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## Material standards design for minimum zone fitting of freeform optics

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### Abstract

In most cases, ultra-high-precision coordinate measuring machines (CMMs) are used to measure manufactured parts especially in the presence of freeform surfaces. The obtained data should be then processed to determine a quality measure of the surface. The least value of peak-to-valley (PV) is the widely used quality measure since it conforms to the ISO Geometrical and Product Specification (GPS) standards. To determine the minimum value of PV, a number of fitting methods exist but minimum zone fitting is the most suitable since it directly minimizes the PV. In the measurement process, fitting algorithms are essential elements. For this reason, their quality must be assessed as well; this could be achieved using either softgauges or material artefacts. In this paper, a design of a reference thermo-invariant material standard for minimum zone fitting is suggested and manufactured. The artefact was then measured by a number of partners participating to the FreeFORM 15SIB-01 project so as a comparison could be made in the light of gathered measurements.

Minimum zone fitting, Freeform, Artefacts, Material standards

### 1. Introduction

Metrology software are critical components of the metrology chain of optical elements. They enable the characterization of manufactured parts and the verification of their conformance to design tolerance specifications so as acceptance/rejection statements could be made.

For the assessment of algorithms' trustworthiness, a validation procedure must be established. This procedure varies according to the function the algorithm is intended to. Softgauges (also called reference data) are mainly used for this purpose. They consist of a set of data points for which the exact value of the measurand is known with an associated uncertainty. *Forbes et al.* present methods to generate reference data for minimum zone and least squares fitting [1]. Other methods exist for softgauge generation for surface texture characterization [2].

Material standards could also be used for the same purpose as in [3] for interlaboratory comparison of metrology capabilities of aspherical surfaces. In this paper, a material standard for minimum zone fitting of aspherical surfaces is designed and manufactured. It is then measured by a number of partners contributing to the ongoing European project FreeFORM 15SIB-01. In the second section, the proposed artefact is described as well as its manufacturing process. In the third section, a short overview of the different measuring machines is given. Then, the minimum zone fitting problem is

described. In the last section, obtained results and conclusions are presented.

### 2. The material standard

The proposed material standard is made of Zerodur<sup>®</sup> which is a glass-ceramic with low thermal expansion coefficient (less than  $0.005 \times 10^{-6} \text{ K}^{-1}$ ) [4]. This material is used for the manufacturing of very large as well as small telescope mirrors in spatial applications and is very common in high-precision metrology requiring low thermal expansion coefficients.

The thermo-invariant standard is designed so as it enables the validation of minimum zone fitting algorithms. It consists of an aspherical surface described using the ISO 10110-12:2007 standard combined with nine steps projected along the normal direction to the aspheric. The final surface has neither axis of symmetry nor degrees of invariance and had a theoretical amplitude (peak-to-valley) which is equal to  $7 \mu\text{m}$  (figure 1).

The added steps could be considered as artificial or simulated form errors added to the aspherical shape. Moreover, in the process of minimum zone determination, the significant points (also called contacting points of the minimum zone) lie exactly on the top of the steps. In this way, the value of the minimum zone could be previously known.

The artefact was manufactured using a process called magnetorheological finishing (MRF) which consists of using material removal for processing optical lenses using magnetic fluid. The Q22 multiple-axis computer controlled MRF machine is illustrated in figure 2 and detailed in [5].

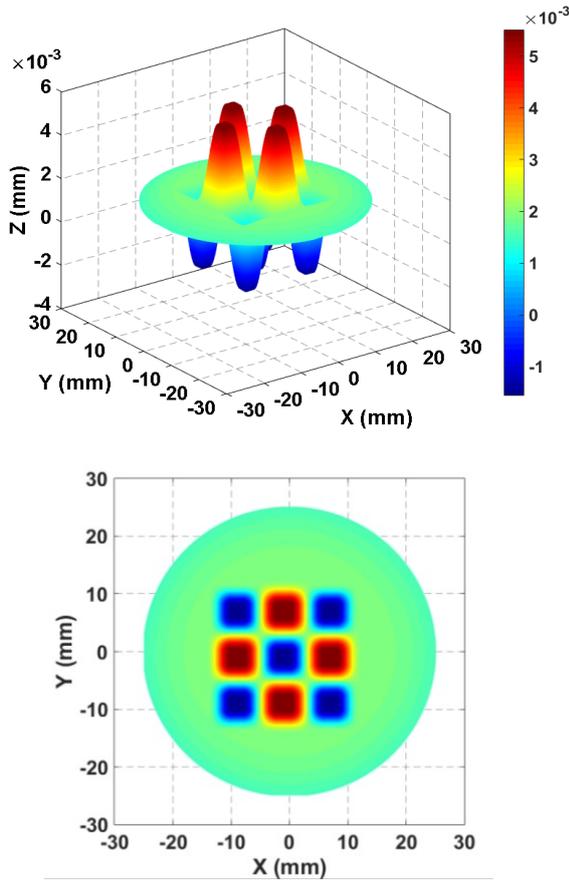


Figure 1. The designed thermo-invariant material standard

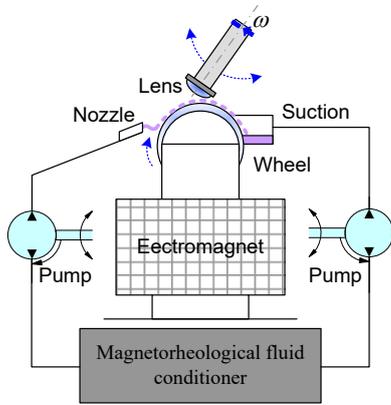


Figure 2. Principle of the Q22 multiple axis computer-controlled MRF machine

Figure 3 presents a picture of the manufactured part. Because of amplitude requirements the surface looks almost flat.



Figure 3. Photo of the manufactured material standard

### 3. Minimum zone fitting

For the comparative study, the value of the minimum zone of the manufactured artefact is sought. In order to define it, form deviations defined as the orthogonal distances between measured data and the reference surface must be determined. The value of the minimum zone is chosen as the least value of the peak-to-valley (the difference between maximum and minimum deviations) among all potential reference surfaces.

This problem is mathematically formulated as follows. Suppose given are a set of  $m$  measured data points  $\{P_i\}_{1 \leq i \leq m}$  and their corresponding orthogonal projections  $\{Q_i\}_{1 \leq i \leq m}$  onto a surface described using an implicit equation  $f(\mathbf{q}, \mathbf{s}) = 0$  with  $\mathbf{q} = (x, y, z)$  are the coordinates of a given point on the surface and  $\mathbf{s}$  are the surface' shape parameters. The minimum zone fitting problem is formulated as in (1).

$$\min_{\mathbf{x}} \phi(\mathbf{x}) \text{ where } \phi(\mathbf{x}) = \max_{1 \leq i \leq m} f_i(\mathbf{x}) \quad (1)$$

$f_i$  denotes the Euclidean distance between the point  $P_i$  and its corresponding orthogonal projection  $Q_i$ .  $\mathbf{x} \in \mathbb{R}^n$  is either the set of intrinsic shape parameters  $\mathbf{s}$  or the motion parameters  $\mathbf{m}$ : rotation and translation applied to  $\{P_i\}$ .

To solve this problem, the Hybrid Trust Region method (HTR) is used [6]. This method consists of approximating the minimum zone fitting problem by the mean of a quadratic programming at each iteration and then applying either trust region step, line search step or curve search step according to the situation faced at each iteration. This method enables to avoid solving the trust region problem many times. The estimated uncertainty on the minimum zone value returned by the algorithm is  $1e-15$  mm.

### 4. Artefact characterization and results

A number of partners involved in the European project FreeFORM-15SIB01 conducted different measurements of the thermo-invariant material standard using their corresponding measuring machines. The participants to this comparison are: The French National Metrology Institute of France (LNE-France), Institute of Plasma Physics of the Czech Academy of Sciences (IPP ASCR – Czech Republic), University of Nottingham England (UNOTT – UK), Thales Angénieux (France), Fudan University (FU – China), Technical Research Centre of Finland (VTT – Finland), The National Metrology Institute of Japan (NMIJ – Japan) and Federale Overheidsdienst Economie, KMO, Middenstand en Energie (SMD - Belgium). Only some results were selected and presented in this paper. The list of included measurements is presented in table 1.

Table 1. Selected measurements for the comparison

Partner	Machine	Number of measurements	Number of recorded data
LNE	LNE ultra_high precision profilometer	1	310 883
UNOTT	ZYGO Nexview NX2 coherence scanning interferometer	1	5 066 734
Thales Angénieux	Subaperture Stitching Interferometry (SSI) QEDTechnologies	1	334 954
IPP	Mahr (MFU)	1	504 821
	Luphos machine (LUP)	1	134 727

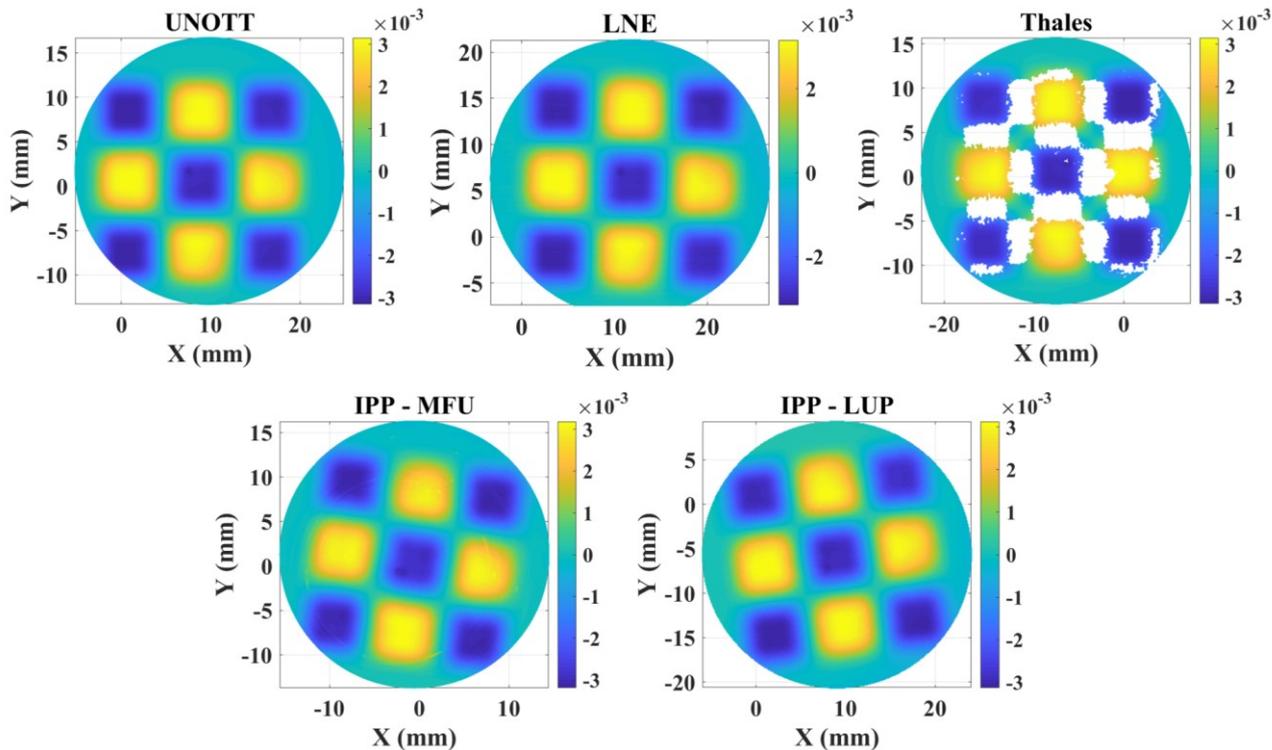


Figure4. Artefact residuals

All recorded data were submitted to the HTR algorithm in order to determine the peak-to-valley for each set. Table 2 shows the obtained results when applying minimum zone fitting as well as least squares. In all cases, the peak-to-valley obtained using least squares fitting is higher than minimum zone one. This confirms that the least squares fitting overestimates the minimum zone value.

Table 2. Obtained peak-to-valley using least squares and minimum zone fitting in microns ( $\mu\text{m}$ )

Partner	Least squares fitting	Minimum zone fitting
LNE	6.385	6,315
UNOTT	6.339	6,304
Thales Angénieux	6.354	6,302
IPP (MFU)	7.186	6,366
IPP (LUP)	6.326	6,263

Results show that the mean of the obtained values of peak-to-valley is  $6.311 \mu\text{m}$  and the standard deviation is  $37\text{nm}$ . The results obtained by LNE, UNOTT and Thales are close to each other. The second measurement of IPP returns the least value of PV, but this result is sensitive to the number of recorded points as well as the applied pre-processing routines. However, the obtained results prove the stability of the algorithm output.

Figure 4 shows the residuals for each measurement after applying minimum zone fitting. The data are represented in the frame associated to the nominal model. The two measurements of IPP are rotated around the Z axis compared to the other measurements. This is essentially due to initial positioning that was performed manually based on markers on the lateral side of the artefact. However, this has no effect on the final value of PV since the nominal shape is rotationally symmetric.

Unlike other measurements, the third measurement represents some missing areas due to measurement system limitations on areas with high slope. This has no effect of the final value of PV since the regions defining the minimum zone were completely detected.

Figure 5 shows the probability density functions of measured data based on kernel density estimation. All functions have the same shape except for the third one which is slightly shifted. This dissimilarity is due to the zones that were not detected by the measuring machine.

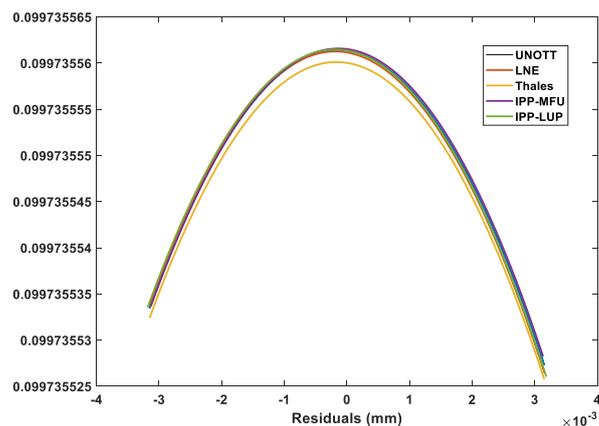


Figure5. Probability density functions of measured data

## 5. Conclusion

In this paper, a thermo-invariant material standard for the validation of minimum zone fitting algorithms was designed and manufactured. The artefact was then measured by a number of partners and the resulted data were analysed by a validated minimum zone fitting algorithm.

Despite the different measuring procedures and pre-processing techniques applied on measured data, the returned minimum zone values are approximately similar. This also proves the stability of the HTR fitting algorithm.

This work will be completed by additional measurements that will be provided by other partners. Moreover, other artefacts will be developed for the validation of fitting algorithms of freeform surfaces according to minimum zone fitting criterion.

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### **References**

- [1] A. B. Forbes and H. D. Minh, 'Form Assessment in Coordinate Metrology', in *Approximation Algorithms for Complex Systems*, Springer, Berlin, Heidelberg, 2011, pp. 69–90.
- [2] R. Leach, 'A programmable software framework for the generation of simulated surface topography'.
- [3] R. Schachtschneider et al., 'Interlaboratory comparison measurements of aspheres', *Meas. Sci. Technol.*, vol. 29, no. 5, p. 055010, 2018.
- [4] 'ZERODUR® Extremely Low Expansion Glass Ceramic: SCHOTT Advanced Optics | SCHOTT AG'. [Online]. Available: [https://www.schott.com/advanced\\_optics/english/products/optical-materials/zerodur-extremely-low-expansion-glass-ceramic/zerodur/index.html](https://www.schott.com/advanced_optics/english/products/optical-materials/zerodur-extremely-low-expansion-glass-ceramic/zerodur/index.html). [Accessed: 18-Oct-2018].
- [5] W. Kordonski and S. Gorodkin, 'Material removal in magnetorheological finishing of optics', *Appl. Opt.*, vol. 50, no. 14, pp. 1984–1994, May 2011.
- [6] Y. Arezki, H. Nouria, N. Anwer, and C. Mehdi-Souzani, 'A novel hybrid trust region minimax fitting algorithm for accurate dimensional metrology of aspherical shapes', *Measurement*, vol. 127, pp. 134–140, Oct. 2018.