Deformable mirrors development program at ESO

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ABSTRACT

Over the last decade, adaptive optics has become essential in different fields of research including medicine and industrial applications. With this new need, the market of deformable mirrors has expanded a lot allowing new technologies and actuation principles to be developed.
Several E-ELT instruments have identified the need for post focal deformable mirrors but with the increasing size of the telescopes the requirements on the deformable mirrors become more demanding. A simple scaling up of existing technologies from few hundred actuators to thousands of actuators will not be sufficient to satisfy the future needs of ESO. To bridge the gap between available deformable mirrors and the future needs for the E-ELT, ESO started a development program for deformable mirror technologies. The requirements and the path to get the deformable mirrors for post focal adaptive optics systems for the E-ELT is presented.

Keywords: Deformable mirror, adaptive optics, actuator array, E-ELT

1. INTRODUCTION

With the start of construction of the E-ELT also the development of a suite of 1rst generation instruments has started. However to achieve some of the ambiguous scientific goals of the E-ELT even more challenging instruments are foreseen for the second generation of instruments. Two of them include dedicated adaptive optics systems for multi object adaptive optics (MOAO) and extreme adaptive optics (XAO) to hunt for earth like planets around other stars. However several key components like deformable mirrors (DM) required for MOAO and XAO are not available today. Without a good knowledge on the DMs it will not be possible to finalize the design of the associated instruments and enter a construction phase. In order to lift the uncertainties on the DMs required for the second generation E-ELT instruments ESO launched in the frame of the enabling technologies program a DM development activity.

2. E-ELT AO INSTRUMENTATION PLAN

In the period from 2006 to 2011 six instruments went through phase-A studies. The conceptual design, instrument performances and requirements to critical components where studied. One outcome is that all instruments require in some modes the help of adaptive optics to exploit the full performance and optimally use the size of the telescope. Therefore the telescope design includes right from the start a deformable mirror (DM), the E-ELT M4[1]. This allows instruments the implementation of adaptive optics (AO) mode without the need for additional relay optics and DMs. The instruments METIS[2] and HARMONI[3] will use the M4 capabilities and implement single conjugate AO (SCAO) or laser tomography AO (LTAO) modes.

The third of the 1st generation instruments, MICADO[4] will operate in conjunction with the post focal multi conjugate AO (MCAO) system MAORY[4].

2.1 E-ELT M4 and MAORY

For M4, a competitive prototype design and manufacturing study was carried out during the E-ELT phase B studies. A prototype mirror was designed and built with 2 different technologies. One proposed by a consortium of MICROGATE and ADS in Italy is based on thin floating glass shell actuated with voice coil actuators and collocated capacitive position sensors. The actuators technology is already established and several DMs are in use at large telescopes. This includes the VLT M2 of adaptive optics facility at ESO which will be installed by the end of 2016. The second M4 prototype was designed by a French consortium consisting of CILAS, GEPI, and ONERA. The proposal is based on PZT actuators using CILAS stack actuators technology. The mirror consists of a silicon carbide reference body carrying high stroke PZT actuators which are connected to a thin glass sheet. Finally ESO decided to use the voice coil technology for M4. The construction contract was signed in June 2015 with an expected delivery in 2022. It will have a clear aperture of 2.4 meters use more than 5000 actuators controlled at 1000Hz to correct for wave front errors of the atmospheric turbulence and other adverse effects. We consider the voice coil actuators with capacitive sensors for position feedback as mature technology.
Both technologies studied for the E-ELT M4 could possibly be adapted to the needs of MAORY. MAORY is currently in the phase B where the preliminary design of the system has to be accomplished. MAORY[13] will incorporate a relay optical system and one or two deformable mirrors with roughly 0.8m diameter. A tradeoff and work to derive the specification for the DM is part of the current design phase.
The need towards DMs for all first generation E-ELT instruments is covered by already running developments or can be covered by an adaptation of existing technologies. The picture changes if one looks to instruments for the second generation. Some key E-ELT science cases are even more demanding towards Adaptive Optics and the associated DMs.

2.2 DMs for the Second generation E-ELT instruments

MOSAIC, a multi object spectrograph will implement several multi object AO channels feeding several integral field units. In multi object AO (MOAO) at the E-ELT, turbulence in the higher atmosphere needs to be corrected in the direction astronomical objects spread over the entire field of view of the telescope. A MCAO system cannot be built for such large fields therefore it is required to correct the turbulence in the specific observation direction of each object separately by one dedicated DM per channel. Frequently there will be no reference star in the direction of the object and a direct measurement of the turbulence. The DM will be controlled in open loop. To increase the observation efficiency many channels will be operated in parallel. The DMs for MOSAI require 2800 to 5000 actuators with 5µm (goal 8 µm) stroke, very good linearity and stability. The DM shall be small otherwise it will not be possible to accommodate many observation channels in the limited volume available for the instrument. In the following it is dubbed compact DM.
One of the highest scientific priorities for the E_ELT is to characterize exo-planets and specifically imaging of Earth-like planets. The type of adaptive optics is dubbed extreme AO system (XAO). The extreme applies for several aspects also for the DM, the actuators count (11000 to 20000), actuators resolution (0.1nm) and speed of the AO loop. The related AO System was studied in the frame of EPICS.

3. EXISTING DMs AND ESOs NEED

To visualize the currently available and existing devices together with the future needs of ESO E-ELT instrumentation program Figure 1 was generated. It shows the actuators count on the Y axis and the DMs clear aperture in X. To visualize large span of values between existing devices and the future DMs logarithmic scales are required. The actuators pitch, a key parameter to distinguish different DM technologies[12] is drawn as diagonal lines. MEMS devices typically have very small actuators pitch below 0.5mm to 1mm. DMs using micro voice coils technology are found in the pitch range of 0.8 to 1.5mm. Discrete PZT actuators are typically used in the pitch range 3mm to 8mm. The upper end of the pitch scale are the voice coils DMs as it is typically used for the adaptive telescope mirrors. DMs in regular operation at ESO are drawn as black circles, other existing DMs and commercially available devices are marked by squares. The requirements to the E-ELT DMs in terms of actuators count and diameter are indicated by a light blue rectangles. Figure 1 does not show all important requirements of DMs, for example it does not show the actuators stroke, linearity or bandwidth. In the area of the compact DMs is a square indicating an DM with 4000 actuators, however this DM has less than 1 µm stroke while the requirement for the compact DM is 5µm (goal 8µm). The closest DM in the required diameter range has less than 1000 actuators while the required actuators count is in the range from 2800 to 5000 i.e. a factor 3 larger in the number of actuators.

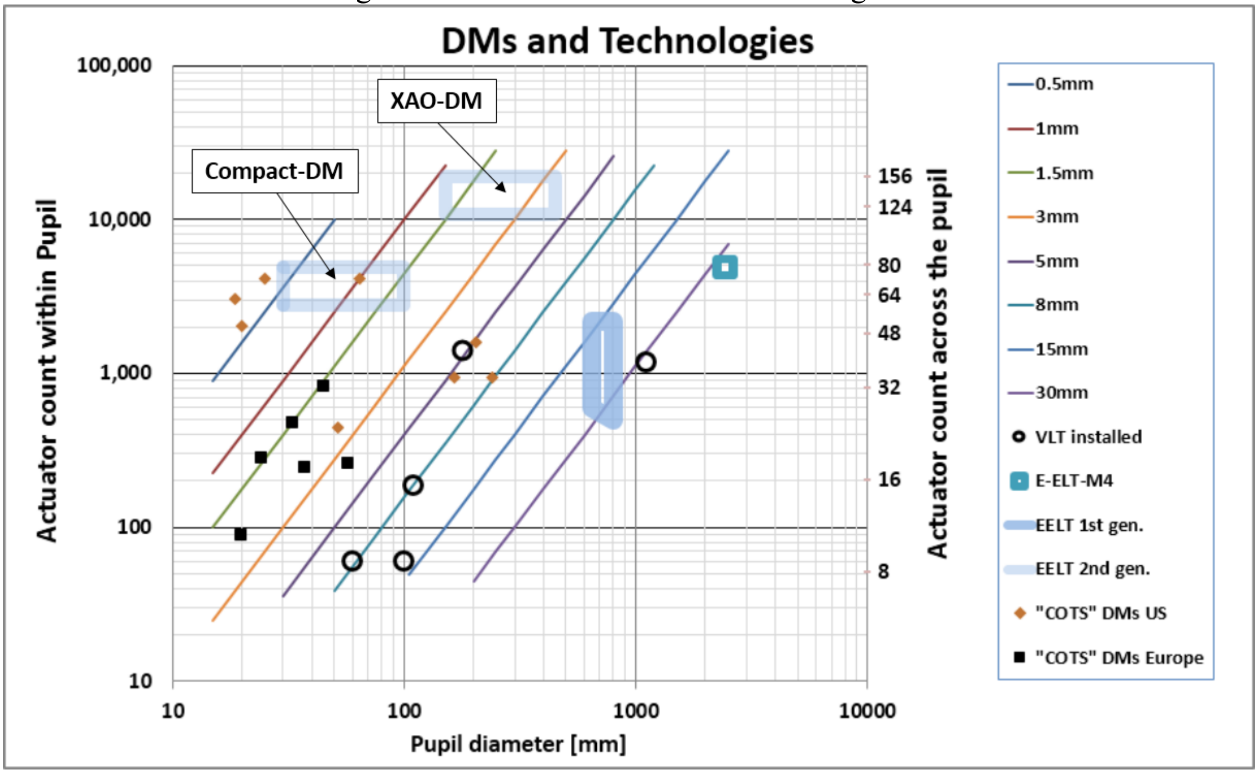

Figure 1: DM development chart

The separation of the required actuator count and DM size from existing devices is even more dramatic for the XAO DM, the closest DM with comparable actuators performance needs to be scaled up in the actuators count by a factor 10. None of the technologies used to build DMs toady allow a direct upscaling without hitting challenging technical barriers either with the size of critical components and parts, the cabling or the drive electronics. The deformable mirrors for MOSAIC and PCS are far from being available and either new technologies are required or existing technologies must be further developed to bridge over current limitations. To start with a consolidated design of an AO system key parameters of the DM must be available. To reduce the uncertainties on key DM parameters ESO launched a R&D program.

4. SPECIFICATIONS

One activity in the program was to collect the DM related specifications from the different pre phase A and phase A studies of instruments incorporating post focal AO. For the compact DM the specification is based on the studies performed for the EAGLE[6] project and for the XAO-DM work for the EPICS[7] has been used. The specifications give for several parameters a range rather than a specific value. At this stage our intent is to not exclude certain technologies early on and to give bidders the possibility to adapt their proposal to matching best to the respective technology taking into account the limitations and risks. In Table 1 key specifications are summarized.

Description	Specification value : Compact DM	Specification value : XAO-DM
DM clear aperture	Ø30mm-100mm, goal Ø45mm.	Ø150mm-450mm, goal Ø270mm. Annular shape with 24% central obscuration
Mirror surface Flatness	<15nm rms, stability of < 21nm rms within 1h	10nm rms, goal 5nm rms, after subtraction of few low order modes(Z4 to Z11)
Actuators count within the clear aperture	2800 to 5000	11 000, goal 20 000
Actuators pitch (derived information, no specification)	0.4mm-1.7mm	0.9mm – 3.7mm
Lowest mechanical resonance frequency (causing a mirror surface deformation)	>500Hz	>1000Hz, goal >2000Hz TBC
Actuators Stroke	>5µm (goal >8µm) (5by5)	>3µm (3by3)
Actuators resolution	-	<0.1nm goal < 0.06nm
Inter-actuator stroke	>1.3µm	>1.2µm
Small stroke settling time incl. latency of the drive electronics	250nm settling to ±10% within 700µs	50nm settling to ±10% within 150µs, goal 100µs
Hysteresis	Included in the linearity spec.	5%
Actuators non-linearity	<3% Goal <1%	<5% Goal <1%
DM surface temperature incl. Housing: deviation from ambient	<±1ºC	<±1ºC
Update frequency of the DM command	200Hz goal 500 Hz	2500Hz goal 4000 Hz
Nonfunctioning actuators. The exact numbers depend on the failure mode.	10-50, goal 0	5-30, goal 0

Table 1 Summary of key specifications for the Compact and XAO DMs

For both DM types the drive electronic is part of the development. In the following some key specifications are discussed in more detail.

4.1 Particular specifications for the Compact DM

The intended use of the compact DMs sets a number of particular requirements. The requirement from MOAO is to increase the energy concentration in a small area like one image pixel to be able to detect fainter objects or to increase the spatial resolution. The DM will be used exclusively in open loop i.e. the WF corrections need to be applied without any feedback to the WFSs. Therefore the requirement to the actuators linearity including hysteresis are very stringent. Also the shape applied to the DM to correct for instrumental effects must be stable at least over the duration of one observation (1h) or over the entire night. The compactness of the device has a crucial impact to the system design for an MOAO system. Not only the pupil size, also the deign volume of the DM housing, cabling and possible needs for cooling must be minimized. The specified range of pupil diameters is limited on the lower edge by the feasibility of the optical design. Small DMs need a stronger beam compression of the 39m entrance pupil which can be achieved either by more complex optical design or by a reduction of the transmitted field of view. The upper limit of the pupil size is driven by the volume required to accommodate all components of the AO optical train. Many parallel channels are required to boost the observation efficiency, however the available volume is limited. With larger DMs only fewer observation channels can be implemented and the constraints to the compactness of the other components are increasing. In the instruments studies a feasible pupil diameter range of 30 to 100mm was identified. Exceeding the limits will eventually impact the scientific capabilities of the instrument.

4.2 Particular specifications of the XAO DM

The challenges and limits to the XAO DM are different from the compact DM ones.
For the exo-earth science the AO system needs to correct the atmospheric turbulence such that the light of the parent star can be optimally suppressed by means of a coronagraph and to enhance the visibility of a faint planet next to it. One good metric for the instrument performance for XAO instruments with coronagraphs is the contrast, i.e. the ratio of the intensity of the PSF center to the background in its vicinity. For the detection of planets in the habitable zone a good contrast very close to the parent star is required. Analysis for the EPICS instrument have shown that a very high AO system bandwidth crucially impacts this performance aspect. An update rate from 2.5 KHz up to 4 KHz will be targeted. One limitation to achieve even higher contrast are quasi static speckles caused by small WF errors of the relay optics. One can suppress quasi static speckles by a method called electrical field conjugation[6] (EFC). By applying a static offset pattern to the WFS measurements it is possible to cancel out the static speckles in a small portion of the field. However to be effective a very high actuators resolution of 0.1nm is required. With an optical interferometer it will be very difficult to verify the resolution specification on the full mirror surface due to laboratory turbulence and other disturbances, however a verification on the actuators dive side will be possible. The reliability of actuators is also very important. At time of acceptance we will allow for a total of 5 nonfunctional actuators and during the 12 years lifetime additionally 5 actuators may break. Together with the drive electronics subjects like low latency data communication abut also volume and power consumption and cooling issues need to be addressed.

4.3 DMs development program

For consolidated design of instruments a prior knowledge of the pupil size is a crucial specification for the optical design of an AO system and the mechanical layout. Similarly the number of actuators cannot be kept open too long during the design phase. ESO launched a Research and development activity to reduce the gap between existing devices and the needs and in order to reduce the uncertainties on critical properties of the DM. The program has started in 2014 with a request for information (RFI). It was possible for European companies institutes to express the interest in participation of a DM development, to propose suitable technologies and a path to develop a DM. In the first half of 2015 technical specifications for 2 types of DMs where written by ESO. In a fixed price call for tender launched end 2015 companies where asked to identify critical aspects on their respective technologies and to propose a development plan addressing the identified aspects with the development of breadboards, demonstrating that the proposed solution is feasible and performs as expected. One contract for the Compact DMs has be launched in June 2016 with ALPAO. In the 2 years of development time ALPAO will build a prototype DM based on the company's existing technology with 1.5mm actuators pitch. The DM will have 3196 actuators with a clear aperture of 95mm diameter. For the XAO DM two contracts where placed in June and May 2016, one with ALPAO and one with the Fraunhofer Institute for Applied Optics and Precision Engineering (IOF) in a consortium with Physik Instrumente. The ALPAO contract addresses work to increase of the size of the membrane, the design of an integrated DM driver and in a separate activity works to reduce their actuator pitch but still keeping high actuators bandwidth. The IOF proposal is based on an array of discrete PZT actuators connected to a face-sheet. Results will be available in mid-2018. ESO will then decide on the next steps of the development. Particularly for the XAO DM further activities will be required to secure the feasibility of the DM. This could be done in the form of a second development phase with the goal to build a prototype of the final DM.

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