Metrology requirements for the serial production of ELT primary mirror segments

Rees, P.C.T. and Gray, C.

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Metrology requirements for the serial production of ELT primary mirror segments

Paul C T Rees *[a], Caroline Gray[a]
[a]Glyndŵr University, National Facility for Ultra-Precision Surfaces, The OpTIC Centre, St Asaph Business Park, North Wales LL17 0JD

ABSTRACT

The manufacture of the next generation of large astronomical telescopes, the extremely large telescopes (ELT), requires the rapid manufacture of greater than 500 1.44m hexagonal segments for the primary mirror of each telescope. Both leading projects, the Thirty Meter Telescope (TMT) and the European Extremely Large Telescope (E-ELT), have set highly demanding technical requirements for each fabricated segment. These technical requirements, when combined with the anticipated construction schedule for each telescope, suggest that more than one optical fabricator will be involved in the delivery of the primary mirror segments in order to meet the project schedule. For one supplier, the technical specification is challenging and requires highly consistent control of metrology in close coordination with the polishing technologies used in order to optimize production rates. For production using multiple suppliers, however the supply chain is structured, consistent control of metrology along the supply chain will be required. This requires a broader pattern of independent verification than is the case of a single supplier.

This paper outlines the metrology requirements for a single supplier throughout all stages of the fabrication process. We identify and outline those areas where metrology accuracy and duration have a significant impact on production efficiency. We use the challenging ESO E-ELT technical specification as an example of our treatment, including actual process data. We further develop this model for the case of a supply chain consisting of multiple suppliers. Here, we emphasize the need to control metrology throughout the supply chain in order to optimize nett production efficiency.

Keywords: optical polishing, optical testing, verification, process optimization, supply chain

1. INTRODUCTION

The serial production of ELT primary mirror (M1) segments presents manufacturers with a number of problems that require attention if they are to be able to respond effectively to the commercial opportunity to participate in the manufacture of these optics:

1. Technical capability (including skills)
2. The time required to complete production
3. The timely creation of manufacturing capacity
4. The cost of manufacturing infrastructure
5. The full cost of production
6. Acceptable scenarios for the manufacturer beyond the completion of production

The metrology capabilities required for the production of ELT M1 segments are key to meeting these challenges. In this paper we outline the metrology requirements for the serial production of ELT segments and explore how production model and choice of metrology technology interact in a production programme of this scale.

In what follows, we present data based upon the ESO E-ELT M1 specification.

*paul.rees@glyndwr.ac.uk; phone 44 1745 535210; fax 44 1745 535101

2. SPECIFICATION

The optical prescription of the E-ELT M1 is given by

$$R = 68685 \text{ mm}$$

$$k = -0.9964064$$

The primary mirror is composed of 798 non-axisymmetric aspherical segments, each hexagonal in shape and of corner-corner dimension approximately 1.44 m. Because of the 6-fold symmetry in the E-ELT M1, these 798 segments represent 133 families of segments of identical prescription. In addition, a further 133 segments (one additional segment for each prescription family) will be fabricated to facilitate operational maintenance of the primary mirror (e.g. recoating) during operation of the telescope, thus making a total of 931 manufactured segments.

We identify two nominal segment prescriptions applicable to the fabrication of E-ELT segments:

1. A circular optic with an overall surface error of nominally 250 nm RMS – This prescription respresents a circular segment prior to cutting to final geometrical form and optical finishing.
2. An hexagonal optic with a surface error of no greater than 25 nm RMS – This prescription represents the final figure of each primary mirror segment.

In respect of the circular optic, Table 1 summarizes the detailed surface specification. This prescription respresents the circular segment prior to cutting to final geometrical form and optical finishing.

In respect of the specification of the hexagonal optic, this prescription is further specified as a residual surface error of 7.5 nm RMS after removal of the low order aberrations given in Table 2.

Note that optical power cannot be disregarded in either prescription.

Table 1. Detailed manufacturing specification of circular polished segments. This intermediate specification defined the surface quality of E-ELT segments immediately prior to cutting to final geometrical form and finishing.

Spatial Frequency Region	**Definition**	**Prescription (RMS Surface Error)**
Low Frequency (LF)	Contains only focus, astigmatism and trefoil	No specific prescription
Mid Spatial Frequency (MF)	Contains all Zernike polynomials up to Z37, assuming Zemax Zernike series using Fringe normalization, apart from LF	70 nm
High Spatial Frequency (HF)	Contains residual after removal of LF and MF and after low-pass filtering with a Gaussian filter of 25 mm FWHM	20 nm
Very High Spatial Frequency (VHF)	Contains residual after removal of LF, MF, HF and after removal of spatial frequencies above 3 mm	4 nm

3. OVERVIEW OF PRODUCTION SCHEDULE

The production of E-ELT M1 segments is expected to have a duration of seven years. During this time, 931 manufactured M1 segments will need to be supplied, plus a provision for manufacturing yield. We set this yield at 97%, indicating that provision for the manufacture of 960 M1 segments is required. The manufacture of 960 M1 segments over a period of 84 months implies an average manufacturing rate of 11.4 segments per month or, assuming continuous production over the seven-year period without provision for holidays, one delivered segment every 2.66 calendar days.

Table 2. Aberration allowances for the final polished segment form.

Zernike Term	Proportion
Power	85%
Astigmatism	95%
Trefoil	85%

Whilst this average figure is informative, it does not make any allowance for the initial production build-up, with its substantial capital expenditure, nor for any completion ramp-down. If a start-up period of approximately 30 months is assumed and a ramp-down period of 6 months, then the overall production profile will look similar to Figure 1. Here, an initial period of 18 months is defined to build capability before any M1 segments can be manufactured. The data in Figure 1 indicate that the minimum full-production delivery rate for completed segments is 16.8 segments per month (or one delivered segment every 1.8 calendar days). This production rate assumes that 18 months is sufficient to build capability to begin production, i.e. to occupy and fit out a production facility.

These delivery timescales are highly aggressive and will affect the choice of production technologies used for manufacture because many established technologies will be too slow to be cost-effective. In what follows, a full-production delivery rate of 16.8 segments per month is assumed.

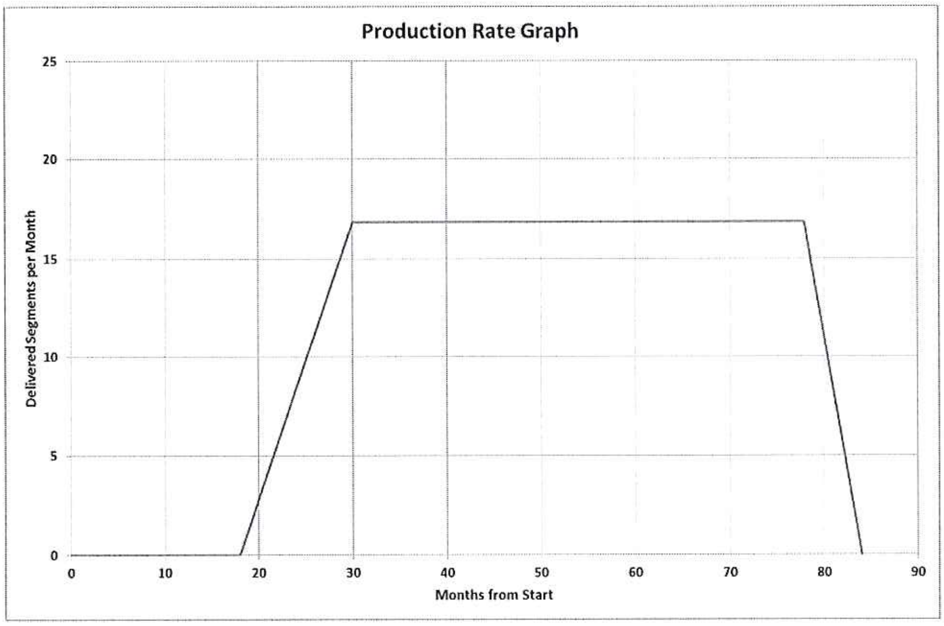

Figure 1. An example segment production profile, assuming a capability building period of 18 months, a ramp-up period of 12 months and a ramp-down period of 6 months.

4. SERIAL PRODUCTION AS A PRODUCTION MODEL

For serial production of the M1 segments we identify the following process steps:

1. Blank incoming inspection – Unpacking, inspection and verification of each delivered segment blank; issue of a goods inwards certificate; setting up quality records for the segment blank for onward processing.
2. Establish processing fiducials – Bond any required reference fiducials to the segment blank; establish the segment local coordinate system.
3. Aspherical grinding – Grinding of the segment to its off-axis aspherical shape.
4. Smoothing – An intermediate abrasive treatment designed as a "standardisation process" to ensure the uniformity of input into the aspherical polishing stage. This process will reduce subsurface damage of the optical surface and any mid-spatial surface features resulting from the grinding process.
5. Prepolish – A non-corrective polishing treatment designed to render the optical surface specular and measurable with an optical interferometer at a visible wavelength.
6. Aspherical polishing – Initial polishing of the circular segment to the required M1 prescription; acceptance testing and certification as per Table 1.
7. Machining – Machining of the circular polished segment to its final hexagonal shape; machining of any interface features.
8. Interface pad bonding – Adhesive bonding of the pads that interface the segment to its in-service segment support; bonding of the pads that interface the segment to the edge sensors.
9. Segment assembly integration – Integration of the hexagonal segment onto its segment support.
10. Finish figuring – The hexagonal segment, integrated to its support, is finish figured to the final segment accuracy; acceptance testing and issue of an acceptance certification.
11. Packing and delivery – Packing the finished segment and its support in its transport container; delivery.

Whilst the specific process will vary with manufacturer, the listed steps provide a probable production sequence for use as a model to investigate the process and verification metrology requirements at each step.

5. METROLOGY REQUIREMENTS FOR PRODUCTION

The process outline presented in the previous section is illustrated in Table 3. Alongside each process step in Table 3, the identified metrology requirements are summarised. For each process step, a number of metrology technologies are expected to be used. The target measurement accuracy identifies the maximum accuracy required during each step.

Many of the metrology technologies identified are available as commercial off-the-shelf (COTS) products or are available to order. However, two areas require bespoke design and manufacture:

1. The manufacture of optical support tooling for each optical treatment process
2. The manufacture of an optical interferometric test

Each of these areas is crucial to technical conformance of the ELT segments.

To understand the impact of the choice of process and metrology technology upon serial production, a model for serial production has been structured as per Table 3. To meet the production rates identified in Section 3, processing times must be scaled by capital equipment holdings required to secure the calculated segment delivery rates.

In this production scenario, the time-line is clearly process driven. It is found that most identified metrology choices easily meet the required segment production rate with holdings of only one operational unit, even after realistic provision is made for segment handling and alignment, and calibration and maintenance of the equipment. The production bottleneck is clearly the polishing and figuring processing and their related interferometric testing. All modern CNC-based polishing technologies require closely coupled accurate metrology in order to achieve rapid convergence to a final polished optical form. It is informative to investigate the relative behavior of CNC polishing and metrology as a function of form accuracy.

Table 3. A list of possible production process steps, along with attributed measurement requirements and applicable measurement technology. In addition to the dimensional metrology technologies listed, temperature, pressure and humidity must be monitored during all testing.

Process Step	**Target Accuracy**	**Target Measurement Accuracy**	**Measurement Technology**
Blank Incoming Inspection	200 µm	40 µm	Laser tracker
Establish Processing Fiducials	200 µm	40 µm	Dial gauge Laser tracker
Aspherical Grinding	20 µm	4 µm	Dial gauge CMM Thickness gauge
Smoothing	10 µm	2 µm	Dial gauge CMM
Prepolish	10 µm	100 nm	Dial gauge Interferometry
Aspherical Polishing	200 µm	< 2 nm	Interferometry Precision profilometer Texture interferometer
Machining	200 µm	20 µm	Dial gauge CMM
Interface Pad Bonding	200 µm	40 µm	CMM Specialist tooling
Segment Assembly Integration	None		Specialist tooling
Finish Figuring	25 nm	< 2 nm	Interferometry
Packing and Delivery	None		

Figure 2 illustrates actual data following the convergence from a 20 µm PV form to the specification identified in Table 1. These data result from a small-tool CNC polishing process and Twyman Green based, full aperture, optical test used to fabricate a prototype E-ELT segment[1]. The graph plots the ratio of interferometric testing time to polishing time against measured surface error of the fabricated optic. It can be seen from Figure 2 that the time taken to polish the segment is greater than the time taken to measure the segment until the circular segment specification is met (the right hand side of graph). If, however, the same processes are progressed to the final segment specification, then Figure 3 results.

It is clear from Figure 3 that beyond a certain surface error, the interferometric metrology dominates the process speed when compared with the polishing process. From the point of view of maintaining production rates, one response to this effect is to buy more interferometric tests. However, the capital cost of these interferometric systems and the required labour rapidly makes this response commercially unacceptable.

What drives this drop in relative metrology efficiency is the optical path length of the test that is non-common path. Because the test used to obtain data for Figures 2 and 3 was based upon a Twyman Green interferometer which has an optical path length of approximately 31 metres, testing time is dominated by data acquisition. Large volumes of data are required to remove the wavefront effects of air mixing in the measurement column. Figure 4 presents an example surface error map resulting from this mixing. To obtain the experimental accuracy stated in Table 3 using this optical test requires the acquisition and summation of over 1500 individual interferograms.

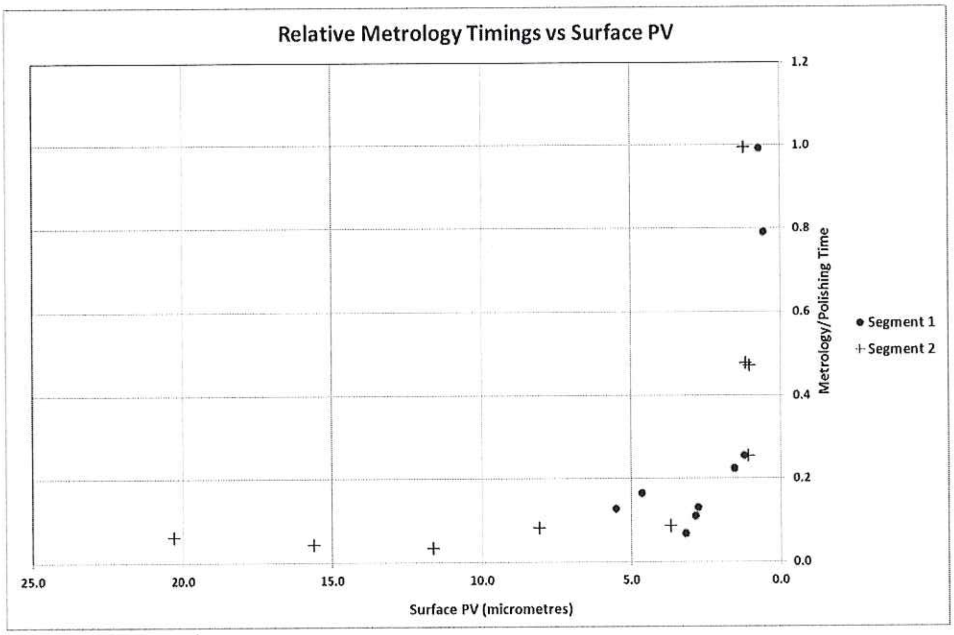

Figure 2. A graph of metrology time/polishing time ratio against surface form error (PV). On the right hand side the plot ends at the circular segment specification. These data were taken from the fabrication of two prototype E-ELT segments. Note that the time taken to interferometrically test the segment is much lower than the time taken for each polishing run until the segment reaches the circular segment specification. At this point, the times are comparable.

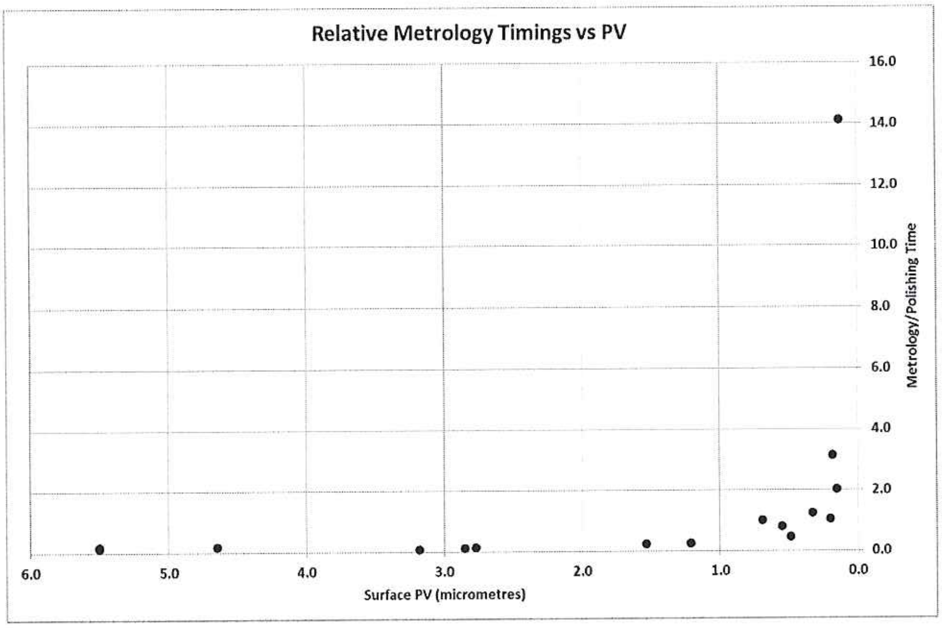

Figure 3. A graph of metrology time/polishing time ratio against surface form error (PV). Here, on the right hand side, the plot ends at the final segment specification. These data were taken from the fabrication of a single prototype E-ELT segment. Note that the time taken to interferometrically test the segment is lower than the time taken for each polishing run for much of the processing. However, near completion, the testing times significantly exceed the polishing times.

To summarize, Twyman Green based interferometric tests are often used in the manufacture of large optics. Whilst such a test design is sufficient to meet the process requirements for the manufacture of circular segments ready for finishing, it is not an optimum technical solution for the finishing process. Lowering the optical path length to, say, 1 metre would enable an interferometric test to achieve its required accuracy with approximately 1/30th of the required data. This suggests the deployment of one of two types of interferometric test for finishing:

1. A full-aperture Fizeau interferometric design[2]
2. Sub-aperture interferometry with subsequent stitching into a single surface error map

Of these two testing methods, sub-aperture stitching interferometry of a large optical surface requires the acquisition of many individual sub-apertures (we estimate approximately 100 for this application) that must subsequently be numerically stitched into a single surface. Without some external datum or optical reference, the stitching of this number of sub-apertures is vulnerable to low-order form errors resulting from accumulated small numerical errors during the stitching.

This suggests a full-aperture Fizeau design to be the most efficient interferometric test during finishing of ELT segments.

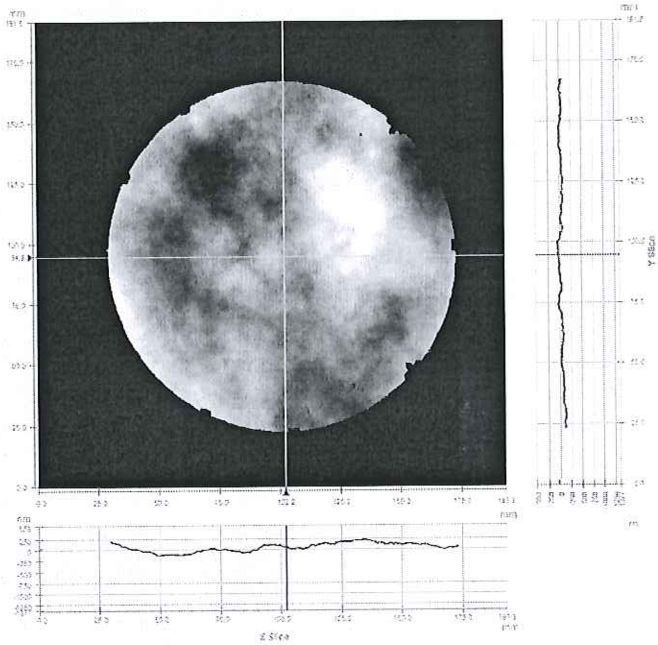

Figure 4. An error map produced by subtracting two interferometric error maps, each created by a single acquired interferogram and acquired within one second of each other. The interferometer exposure time was less than 2 milliseconds. The result is a measure of the wavefront effect of refractive index variations in air throughout the column of the interferometric test. The test artefact was a sphere of 1360 mm diameter and of nominal radius of curvature 13645 mm. The measured effect of the refractive index variations in the air was 80.6 nm RMS.

6. SINGLE AND MULTIPLE SUPPLIERS

The existence of two segment specifications, one an intermediate circular segment prescription, the other the finished E-ELT segment, suggests a natural process break where multiple suppliers may be able to provide the required total segment production capacity.

Using multiple suppliers has the potential to spread commercial risk and to obtain the needed production capacity throughout a large project. However, the challenge in respect of metrology when using multiple suppliers can be summarized as:

1. Each supplier must have all metrology (and other) equipment resources required for segment production.
2. There is an increased burden on metrology for verification when products are passed between suppliers in the supply chain.
3. There is an increased calibration burden upon all suppliers to ensure that the final product is fully conformant.
4. Greater handling and shipping costs must be borne by the production project.

All of these requirements have a tendency to increase unit cost when compared with the forecast unit cost from a single supplier with the required manufacturing capacity.

Once again, the process efficiency of the interferometric test will have an impact on the supply chain. An inefficient test design will act to increase capital expenditure required at project start-up for each supplier and will affect unit cost. The choice of interferometric test can affect the capital expenditure required for the production of circular segments by more than 10%.

If it is assumed that a single supplier of finished segments is used, but with multiple suppliers of circular segments into this finishing process, then the need for each circular segment supplier to procure all capital equipment required for circular segment production will affect the total cost of supply. Modelling this capital expenditure suggests cost increases of greater than 60% are possible for multiple supplier models.

7. CONCLUSIONS

We have identified the verification requirements derived from the technical production requirements for the serial production of E-ELT primary mirror segments. From the top-level model for segment production output, we have derived a breakdown of activities for both figuring process and metrology. We have identified appropriate metrology methods that conform to the process duration breakdown.

From this analysis we can draw the following conclusions regarding the metrology requirements for serial production of ELT primary mirror segments:

1. The speed of interferometric testing clearly affects the segment delivery rate.
2. The required speed of interferometric testing during finishing suggests either stitching interferometry or a full-aperture Fizeau is required.
3. The choice of interferometric test will have an impact on unit cost, even for circular segment production.
4. A multiple supplier production model, whilst effective in achieving capacity, can significantly increase unit cost.

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