable mirrors of 2.5 and 4 m respectively conjugated to 0 and 8 km allowing the implementation of a first generation of Multi-Conjugate Adaptive Optics (MCAO) with 2 DMs. The telescope FOV is also very important to be able to perform Natural Guide Star Ground Layer Adaptive Optics (GLAO) or MCAO. For these reasons, the available diffraction limited FOV is 5 arcmin in the NIR and 10 arcmin seeing limited.

Another interesting topic investigated in the frame of the RTN was the importance of \( L_0 \) in imaging through the turbulence in the case of ELT [2]. Surprisingly, when \( L_0 \) becomes very small compared to the telescope diameter, the FWHM of the turbulent PSF reaches the diffraction limited PSF (Figure 3). The Strehl ratio (K) is nevertheless very small <5%. Figure 4 provides the Karhunen-Loeve modal expansion of the wavefront for the 8 and 100-m telescope cases for two different \( L_0 \): 25 and 500-m and an optimist value of \( r_0=1 \)m in K-band. We see that the total wavefront variance decreases when the \( L_0 \) decreases and that the amplitude of the low order modes is reduced when the \( L_0 \) is “small” with respect to the telescope diameter. It is important to note that the \( L_0 \) median value reported up to now seems to be in the order of 22 m [10] and [4]. These results will have the following impacts:

- If multi LGS AO or MCAO systems are used on an ELT, the amplitude of the low order modes to be corrected with a NGS to stitch the LGS wavefronts will be very small. In certain AO applications – partial correction or “seeing reducer” – we may even envisage to not correct for these and be able to have 100% sky coverage with the multi-LGS MCAO system.
- Since the deformable mirror mechanical stroke requirements are usually driven by the amplitude of the low order modes, the stroke specification for these DM can be reduced compared to the expected value from the Kolmogorov spectrum.
- Low order mode AO system will probably bring less image quality improvements on ELT than on 10 m telescopes.

Another important atmospheric parameter was identified to be critical for the design of GLAO and MCAO: the \( Cn2 \) profile. For that reason, we initiated the development of the Multi-Aperture Scintillation Sensor (MASS) [5] which
measures scintillation of single stars in four concentric zones of the telescope pupil. From this scintillation information, vertical turbulence profile with a resolution of $\Delta h/h=0.5$ can be reconstructed. Since MASS cannot determine the ground layer directly, a combination of MASS-DIMM was proposed to deduce the amount of turbulence at the ground. First campaign of MASS-DIMM at Paranal observatory in 2003 [6] has shown that 60% of the turbulence is localized in the first 1000m 50% of the time. In case of good seeing, the amount of ground turbulence is statistically even more important.

![Figure 3: OWL PSFs without AO correction. The rightmost graph gives the diffraction limited case. From left to right, 4 PSFs are plotted for $L_0$ values of 1000m, 25m, 15m and 10 m, respectively. All the PSFs are computed in K-band. The $r_0$ value is 80cm.](image)

These results have motivated the RTN to develop GLAO concepts for OWL and VLT. In the case of very large FOV -6' to10' - GLAO systems, the gain in ensquared energy becomes very sensitive to the detailed structure of the Ground layer within the first 1.5 km. It is therefore very important to have access to equipment able to provide statistic measurements of the ground layer structure with a reasonable altitude resolution: 150 m or so. For that reason, a specific instrument based on the concept of SLOpe Detection and Ranging (SLODAR) was developed and tested on the sky recently [7]. We expect to have the SLODAR installed at Paranal end of 2004.

Ground Layer Adaptive Optics has been simulated for several telescope diameters Figure 6, [48].

![Figure 4: Karhunen-Loeve modal spectrum of the wavefront phase for VLT and OWL with $L_0=25$ and 500m; $r_0=1$ m in K-band.](image)

![Figure 5: Decomposition of the $Cn2$ profile above Paranal in four layers for all seeing & seeing <0.5". Statistically the layers are considered independently](image)

![Figure 6: Ensquared Energy of a GLAO system versus diameter of the telescope](image)
3. 3D WAVEFRONT SENSOR AND MCAO CONCEPTS

The concept of MCAO was originally proposed by J. Beckers in 1988 [8]. However, his simplified analytical approach addresses neither the issue of the turbulent volume sensing, nor that of the DM control. A tomographic approach has then been derived to reconstruct the phase in the turbulent layers from the wavefront sensing data recorded on several guide stars. The inversion of the problem was initially performed with a least square approach [9], [10], [11], [12] then regularization of the inversion was proposed based on prior information on the turbulence statistics [13], [14]. The realistic case of a number of DMs much smaller than the number of turbulent layers was extensively studied [15], [16], [17], [18] and [19]. Research performed in the frame of the RTN has shown that in realistic turbulence conditions, one arcmin FOV can be obtained with 2-3 DMs on an 8-m telescope in NIR [18]. It has been shown that the performance is not very sensitive to the altitude of the conjugated DMs. The correction phase on the DMs is a filtered version of the phase in the volume and an optimal filtering can be defined to optimize the image quality in a specific FOV [20] and [21]. To optimize the filtering, the estimator uses the available prior information on the turbulence and on the WFS noise statistics. This is crucial to obtain good performance in particular in the case of large angular GSs separations [21], [22] and [23]. Several 3D wavefront sensing or tomography schemes have been proposed to satisfy the MCAO needs:

- "star oriented" technique which measures the resulting wavefront in each guide star direction, Figure 7
- "layer oriented" technique which measures the WF in several planes conjugated to several altitudes [24], Figure 8

The later consists in measuring the residual distorted phase after correction in several planes conjugated to different altitudes. It allows using a large number of faint stars and potentially improves the sky coverage with NGSs. Close loop operation of Layer Oriented MCAO system has been studied [25].

The two approaches have been compared [26], [27], [28]. [26] discusses the comparison between the two WFS techniques through numerical simulations, and proposes several ways of reconstructing the wavefront from layer-oriented measurements (global or local reconstruction). [27] compares the two approaches from a theoretical point of view, by estimating the WFS signal to noise ratio in both cases and provides the influence on the SNR of the guide star configuration (magnitude, number), of the detector and background noise. More recently an analytical approach has been proposed to compare the layer/star oriented concepts in the context of Ground Layer AO [29]. An extension of the Layer oriented concept to the so-called Multiple Field of View Layer Oriented has been proposed [30], [51] to increase further the sky coverage with NGSs by using a larger search FOV for NGSs to sense the turbulence at low altitude and keep the limited search FOV for higher altitude turbulence. An overview of the different MCAO concepts proposed in the past few years can be found in [31]. This short study also discusses the factors limiting the performance of such systems.
The system control law is a particularly important element of the system. In classical AO the control usually consists in integrator laws, possibly with gains optimized mode per mode, so-called Optimized Modal Gain Integrator (OMGI). The voltages deduced from this approach minimize the residual WFS measurements. We have shown that high performance in MCAO requires implementing a more complex control law which uses prior information on the turbulence statistics and its distribution in altitude. In this context we have defined a global optimal control explicitly constituted of two steps: an estimation step which gives an optimal reconstruction of the turbulent phase in the volume, followed by a control step that deduces, from the estimated phase, the mirror voltages optimizing the image quality in a specified FOV. This approach is based on Kalman filtering theory [31], [32], [33]. Numerical results are also given for both classical AO and MCAO. The Kalman control performance is compared to that of the OMGI. The OMGI is generally used in classical AO, we therefore define a generalized OMGI that applies to MCAO. The gain brought by the Kalman control is quantified and is shown to be significant for near infrared MCAO observations on 8m class telescopes [34]. In [34], the Kalman based control has been characterized with transfer functions which allow comparison to more standard approaches. It is also shown that, in the Kalman framework, the system model can be easily modified to account for static aberrations and vibration effects. A recent study of the generalized OMGI, in the context of ESO MAD demonstrator has been studied [35]. The most promising control approaches will eventually be compared on MAD.

Figure 9: Strehl versus field angle for normal AO, MCAO with an OMGI and with a Kalman based control

4. A NEW WAVEFRONT SENSOR: PYRAMID WFS

The Pyramid WFS has been proposed by R. Ragazzoni in 1996 [36]. The pyramid sensor is based on the original Foucault Knife Edge test [41], where the knife is replaced by a pyramidal refractive prism. This WFS has been actively studied in the frame of the RTN. Several very interesting properties of the pyramid WFS have been identified by analytical and numerical methods: better sensitivity with respect to the Shack-Hartmann sensor [36], [37] and reduce sensitivity to aliasing [46]. The Pyramid sensor which is a pupil plane WFS permits to optically co-add a large number of reference stars in the Layer-Oriented scheme [24]. Combined with the significant improvement in limiting magnitude this concept may extend the use of NGSs for MCAO systems on ELTs. A design of a 3D layer-oriented pyramid WFS was proposed [39] and built for the ESO MCAO demonstrator: MAD [40] planned to be extensively tested on sky. Diffractive effects seem to be predominant in the Pyramid WFS, therefore geometrical model with the addition of a circular dynamic beam modulation is not sufficient and Fourier optics is mandatory to study its behavior.

The Code for Adaptive Optics Software (CAOS) [41] has been upgraded with an end-to-end module based on diffraction optics. This code permitted to study properties of the Pyramid sensor like the possibility to use diffraction and interference effects in stellar Interferometry [42]. Detailed simulations with CAOS have shown that the layer oriented with a pyramid WFS without modulation is feasible for MAD [43]. This aspect was also studied in [44].
An analytical model [45] has been developed in order to understand better the properties of the Pyramid sensor in closed loop: it has been shown that this sensor combines properties of both slope sensors, and direct phase sensors, explaining the differences in terms of noise propagation and aliasing with respect to classical slope sensors like the Shack-Hartmann. Thanks to the ESO Beowulf cluster [46], parallel numerical simulations have been performed to evaluate pyramid and Shack-Hartmann WFS performance on ELT AO [47] and Extreme AO systems [48], [53]. AO simulation results with a Pyramid WFS in the visible and IR on a 100-m telescope are shown in Figure 10 and Figure 11.

Figure 10: Simulation of a 100-m telescope with a Pyramid AO system, \( r_0=0.15 \text{m}, \tau_0=3 \text{ ms}, \) \( 100^2 \text{ sub-aper.} @ 0.7 \mu\text{m}, \) Flux=100h\( \text{v}/\text{m}^2/\text{frame}, \) RON=3e\(^{-}\), 8k corrected modes,).

Figure 11: Corrected PSF for different NGS fluxes. Note closed loop Strehl \((K)\approx0.4\) with 5h\( \text{v}/\text{sub-aper.}, \) & RON=3e\(^{-}\). IR WFS shows ultimate correction with Pyramid WFS in linear regime and lower sensitivity to aliasing.

5. MULTI-CONJUGATE ADAPTIVE OPTICS DEMONSTRATOR: MAD

Figure 12: MCAO demonstrator: MAD

Figure 13: 3D Layer oriented WFS for MAD based on Pyramid sensors
As shown in this paper, intense researches have been performed in the field of AO-GLAO and MCAO over the last 5 years by the RTN and also by the rest of the AO community. ESO together with the RTN partners have identified the need for the development of a demonstrator allowing us to learn and show how MCAO could actually perform on-sky. For that reason, ESO proposed the development of a MCAO demonstrator: MAD [50]. MAD will permit the study of the different MCAO concepts proposed recently (star-oriented, layer oriented, local reconstruction, Global reconstruction, Kalman filtering, and 3D Shack-Hartmann or Pyramid WFSs) [40], Figure 12 and Figure 13. It will also allow us the study of GLAO concept and performance. To perform extensive testing of the MCAO system in the laboratory a 3D turbulence generator - Multi-Atmospheric Phase screens: MAPS-, was designed and developed [52]. The problem of calibration of an MCAO system was also thought through [53]. The Assembly Integration and Testing of MAD is being completed and progressive laboratory testing of all the GLAO-MCAO configuration will start in October 2004.

6. MICRO DEFORMABLE MIRRORS RESEARCH AND DEVELOPMENT

Next generation giant telescopes as well as next generation instrumentation for 10m-class telescopes relies on the availability of highly performing adaptive optical systems. AO systems under study (MCAO, XAO, low order AO for distributed partial correction AO) will require a large variety of DMs with very challenging parameters. The development of new technologies based on Micro-Opto-Electro-Mechanical Systems (MOEMS) is promising. The major advantages of the Micro-Deformable Mirrors (MDM) are their compactness, scalability, and specific task customization using elementary building blocks. In the frame of the RTN, Laboratoire d’Astrophysique de Marseille (LAM), is developing and characterizing these new devices, in close collaboration with a French laboratory expert in micro-technologies, the Laboratoire d’Automatique et d’Analyse des Systèmes (LAAS) in Toulouse, for their realization.

A schematic view of our design of the MDM is presented in Figure 14. The MDM is designed around three building blocks, the mirror surface attached to an actuator array, using the electrostatic effect, on top of the driving electronics realized in the silicon substrate. A high optical quality mirror is the most challenging building block for this device. The originality of our approach lies in the elaboration of a sacrificial layer and of a structural layer made of polymer materials, using a low temperature process. With this structure, very efficient planarization has been obtained: the long-distance flatness is below 0.2 µm, the print-through of localized 9µm steps is reduced to below 0.5µm and a rms roughness of 15 nm has been measured over the surface [55]. The integration of this mirror surface on top of an actuator array is under investigation.

We chose this low-temperature process in order to be able to implement this mirror layer on top of actuator arrays built with different technologies. Two different technologies are investigated for the moment:

- LAAS in-house low-temperature process, identical with the mirror technology. A piston actuator structure with the sacrificial layer etched (500 µm square piston area) is presented in Figure 14. Deformation of the plate is mainly due to the stress induced by the metallic layer deposited on top of the plate (upper electrode).
- External surface micro-machining Cronos foundry (USA) with poly-silicon technology. Number, thickness and material of the layers are fixed and cannot be tailored. A representative device is the tiltable mirror shown in Figure 14. The dimensions of the plate are 170*100 µm², the torsion bar is 10µm wide. A gold reflective layer is coated on top. The SEM view shows clearly an important bending of the piston surface due mainly to the differential stress between the poly-silicon structural layer and the gold coating. This effect on an optimised technology shows the difficulty to obtain perfectly flat surfaces.

**Figure 14:** Schematic view of a Micro-Deformable Mirror (MDM); SEM view of a mirror surface made with polymer; SEM view of actuators realized at LAAS and in the Cronos foundry.
A dedicated characterization bench has been developed for the complete analysis of building blocks as well as operational deformable mirrors. This modular Twyman-Green interferometer allows high in-plane resolution (4µm) or large field of view (40mm). Out-of-plane measurements are performed with phase-shifting interferometry showing highly repeatable results (standard deviation<5nm). Features such as optical quality or electro-mechanical behavior are extracted from these high precision three-dimensional component maps. First measurements on the chip realized in Cronos foundry are shown in Figure 15. Interferometric fringes are visible on the 1 cm² chip with astigmatism figure, due mainly to the gluing on the electronic board. With the same bench, fringes on 100 µm actuators could be obtained. Deformation of the surface is clearly visible. Range is increased without loosing accuracy by using two-wavelength phase-shifting interferometry authorizing large steps measurements such as 590 nm print-through steps caused by the Cronos process. Dynamic analysis like vibration mode and cut-off frequency is realized with time-averaged interferometry. Rotation mode frequency of 31±3kHz of the micro tiltable mirror Figure 15, and a resonance with a tuned damping at 1.1 kHz of the commercial OKO deformable mirror are revealed [56].

Figure 15: Interferometric measurement on the MDM characterization bench for large & narrow FOV; Frequency response of the Cronos mirror.

7. COPHASING OF LARGE SEGMENTED MIRRORS

Accurate and robust cophasing techniques of large segmented mirrors are obviously crucial for all future high angular resolution ELTs. The RTN participants have put their effort in two aspects:

- Determine the specification for segmentation errors: segment distribution, piston, tip-tilt, gaps, figuring, turned down/up edge effects
- Study different on-sky wavefront sensors for cophasing

Detailed analytical tools have been developed by the RTN to investigate the effect of segmentation on the OWL Point Spread Function (PSF) [57] and [58]. F provides an example of the OWL PSF affected by the segmentation errors. Four different wavefront sensing techniques have been studied for cophasing of large segmented mirrors [59]:

- Shack Hartmann wavefront sensor [60]
- Curvature wavefront sensor
- Mack Zehnder wavefront sensor [61] [62]
- Pyramid wavefront sensor [63]

Two of these techniques have been studied experimentally:

- Diffraction Image Phase Step Sensing (DIPSS) based on curvature sensor
- Mach Zehnder Sensor (MAZES) based on Mach-Zehnder interferometer

Pyramid Sensor although promising has not been yet studied in details.

Direct computer simulation, theoretical study and finally, the laboratory experiments have been performed allowing a cross-check of the results obtained at each stage. Both techniques (DIPSS and MASE) have shown similarities, because in both cases the signal used for the segment phase retrieval is proportional to the second derivative of the phase of the incoming wavefront: one physical parameter defines the signal in each method, defocal distance in DIPSS and diameter of the spatial filter in MAZES. The two complementary interferograms of the Mach–Zehnder interferometer
corresponds to intra-extra-focal curvature images. The output signal is obtained by the subtraction of the two images in both cases. The following summarized the results:

- Signal well localized near the segment boundary and depends on the relative local phase step simplifying the phase reconstruction using SVD method.
- In the case of MAZES the analytical shape is also obtained taking into account the gap between segments and the rolled-off edges. This provides an advantage for the phase retrieval using the fitting procedure.
- Low sensitivity to the atmospheric turbulence with the right selection of the system parameters.
- Residual phasing error down to 15-20 nm rms.
- Both techniques suffer from the limited capture range (+- λ/4) and require the multi wavelength approach.
- Star limiting magnitude (estimated from the photon noise) is 13 assuming the 10nm residual error and 15 assuming 20nm residual error.

**Figure 16:** Simulated 7 segment mirror with a random tip-tilt distribution (rms = 1 rad) and the corresponding Mach-Zehnder signal. Wavelength is 0.5 µm, pinhole diameter is 0.7″. The middle gray color corresponds to zero phase value on the left picture and zero signal value on the right one.

More information about the optimization of MAZES to retrieve the piston, tip-tilt and measurement error using the symmetric and anti-symmetric component of the signal are provided in [64]. Following the simulations a test setup based on MAZES was developed by Laboratoire d’Astrophysique de Marseille (LAM) Figure 18 & Figure 19.

**Figure 17:** Analytical signals for MAZES and DIPSS with parameters adjusted to obtain the same signal width.

**Figure 18:** MAZES experimental setup (left) and detail of a segment simulator assembly (left). (A) Turbulence generator using rotating phase screens, (MZ) interferometer, (D1 & D2) Detectors, (S) fiber-fed diode, (B) set of 6 segmented mirrors with -30nm, 0nm, 30nm, 75nm, 150nm, and 230nm piston amplitude.
Figure 19: (a) & (b) Intensity distribution in arm 1 & 2, (c) interferogram, (d) normalized signal

Simultaneous laboratory tests of DIPSS and MAZES with and without turbulence were performed at ESO in collaboration with GTC Figure 20.

Figure 20: Experimental signal from DIPSS obtained without and with turbulent generator.

8. CONCLUSIONS

We have given an overview of the 2000-2004 research activities and collaboration of the European Research and Training Network on Adaptive Optics for the Extremely Large Telescope. AO, GLAO and MCAO concepts have been developed using new kind of wavefront sensors like the pyramid WFS or the 3D layer oriented WFS concept. Analysis of the turbulence characteristics, outer scale and turbulence profile, has been used to study the performance of these future systems. An MCAO demonstrator has been designed and built and will extensively be tested in the laboratory and on-sky. Development of MOEMS is going on. Significant results have been obtained in the field of cophasing of large segmented mirror. Finally, intensive training through research of the Young Researchers has been provided using the numerous disciplines required in Adaptive Optics.

ACKNOWLEDGEMENTS


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