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Technologies for the fabrication of the E–ELT mirrors within the T–REX project

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Abstract. With its primary mirror with 39 m of diameter, the E–ELT will be the largest optical/near-infrared telescope in the world and will gather 13 times more light than the largest optical telescopes existing today. The different optical sub–systems of E–ELT, including the primary mirror based on hundreds of reflecting tiles assembled together, represent key components for the implementation of the telescopes. A huge amount of aspherical reflecting elements have to be produced with "state of the art" figuring and polishing technologies and measured with proper metrological equipments. In the past couple of years, in the context of the T–REX project, a specific development program was carried out at the Brera Astronomical Observatory–INAF in order to address a numbers of technology aspects related to the fabrication of the E–ELT mirrors. In this paper we give a short overview of the activities that have been carried out. Other papers in this volume report on specific activities that have pursed within such a development program.

Key words. Telescopes: E-ELT – Astronomical optics: aspherical mirrors – Fabrication Techniques for optics: bonnet fpolishing and ion figuring – Metrology: interferometry, profilometry, deflectometry

1. Introduction

E-ELT will be the world largest telescope of 40-m class and will guarantee the leadership to Europe for ground-based optical astrophysics for decades. The final E-ELT project features a telescope able to provide images with highest spatial resolution, thanks to the use of very innovative adaptive optics. The E–ELT optical design (Cayrel 2012) differs from other ELT designs mostly by including adaptive optics into the telescope. This drove the optical layout to five mirrors: a three mirror anastigmat with two flat folding mirrors providing the adaptive optics, resulting in an exceptional image quality, with no significant aberrations in the 10-arcmin field of view. In this context, M1 (the f/0.93 elliptical segmented primary mirror of E–ELT) has a diameter of approximately 39 m and a 11.1 m central obstruction. It is characterized by a six–fold symmetry and the segments are distributed in six sectors of 133 different segment types, or segment families. The total number of segments and associated supports is 931 (7 x 133), out of which only 798 (6 x 133) are installed in the telescope at any given time. The segments are hexagonal in shape with the maximum corner–to–corner

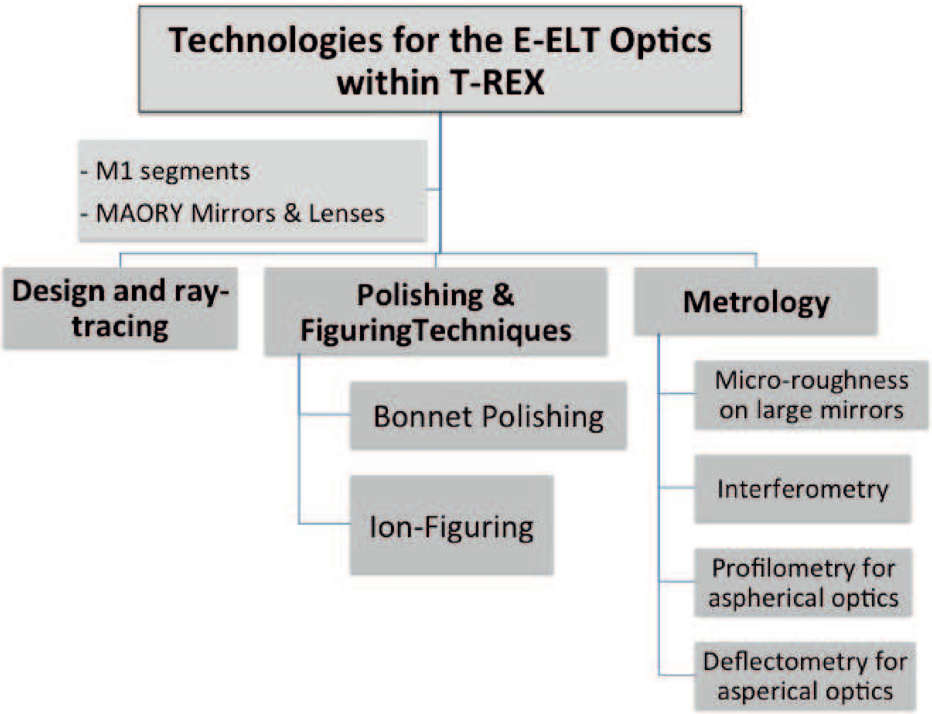

Fig. 1. Organization of the activities carried out within the T–REX project devoted to the development of the E–ELT optics.

dimension is 1.45 m. The industrial production of the M1 segments has to be performed in just 3.5 years and presents challenging aspects to be addressed in a pre–industrial development phase. The foreseen delivery rate is of at least 18 mirrors/month, with production peaks of 36 mirrors/months. The requirements on the surface accuracy are very stringent, with a maximum residual misfigure, averaged over the total number of segment assemblies, of 15 nm RMS WFE, while the accuracy of the knowledge of the reference radius of curvature shall be at least 14mm RMS. Other key optical elements, with large mirrors and lenses, will be used for the implementation of MAORY (Diolaiti, et al. 2014), the multi-conjugate adaptive optics module able to correct the atmospheric turbulence effects for the imaging camera onto large field of view. The MAORY module allow us to achieve a wavefront correction by means of two post-focal deformable mirrors complementing the ground-layer correction and field stabilization provided by the E-ELT mirrors M4 and M5. From the optical design point of view MAORY is a finite conjugate relay formed by two pairs of aspheric off-axis mirrors. Three flat mirrors fold the relay to fit the reserved area on the Nasmyth platform; two out of these mirrors are deformable and compensate the atmospheric turbulence. The optical relay makes an image of the telescope focal plane with unit magnification. The on-sky angular field of view is 160 arcsec in diameter. The optical quality required for the not-deformable mirrors (the largest one being an elliptical mirrors with 1.2 m diameter) is similar to that of the M1 segments. A huge amount of aspherical reflecting elements and lenses have then to be produced with state of the art figuring and polishing technologies and proper metrological equipments have to be developed for the characterization of the optics. In the past couple of years, in the context of the T–REX project, a specific development program was carried out at the Brera Astronomical Observatory-INAF. In this paper we give a short overview of the activities that have been carried out. The study logic is represented in Fig. 1. The efforts were focussed in the development of the fabrication of the mirrors of M1, M2 and MAORY and included activities on simulations, fabrication technologies for the optics and metrological methods. We also took care of the executive design of the M4 adaptive mirror and to set up a proper metrology and calibration approach.

2. Figuring and polishing techniques

In order to demonstrate, at a pre-industrial level, the technological capability to realize the mirrors of E–ELT we have developed within T–REX methods for the precision figuring and polishing of large substrates. The technologies should be also applicable for the fabrication of aspherical optics, as foreseen for M1 and MAORY. To this end, we have implemented in our labs two big facilities, based on the bonnet–polishing and ion–figuring approaches. The two methods are complementary to each–other, in the sense that they can be used in sequence to achieve an effective fabrication process, able to meet the surface accuracy requirements minimizing the production time (in this respect, a similar strategy is already indicated by ESO for the production of the M1 mirror segments).

2.1. Bonnet polishing

In the labs of the Brera Astronomical Observatory-INAF we have installed and it is now operated a 1200 model of the IRP (Intelligent Robotic Polisher) series machine made by Zeeko Ltd. in UK., making use of the so called bonnet polishing. The largest manufacturable optics is about 1200 mm. In the bonnet polishing (Walker, et al. 2006), a spinning, inflated, membrane–tool is compressed against the surface of the part to be machined, creating an area of contact that defines the removal footprint. The tools operate in the presence of polishing slurry. Standard bonnets of different diameters can be exchanged on the polishing machine, ranging from 20 mm to 480 mm of radius of curvature. The diameter of the footprint can be changed by varying the axial position of the bonnet with respect to the surface of the part to be machined or by varying the internal pressure of the tool, which is strictly related to its hardness. by acting on the process parameters, such as tool pressure, precession angle, compression offset and head speed, it is possible to select the desired removal function. Acceptance tests using the bonnet corrective polishing have been successfully completed on the machine at our site and the pass–off tests have been recently performed with success. Among them, a BK7 mirror 100 mm in diameter, concave of 500 mm radius, was polished in a few hours. Starting from a PV initial form error of 786 nm PV and 136 nm rms, the surface profile has been improved to a residual error of just 104 nm PV and 12 nm rms.

2.2. Ion figuring

The Ion Figuring uses a beam of Argon ions to remove material from an optic surface by means of kinetic impact. The process is done under vacuum, to permit to the ions a sufficiently large mean free path. The ions are accelerated by means of a suitable potential difference between the grids of the source and hit the surface at a typical distance of about 10 cm from the grids. Generally, the power of the source is kept fixed and the beam moved with variable speed to remove different quantities of material and correct the residual errors on the optical surface. The removal rate is very constant, after. Before using the IBF process, it is necessary to characterize the shape and removal rate of the beam obtaining the so-called removal function. Since it is a non-contact technique, it is able to correct with high precision the edges of the optics. The system has been completed in 2013 and has seen its first light on a large optic recently, with the start of an investigation on the IBF correction of segments for the E-ELT. The facility (Ghigo, et al. 2014), is composed by a large stainless steel vacuum chamber having a diameter of 2 m and a length of 3 m. To test the capability of our process, a hexagonal Zerodur mirror 1 m corner was treated with ion–figuring in our facility. In a few hours, starting from an error profile of 100 nm RMS, it was achieved a residual error of just 4 nm RMS

3. Metrology

In order to make possible the realization of optics with high accuracy, it is necessary to develop proper metrology equipments and characterization methods. They are needed for allowing us to characterize the surface errors across a large range of spatial wavelength also in case of large size and aspherical optics. To this aim, within T–REX, we acquired important metrological instrumentations, like e.g. the MicroFinish Topographer (MFT) by the Optical Perpective Group, and the FARO Arm and Laser Tracker (http://www.faro.com/products/metrology) for allowing high precision alignment of optics (Aliverti, et al. 2015) . Their capabilities has been demonstrated by our group in the alignment procedures of the ESPRESSO spectrometer at VLT. Other activities have been devoted to development of the interferometric characterization tests of the adaptive M4 Unit of E–ELT (Pariani, et al. 2015), using a sticking procedure for summing together the interferometric images referring to different parts of a mirror. Moreover a versatile interferometer, equipped with a reprogrammable Computer Generated Hologram based on photochromic materials (Pariani, et al. 2011), was studied for tallowing the measurements of many aspherical mirrors of similar size (as e.g. the segments of the M1 primary mirror of E–ELT). Approaches alternative to interferometry, able to grant a large flexibility and not limited by problems like the turbulence of the air during the measurements, were also developed. The design and bread-boarding of facilities based on profilometry (Civitani, et al. 2010) and deflectometry (Sironi, et al. 2014) was done, with very promising perspectives of the application for the E–ELT optics.

4. Conclusions

In this paper we reported on the development of fabrication and characterization methods to be used for the production of the E–ELT mirrors. These activities a have been carried out during the past few years at the Brera Astronomical Observatory–INAF, in the context of the T–REX program. "State of the art" figuring and polishing technologies, like the bonnet polishing and ion figuring, have been studied and large facilities for their application have been implemented. Metrological methods and instrumentations have been developed and operated, in order to permit the surface characterization also of large aspherical optics. We aim to use the aquired know–how and equipments for the fabrication of the mirrors of E–ELT, with particular reference to the M2 adaptive mirror, to the segments forming the M1 primary mirror and to the optics of the MAORY multi-coniugate adaptive optics system. Other papers in this volume report on specific activities that have pursed within such a development program.

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