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Nanometre-accurate form measurement machine for E-ELT M1 segments

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ABSTRACT

To enable important scientific discoveries, ESO has defined a new ground-based telescope: the European Extremely Large Telescope (E-ELT). The baseline design features a telescope with a 39-m-class primary mirror (M1), making it the largest and most powerful telescope in the world. The M1 consists of 798 hexagonal segments, each about 1.4 m wide, but only 50 mm thick. In the last stages of the manufacturing process of these M1 segments, a nanometre-accurate metrology method is required for the M1 to be within specifications. The segments have to be measured on their whiffle-tree support structures with a nanometre-level uncertainty, with a total budget on form accuracy of 50 nm RMS for any segment assembly. In this paper a measurement machine design is presented based on a non-contact single-point scanning technique, capable of measuring with nanometre accuracy, being universal, fast and with low operational costs, providing suitable metrology for M1 segments. A tactile precision probe is implemented to be able to use the machine in earlier stages of the segment manufacturing process. In particular, this paper describes the design of the air-bearing motion system and the separate metrology system based on a moving Sintered Silicon Carbide tube, a fixed Zerodur metrology frame and an interferometric system for a direct and short metrology loop. Preliminary calculations show nanometre-level measurement uncertainty after calibration.

1. Introduction

Worldwide, extremely large telescopes are considered one of the highest priorities in ground-based astronomy to enable important scientific discoveries. ESO defined the new giant telescope needed by the middle of the next decade: the European Extremely Large Telescope (E-ELT). The baseline design features a telescope with a 39-m-class primary mirror, making it the largest and most powerful telescope in the world. Details of the telescope and its requirements can be found in the E-ELT Construction Proposal [1]. Metrology equipment with nanometre-level uncertainty is required for the final metrology of the mirror segments, this is challenging in view of the required dimensions of almost 1.5 m corner to corner.

After an introduction to the E-ELT primary mirror and some current metrology methods, a single-point scanning technique is proposed in Section 1. The conceptual design of the machine is described in Section 2. Section 3 shows the design of the motion system and Section 4 explains the design of the metrology system. Finally, an uncertainty estimation of a segment measurement, after calibration, is given in Section 5.

1.1. E-ELT primary mirror

The E-ELT primary mirror (M1) is an elliptical concave mirror with a diameter of approximately 39 m, an 11-m central obscuration and a 69-m radius of curvature (ROC). The M1 mirror is made of discrete optical elements: the primary mirror segments. The segments are near-hexagonal, maximum 1429 mm in size (corner to corner), 50 mm thick (thickness at the centre) and made of low thermal expansion glass. As the primary mirror is not spherical, the hexagonal segmentation pattern has a sixfold symmetry. The segments are grouped in six sectors of 133 segments, thus the primary mirror consists of 798 segments (see Fig. 1). All 133 segments of a sector are different in shape and optical prescription [1].

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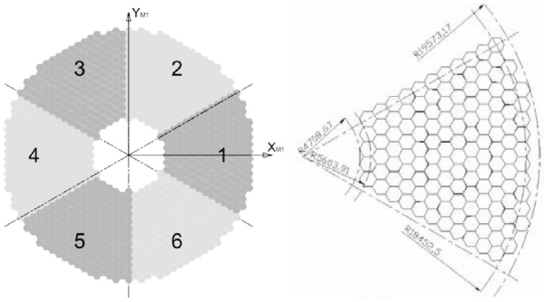

Fig. 1. Primary mirror segmentation pattern [1]. The segments are grouped in six sectors of 133 segments; all 133 are different in shape and optical prescription.

The reflective coating lifetime of a segment is about 18 months, which results in one or two segments having to be replaced every day. Producing 931 segments, having seven segments per family (133 families), allows for a realistic operation scheme. A segment taken out of the telescope can immediately be replaced by another of the same family, which has been prepared beforehand.

1.2. Segment assembly

A common support structure is used for the hexagonal segments. Slight counterweight adjustments are needed to compensate for the segment in-plane shape variation between the 133 segment families.

The segment and its whiffle-tree support form a segment assembly, together weighing about 250 kg. The segment support is integrated into the segment. The segment assembly is installed on a fixed frame assembly, which in turn is permanently attached to the telescope's main structure. Once installed on the fixed frame assembly, the segment assembly is moved in piston and tip-tilt using three position actuators. The fixed frame, as its name suggests, will stay fixed to the telescope's main structure, while the segment assembly will be extracted for maintenance purposes. Hence, the form of the segment on its segment support (the segment assembly) has to be measured within the accuracy requirements. The prototype segment assembly as designed by TNO [2–4] is depicted in Fig. 2.

The first eigenfrequencies of the segment assembly are in the 30–60 Hz range. The first eigenfrequency around 30 Hz is the rotation about the out-of-plane axis of the segment (zenith).

1.3. Metrology requirements and current metrology methods

The optical quality of the segments must be outstanding. Nanometre form accuracy is required with a fixed radius of curvature to be able to let the primary mirror act as one large mirror. Non-contact, nanometre-accurate metrology equipment must be available to be able to produce these segments. The maximum allowable form error of any segment assembly may not exceed 50 nm RMS. After removal of the focus, astigmatism and trefoil [5] component this error may not exceed 15 nm RMS [1]. Note that the maximum allowable measurement uncertainty is part of this budget, which results in a required measurement uncertainty of less than 15 nm RMS.

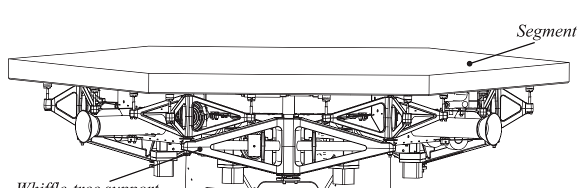

Fig. 2. The prototype segment assembly as designed by TNO [2–4]. A segment assembly consists of a segment and a whiffle-tree support structure.

Many techniques have been developed to measure mirrors and mirror segments for the existing ground-based telescopes. One of the most promising techniques is measuring the mirror segments using an imaging technique: Fizeau Interferometry with Computer-Generated Hologram (CGH) correction [6]. Other techniques capable of measuring Ø 1.5 m segments consist of scanning techniques like swing-arm profilometers and non-contact profilometers. Sub-aperture stitching is also possible, but is less efficient at these dimensions. A brief summary of the three-mentioned measurement techniques is given below. Note that this description is not comprehensive, it is merely intended to explain the need for other metrology techniques.

- *Phase-shifting interferometry (PSI)*. PSI is a fast method with respect to measurement time, as the whole surface is imaged at once. If the deviation from spherical of the surface under test exceeds several micrometres, the fringes become too dense to resolve, limiting the applicability of aspheres. Applying Computer-Generated Holograms resolve this issue, but large test towers and long, sensitive, beam paths are required in a classical PSI setup. Burge et al. [6] propose an adapted setup with a spherical reference lens (Ø 1500 mm) only requiring a 10–12 m test tower and decreasing the sensitive distance through air to 10 mm.

  Although measurement times are very short, the accuracy and alignment of the CGH and the large reference sphere are crucial for the accuracy of the measurement. Errors in the CGHs (133 CGHs, one for every segment family) result in systematic errors and also give problems with traceability, while an error in the reference surface of the reference sphere has exactly the same impact as an error on the segment surface. Moreover, to create phase shift, the reference lens is moved using piezo-actuators. While moving the reference sphere is preferred over moving the segment assembly, this would still be at least 200 kg of moving mass. Alignment of the segment itself is also crucial. Furthermore, this method is labour intensive, as the CGH needs to be replaced and aligned again for every segment. As several dozens of segments will be in process, all in different stages of the manufacturing process, segments have to be measured in mixed order. This can give rise to logistic problems.

  Although measurement times are very short, setup, alignment and calibration times will be long and therefore cost of operation will be high. The need for 133 different surface-specific CGHs makes this method non-universal.

  The predicted accuracy of this method is around 14.4 nm RMS [6]. After removing the power and astigmatism component, the measurement errors are stated to be 6.4 nm RMS.
- *Swing-arm profilometry*. A swing-arm profilometer [7] is able to scan a spherical surface using only two axes of rotation, while keeping the probe perpendicular to a best-fit sphere. Aligning the rotation axis and the probe to the (non-physical) centre of curvature of the surface is difficult, especially because the surface is aspherical. A probe connected to a correctly adjusted swing-arm will always be nominally normal to the surface under test if the surface under test is a sphere. In the case of an aspheric surface, this no longer holds; the surface departure from the adjusted sphere will be measured, enabling local distance and slope variations. Furthermore, the influence of gravity on the arm is continuously changing, which results in changing forces and thus deflections during measurement. This introduces uncertainty to the position of the probe.

  Callender et al. [8] designed their NPL/UCL swing-arm profilometer using a high-precision stage to account for the local distance and slope variations with a wavefront curvature sensor or a Fisba μ-phase interferometer. The repeatability they achieve