

# Bonnet Polishing and Fluid Jet Polishing

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## 1. Introduction

### 1.1 The need for free-form surfaces

The capability of producing free-form surfaces – surfaces not limited to regular forms constrained by symmetry – opens up new vistas for optical designers. Such surfaces introduce new degrees of freedom into the optical design optimization process. This opens the door for imaging solutions with improved performance, and/or reduced complexity, lower mass and smaller package size. In illumination applications, free-form surfaces permit the spatial distribution of illumination to be tuned far more effectively than could be achieved with regular aspheric surfaces. The challenges have been how to manufacture, measure, and test such surfaces. This paper presents some useful steps in this direction.

### 1.2 Free-form polishing technology

Zeekos's *Precessions*<sup>TM</sup> CNC polishing process<sup>[1-12]</sup> has two principal functions – to remove surface and sub-surface damage from a ground part, and then to correct the form. The process operates by scanning a local spot of removal across the global surface, varying the spot size and dwell-time (or, in practice, the traverse-rate) to concentrate removal more on the areas that are too high than those that are too low. Several removal processes are currently available – inflated membrane (“bonnet”) based polishing, fluid-jet polishing<sup>[13]</sup>, and a family of hybrid “grolishing” processes<sup>[10]</sup> intermediate between polishing and grinding.

The form-correction software requires three key pieces of input information, i) the target form, ii) the measured form, or form-error, and iii) the tool influence function i.e. the local imprint left by the tool operating on a single site on the surface. A numerical optimization method is then used to define the optimum dwell-time map on the surface to correct the form error. Because of the inherent complexity of the surface chemistry and physics of polishing at the nano-scale, 100% predictability of removal is never achieved; there is always a residual error. Therefore, the process is iterative, requiring cycles of metrology and material removal to converge on the final target form.

### 1.3 The importance of metrology data

The total time required depends critically on the convergence rate of the process. Key factors affecting convergence are the correct interpretation of the metrology data, the quantitative accuracy and repeatability of the metrology, and the integrity of the geometric relationship between the coordinate frame of the metrology data and that of the machine-tool. Specific problems that have been encountered with different metrology devices and formats are given in the next section.

### 1.4 Specific metrology issues

Interferometers and optical wavefront sensors

- ambiguity of height being referred to the surface or the reflected-wavefront (factor of two or four depending on the setup)
- ambiguity of sign in XY plane (upside-down or mirror image)
- ambiguity in magnification and orientation of interferometer data
- geometric distortion in the XY plane of the interferometer data
- difficulties locating fiducials on the wavefront image
- slope limitations causing whole areas to be irresolvable

Profilometers and CMMs

- setting accurate and reliable datum points when measuring in 3D
- compensating for thermal drift occurring over the scanning period
- compensating mechanical and geometrical issues, such as tilt and decentering when using a rotary stage with a profilometer

These problems can become severe for aspheric surfaces, and extreme for free-forms surfaces. Further complications arise when the metrology data needs to be registered with CAD design data as well as with the machine-tool coordinate frame. Data fusion or stitching in the spatial or spatial-frequency domain between different metrology devices also introduces its own problems of maintaining integrity across the fused data set.

### 1.5 The generality of the problem

The authors grasped that these issues are not unique to specific polishing technology, but are encountered in numerous other iterative manufacturing processes requiring metrology input, which are generally combined to produce a single component:

- precision grinding
- precision diamond turning
- ion beam deposition or removal
- Reactive atomic plasma technology (RAPT)

This evident need for standardization and a holistic approach to handling metrology data led us over a period of time to develop software tools addressing these various issues. It became apparent over time that these tools could be gathered into a single toolkit application, dedicated to solving metrology issues and orientated toward precision and ultra precision manufacturing processes.

## 2. Metrology Toolkit Software

### 2.1 Metrology devices

Surface texture analysis is an area of metrology that has been extensively studied, and is covered by many commercial software applications supporting a wide range of scanning and imaging instruments. Large-scale dimensional analysis (form error) however, has not received such intensive coverage and few alternatives are available to exploit the potential capability of metrology instruments to support form-control on general free-form shapes.

The main measurements solutions for measuring free-forms are listed below, with their advantages and limitations:

- CMMs
  - o pros: can measure and fit most free-form shapes, provided a CAD file of the part is available and 3D software exists for the instrument.
  - o cons: highest accuracy only ~1um (Zeiss UPMC), machine with 3D software often costly
- 3D Scanners (laser triangulation)
  - o pros: can measure and fit most free-form shapes, if suitable software is available, low cost
  - o cons: low accuracy ~10um, thus not suitable for imaging optics

- Profilometers
  - o pros: good sensitivity in Z direction (<=100nm) when used in 2D mode on rotationally symmetrical shapes
  - o cons: raster scanning causes the stylus to deflect slightly because of Y slope component. Rolling ball algorithm compensates only for X slope, thus making raster-scan suitable only for near flat shapes
- Nanomefos<sup>[14]</sup>
  - o pros: designed to achieve 10nm range accuracy
  - o cons: still in development, restricted range of measurable shapes (limited deviation from a best fit sphere)
- UA3P (Panasonic)
  - o pros: ability to raster or spiral scan free-form shapes, stated accuracy <=100nm
  - o cons: cost of machine + software

differential equations describing the function of the optical component

- CAD file containing a combination of primitives and b-splines

In order to unify the handling of free-form surfaces, the use of non-uniform rational b-splines (NURBS<sup>[15]</sup>) was adopted. The Metrology Toolkit features a surface editor that allows defining free-forms in any of the above formats, and then automatically converts the surface into a NURBS object. Additionally, many modern CNC controllers offer the ability to feed tool paths directly in NURBS format<sup>[8,16]</sup>, which offers increased process control and accuracy.

### 2.5 Metrology instruments compatibility

Metrology data is generally expressed in one of the following formats:

- linearly or non-linearly spaced XYZ arrays or vectors (profilometers, interferometers)
- scattered or randomly distributed point clouds (scanners, CMMs)

## 2.2 The advent of the metrology toolkit

The software solutions presently available for measuring free-form shapes are lacking any interfacing with precision manufacturing equipment.

The Metrology Toolkit was thus developed to facilitate the fitting of form error from a wide variety of instruments and enable the interfacing with precision manufacturing equipment. The following considerations were taken into account in the design of the software:

- compatibility with free-form definition methods
- compatibility with a wide range of measuring instruments
- compatibility with a wide range of manufacturing machine tools
- functionality allowing correctly to format and process data sets

Certain distributions, such as profilometer data, may be linear in spherical coordinates rather than Cartesian. When projected to Cartesian the distribution may no longer be linear, with the transformation breaking down entirely at the edge of a hemisphere. However, all distributions are special cases of the general random point cloud distribution. The Toolkit algorithms were implemented to solve this general case, and are thus compatible with any more-specific distribution (some code optimizations were subsequently performed to speed-up calculations whenever certain distribution properties are detected). Data fusion of different metrology sources is also possible thanks to this approach.

### 2.6 Manufacturing equipment support

Most precision manufacturing equipment relies on software generating G-Code CNC files that are fed to a numerical controller (Fanuc, Bosch, Siemens, Cranfield). The Toolkit can make modifications directly to the G-Code, enabling integration without the need to modify the equipment's original software. Through an iterative approach, machine systematic errors can be compensated and form error reduced.

### 2.7 Processing and formatting functionality

The Toolkit integrates various processing and formatting functions enabling expression of the data in an intelligible way to manufacturing equipment and/or user.

- data sets can be referenced to part design with functions that retrieve and create fiducials
- simple geometrical transformations are available: mirror, offset, tilt and rotate
- incomplete or corrupted data sets can be re-sampled, trimmed, de-noised, smoothed, interpolated and extrapolated
- datum points can be converted to deviation data using the aspheric and free-form fit functions
- several data sets can be fused to create new point clouds

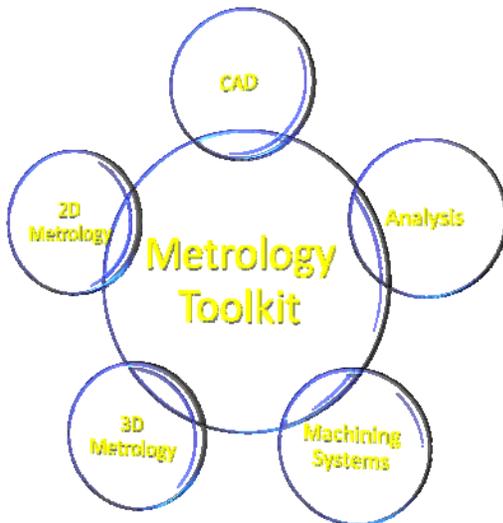


FIGURE 1. Metrology Toolkit integration diagram.

## 2.4 Free-form definition methods

Free-form shapes are commonly defined in the following formats:

- analytically: section of a primitive shape (sphere, cylinder, ellipsoid, toroid...) combined with a polynomial expression  $z = P(x,y)$
- numerically: XYZ array or point cloud derived from numerically solving a system of partial

## 3. Case Study 1 – Manufacturing a free-form optic

A practical experiment to demonstrate the integration of the software in a manufacturing environment was conducted, using a precision grinder and the *Precessions* process to produce a free-form optic. The measurement device used throughout this experiment was a Zeiss UPMC CMM.



FIGURE 2. Free-form optic inside Zeeko polisher.

The part was first ground with a spiral tool path that had been derived from the theoretical design. The optical surface was then measured on the CMM and the Toolkit was used to fit the datum points to the design in order to produce a deviation map (error map).

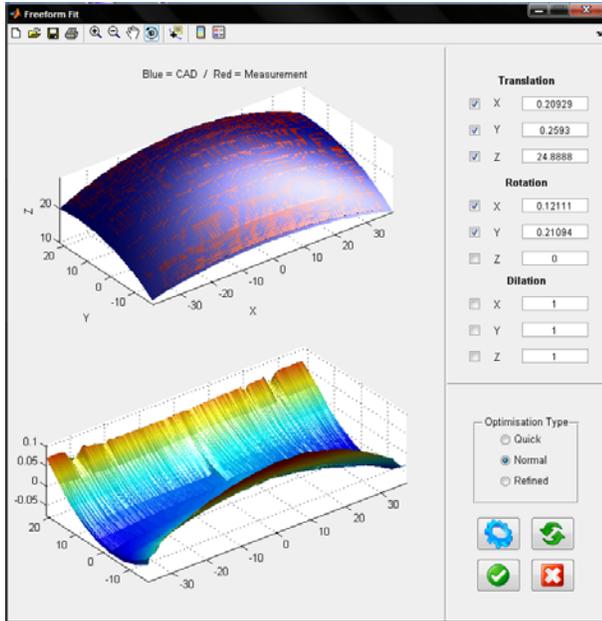


FIGURE 3. Original grinding error: 180µm PV.

The error map showed 180µm PV of deviation on the clear aperture, with a main cylindrical component and an underlying see-sawing effect. This error map was used within the Toolkit to apply compensations on the grinder's G-Code CNC file. The part was then re-ground and re-measured.

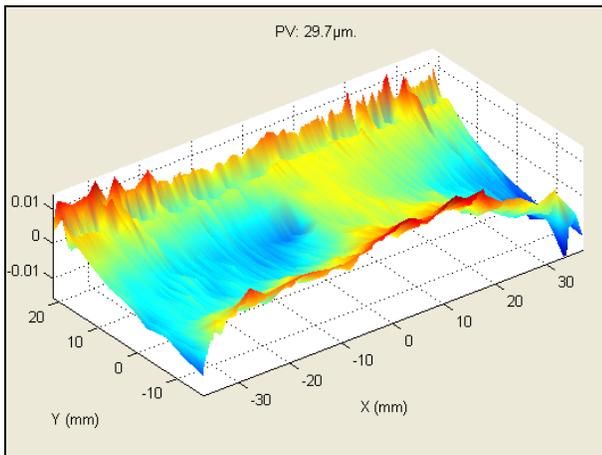


FIGURE 4. Grinding error after compensation: 29.7µm.

The measurement analysis in the Toolkit showed that this compensation reduced the PV of the error from 180µm down to

29.7µm. The cylindrical component was almost entirely removed, and the amplitude of the see-sawing effects was greatly reduced.

The part was then polished using the *Precessions* corrective polishing software, to remove surface and sub-surface damage while further improving the form error PV. The Toolkit could export the error map to *Precessions*, where it was analyzed against the influence of the polishing process in use, to produce a polishing tool path with varying speed and spot properties.

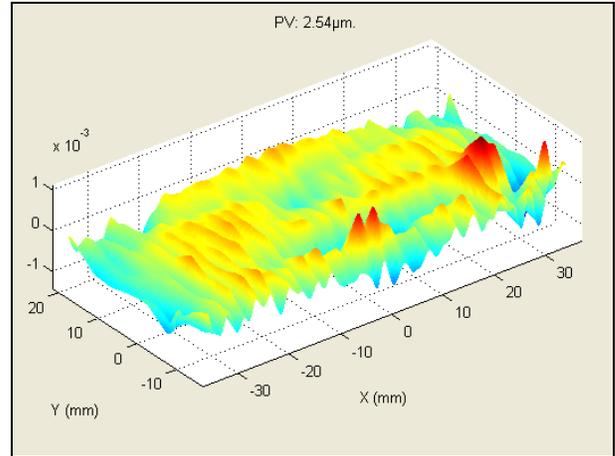


FIGURE 5. Final error after *Precessions* runs: 2.54µm.

After two *Precessions* runs the form error was reduced to 2.5µm PV. This clearly demonstrated the capability of the Toolkit successfully to interpret the data from the CMM, and convert it into useful compensations for the grinding and polishing processes. Limiting factors to reaching sub-micron form error were found to be:

- accuracy of CMM measurement (~1µm)
- density of CMM data (2mm data points spacing)
- shortest grind ripples would have required the use of fluid jet polishing or grolishing, not available for this project

#### 4. Case Study 2 – Overcoming metrology limitations with data fusion and distortions compensation

An experiment was carried out to demonstrate the usefulness of data fusion, and the capability of the Toolkit to deal with spatial distortions. A 190mm diameter parabolic concave mirror was ground on a precision grinder, and pre-polished on a Zeeko IRP polishing machine. The mirror was then measured with a Zygo interferometer in double pass mode using an auto-collimation flat mirror.

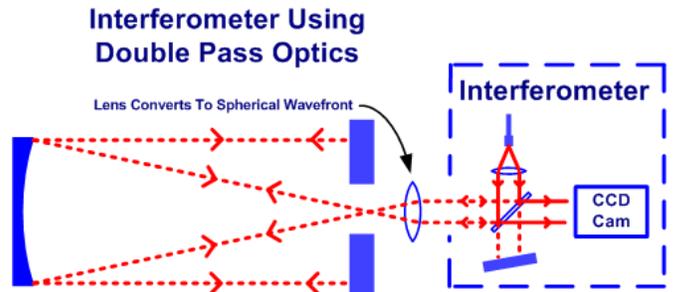


FIGURE 6. Double pass setup using flat reflector.

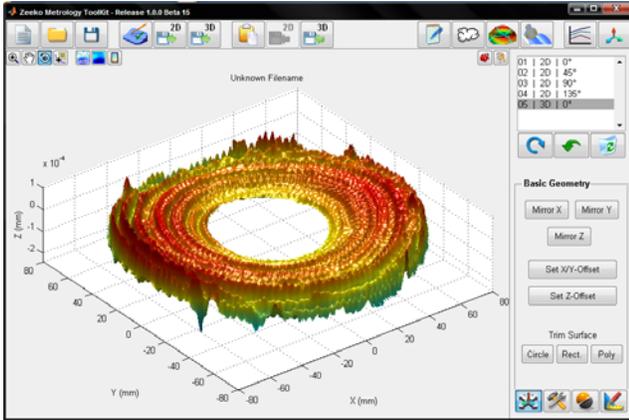


FIGURE 7. Visible area: 160mm.

The interferometer could resolve fringes up to a diameter of 160mm, while the clear aperture extended to 185mm. Measurements of the mirror on a Form Talysurf profilometer revealed that slopes in the region beyond 160mm were severe, due to the presence of a 'lip' defect.

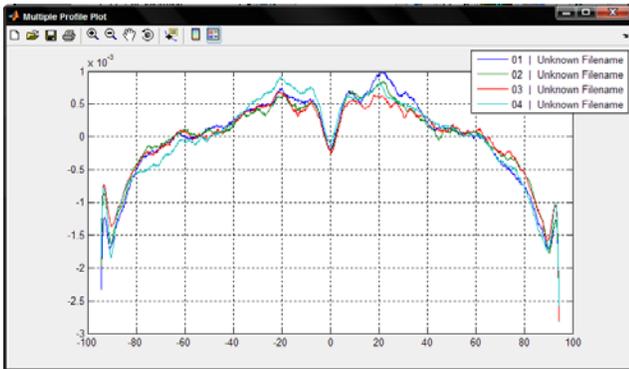


FIGURE 8. 2D profiles reveal problematic area.

While the profilometer data could be used to correct this edge defect, its lower accuracy and density would have degraded the precision of measurement in the area visible on the interferometer. The Toolkit could address this issue by stitching together the interferometer and profilometer data sets through a prioritizing algorithm.

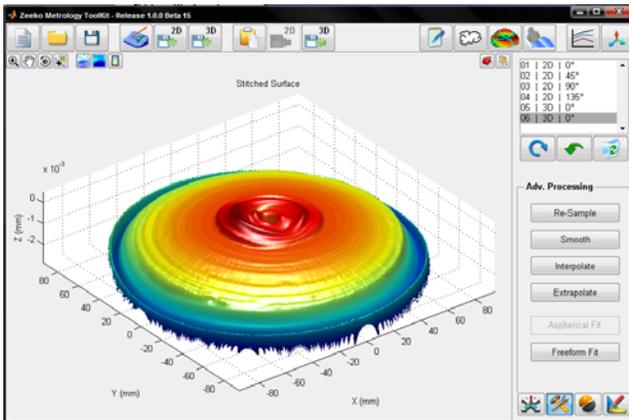


FIGURE 9. Toolkit fuses data sets into a single map.

Additionally, the merged error map contained the residual spherical power, missing in the interferometer measurement but present in the profiles. Using this error map, a single *Precessions*

run improved the form error sufficiently for the mirror to be resolvable on the interferometer up to a diameter of 190mm.

However, further *Precessions* runs seemed to reach an improvement barrier at 150nm PV of form error, the surface features showing peak-to-peak distances equal or smaller than 6mm. An investigation was carried out to ensure that *Precessions* was asked to correct the 'right error' at the 'right location'. A literature survey revealed that optical errors in interferometers can include imaging distortions and ray-mapping errors<sup>[17]</sup>. In order to characterize the distortions associated with our double pass setup, six sets of three fiducials were placed on the surface, to calibrate a succession of six diameters spanning an interval from 62mm to 164mm.

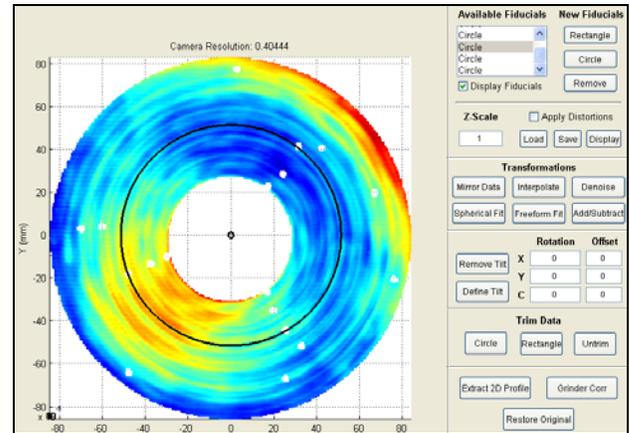


FIGURE 9. Three fiducials calibrate one diameter.

The Toolkit was able to register each set of fiducials as a separate diameter calibration. Plotting the camera resolution, as a percentage of the value at 164mm against the diameter span, showed as much as 3% of variation. On a 190mm diameter mirror, this variation would amount to 3mm of radial inaccuracy in the localization of peaks and valleys.

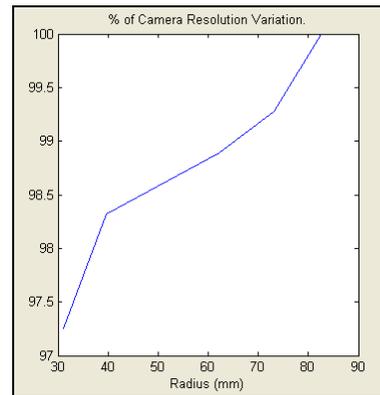


FIGURE 10. Camera resolution variation.

The Toolkit fiducialisation functions enabled us to take into account all six calibrations, and rescale non-linearly the error map in the XY domain. The morphed error map was then exported to *Precessions*, and a further corrective run was attempted.

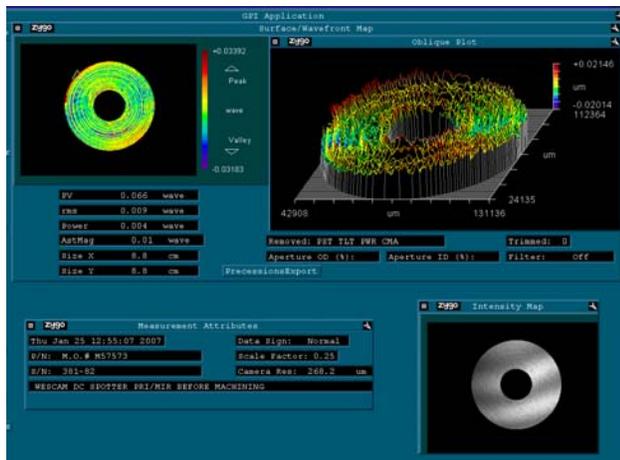


FIGURE 11. *Precessions* achieves 40nm PV ( $\lambda/15$ ) using the morphed error map.

The 150nm PV barrier was overcome, and a single corrective run brought the global form error to 40nm ( $\lambda/15$ ) over the full 185mm clear aperture. This process was successfully repeated on several dozen parts, with global form error consistently brought to less than 60nm PV, which demonstrated the capability of the Toolkit accurately to fuse data sources, and compensate mapping distortions.

## 5. Discussion and Conclusion

This paper has illustrated the practical importance of considering metrology as an integral part of the process-loop for manufacturing aspheric and free-form optics. There are pitfalls in all methods of testing optical surfaces, but we have found that these pitfalls are substantially amplified in components with free-form surfaces, and surfaces with high local or global slopes. We have shown the importance of proper mathematical descriptions of the surface. We have also emphasized the need for a rigorous approach to handling the metrology data, and to consider how the surface-description and metrology data relate to the machine tool used to correct measured errors. Specific software tools have been described that can greatly assist the manufacturing process-chain, with relevance to several different processes.

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