Fast manufacturing of E-ELT mirror segments using CNC polishing

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ABSTRACT

We report on the first-ever demonstration of grinding and polishing full-size, off-axis aspheric, mirror segments as prototypes for an extremely large telescope, processed entirely in the final hexagonal shape. We first describe the overall strategy for controlling form and mid spatial frequencies, at levels in the vicinity of <10nm RMS surface. This relies first on direct CNC grinding of the base-form of these 1.4m segments, using the Cranfield BoX™ machine. The segments are then mounted on a custom designed (Optic Glyndwr Optoelectronic Engineering Group) three segment hydraulic support, and CNC polished on a Zeeko IRP 1600 machine using a variety of custom tooling. We overview the full-aperture and sub-aperture metrology techniques used to close the process-loop and certify quality, all of which operate with the segment in-situ on the IRP1600. We then focus on the pristine edge-definition achieved by the combination of tool-lift and smoothing operations; results never previously demonstrated on full-size pre-cut hexagonal segments. Finally, the paper discusses the feasibility of scaling the process to deliver 931 segments in seven years, as required for the E-ELT project.

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

1. INTRODUCTION

This paper describes the first-ever demonstration manufacturing prototype, full-size, off-axis aspheric, mirror segments for extremely large telescopes, processed entirely in the final hexagonal shape. We focus on the development of CNC polishing using a Zeeko IRP1600 machine, and a range of in-situ metrology to close the process-loop and certify quality. We present results on control of form and mid spatial frequencies, and focus on the unprecedented ability to control edges on large hexagonal segments. Finally we consider up-scaling for segment serial-production for the E-ELT construction-phase.

2. DEFINING THE PROBLEM:- THE E-ELT PROTOTYPE SEGMENT SPECIFICATION

The ESO E-ELT was originally configured as a 42m aperture f/1 telescope [1], and the project described in this paper is in this context. The manufacturing specification [2] issued for the segments was groundbreaking in the enormity of the task of producing a diffraction-limited segmented primary mirror. The challenge can be broken down into four principal areas:- *Metrology*, *Optical Polishing*, *Segment Support System* and *Speed/Scalability* for serial manufacture. Each of these areas has required an extensive development program in order to meet both the extremely tight tolerance demands and the high volume requirement. This paper outlines these challenges independently, but is primarily aimed at presenting the combined results of these areas during process development, and to discuss the challenges ahead for serial manufacture.

The overall challenge comprises the tight surface-tolerances, combined with the high volume manufacture required to satisfy the ESO E-ELT build schedule. Optic Glyndwr and partners have been working towards a manufacturing process that can deliver the accuracy, quality and volume required. Process repeatability and scalability are thus key issues.

Other goals that arise in a mass-production environment are as follows:-

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1. Minimizing handling of segments, reducing reject-rate due to accidental damage
2. Maintaining the integrity of the relationship between the coordinate-frames of the segment-surface, metrology data and CNC polishing machine, as is essential for deterministic corrective processes
3. Minimizing manual interventions and operations on segments
4. Achieving a streamlined process flow
5. Providing a capability for segment re-work after accidental damage

The above point towards conducting as many process-steps as possible on segments pre-cut hexagonal, and testing segments in-situ on the polishing machine. In contrast, the current state-of-the-art is to grind and polish oversize round blanks to the aspheric form, cut hexagonal (thereby introducing distortions due to redistribution of the stress-field), and finish using ion-figuring. This process-route has been driven primarily by the perceived impracticality of directly polishing hexagons, whilst retaining sharp edges that are not turned-down.

3. THE TECHNICAL APPROACH ADOPTED

As previously reported, we have been working on the alternative strategy, in which all process-steps from grinding the base asphere, through to final polishing and figuring, are indeed conducted on hexagons pre-cut to the final shape. This pre-supposes that effective edge-polishing can be attained. Combined with the use of on-machine metrology throughout corrective polishing, it is then possible to achieve a streamlined production process.

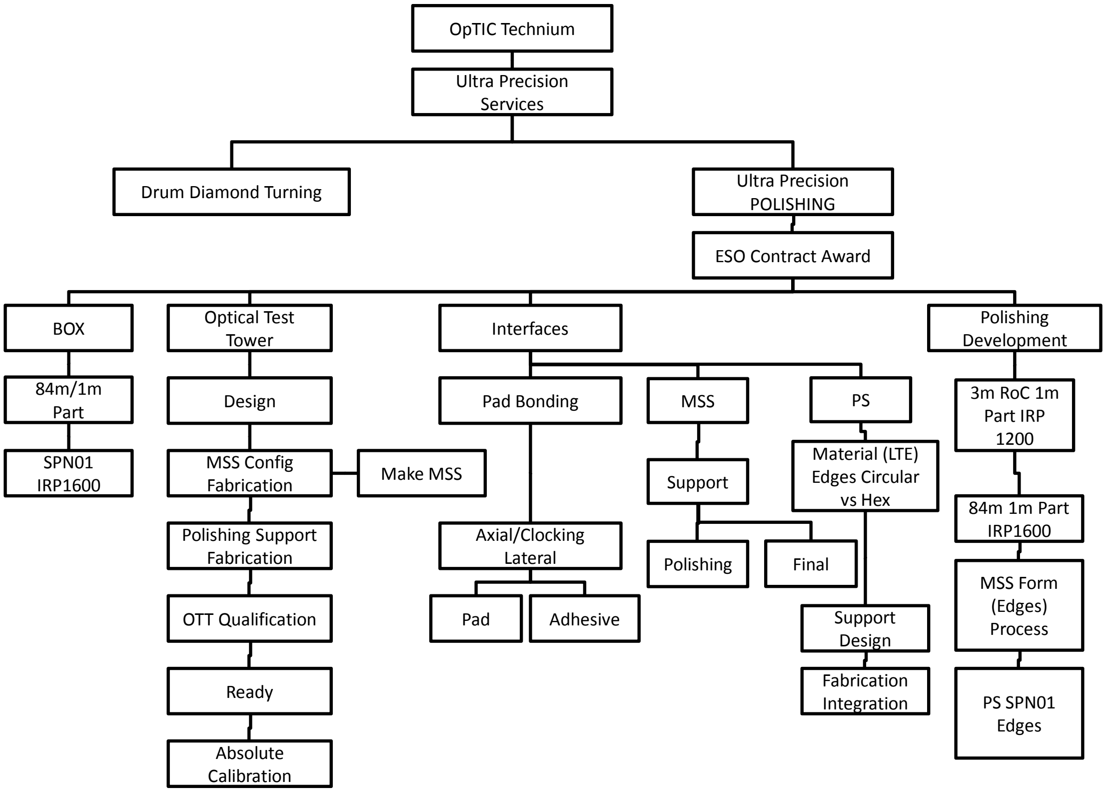
The technical challenge of the prototype segment contract awarded by ESO was approached in three parallel areas:- the requirements for engineering infrastructure, metrology and polishing. An outline of the key milestones is shown below.

Concerning infrastructure, the project has utilized existing 600mm and 1.2m Zeeko CNC machines for R&D, together with associated metrology equipment. As regards full-size segments, the project started with a building-shell at OpTIC-Glyndwr. Major construction work was then required both to pile the floor to carry the required load, and to extend the roof to accommodate a 10m high Optical Test Tower (OTT). The first IRP1600 (1.6m capacity) CNC polishing machine was designed and built by Zeeko for the project, installed in the OpTIC building, and the OTT Designed at OpTIC-Glyndwr was then assembled around it. Auxiliary metrology instrumentation implemented for the project comprises a 4D vibration-insensitive white-light interferometer for texture-measurement, a stitching sub-aperture interferometer, and a scanning profilometer (see Sect. 5.3), all mountable on the IPR1600 for in-situ metrology of segments.

The proposed process chain starts with ultra-precision CNC hard-grinding the off-axis aspheric form directly into the hexagonal segment [3,4]. Cranfield University upgraded their BoX machine from 1m to 1.5m capacity for this purpose. Grinding is followed by dimensional metrology using a coordinate measuring machine. The rear mounting pads are then cemented to the segment, which is then integrated with its polishing support system.

The basic polishing process adopted is the Zeeko bonnet-based process [5], implemented on the IRP1600. In this process, a rotating, precessing, compliant spherical tool (the ‘bonnet’) is traversed over the surface of the part in a raster pattern. By progressively changing the “Z-offset” (linear distance by which the bonnet is compressed), the spot-size of the influence function can be modified continuously – in particular, spot-size can be progressively reduced as the edge is approached. This type of tooling is complemented by pole-down rotating pitch tools, which also operate on the Zeeko machine. The machine is located under a full-aperture test tower for on-machine metrology, and supplemented by on-machine white-light texture interferometry and sub-aperture stitching interferometry. Zeeko-process is usually divided into two regimes:- *Pre-polish* which removes sub-surface and surface damage, and *Corrective Polish* which achieves the form specification.

The amount of sub-surface damage tends to set the minimum depth of pre-polish, and ultra-precision grinding can constrain this to <10 microns [6]. It is possible to interpose one of a family of intermediate fast smoothing processes (termed “grolishing”) [7] between grinding and polishing to accelerate total process speed. These processes may use bound or free abrasives such as diamond or C9/C12. This method has not been deployed in the work reported due to concerns of contamination of the IRP1600. A grolishing option for the future is currently under investigation.



Flow chart outlining the main areas of process development activity

4. RESULTS ON SUB-SCALE SAMPLES

Extensive trials to optimize the polishing process have been conducted on sub-scale parts (200mm to 1m across corners hexagons). The optimum polishing process comprises use of the maximum pseudo-Gaussian polishing spot, to remove rapidly the surface-roughness, sub-surface damage and form errors from grinding. The philosophy adopted is to focus on the segment's main useful area, avoiding a down-turn anywhere, and always maintaining an up-stand within the specified 10mm wide edge-zone. Subsequent smaller-spot polishing then serves to correct the remaining form error and edge-upstand. The up-stand is finally removed with a rigid tool constrained in size by aspheric mis-fit [8]. In order to achieve this goal, independent work on modeling, and experiments on witness-parts, have been conducted.

To model the tool's performance accurately in the edge zone of the part, a series of influence functions (IFs) have been generated specifically in that area. These IFs augment the ones acquired in the bulk area, to give a better representation of the polishing process over the whole area (including the edges) of the part. Simulation software, capable of predicting the edge profile has been developed in MATLAB. The empirical Influence Functions, both on the part and overlapping the edge, are interpolated, scaled according to the dwell-times, and summed for each pixel over the part.

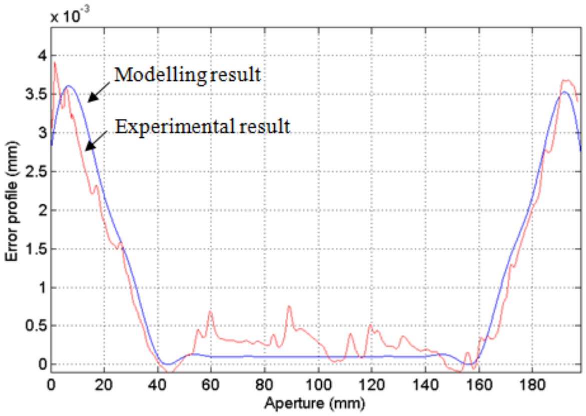


Figure 1 Modeling and experimental results of tool lift

The aim of the modeling was to achieve the targeted material removal, whilst keeping the slopes of the error in the edge-zone sufficiently small so that they can be measured using an interferometer. At each position in the edge zone, the slope of the error has been kept under the limit that the interferometer can resolve, by adjusting the tool offsets and the local dwell time. This model has been verified by an experiment on a 200mm across corners, hexagonal Zerodur part, polished with an R160mm bonnet tool and 45 mm spot size. A comparison is shown in Figure 1 after correction for base-radius and volumetric removal rate. It can be seen that the modeling and experimental results show reasonable agreement, providing a useful tool for further work. More details can be found in [9]

In order to demonstrate a scalable process-chain that can be transferred to real-sized ESO segments and to accelerate R&D, sub-scale samples of borosilicate hexagonal-shaped glass with corner-to-corner size of 400 mm have been used. A summary of these results is reproduced from [10] as Figure 2 below, to facilitate comparison with full-size segment results in Figures 11 and 12. The surface form was spherical with ROC of 3 meters, which has been adopted as a standard setup for on-machine metrology using the 3m test tower directly above the IRP1200 machine. In this process, an R200 bonnet was deployed, delivering a 55mm spot size. This was used in pre-polish to achieve a higher removal rate than an R160 bonnet previously used. An R80 bonnet and 20mm spot size were then used to correct form. Finally, the entire surface was polished by a pitch tool on the Zeeko machine.

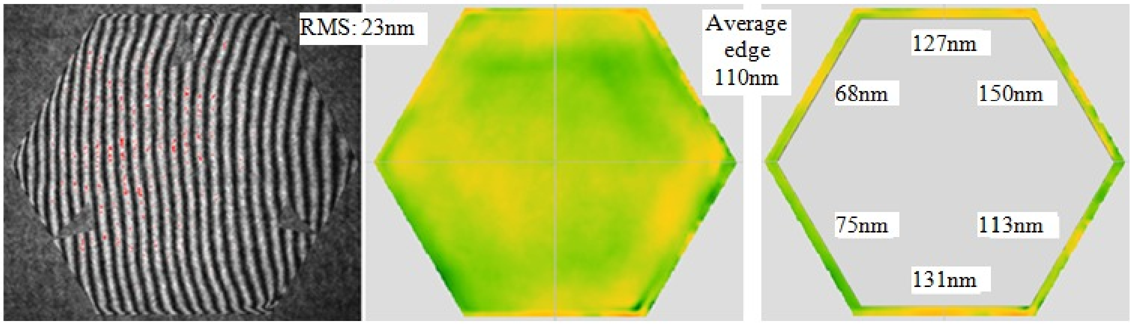


Figure 2 Final results on the 400mm across corners part: fringes (left), phase map (centre) and PVq (95%) edges (right)

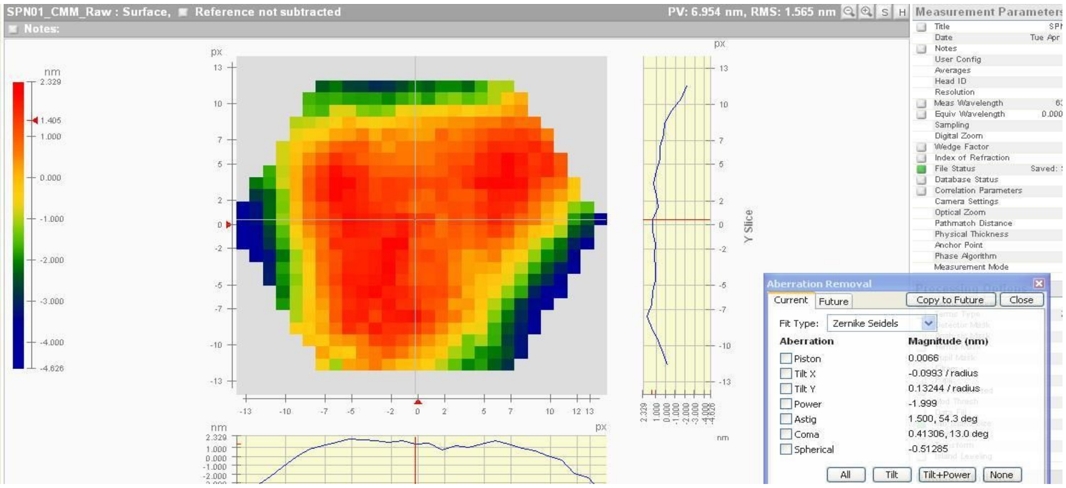
5. EXPERIENCE AND RESULTS PROCESSING FULL-SIZE SEGMENTS

5.1 SPN01

The first full scale segment polished was SPN01 which corresponds to a segment at the edge of the original 42m aperture E-ELT primary mirror, with a base-radius of 84m. This segment therefore provided a test-case having the largest aspheric departure from its nearest-fit sphere of any segment. The Zerodur blank was delivered by Schott cut to the final hexagonal form, and with the rear recess milled in to accommodate the lateral support system.

5.1.1 SPN01 Generating the asphere on the full-size segment

At Cranfield University, the segment was mounted rear-downwards on a flat diamond-turned aluminum platen. It was then precision-ground to the ESO-specified off-axis aspheric form, using their BoX^{TM} CNC grinding machine. The surface form error reported by Cranfield was 6.5um PV. This was established by measurement using their CMM, sampling on a 50mm rectilinear grid (see Figure 3).



SPN01_CMM_Raw : Surface, Reference not subtracted

PV: 6.954 nm, RMS: 1.565 nm

Aberration Removal

Fit Type: Zernike Seidels

Aberration	Magnitude (nm)
☐ Piston	0.0066
☐ Tilt X	-0.0993 / radius
☐ Tilt Y	0.13244 / radius
☐ Power	-1.999
☐ Astig	1.500, 54.3 deg
☐ Coma	0.41306, 13.0 deg
☐ Spherical	-0.51285

Figure 3 CMM map of grinding errors achieved on SPN01(courtesy Cranfield University)

5.1.2 SPN01 Pre-polish

The segment was transferred to the National Facility for Ultra Precision Surfaces at OpTIC-Glyndŵr in North Wales, and integrated with the custom-designed hydrostatic axial support system and lateral support system. The axial system was configured with 27 supports, conforming to the E-ELT specified support locations. The supported segment was mounted on the IRP1600 machine under the 10m high Optical Test Tower (OTT), and clocked for lateral position. The surface was then probed with the polishing bonnet using the standard Zeeko function to define the segment surface location in machine coordinates.

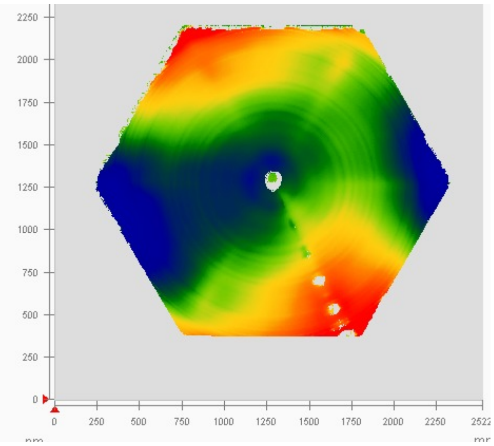


Figure 4 SPN01 full-aperture interferometry after pre-polishing

The purposes of the pre-polishing phase were i) to remove the regular circular grinding marks ("cusps") from the ground surface, ii) to remove sub-surface damage, iii) to deliver a specular surface amenable to interferometry, and iv) whilst minimizing degradation of the form delivered by grinding.

Pre-polishing was performed using a bonnet tool, with the tool-path programmed for uniform stock removal. The result of the pre-polish is shown above in Figure 4. Note that the OTT could not resolve the edge data fully, due to high local slope errors. The small circular features along a radius are not on the surface – they are secondary orders from the CGH that provides the null function in the test. There were also a number of rings on the surface created by the grinding process. These, although pronounced at the pre-polish stage, were subsequently removed by the correction process.

5.1.3 SPN01 Iterative correction phase

The method used for segment form correction is an iterative process using data obtained from the Optical Test Tower via null optics, 4D interferometer and 4Sight software. Absolute determination of the segment surface was performed by measuring differentially with respect to the 1.5m hexagonal Master Spherical Segment. This 150mm thick master had previously been calibrated using rotations and shears, to decouple surface errors from measurement errors.

In addition, confirmatory *direct* measurements of absolute base radius have been performed using a scanning non-contact profilometer, based on the penta-prism/autocollimator principle. This was developed at OpTIC-Glyndwr, and can be used either on the bench, or deployed on the IRP1600 machine for in-situ measurement.

The computed SPN01 error map was then input to the Zeeko^{TM} Tool Path Generator (TPG) software, which creates a feedrate-moderated correction tool path for the IRP1600 polishing machine. The tool-lift (variable spot size) algorithms were used for managing the segment edges to ensure that they were always turned up and by a minimum extent.

The error map then had the ESO Zernike removal-allowances applied to the bulk area (10mm inbound from the edge). The ESO Zernike removal-allowances are shown in Table 1 below. These reflect the efficiency of the correction by the telescope optics systems or by active deformation of the prototype segments under test. Applying these allowances produced the current result of 18.1nm RMS for SPN01, as shown in Figure 7 below.

Z3	85%
Z4 and Z5	95%
Z8 and Z9	85%

Table 1 Zernike allowances taken from the ESO prototype segment specification document [2]

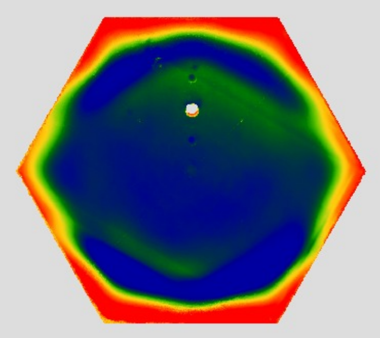


Figure 5 Corrective process mid-way through. Note the full aperture is visible, edges turned-up, and total surface error is 1.757µm RMS

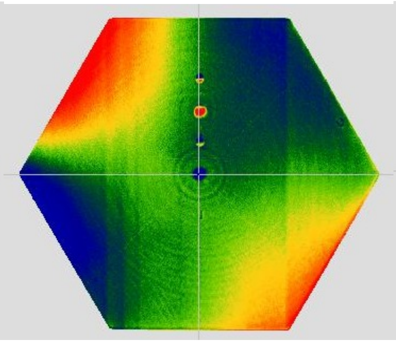


Figure 6 SPN01 – 55.1nm RMS Measured result prior to removal of Zernike allowances

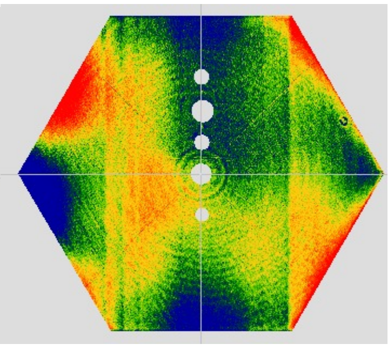


Figure 7 Current result on SPN01 of 18.1nm RMS after removing Zernike allowances

5.1.4 SPN01Convergence

The process-convergence through the equipment commissioning phase, process development and subsequent polishing, is shown in Figure 8 below. Two zones can be identified. Runs before 26 correspond to early machine/OTT de-bugging and process development. The three key "big issues" identified in this phase were as follows:-

1. Achieving rigorous and consistent mapping of the coordinate frames of measurement data, segment surface, and CNC polishing machine.
2. Maintaining a consistent specific gravity of the re-circulated cerium oxide polishing slurry, and avoiding settlement on the part or elsewhere. This required re-engineering of the slurry system to increase flow-rate and optimize both delivery and collection.
3. Hysteresis in the hydrostatic support system, caused by contamination with solidified slurry. Slurry-ingress has been a consistent issue despite numerous revisions of the design. Only very recently have we implemented a properly engineered slurry barrier system, manufactured by rapid prototyping techniques, and in which we now have some confidence.

A convergent process is evident post Run 26. Continuing issues were experienced with the control of astigmatism due to hysteretic behavior of both the OTT and the segment support system. These were controlled and managed at a 100nm Pv level for OTT, and 50nm Pv for segment support, the latter via repeated actuations of the support and statistical management of the data. As the quality of the surface and data improved, it became viable to re-calibrate the measurement of absolute base-radius, and this is the origin of the sudden apparent increase in form error.

The segment polishing process was halted at an RMS figure of 18.1nm. This was due to the impractical measurement times needed to collect sufficient data for a statistical uncertainty-of-measurement to support further convergence. To progress SPN01 any further required improvements to the OTT. The next segment SPN04 was therefore mounted on the machine and its coarser polishing phases started, whilst the issues were studied and improvements made. The OTT was consequently instrumented with temperature sensors and data-logging, and inspected with an IR camera. Semi-permeable shrouding was installed alongside other improvements, which enhanced the data statistics significantly.

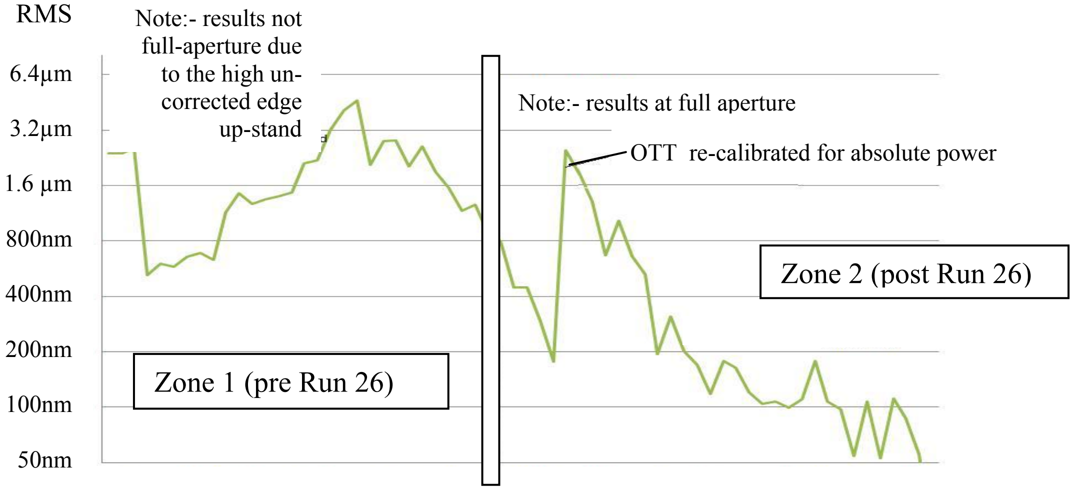


Figure 8 Outline of SPN01 surface convergence, including absolute power

5.2 The second segment SPN04

SPN04 was ground to the off-axis aspheric form as per SPN01, and then pad-bonding and mounting on the hydrostatic polishing support performed. The initial expectation of the surface form-error from grinding was ~ 10um PV, once integrated with the segment support. This was in line with experience gained from SPN01. However, the form of the segment post-grinding, and after segment support integration was > 40um PV. This fourfold degradation in input-quality to polishing was outside the scope of prior process development. It therefore presented a challenging test of the ability of the developed polishing process both to converge and maintain edge quality.

5.2.1 SPN04 Processing

Using the process knowledge gained from SPN01 an *a-priori* estimated convergence target was produced for SPN04 processing. The actual convergence was then plotted against this prediction in order to monitor process convergence (Figure 11).

Figure 9 below shows the result after pre-polish. Note that the full aperture is immediately in the view of the optical test, and the mid-spatial grinding structure is removed sufficiently to allow full aperture imaging of the segment. This was achieved after just six hours polishing. Figure 10 shows the current condition of SPN04

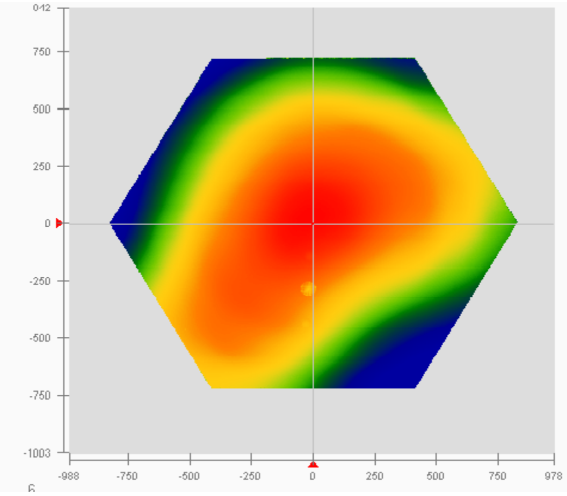


Figure 9 SPN04 post pre-polish result
6343nm RMS (no Zernike allowances)

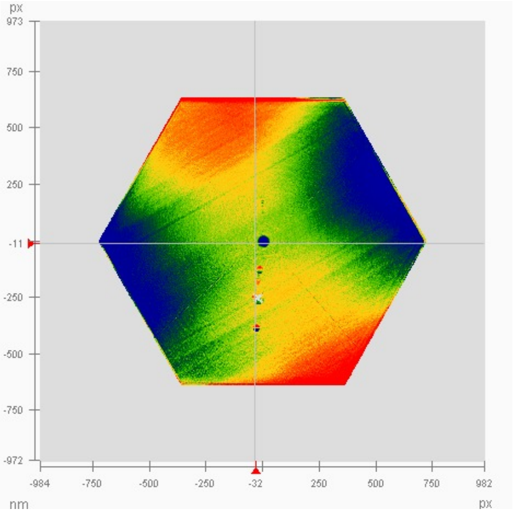


Figure 10 SPN04 current status post Run set 12
83.9nm RMS (no Zernike allowances)

5.2.2 SPN04 Edge-control

One of the unique features of the process developed is the ability to maintain the form accuracy to the very edge of the segment, whilst removing tens of microns of stock. This offers a number of advantages in serial manufacture such as i) the ability to work the cut segments to final form, ii) capability for segment re-work after accidental damage, and iii) speed and quality of the input to any Ion Beam Figuring (IBF) finishing pass after mounting on the telescope support system. In regard to the last, form can be taken closer to the finished requirement reducing the number of IBF iterations.

The mechanism for controlling the edges was discussed previously in section 3 but in brief involves the control of the polishing spot size on the Zeeko IRP1600 machine in order to purposely create an up-stand around the edge of the part. This is then removed using a secondary pitch polishing process on the same machine. This secondary process also has the advantage of removing the mid-spatial structure created by the small spot process leaving a “smoothed” surface.

The edge control results are demonstrated in Figures 11, 12 below via both test-plate and Form Talysurf Intra results respectively. These clearly demonstrate controlled polishing to the chamfer edge. This has been maintained throughout the full 40um plus correction polish which demonstrates the process to be both repeatable and robust.

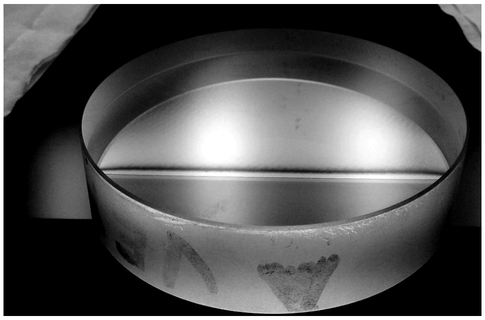


Figure 11a Test plate result showing induced edge up-stand

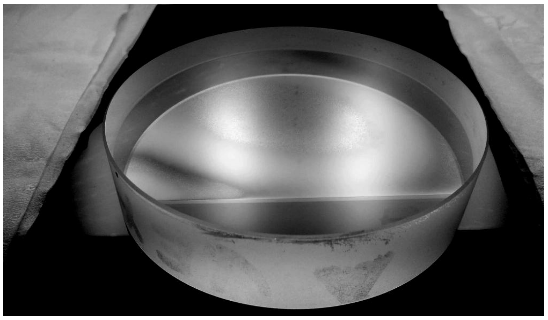


Figure 11b Test plate result with induced edge up-stand removed

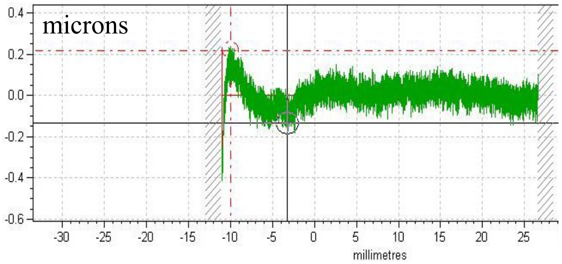


Figure 12a FTS Ultra profilometer result showing ~0.3um induced edge up-stand over 10mm edge region.

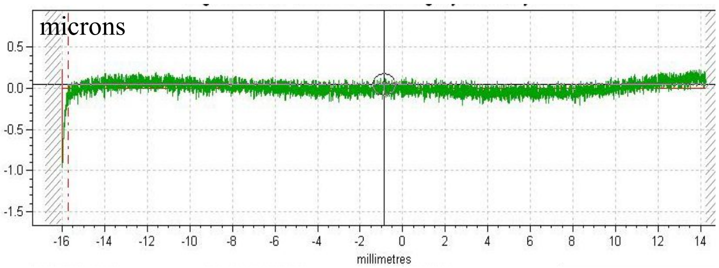


Figure 12b FTS Ultra profilometer result showing continuous edge form

5.3 Comparison of convergence for SPN01 and SPN04

Figure 13 compares SPN01 convergence with the achieved convergence on SPN04, alongside the prediction from the experience of SPN01.

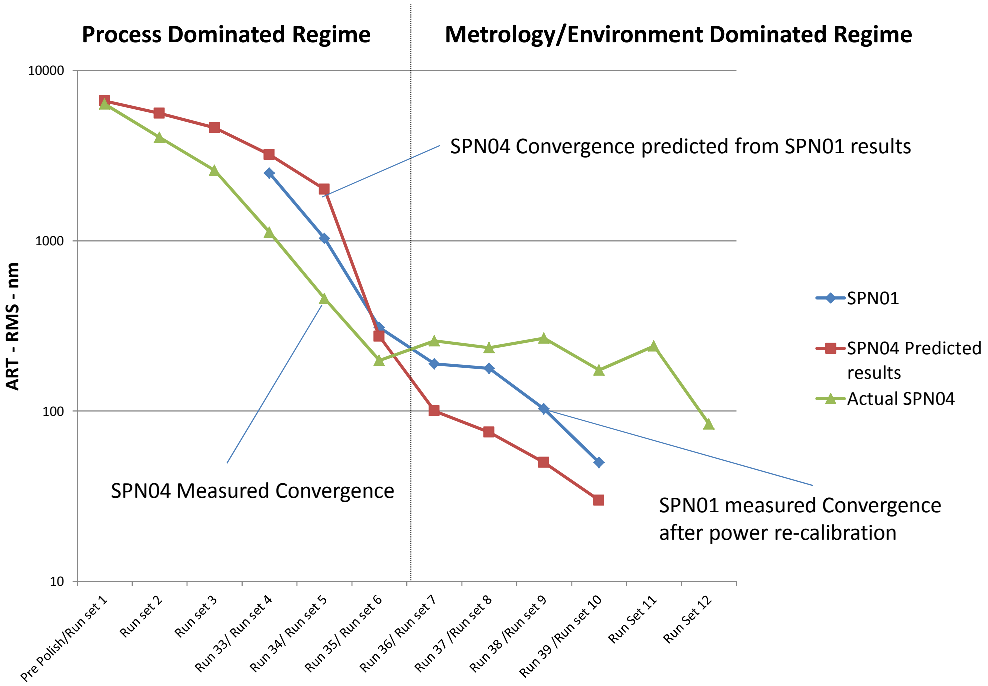


Figure 13 Convergence SPN04 in comparison with SPN01

Note the convergence results on SPN04 shown in Figure 13 above show a stall in the process convergence between Runs 6 and 10. This correlates with three events all affecting our ability to converge.

1. The segment support was found to be exhibiting hysteresis which was causing astigmatic effects of the order of 200-300nm. The cause of this was found to be slurry ingress from leaking waterproofing during the polishing process. This was discovered post run 6 (153nm RMS result) and the segment was subsequently removed from the support and the support system was cleaned down and overhauled. Once the segment was re-integrated with the support the effects of the hysteretic behavior were clear and the RMS error of the segment was set back to 382nm RMS.
2. Following the segment support issue the convergent process began again until, following an IT network issue, an incorrect surface correction file was used for correction 8.1. As a result, convergence was compromised as the form regressed to 496nm RMS. Once the data issue was understood and rectified, convergence resumed.
3. The third issue, and the one which has caused the most sustained challenge for convergence, was caused by the weather. For the geographical location of the building in N. Wales, at a latitude >53°N, the summer period has been unusually hot (in excess of 30°C), and with strong diurnal variations. This condition has been consistently beyond the design-capabilities of either the building insulation or the active environmental control of the lab. This effect has led to temperature-variations both top-to-bottom and front-to-back of the OTT by up to 2°C (c.f. a calculated requirement of 0.5°C). This temperature variation has impacted both the stability of the air-path in the OTT, and the geometric relationships of the segment and auxiliary optics. This has particularly disturbed our ability to measure astigmatism and, to a lesser extent, absolute power. Air-path effects have been managed by improving shrouding, the use of fans to stir the air and minimize systematic effects, and then the acquisition of many hundreds of frames with the 4D simultaneous phase interferometer.

Following Run 10, the weather pattern has returned to more normal conditions for the site, and convergence has been re-established.

The three issues raised above all contribute to the stalled progress of SPN04 and we are now confident that convergent process is re-established. The main lesson drawn from this experience is that at the sub 100nm RMS level <u>all</u> factors need to be balanced and monitored at all times. The balancing of environmental and mechanical interfaces is crucial to success.

6. CONCLUSIONS AND FUTURE PLANS

6.1 Experience to date

The project has been ambitious in starting with an empty shell of a building, requiring major construction work to fit it out, plus designing, building, installing and commissioning the first 1.6m Zeeko machine and Optical Test Tower. The auxiliary measurement equipment, data and process-monitoring systems etc. have been developed in parallel.

In terms of fabricating full-size segments, the project team has achieved significant technical advances, principally:-

1. Deployment of the aspheric process to polish the MSS to 18.6nm RMS with a smooth surface ~ 4-5nm RMS for mid spatial frequencies
2. Certified full-aperture optical test that has characterized the MSS with an uncertainty of 4nm RMS
3. Full aperture optical test for measuring the aspheric form of the aspheric segments, including a differential measurement of base-radius with respect to the MSS. Certified and accepted by ESO to the final ESO E-ELT prototype optical specification.
4. A scanning pentaprism/autocollimator profilometer for bench or on-machine measurement, demonstrated to meet the ESO requirements for independent measurement of the 84m base-radius to accuracy of 10mm.
5. A predictable, scalable, convergent polishing process capable of directly polishing hexagonal components to the very edge of the component, even with >40 microns input form-errors, and within the levels required by the ESO E-ELT project.

After de-bugging the facility, software and processes, the main challenges that have led to schedule-slippage are i) hysteresis in the support system due to slurry-ingress, and ii) control of the thermal environment of the OTT. This last has been amplified by unseasonably hot and varying temperatures at a critical point in the project.

6.2 Production planning

Part of the contractual obligation of Glyndŵr University, following the processing of prototype segments, is to provide a bid for the volume segment manufacture for the E-ELT primary mirror. The demand for segments for this telescope is greater in both quantity and technical specification than any previous telescope, and makes the transition from small-volume prototype-manufacture to mass-production.

The advantage of the process-chain reported in this paper is that is ideally-suited to a production-line environment. The most risky operation (cutting hexagonal) is performed before significant value is added to the blank. After cementing the radial and axial pads to the blank, no manual interventions are subsequently required. Handling the blanks is clearly amenable to automation, as are setup processes such as centering and leveling segments, calibration and analysis of OTT metrology data, computation of CNC tool-paths, and deployment of auxiliary metrology instrumentation. The keys to optimizing process convergence (and so reducing cost) then lie in improving slurry-management, protecting the support-system from contamination, and enhancing environmental control of the full-aperture optical test. These are engineering challenges we are sure will be overcome – we are confident that the process itself is both sound and fit for purpose.

A major advantage of the developed process is that it is a scalable CNC technique which offers volume manufacture options where operator training requirements are reduced to production process level. This in turn facilitates manufacture on the scale demanded by the ESO E-ELT telescope project.

In a European context, it is not impossible that the segment manufacturing might be distributed over more than one site (either by dividing the total work-package, or dividing process-steps). We have demonstrated a palate of process-steps and metrology techniques which would give considerable flexibility in such a case.

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