INTERACTIONS BETWEEN MANUFACTURE AND MEASUREMENT OF OFF-AXIS ASPHERES

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INTRODUCTIO

In this paper we reflect on our experience at the National Facility for Ultra Precision Surfaces in North Wales, manufacturing 1.4 m hexagonal, off-axis mirror segments, as prototypes for the European Extremely Large Telescope. The telescope optical configuration assumed for the work herein reported, was the original 42 m aperture design [1] (subsequently de-scoped by ESO to 39m).

The prototype E-ELT segments are particula challenging in regard to the long radius of curvature (84 m +/- 200 mm), off-axis aspheric form, edges, and the requirement to *match* segments in terms of base-radius and conic constant. Any surface-error consequent upon mis-match, simply constitutes a term overall error-budget required to meet the form specification (worst segment:- 50 nm RM surface; average segment:- 25 nm RMS surface). The first segment ROC can therefo drift within the stated +/-200 mm tolerance, bu subsequent segments must then match the first one. We discuss how this has been achieved, by directly grinding the base off-axis asphere i the hexagons using the Cranfield University BoX machine [2], and then polishing on a Zeeko CNC machine at the National Facility in North Wales.

We have also identified some interesting parallels between aspheric mis-fit of surface and tool on one side, and effects of dynamic range of an interferometer on the other. The ability to perform corrective processing of grey parts is economically attractive but presents issues for metrology. We also discuss how the requirements for the support system for the part are different for metrology and fabrication, and its resolution.

ASPHERIC MISFIT

Grinding and polishing

The segment process starts with BoX-grinding the off-axis asphere [2], which for the peripheral segments are ~200 µm aspheric with respect to the sphere best-fit to the specific segment. part is then processed using a combination of bonnet-polishing and hard-tool smoothing, both with re-circulated cerium oxide slurry. Aspheric misfit is not an issue for bonnet-polishing, as the bonnet naturally molds around the local asphere.

However, with hard (e.g. pitch) tools, the misfit as the tool traverses over the asphere limits the maximum practical tool-size. This is exacerbated if tool-rotation is used to achieve adequat removal-rate, because the tool, perforce, mu itself be rotationally-symmetric. The tool is pressed on the part at the start of the raster tool-path, and then misfit increases along the path. We have previously considered misfit quantitatively in some detail [3], and shown that the maximum for a 100 mm diameter rotatin hard tool, traversing over an outer E-ELT segment, is ~800 nm. The corresponding f for a 150 mm tool is ~1.6 µm.

When polishing segments, empirical evidence indicates that a 150 mm pitch tool starts to leave mid-spatial frequency artefacts, whereas a 10 mm one does not. We interpret this as corresponding to the predominantly 1-2 µm particle size of the Cerox Super 1663 ceriu oxide used [4]. We contend that the particles act as a buffer, when particle-size exceeds misfit This has the implication that larger tools could be used, providing that the abrasive particle size is increased in proportion to the misfit. C5 and C9 (μm and 9 μm) aluminium oxide ar obvious candidates.

Interferomet

There are parallels with interferometry, and in particular, our use of a sub-aperture non-nulling interferometer for:-

- measuring regions overlapping edges, at the higher spatial-resolutions needed to resolve details of edge-profiles in process-diagnostics
- infilling missing data in full-aperture nulling interferometry (due to CGH artefacts, and a small central obstruction in the optical test)

Re-focusing a sub-aperture interferometer at given location on the surface of a segment bears similarities to pressing a hard, rotating tool at that location as described above: tool-rotation forces the its profile to be axially-symmetric. Interferometer departure from null is given by the difference between the spherical reference wavefront, and the aspheric test wavefront, as the interferometer tracks across the surface. The limiting factor is then the *slope* of the misfit over the sub-aperture, due to finite pixel-samplin optical transfer and phase ambiguities.

We conduct stitching interferometry in-situ on the 1600 Zeeko machine. This uses a dioptric beam-expander with a clear aperture of 180 mm, feeding a 4D Technologies 6000 compact simultaneous-phase interferometer (995x100 pixels). There are 700x700 pixels across the 180 mm pupil, so one pixel projects to 257 μm x 257 μm on the segment surface. Phase ambiguity occurs if there is ≥1λ OPD between adjacent pixels, i.e. ≥ ~ 316nm height variation over a lateral 257μ on the surface. Theoretically, a pure tilt term of 221μ PV over the 180mm pupil would therefore correspond to the onset of phase-ambiguity. In practice, we find that the limit is approximately 140 fringes over the 180 mm diameter pupil, corresponding to a surface slope of approximately 246 μ rad.

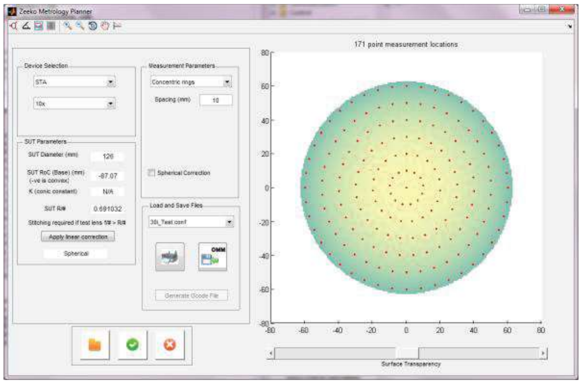
SURFACE TEXTURE AND MEASUREMENT

The ESO E-ELT specification requires a surfa texture of <3 nm Ra (requirement) and <2 n Ra (goal). Owing to the size and weight of th segments, measurement using a standard bench top white light interferometer is impractical. On-machine techniques requiring contact with the polished surface, such as stylus and replication, are deemed too high risk and so avoided.

Texture measurement is carried out using the Surface Texture Analyser (STA1, or 4D NanoCam), provided by 4D Technology, Arizona. This device mounts directly into the tool spigot of the Zeeko IRP machine (FIGURE 1 thereby allowing the CNC system to position and align the device for measurement. The IRP machine range has been developed with sma footprint polishing processes in mind, such as millimeter-scale fluid jet polishing [5]. Thi positional accuracy allows the STA to be positioned at the same surface location following successive processing runs, to observe the effects of polishing on surface texture and sub-surface damage. In testing, it is observed that an on-machine positional repeatability of <9 *μ* be achieved [

FIGURE 1. STA fitted to the IRP1600 tool-chuck, testing a full-size segment.

The use of CNC axes to position the measurement device also provides an opportunity to automate the testing process. Zeeko are completing development software application to allow the definition of a testing regime, in a similar manner to a polishing tool path (FIGURE 2). This measurement plan i then executed by the same application, whi uses feedback from the interferometer automatically to align the device and command measurement. Following some initial set up tasks, user input is not required. Output data is automatically saved and a report produced containing data statistics and an indication of measurement quality.


Zeeko Metrology Planner

Device Selection
STA
10x

Measurement Parameters
Concentric rings
Spacing (mm): 10
☐ Spherical Correction

SUT Parameters
SUT Diameter (mm): 126
SUT RoC (Base) (mm) (-ve is convex): -87.07
K (conic constant): N/A
SUT R#: 0.691032
Stitching required if test lens f/# > R#
Spherical

Load and Save Files
38i_Test.conf

FIGURE 2. Example STA measurement plan created using Zeeko Metrology Control Suite.

FIGURE 3 shows an example measurement the first segment completed by the consortium and certified by ESO. This measurement is typical of texture across the bulk of the surface at 0.93 nm Sa over a ~0.9 mm x 0.9mm area, well within the ESO specification. This measurement was obtained with a 10x objective, providing a pixel size of
has Zernike terms up to and including coma removed. Following smoothing, there is no evidence of pre-polish or sub-surface damage artifacts.

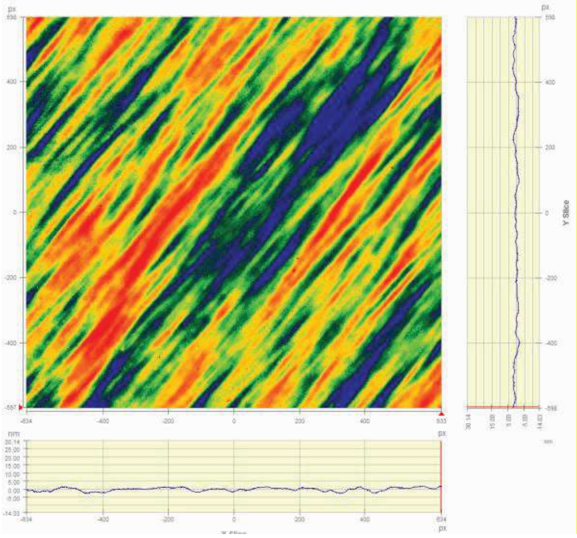


FIGURE 3. ESO E-ELT prototype segment texture measurement. Sa = 1nm after removal of relevant form terms.

Such process automation will prove crucial in meeting production rates f

TRACKING BASE-RADIUS

With monolithic primary mirrors, a small err base-radius is accommodated by re-focusing telescope. For a segmented primary this still applies – but only for the mirror as a whole – hence the +/-200 mm tolerance on base-radius. As mentioned above, the matching of segments is much more challenging, particularly over a production schedule that will span several years, and given thermal drifts in the 10m high Optical Test Tower. Removing the power term from interferometry data is not an option; the segments must be corrective-polishe *absolute* form-data, rather than data *relative* to the nearest-fit sphere.

The only tenable solution of which we are aware is a *transfer standard*. This must both be highly stable, and be smooth, though global form is less critical. We therefore polished an over-size R=84 m Zerodur Master Spherical Segment (MSS) to 18 nm RMS, with 4.2 nm RMS for spatial scales <100 mm RMS and 5.5 nm RMS for spatial scales <250 mm [9]. The blank is 200mm thick (c.f. 50 mm for segments), and s some 64 times stiffer than a segment. This allows mounting on a simple support system, further reducing uncertainties in form.

The MSS is deployed directly over the top of the segment, which is left undisturbed on the IRP1600 machine. Full-aperture segment interferometry is then bracketed with metro of the MSS. The only other difference in the respective test configurations is the exchange of the segment-CGH for another designed for testing the sphere.

SEGMENT SUPPORT SYSTEM ISSUES

Support Requirements

Segment support systems are required to fulfil two purposes:

- Under process forces, to mainta geometric *position* of the segment in the machine CNC coordinate frame, and maintain *distortion* of the segment at a level that does not compromise the surface-figure for the process being used.
- For metrology, maintain distortion of the segment at a level that does not contribute

significant errors to the measurement of the surface-figure at the relevant process-step.

Grinding Su

For grinding the segment using the BoX machine, and subsequent measurement using a coordinate measuring machine (both at Canfield University) the segments were mounted on to a platen made of high grade aluminium, precision diamond-turned flat and parallel [2]. However the rear surfaces of the segments are true and flat at the level of only 100-20 µ PV. Therefore, the support points/areas were ill-defined, leaving potential for i) unquantifiable gravity-induce distortions of the segment and ii) both rocking and distortion under grinding forces. Issue i) above would indicate a surface that is machined true to the design-form (and so verifiable by CMM data acquired with the segment on the same support platen), but the segment material not being in the stress-free state. Effects of ii above should be visible in the CMM data.

The first prototype segment (Zerodur), ground to the off-axis asphere, was measured on its grinding support by CMM. The form was within XX µ PV, giving confidence in the grinding operation. The second segment (ULE) was also ground on the BoX, but CMM data wa unavailable. Therefore, the part was given a rapid pre-polish on the Zeeko machine, just sufficient to glaze the surface for a preliminary interferometric measurement, and this revealed in excess of 40µ PV form error. We suspect that the segment may have rocked in grinding, although it is possible that the Twyman effe contributed to this. Golini and Jacobs [7] have observed in regard to ULE that, "the grinding surface stresses, known as the Twyman effect, increased dramatically in the transition from brittle to ductile mode grinding". In this context, it is notable that the BoX process exhibits aspects of ductile removal.

We have constructed a 1 m prototype hybrid support system, originally intended for polishi (FIGURE 4). This was a hydrostatic system using eighteen Bellofram rolling diaphragms, configured in three sets of six, each of the sets actuated by a separate fluid-disp actuator. Each Bellofram unit incorporated a bespoke 'hydro-expanda ' locking mechanism, so that the part could first float, and then locked in position. Hysteresis in the hydro-expandable locks proved excessive for polishing, but this solution shows considerable promise for grinding, where the tolerances are in the micron rather than nm regime.

FIGURE 4. Original prototype hybrid lockable hydrostatic support system.

Polishing Support

Segments are polished on the Zeeko 1.6 m CNC polishing machine [8], mounted on a standardised support system, and measured in-situ by a variety of techniques:

- Full-aperture nulling interferometry
- Sub-aperture stitching interfer
- White-light texture interferometry
- Non-contact profilometry (autocollimator - pentaprism test)

The requirements on the support system for the metrology which closes the corrective proces loop, are a couple of orders more critical than for grinding. In particular, the support system is required to emulate that which will be used in the telescope, assuming the telescope zenith-pointing. In this configuration, corrective polishing will remove the signatures of gravity deflections where 'seeing' will be best (minimu atmospheric air-path). At other zenith distances, there will be some degradation of performanc

Given this requirement, the segment is supported on a 27-point hydrostatic whiffle-tree (FIGURE 5). The support is based on Bellofram, configured in three sets of nine each set with a separate fluid-displacement actuator. A metal diaphragm-flexure locate rear bore in the segment to provide lateral constraint. The precise locations of these support-interfaces on the rear of a segment, and the detailed interface designs, accord with the ESO specification [1]. Within the limits of residual hysteresis, this ensures that the measured surface-form will truly reflect performance in the telescope, *providing* that additional constraints deployed to resist the lateral components of polishing forces are removed.

The hydrostatic whiffle tree is not suitable for polishing because it is “soft” and the segment can tip/tilt under vertical polishing forces as the hydrostatic fluid re-distributes. The effect of such motion is to disturb the Z-offset of the bonnet polishing process i.e. the bonnet compression against the surface, and so the polishing sp size and volumetric removal rate. For this reason, the fluid-displacement actuators are used to lower the segment onto a separate support for polishing.

FIGURE 5. Dummy full-size segment integrated with polishing/metrology support system.

TIME FOR DATA-ACQUISITION COMPUTATION

The Optical Test Tower provides full-aperture null interferometry of the segment whilst i on the Zeeko machine. A 4D Technologies Phase Cam 5030 interferometer provide simultaneous phase acquisition to freeze vibration. The 10m high air-column is randomised with fans. A typical measurement sequence, when near to final form, will involve acquiring multiple data-sets, each after exercising the hydrostatic support system to average residual hysteresis, and interleaved with data-sets acquired with the MSS inserted to provide re-calibration of the test-tower optics. This can amount to nearly 4,000 data-frames. The total time to acquire, store and process this data is ~3 days, whereas the total accumulated exposure is only a few seconds. Th contributors to this overhead include:-

- CCD readout
- Frame-grabbing
- Disk storage
- Data-frame select/reject
- Data averaging of selected frames (tower thermal constants
- Calibration of the test-tower optica system from MSS data
- Data analysis to create final error

In the context of segment serial production, it is clear that significant investment will be required in at least the following upgrades:-

- Higher-power laser for the simultane phase interferometer
- Fast data acquisition ha
- Improved IT infrastructure for data processing
- Additional software for pipe-lining automating data acquisition and proce
- Improved thermal environment to redu thermal ‘noise’ and so number of data frames requir
- Automated MSS deployment

CONCLUSION

The prototype segment project has demonstrated effectively, for the first time anywhere, an end-to-end process chain operates entirely on segments pre-cut to the final hexagonal shape, *whilst meeting the edge-quality specification.*

The first segment (designated SPN04) was the segment on which much of the process development and diagnostics was conducted. It received formal acceptance from ESO, acceptance tests were witnessed by ESO at the National Facility site in North Wales

The second segment SPN01 has been completed and is awaiting the ESO visit for acceptance tests. The final surface error was measured to be 25nm RMS, and 7.6nm RMS after removing the ESO low-order allowances.

These represent the first prototype E-ELT segments produced anywhere that have achieved surface residuals of this quality.

The third segment SPN03 has been ground to the aspheric form, and is being prepared for the polishing cycles on the IRP1600 machine.

The project has highlighted the complex interactions between manufacture and measurement in several notable aspects. These are accentuated by the need i) to assert *matching* of segments as well as their overal form, and ii) by the base-radius of 84m whic adds complexity to the optical test system, in order to avoid testing over long air-paths. The key issues are summarised below:-

- The interesting parallel between aspheric misfit in polishing and dynamic range in interferome
- The critical effects (particularly approaching the sub-10nm level) of residual support system hysteresis on measurem
- The benefits of conducting metrology entirely on the polishing machine, avoiding disturbance of the part, down-time, and potential accidental damage, when repeatedly removing and replacing the segment at each measurement/polish cycle
- The disadvantage of on-machine metrology, as metrology ties-up machine resource when it could be polishing another segment.
- The need for a stable transfer standard to assert matching of base-radius of multiple segments over the several years duration of the manufacturing life-cycle for full-scale segment manufacture.
- The need to reduce the frequency of MSS calibrations by improving the thermal stability of the test environment
- The impact on total manufacturing time caused by data acquisition and processing overhead.

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