New Results from the *Precessions* Polishing Process Scaled to Larger Sizes

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ABSTRACT

The *Precessions* process uses an inflated membrane-tool that delivers near-Gaussian polishing spots. The tool-motion over the part can be constructed to preserve an aspheric form whilst removing damage from preceding processes, or control the form through a tool-path prescribed by numerical optimization. The process has previously been validated on surfaces up to 200mm diameter and used extensively in industrial environments. In this paper we report the first trials on a substantially larger part – a 500mm diameter f/1 ellipsoidal mirror – as part of the UK's technology-development for Extremely Large Telescopes. We draw attention to subtle problems that have arisen along the way. We also report on developing the process for free-form surfaces, in contrast to the axially-symmetric parts worked hitherto. The paper concludes with an assessment of the lessons learnt from the experiments, as they may impact on realization in a practical ELT segment fabrication facility.

1. Introduction

Various stages in the development of the *Precessions*™ polishing process have been reported elsewhere [1,2,3,4,5,6,7,8]. In summary it is an automated polishing process, based on precise CNC control of the position and orientation of a spinning, inflated, membrane-tool with respect to the part's surface. As the tool is advanced towards the surface, it creates an area of contact – the 'polishing spot' – the diameter of which can be continuously varied. The process uses standard polishing cloths attached to the membrane, together with standard polishing slurries. Therefore, craft experience can easily be accommodated in the CNC process.

The process has two principal modes of operation – 'pre-polishing' and 'form-correction'. The former takes a part from (typically) a high-precision CNC grinding machine. It removes the grinding marks and sub-surface damage, resulting in an optically polished surface preserving the original (typically aspheric) form. In the axially-symmetric case, the tool is spun about its axis pole-down on the surface, and repetitively traverses a diameter of the part as the part is synchronously rotated (i.e. at the same rpm). The combination of W influence function from the spinning pole-down tool, and synchronous rotation, gives a uniform removal across the part including centre. It therefore avoids the commonly-observed tendency to over-cut the central zone when the polishing spot overlaps centre. Case-studies were previously presented [e.g. 4,7]. For non axially-symmetric parts, the tool-path for pre-polishing may be a raster [8].

The second mode of 'form correction' uses the same inflated tool, but with the rotation axis inclined to the local normal and precessed in discrete steps around it. The influence function of the tool, which in this geometry is near-Gaussian, is experimentally characterized for different examples of its continuously-variable spot size. The resulting influence function, and the measured error-profile of the part, provide the principal input to a numerical optimization process. This computes run-parameters for a polishing cycle in order to minimize the residual form-error. In the axially-symmetric case, the optimizer computes the radii of a series of concentric polishing zones, and the dwell-

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time and spot-sizes for each. The machine CNC transforms the result into a spiral tool-path for execution on the machine. In the free-form case, a raster tool-path is typically used instead.

2. The IRP200 and 600 machines

Zeeko machines with 200mm capacity (IRP200 and the identical Zeeko-Loh A_{II}) are in routine production in industry. The machines utilize a horizontal spindle – that is, the axis of the part is horizontal. Typically, these machines are used to polish modest to severely aspheric surfaces in the 50-180mm diameter range, taken off precision grinding machines that leave several microns of form error. The Zeeko machines are used to polish the surfaces then correct form to the level of 0.15 to 0.3 microns peak-to-valley residual error. This will typically require between one and three polishing cycles. The process on these machines has not been optimized further in terms of ultimate form, as the residual errors already achieved meet most customer requirements. Nevertheless, by moderating the removal rate, we believe that the form-error can be reduced to an arbitrary low level, dependent upon the quality of the input metrology.

The 'work-horse' for developing the large optics process has been UCL's 600mm capacity prototype IRP600 machine. This machine is of the opposite configuration to the 200-series, with the part's axis being vertical, and the part supported on a large horizontal turntable. The configuration is more satisfactory for larger parts, as these may require more complex support systems. The configuration also permits on-machine metrology with a vertical path if required.

There is also a variant of the IRP600 – the FJP600 – which uses a fluid-jet polishing process instead of the inflated bonnet described above. This can deliver much smaller Gaussian spots (<1mm diameter), of particular interest in the mould industry where polishing can reach into internal corners etc. However, this technique may also prove useful for correction of localized defects on optical surfaces, and edges in particular.

Figure 1 IRP200 machine

Figure 2 Prototype IRP600 machine

Figure 3 FJP600 Fluid-jet machine

3. Definition of the 500mm Program

GSMT and NOAO have kindly provided us with a 506mm diameter Cervit^{TM} ultra low expansion ceramic blank, 73mm thick, to aid scaling up of the Zeeko technology to larger parts. This size is an ideal stepping-stone from <200mm lenses to the 1-2m class mirrors required for the segments of Extremely Large Telescopes. The part is not perfect, having some inclusions which leave signatures in the surface testing.

The first aim of the Programme was to undertake process-development to understand any differences there might be between the smaller and larger scale processes. As part of this, the goal was to work the 500mm blank into an axially-symmetric aspheric form that is easy to measure. An on-axis ellipsoid of revolution was selected, as it can be tested between its two conjugates with a return-sphere. This will give the future opportunity of re-figuring this into an off-axis ellipsoid of the same base-radius, by a series of polishing/metrology cycles ‘walking the conjugates laterally apart’ i.e. orthogonal to the optical axis.

The on-axis ellipsoid is defined below and in Figure 1:-

Conic constant k	-0.158
Radius of curvature of sphere which oscullates about the vertex	1000.0mm
Distance of inner conjugate from pole of ellipsoid	715.6 ±1 mm
Distance of outer conjugate from pole of ellipsoid	1659.7 ±1 mm
Radius of curvature of best-fit sphere	1002.5 mm
Aspheric departure from sphere which oscullates about vertex	82 µm
Aspheric departure from best-fit sphere	20µm

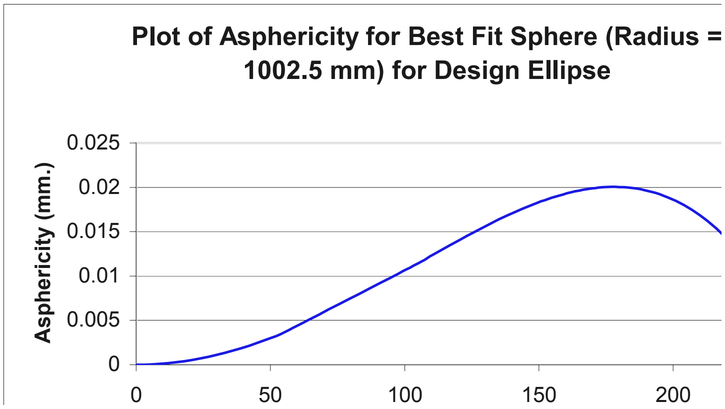


Figure 4 500mm diameter part: design aspheric-departure from the nearest-fit sphere

For optical testing, the mirror is aligned with the outer conjugate coincident with the focus of the interferometer’s transmission sphere, and the inner conjugate coincides with the concave return sphere, or a spherical ball, as shown. Certified metering rods produced by Taylor Hobson are used to establish the correct separations. Three Wyko interferometers are available at UCL – the IR3 form-interferometer operating at 10.6 µm wavelength, the 6000 form interferometer working at the 632.8nm HeNe wavelength, and the in-situ RST500 texture interferometer.

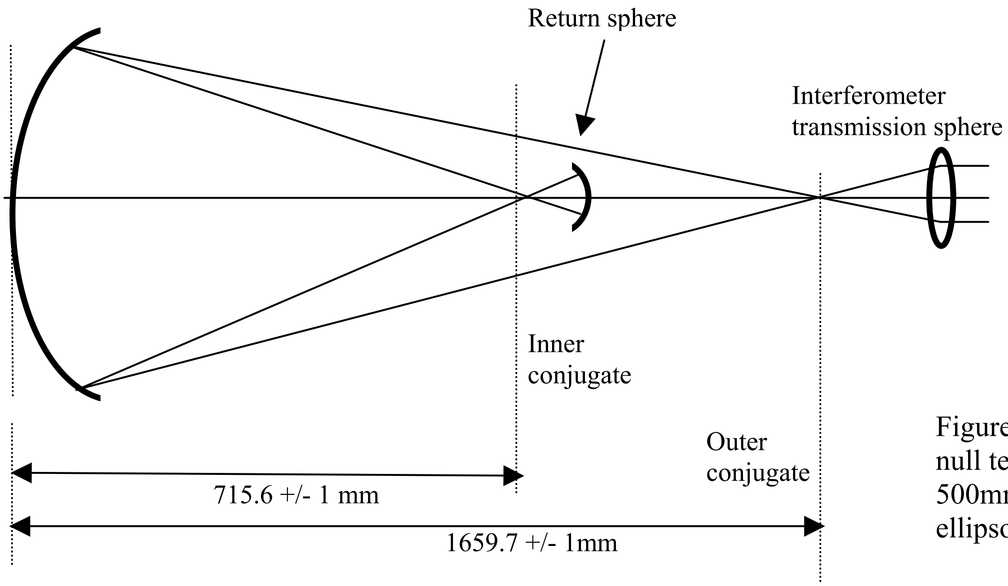


Figure 5 Optical null test for 500mm diameter ellipsoid mirror

4. Grinding the Mirror

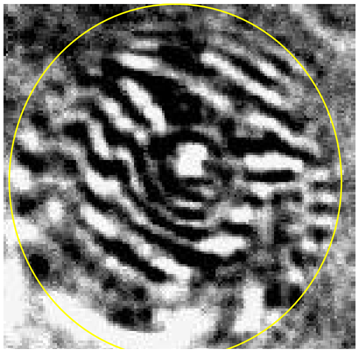


Figure 6 IR3 interferogram of ground surface. No data at the centre due to obstruction of return sphere.

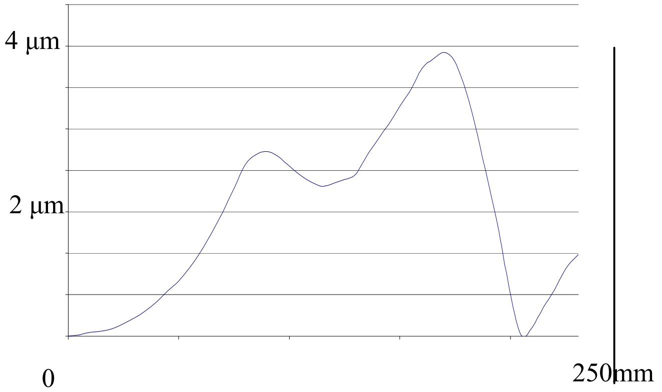


Figure 7 Manual trace of IR3 fringes after grinding. Data was interpolated into obscured central region for input to form-control optimiser software

Inventex Inc ground the asphere as specified above, including a central dimple marking the precise axis of symmetry of the ellipsoid of revolution. The resulting surface-texture was measured to be Ra~26nm with a Wyko RST500 interferometer. There were some grinding marks some 200nm deep and a few small pits (which probably originated in bubbles in the original Cervit substrate). It was found impossible to achieve fringe-visibility with the Wyko 6000 visible interferometer. More surprisingly, we also had problems using the Wyko IR3 10.6 µm interferometer. Figure 6 shows fringes (double pass as per the layout of Figure 5) from this instrument. Fringe-visibility was too poor to close phase and reconstruct a phase map.

5. Polishing the mirror

UCL's IRP600 was built as Zeeko's prototype, and its design predated much of the process development. One particular limitation is that the C axis speed (turntable rotation) is limited to 35 rpm, c.f. 1500rpm on the 200mm machines. In pole-down pre-polishing, both tool and turntable rotate synchronously i.e. at only 35rpm max., leading to low removal rates. The part was therefore pre-polished using the precessed tool at 500 rpm, relying on the optimizer software to correct form at the same time.
Another limitation was the limited tool-spindle torque, which inhibited use of the large polishing spots that would have been desirable in the earlier stages of the work. The polishing head has since been replaced with a high-torque version.

The Wyko IR3 data was hand-analysed, to determine the error-profile for input to the optimizer. This was fraught with several problems, as below:

1. The double-pass null test of the uncoated mirror attenuated the fringe-intensity to a level ~ $2x10^{-3}$ with respect to an equivalent single-pass coated mirror. This seriously degraded SNR, and has proved a particular problem with the infrared interferometer.

2. Significant errors arose in measuring surface-height, due to poor SNR and high local slope errors in the ground surface and in early stages of polishing.

3. It was difficult to define the exact location of the edge of the part, due to poor SNR, and high slopes at the edge. This led to a lateral scaling error in the metrology data. The tool's radial positioning then failed precisely to match the high zones on the part. Because of this, polishing runs exacerbated zonal errors in some cases, as indicated in the sketch Figure 8.

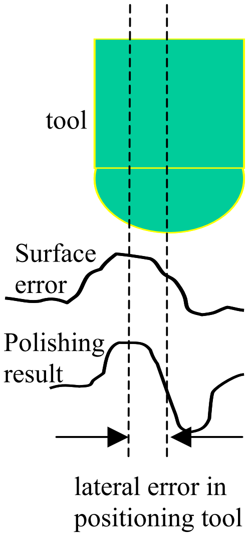


Figure 8. The effect of a tool lateral positioning error on removing a surface peak

4. The return-sphere in the test obstructed the centre of the part, which therefore could not be measured.

5. It was not possible to use the metrology rods to ensure the correct conjugate distances and still record useful fringes – instead, the interferometer had to be re-focussed to minimise fringe-density. In this case, the interferometer effectively compared the aberrated wavefront from the mirror with a spherical wavefront of arbitrary radius, and so gave no direct information on *absolute* surface height. This had two main consequences:

   i) When measured form deviated from the optimizer prediction, it was impossible to interpret the result in any absolute sense regarding at which radii too little material was removed, or where too much. This made diagnosing sources of process variability extremely difficult.

   ii) The precise base-radius of the asphere was unknown. In many cases this is of no great consequence, as the mirror in use can be re-focussed. However, in our case it undermined application of the technology to ELT segment fabrication where matching of the base radii between segments is of paramount importance.

Nevertheless, some progress was made, and the results of the final two runs using metrology data from the Wyko IR3 are shown in Figure 9.

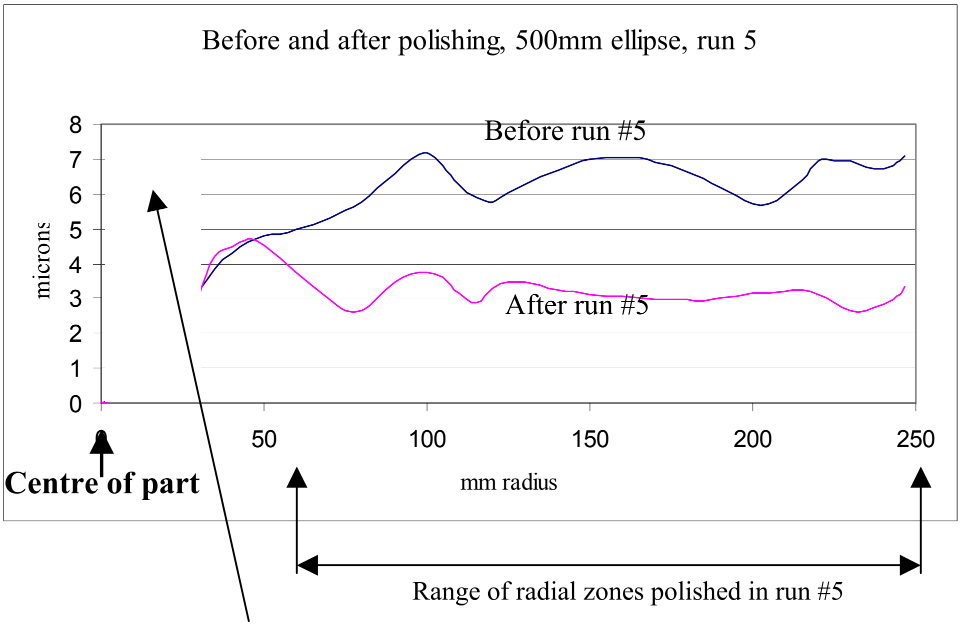


Figure 9. Estimated form before and after Run # 5, based on manual analysis of IR3 data.

6. Form control using absolute metrology

In view of the problems with infrared interferometry outlined above, the IRP600 was moved into the premises of Taylor Hobson Ltd of Leicester, UK, where access was provided to their 300mm Extended-Range Form Talysurf. This is a contact profilometer of 300mm scan-length.

Profilometric traces Z versus X were obtained from the edge of the part, through centre and 50mm past centre. The data-set contained the usual slope-term and arbitrary end-point. The data were then subject to the following procedure:

1. Identify the dimple ground into the centre of the part, providing an X-fiducial for the profilometry
2. Reflect the data about the centre of the part
3. Repeat, adjusting the X-offset of the data, and subtracting a slope term, until the 50mm overlap region exactly matched between the data and in its reflection

A measurement following Run #5 is shown as Trace 1 in Figure 10, and this may be compared with Figure 9. The peak-to-valley is similar, and there is general agreement, given the arbitrary focus term implicit in Figure 9.

Initial polishing trials revealed a systematic difference between the removal rates in the central and outer halves of the part, and this was initially attributed to the formation of a central puddle of slurry in the concavity of the part which could not be easily dispelled by suction. However, subsequent work showed that slurry-puddling was *not* the problem, and that the observed effect was due to an inappropriate software restriction on the C-axis (part rotation) speed. Subsequent polishing runs after correcting the software demonstrated that form could be controlled quantitatively, but some mid spatial frequency errors in the central half of the part originating in the previous work could not effectively be removed. This problem probably applies to all Gaussian processes, and is a consequence of Nyquist sampling theory. This indicates that *actively* correcting a spatial frequency on the surface by local polishing requires a Gaussian profile that delivers at least twice that spatial frequency. Much finer structure, e.g. surface-texture, can still be *passively* removed in our process, as the polishing cloth effectively rides the peaks in the surface.

Given the Nyquist limit, a ring-tool embodying a compliant layer and hard facets was developed for use on the IRP600 machine. This passive smoothing method proved very successful, and also demonstrated the versatility of the machine in allowing know-how in classical processes to be ported easily onto the machine and thereby automated. Trace 2 of Figure 10 shows the result of *Precessions* polishing to control form, with an intermediate stage of ring-tool work to remove the mid spatial frequencies. Figure 11 confirms that the data reduction process comprising stages 1,2,3 above had been correctly conducted, leaving no discernable ‘cone error’ about centre.

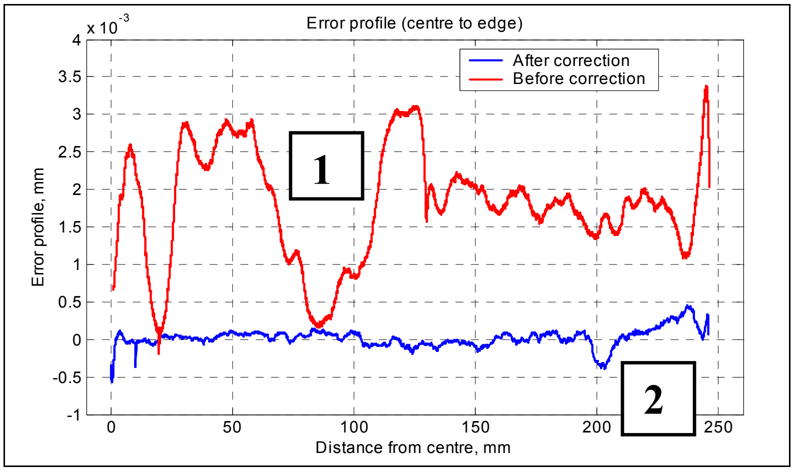


Figure 10.

Trace 1. Form Talysurf scan of the part from centre (left) to edge. The part had not been polished since Run #5 (Figure 9)

Trace 2. Form Talysurf scan after polishing runs using this metrology data.

Note. Sharp central depression is the ground-in fiducial

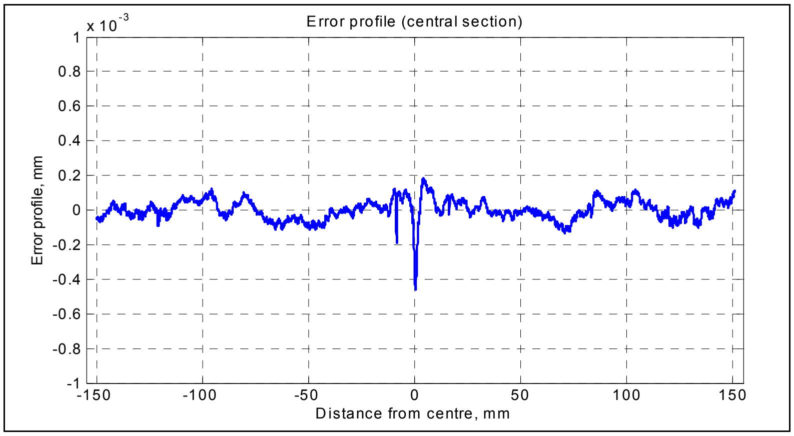


Figure 11.

Form Talysurf scan of central 300mm diameter area of part, corresponding to the lower plot of Figure 10.

Note. Sharp central depression is the ground-in fiducial on the axis of the part.

7. Visible Interferometry

The Extended-range Form Talysurf has been used for all the form-correction experiments after Run 5 (Figure 9). Shortly before submitting this paper, an interferometer became available at the Taylor Hobson site, by courtesy of Fisba. Vibration and thermal disturbances in the factory environment precluded acquisition of satisfactory phase data using the double-pass null-test of Figure 5. However, fringes could be obtained over some 300mm of the part, with the interferometer lens at the nominal centre of curvature of the mirror. This gave a non-null configuration, the fringes following the doubled asphericity of the surface due to the reflection. Unfortunately, we were unable to reconcile the measurements of the form of the part as measured by the Form Talysurf and the Fisba. This is currently under investigation, but the reason appears to be due to differences in the way that their respective software fit aspheres to the data.

The IR3 lateral scaling error and lack of absolute base-radius were described in Section 5. However, experience with the Fisba (and also a Wyko 6000 visible interferometer at UCL) revealed a more serious problem; that is, geometric distortion (pincushion or barrel) in the interferometer lens that distorts the radial distance-scale in a non-linear manner. We have measured the distortion in the 40° and 19° Fisba lenses as 11% and 5% respectively. Now, a 1% geometric distortion on a 500mm part will introduce 5mm errors in the absolute positioning of, for example, a raised zone. If this is attacked with a 5mm FWHM polishing spot at some stage of the process, the effect of Figure 8 can be created. The consequence is that the metrology data *must* be in a coordinate frame that is rectilinear and accurately referenced to the CNC machine coordinate frame. This effect may well have contributed to the problems experienced with the IR3.

8. Free-form Surfaces

By exploiting the 7-axis CNC capability of the Zeeko family of machines, free-form surfaces can be polished using a raster tool-path. To control form, a new 3D version of the '*Precessions*' numerical-optimisation software has been developed.

The first results were recently presented [8]. These demonstrated the creation of the Zeeko logo (Z and spot) in both flat and concave surfaces, to the correct geometry and absolute depth within 10%. This was produced by rastering the tool over the surface whilst modulating the traverse-speed to control dwell-time.

The next stage in the process development was to polish a pre-determined free-form departure into a flat surface. The result is shown in Figure 11, where the top left figure is the predicted removal, top right is the measured result of polishing (Zygo interferometer), and the lower figure is the difference (resulting error). 2-3 microns of free-form removal has been correctly produced with an error of approximately 10%.

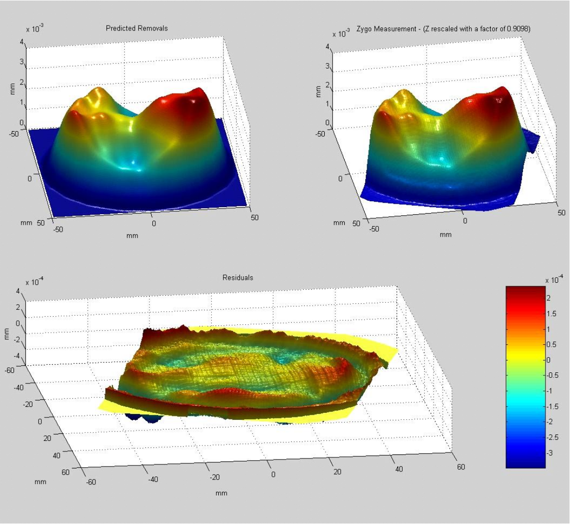


Figure 12 Free-form polishing of flat-surface.

Recently, experiments have started on truly free-form optical surfaces. We present here the result obtained on a section of a commercial part (Figure 12), which is a highly-distorted saddle.

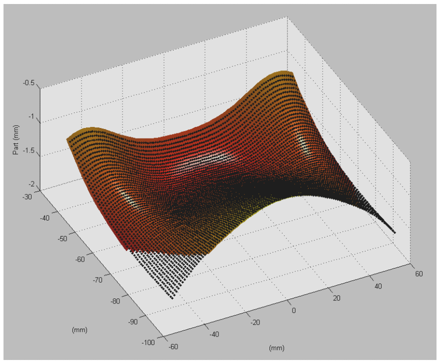
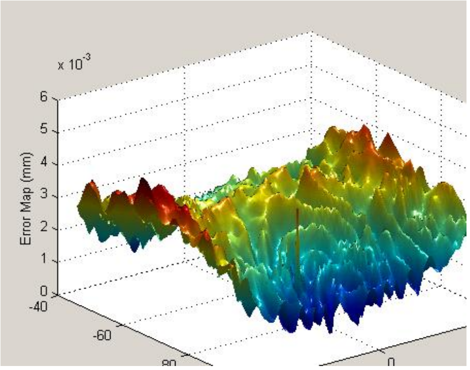


Figure 13 Surface of a truly free-form part

The part of Figure 12 was measured on a PGI1240 Form Talysurf, equipped with a motorized Y-stage to permit rastering of the 3D profile. The resulting form-error is shown in Figure 13. The result after two runs of free-form polishing (100 minutes total), is shown in Figure 14. A p-to-v error of approximately 5 microns has been reduced to 1 micron. We expect that the form-error in further runs will be reduced further.



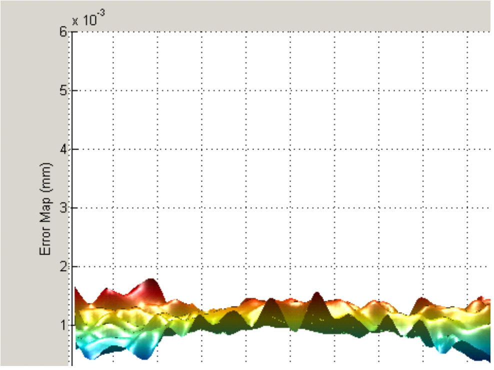


Figure 14 Initial error on free-form part

Figure 15 Error on free-form part after two polishing runs

9. Conclusions

The work in this paper has confirmed that the *Precessions* process, well established on the 200mm machines at industrial sites, can be scaled up to deliver deterministic removal of material on larger parts. The proviso is that the input metrology must be adequate in absolute terms.

Metrology has been by far the most serious issue with the 500mm part, due principally to errors in the coordinate-relationship (R and Z) between the optical metrology data and the CNC machine. We have been disappointed by infrared interferometry on grey surfaces, due to the poor SNR from test optics in double-pass, and an inability to close-phase in the presence of local surface-slopes from grinding. The Form Talysurf stylus profilometer has proved extremely effective, down to its intrinsic limit of accuracy in the 0.2 micron regime. Visible interferometry has revealed its own problems in relation to CNC local polishing; specifically, ambiguity in both the absolute base-radius and the lateral-scale, and second-order effects due to geometric distortion in interferometer lenses.

The relationship between aspheric fitting in the interferometer and Form Talysurf software is clearly not properly understood, and will be rectified in the next stage of the work by analyzing the raw data from both instruments in a bespoke MATLAB routine. To proceed with the 500mm part beyond the work reported in this paper, a combination of i) use of the Form Talysurf to establish base-radius and ii) visible interferometry calibrated and corrected for geometric distortion and scale, appears to be the optimum approach. This will also permit full 3D coverage of the surface. We believe that a hybrid approach combining both optical and profilometric methods will be required for ELT segments.

The early use of small polishing spots, unavoidable due to the restricted tool-spindle torque available at that time, combined with the effects of positioning errors from the metrology, left high spatial frequency defects. These could not be recovered by active polishing as this would have demanded ever-smaller spots. A better strategy would be to start with the largest polishing spots possible, then to work to smaller spots as the work progresses. This is valid from the perspective of Nyquist sampling theory, and has the added bonus of providing increased sensitivity of polishing as final form is approached. Nevertheless, we have had success using a classical ring-tool on the CNC machine in order to smooth the part. This demonstrates the versatility of the machine in supporting accumulated craft expertise. Two 1m machines are currently being designed, and the above experience is proving invaluable, particularly in terms of tool-spindle torque requirements and maximum turntable rotation speed.

The preliminary results on raster free-form polishing are extremely encouraging, and the correct operation of the new 3D optimizer software has been amply demonstrated.

10. Acknowledgements

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