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Edge-control and surface-smoothness in sub-aperture polishing of mirror segments

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ABSTRACT

This paper addresses two challenges in establishing a new process chain for polishing hexagonal segments for extremely large telescopes:- i) control of edge and corner profiles in small-tool polishing of hexagons, and ii) achieving the required smoothness of the bulk aspheric form. We briefly describe the performance of a CNC-grinding process used to create the off-axis asphere, which established the input-quality for subsequent processing. We then summarize processes for smoothing ground mid-spatials and pre- and corrective polishing using Zeeko CNC machines. The impact of two cases is considered; i) all processing stages are performed after the segment is cut hexagonal, and ii) final rectification of a hexagon after cutting from an aspherised roundel, as an alternative to ion-figuring. We then report on experimental results on witness samples demonstrating edges and corners close to the E-ELT segment specification, and results on a full-aperture spherical segment showing excellent surface smoothness.

Keywords: ELT, E-ELT, segment, edge, mid-spatial, polish, Precessions

1. INTRODUCTION

This paper describes work developing a new methodology for manufacturing mirror segments for extremely large telescopes, especially the European Extremely Large telescope (E-ELT). The original design deployed 984 x 1.4m across-corners segments, with a total requirement of 1,148 segments including one complement of spares (based on 6-fold symmetry) [1, 2]. In June 2011, ESO de-scoped the telescope to 39.3m aperture on cost-grounds. The corresponding segment numbers are now 798 in the telescope and 931 with the required spares.

The state-of-the-art in segment fabrication is established by current 10m-class optical/IR telescopes. The primary mirrors of Keck 1&2 [3], and Grantecan [4] each have 36 off-axis aspheric segments, these being of 1.8m and 1.87m across corners respectively. E-ELT clearly represents a step-change in mass-production of segments, emphasized by the change in off-axis aspheric form from the centre of the primary pupil to the edge. It is true that SALT has an intermediate number of segments – 91 x 1019mm [5], but these are all of the same spherical form and so considerably easier to mass-produce.

The key technical challenges in terms of manufacturing processes (as distinct from metrology) are i) control of edge mis-figure, ii) achieving smooth surfaces, and iii) process-speed. The Keck project addressed these through their

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pioneering work applying "bend and polish" techniques to off-axis aspheric segments. Each segment started optical fabrication in its circular shape (a 'roundal'), was mechanically distorted to the inverse off-axis asphere, and then polished spherical. The applied forces were then relaxed to create the desired aspheric form. The segment was then cut hexagonal, which introduced distortions to the form [6], and these were rectified by ion-figuring.

We identify a number of issues, should this generic type of approach be applied to segment mass-production. Stressing the blank requires manual interventions to attach and detach the stressing fixtures, which introduces handling risk and does not lend itself easily to automation. There is a danger that a stressing fixture, attached with a reversible cement, may accidentally become detached during polishing. Cutting hexagonal also introduces risk at a stage when the blank has significant added value by virtue of the prior process-steps. In regard to ion-figuring, this requires additional handling and installation in a vacuum chamber, with attendant pump-down times. In the context of the original CELT project (precursor to TMT – the Thirty Meter Telescope), D.W Kim and S.W. Kim reported [7] that ion figuring exhibits 'extremely low removal rates'. They described a study showing that 6 ion figuring chambers would take about 8 years to complete the 1080 x 0.5m diameter segments for the then-proposed CELT telescope [8]. E. Williams et.al commented [9] that, 'whilst one ion-beam 'hit' was sufficient for the Keck segments, two or three would be expected for the TMT segments [9].

With these points in view, we report on development of a new process-chain based on bespoke developments of the Zeeko *Precessions* process [10], through a series of experiments using witness parts. In this chain, all the processes on the optical surface are conducted with the blank pre-machined to final external dimensions, and where ion figuring is not required. We also comment on an intermediate process-chain where a roundel is aspherised using computer controlled polishing, cut hexagonal, and finished by computer controlled polishing.

2. THE E-ELT PROTOTYPE SEGMENT SPECIFICATION

ESO's specification [2] for the prototype segments, defines the 'useful area' as the global surface of the segment excluding an edge-zone 10mm wide (requirement), or 6mm wide (goal) – as per Fig.1. The maximum edge-misfigure in the edge-zone is specified to be <400nm PV wavefront, and the average of the six edges <100nm PV wavefront. Surface values are of course half these. This specification introduced two ambiguities which we have resolved as follows:-

- PV is very sensitive to any noise or anomalous pixels in the interferometer data. We have adopted the PVq (95%) metric, which is more representative of the stray-light and infrared emissivity which the segments are to deliver.
- The datum with respect to which the edge-misfigure is to be measured is ambiguous. This has been resolved through the following procedure that we have systematically adopted for measurement:-

1. The part is measured over its full aperture using a simultaneous-phase phase-shift interferometer.
2. A 0.5mm wide margin around the edge is removed from the data, to represent an allowance for final beveling after all other processes are complete.
3. Tip/tilt, de-focus and astigmatism are removed from the resulting data-set.
4. The Useful Area is defined as the surface excluding the 10mm wide edge-zone.
5. The Useful Area is cut out of the data-set and analysed to provide a measure of RMS.
6. The remaining 10mm wide hexagonal ring is divided into six individual trapezoidal segments, each of which is analysed separately to provide the PVq (95%) edge misfigure numbers.

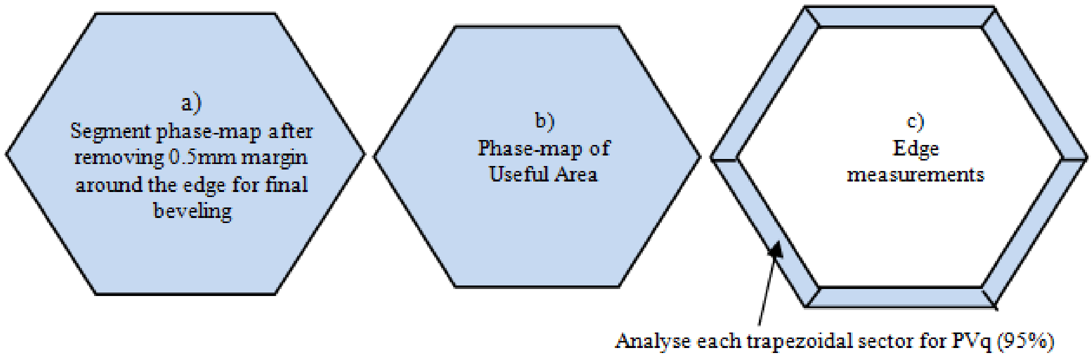

Figure 1. Procedure for analyzing segment interferometric data for edge misfigure RMS of useful area.

In terms of surface-smoothness in the Useful Area, ESO has specified [2] a set of allowable Zernike terms that may be removed from the data. The maximum permitted residuals after removing these allowances are 30nm RMS wavefront for any segment, and 15nm wavefront for the average over the total set of prototype segments.

3. OVERVIEW OF THE NEW MANUFACTURING APPROACH

The objective has been to develop a manufacturing process-chain which lends itself to scale-up for mass-production. This implies the minimum manual interventions, and the maximum scope for automation.

We separate this new manufacturing approach into different process-steps, described below:-

1. The starting point. This is a hexagonal blank finished to its final hexagonal external dimensions by the blank manufacturer, and with a small allowance on overall thickness to accommodate subsequent processing of the optical surface.
2. Production of the off-axis aspheric form. This is produced by ultra-precision hard-grinding using the Cranfield University BoX™ grinding machine. Its design was optimized for low-slope optics, having the minimum number of degrees of freedom in order to maximize dynamic stiffness. The grinding leaves clean edges with no measurable misfigure. Grinding an off-axis aspheric full-size segment, the form-error is <1 µm RMS and 6 µm p-v form-error (measured by coordinate measuring machine, with the segment still mounted on its precision diamond-turned, hard grinding fixture) [11, 12]. Sub-surface damage is ~ 6 µm on Zerdor; a little more on ULE [13]. The ground surface exhibits a mid spatial frequency component which need to be removed in subsequent processes.
3. Half of the 1mm wide specified bevel is applied. This gives a contingency for any highly-localised edge-roll which is produced further down the process-chain.
4. Grolishing (optional). This comprises a family of processes [14] between grinding and polishing that operate on the Zeeko machines. Of particular relevance is the development of a brass button which may conveniently be mounted on a bonnet. This is used with C9 aluminium oxide abrasive, and rastered across the part. It provides fast smoothing of the BoX-ground surface, and has proved effective in removing the BoX mid spatial content prior to pre-polishing. The issue of tool-misfit over the asphere has been examined in detail [15] and the tool-size is chosen to avoid introducing new mid-spatials. The concern in applying this process on a Zeeko machine dedicated to segment polishing is contamination of the polishing slurry used for subsequent processes with C9 abrasive.

5. Pre-polishing. The purpose is to remove surface and sub-surface damage, leaving a surface amenable to full-aperture interferometric measurement. This process is performed using bonnet raster-polishing on a Zeeko CNC polishing machine, deploying the largest bonnet available to give the highest removal-rate. However, this method has proved unable to remove the BoX^{TM} mid spatial frequency errors in a useful time, because the natural ability of the compressible bonnet to accommodate the change in surface-curvature over an asphere, also makes it adapt to BoX-induced mid spatial frequencies.
6. Pitch-polishing. A small pitch button used on the Zeeko machine has proved capable of removing mid spatial frequency errors from the BoX^{TM}, although it is significantly slower than the C9 process. It is also effective in removing residuals left from bonnet polishing (effectively a Gaussian process). Pitch button polishing also plays a role in final edge control as described later in this paper. As with grolishing, the tool-size is selected according to the constraints of aspheric misfit.
7. Corrective polishing. This proceeds through a succession of bonnets and spot sizes, following the general principles of Nyquist sampling i.e. commence with a large spot, and then its residuals can be attacked with a spot delivering twice the spatial frequency. Following full-aperture interferoemtry, the corrective loop can be closed using a simple feed-rate algorithm (Zeeko's *Tool Path Generator*, TPG), or numerical optimization (Zeeko's '*Precessions*') as appropriate.
8. The final 0.5mm of bevel is applied giving the 1mm total as specified by ESO.

4. EXPERIMENTAL RESULTS ON EDGE-CONTROL

4.1 Edge processes with hard tools and bonnets

We consider small hard tools that may be for grolishing or pitch polishing as above, and which are rotated about their axes for maximum removal rate.

A hard tool traversing the part in a pre-determined tool-path (e.g. a raster) would remove a uniform layer were the tool-path arranged so that the tool leaves the part completely. In reality the tool needs some tip/tilt compliance so that it makes intimate contact with the part's surface. Should the centre of the tool leave the edge of the part at the ends of the tool-path, the tool will rock about the edge of the part. This limits the practical tool-overhang for stable operation. For this reason, the removal-process is inevitably incomplete near the edge of the part, which tends to turn the edge-zone *up*. The corners of a hexagon add further complexity, as the tool-overhang is different from corner to edge, and corners are systematically raised compared with edges.

Another factor arises in that the area of the tool in contact with the edge decreases as the tool overhangs. For a given tool-mass or constant applied force, the pressure exerted by the tool increases with overhang. This tends to roll the edge-zone *down*. Furthermore, as the speed-vector of the rotating and partly overhanging tool attacks (rather than trails) the edge, it can create a zone of increased local pressure in the polishing slurry, which can roll the extreme tip of the edge *down*.

In the case of compliant bonnets where the polishing spot overhangs the edge, the bonnet material can 'mould itself' around the edge, giving an additional mechanism for turning edges *down.* However, a bonnet gives additional flexibility compared with hard tools, as raising and lowering the bonnet with respect to the part, enables the spot-size to be actively changed between specified maximum and minimum values along the tool-path.

The opposing mechanisms outlined above are amenable to optimization with regard to edge-control, and results obtained on witness parts are presented below.

4.2 Edge process results with grolishing tools

The results presented in Figure 1 are for a 50mm brass-button grolishing tool on a Zeeko machine, operating with C9 aluminium oxide abrasive slurry. In the four sets, the edge-overhang at the ends of the tool-path were 9, 12, 13 and 14mm, respectively. Each set of three plots corresponds to three directions across the centre of a hexagon, at 120^o. Upper sets of three are across flats, and lower sets across-corners.

It will be seen that by changing the overhang, the residuals can be 'tuned' from turned-down to turned-up. The 12mm to edge distance gives the optimum overhang in this configuration.

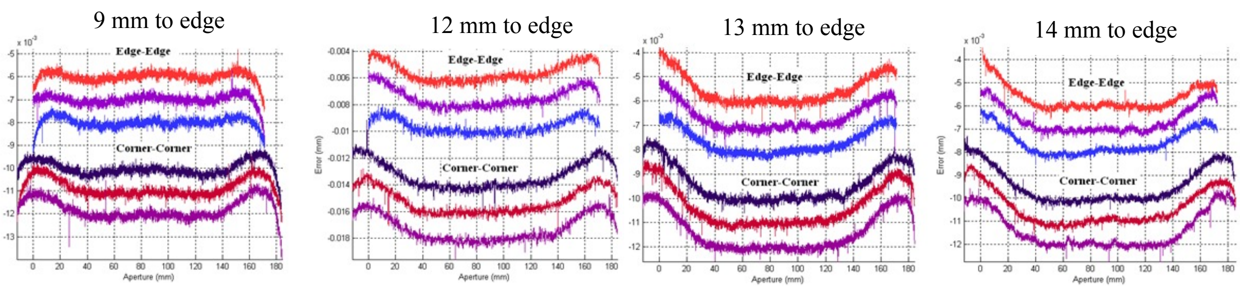

Figure 2. Edge and corner profiles with different tool-overhangs in grolishing.
Upper sets of three: edge-to-edge, Lower sets: corner-to-corner.

4.3 Edge process results with bonnet polishing

In bonnet polishing, once the leading edge of the full-size spot encounters the edge of the part, the spot-size is reduced by optimizing the trajectory by which the bonnet is raised off the part. The spot's leading edge can then remain registered with the edge of the part, avoiding any overhang. This is shown schematically in Fig. 3, where a raster tool-path progresses towards the edge (dashed). The raster performs its turn-around in air (not shown).

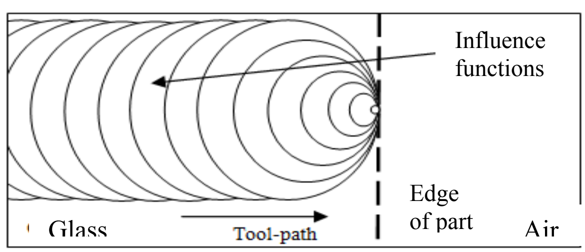

Figure 3. The use of tool-lift to reduce spot-size in the vicinity of an edge

A series of test-runs have been performed on 200mm across-corners hexagonal Zerodur parts, and 300mm and 400mm borosilicate glass part. All were prepared to R=3m concave by machining, then abrasive-lapping on a cast iron tool. The process chain is described below and has proved to be reproducible over numerous witness parts. A total removal of 15 microns p-v was targeted through the pre- and corrective-polishing phases, to give sufficient stock to guarantee that all the surface and sub-surface damage from BoX grinding is removed.

The parts were then bonnet pre-polished on an IRP1200 Zeeko machine. Early work deployed a 160mm radius-of-curvature ('R160') bonnet, precessed at 15 degrees, and with Z-offset (bonnet compression) to deliver a 45mm full spot-size. This was upgraded to an R200 tool, delivering spot size of 200mm, and increased volumetric removal rates.

Measurements were conducted using an extended-range Form Talysurf stylus profilometer, and using a 4D Technologies 6000 simultaneous phase interferometer. In the latter case, extreme care was required to avoid rolled edges being missed because the fringes were too tightly-packed to be resolved. This effect can give an optimistic impression of edge-quality. With this in view, data were also acquired with small isosceles triangular masks attached to the surface, positioned with the points precisely on the edges of the optical area of the part (i.e. the start of the bevel).

The tool-path and tool-lift parameters were designed to leave a broad edge-zone, nowhere dipping below the extrapolated bulk form, and everywhere measurable using full-aperture interferometry with lateral sampling approximating to that for a full-size segment. The process has proved very flexible in controlling the maximum surface-slope in the edge-zone for pre-polishing in this way.

The parts were then subject to corrective polishing using an R80 bonnet and 20mm spot size, in order control both the form and the detailed profile of the edge feature. The surface of the part was then treated with a small rotating pitch tool on the Zeeko machine. The tool was designed according to the aspheric misfit principles in [16]. It was then experimentally qualified on a witness part with a cylindrical term representative of the dominant aspheric term in the segment. This ensured that aspheric mis-fit on a segment would not introduce new mid spatial frequency features.

The interferometer data has been analysed according to the protocol described in Section 2, and the numbers quoted for the individual edges represent PVq (95%) after allowing for the final 0.5mm of edge-bevelling.

Figure 4 shows final results on a 200mm across-corners Zerodur part. In this case, the part was too small to show distinctly the separate bulk and edge-zone areas after pre-polishing. In contrast, Figure 5 shows a 400mm part after the pre-polish phase, clearly demonstrating uniform removal over the bulk, and the controlled raising of the edge-zone. Figure 6 shows this same 400mm part after corrective polishing and pitch polishing on the Zeeko machine.

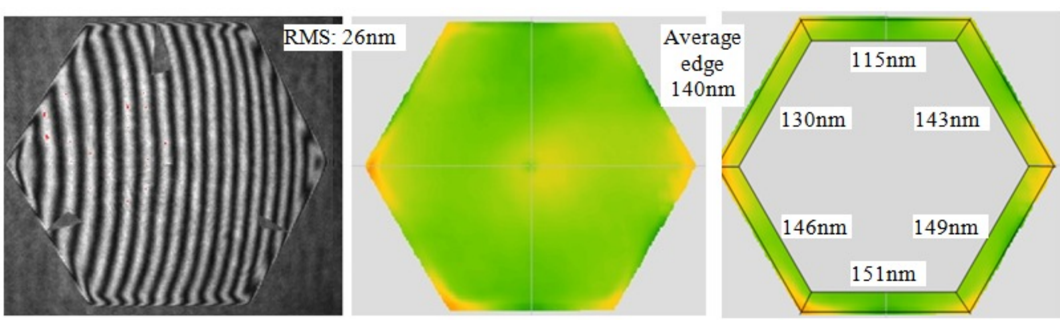

Figure 4. 200mm part after pre- and corrective polishing and pitch process. Edge numbers are PVq (95%).

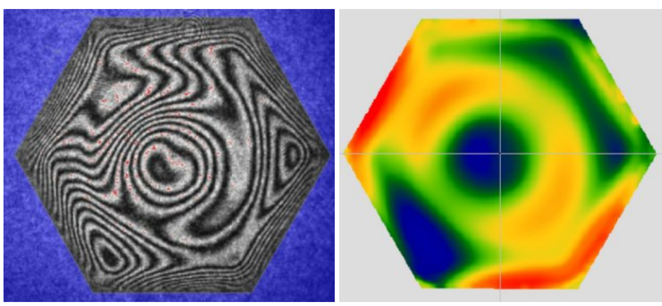

Figure 5. 400mm part after hand-smoothing followed by Zeeko pre-polishing.

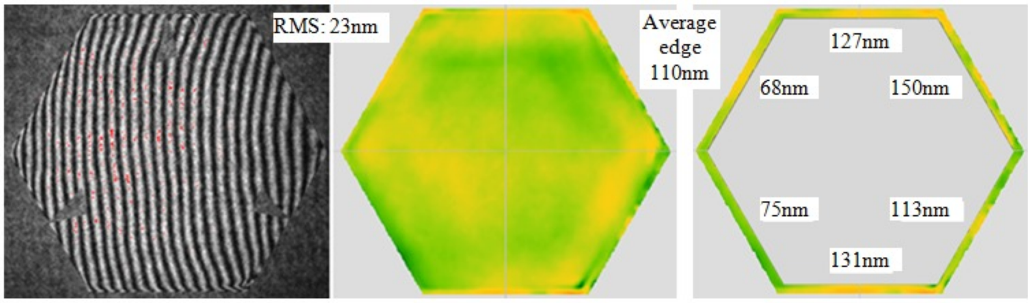

Figure 6. 400mm part after pre- and corrective-polishing and pitch process. Edge numbers are PVq (95%).

5. SURFACE SMOOTHNESS

The above results have demonstrated that the combination of bonnet and pitch polishing deployed on the Zeeko IRP1200 machine at OpTIC can control surface smoothness as well as edge-profiles. This methodology has been deployed at OpTIC to manufacture a 1.45m across-corners Zerodur concave spherical mirror, using the new Zeeko IRP1600 machine. The part is of 84m radius of curvature, matching the base-radius of the prototype segments. The Zeeko machine is located directly under a Test Tower for full-aperture measurement (Figure 7). This has both advantages and disadvantages, summarized below, although the final tradeoff between on and off machine testing is yet to be conducted.

- Handling of segments and danger of accidental damage is minimized, as segments can be tested in-situ on the Zeeko machine's turntable ('C axis').
- More rapid testing turnaround times, with the minimum need for realignment of the test
- Some heat-injection from the polishing machine into the Test Tower, requiring thermal management
- In production, a single test tower could potentially service multiple machines

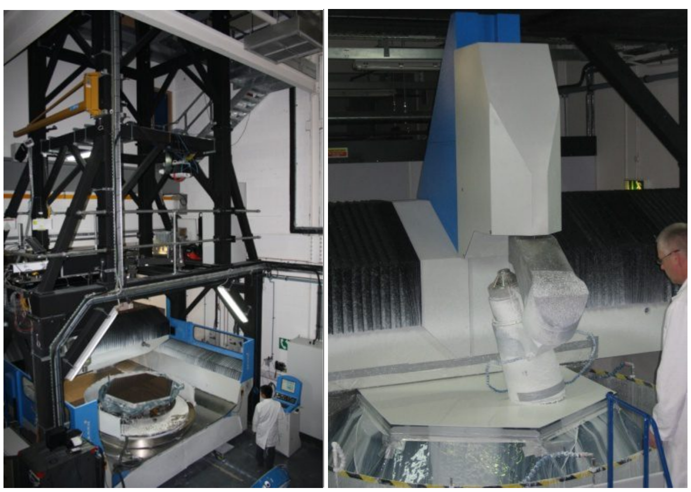

Figure 7. Zeeko IRP1600 machine under Test Tower at OpTIC.

The final results for the clear-aperture of the 1.45m across-corners, R=84m spherical part are shown in Figure 8 and Table 1, demonstrating surface-smoothness. The radial features are artefacts from diffraction in the test configuration.

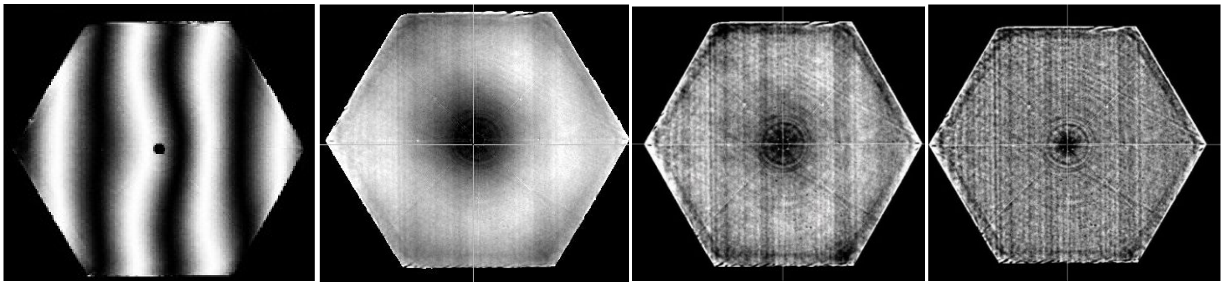

Figure 8. a) Interferogram b) Phase map c) spatial scales <250mm d) spatial scales < 100nm

Table 1. Results for 1.45m across-corners spherical mirror.

	RMS error
Overall surface, useful area	16.8nm +/- 2nm
Surface error for spatial scales <250nm	5.5nm
Surface error for spatial scales <100nm	4.2nm

6. CONCLUSION

For the first time, we have demonstrated a method for segment fabrication that allows all process-steps on the optical surface to be conducted with the blank in its final hexagonal shape, and after all machining operations have been completed. The single caveat is that only half of the specified 1.0mm bevel is applied after grinding the off-axis asphere and before polishing. The final 0.5mm of bevel is applied after all other process-steps have been completed to specification, providing a contingency for any roll of the extreme edge in polishing.

The process chain uses a combination of ultra-precision aspheric grinding on the Cranfield BoX^{TM} grinder, with bonnet and pitch polishing on the Zeeko machine. We have also introduced the option of C9 grolishing, to speed the removal of mid-spatial frequency features originating in the grinding process, and pointed out the potential contamination issue.

We have reviewed the ESO specification for the prototype segments, and demonstrated control of edges on 400mm witness hexagons that is extremely close to, but not quite meeting, our interpretation of the specification. We have also described results polishing a 1.45m hexagonal spherical part with R=84m using the bonnet/pitch process, and demonstrated excellent control of the mid spatial frequency content.

In the next phase of the work, we are developing a fine edge-rectification method that will be constrained to the edge-zone of the segment. In parallel, we are developing R400-class bonnets, which will be inserted before the R200 process, speeding the pre-polish phase. Meanwhile, prototype aspheric segment fabrication is in progress and will be separately reported.

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