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Tolerancing an optical freeform surface: an optical fabricator's perspective

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ABSTRACT

Freeform optical shapes or optical surfaces that are designed with non-symmetric features are gaining popularity with lens designers and optical system integrators. Tolerances on a freeform optical design influence the optical fabrication process. Case studies and soft tolerance limits for easier fabrication will be discussed. This paper will also give a high level overview of a freeform optical fabrication process that includes generation, high speed VIBE polishing, sub-aperture figure correction and testing of freeform surfaces.
Keywords: Freeform, optics, manufacturing, tolerance, fabrication, asphere

1. INTRODUCTION

Freeform optical shapes or optical surfaces that are designed with non-symmetric features are gaining popularity with lens designers and optical system integrators. Optical fabricators typically distinguish a freeform from other optical shapes by their lack of symmetry and fabrication method. Figure 1 simply illustrates the transition from simple flat and spherical surface that have radial symmetry and constant radius to aspheres that still have radial symmetry to a freeform surface that has little to no symmetry and has non-constant slope or curvature.

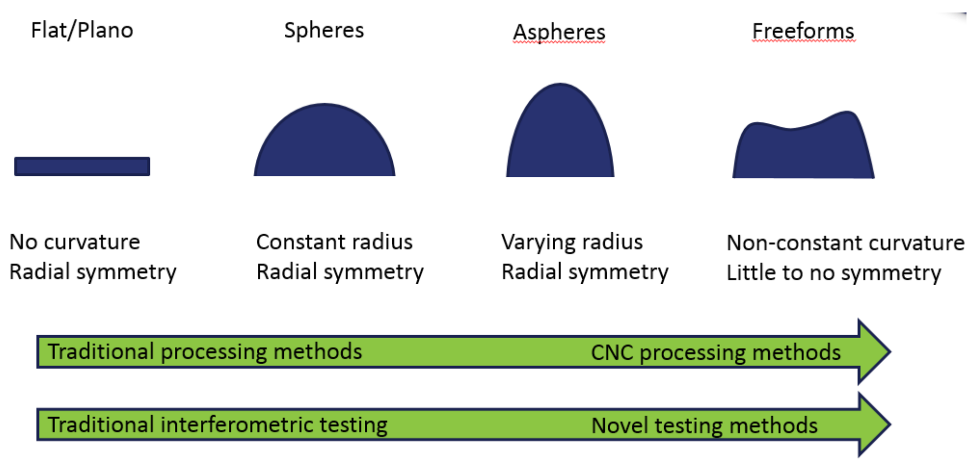

Figure 1: Illustration of the difference in common types of optical shapes.

There are many different methods to describe a freeform optical surface [1-5]. Common types of freeforms shown in Table 1 include toroid, atoroid/biconic, acylinder, anamorph, off-axis parabola, equation based freeform and XYZ freeforms, among others. From the manufacturer's perspective, the best way to define a freeform surface should be whatever form is easiest for the optical designer to use and optimize. Often optical fabricators are asked which surface definition is preferred, however the description itself is not what makes one freeform easier to manufacture over another, what is important to the optical fabricator is the information included with the surface definition and optical tolerances. The most important information to include with the optical freeform design are physical datums (fiducials), the equation and/or solid (3D) model used to define the surface, a 2D sag table, well defined XY orientation, a clear definition of wedge and thickness and ensuring that the design well behaved outside the clear aperture is preferred. The following sections outline a general freeform manufacturing and testing process and a guideline for tolerancing freeform surfaces.

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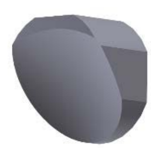
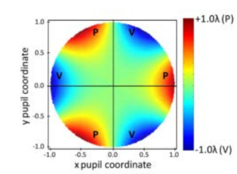
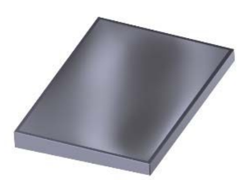
Common Freeform Name	Common Freeform Description	Example
Toroid	$Z=\frac{C_xX^2+C_yY^2}{1+\sqrt{1-C_x^2X^2-C_y^2Y^2}}$ $\quad C_x=\frac{1}{R_x}$ $\quad C_y=\frac{1}{R_y}$	
Atoroid/Biconic	$Z=\frac{C_xX^2+C_yY^2}{1+\sqrt{1-(1+k_x)C_x^2X^2-(1+k_y)C_y^2Y^2}}$ $\quad C_x=\frac{1}{R_x}$ $\quad C_y=\frac{1}{R_y}$	
Acylinder	$Z=\frac{C_xX^2}{[1+\sqrt{1-(1+k)(C_x^2X^2)}]}+\alpha_1X^2+\alpha_2X^4+\alpha_3X^6+\alpha_4X^8+\alpha_5X^{10}$ $\quad C_x=\frac{1}{R_x}$	
Anamorph	$Z=\frac{C_xX^2+C_yY^2}{1+\sqrt{1-(1+K_x)(C_x^2X^2)-(1+K_y)(C_y^2Y^2)}}+AR[(1-AP)X^2+(1+AP)Y^2]^2 +BR[(1-BP)X^2+(1+BP)Y^2]^3+CR[(1-CP)X^2+(1+CP)Y^2]^4 +DR[(1-DP)X^2+(1+DP)Y^2]^5$ $\quad C_x=\frac{1}{R_x}$ $\quad C_y=\frac{1}{R_y}$	
Off-axis parabola (OAP)	$Z=\frac{C_xX^2}{[1+\sqrt{1-(1+k)(C_x^2X^2)}]}+\alpha_1X^2+\alpha_2X^4+\alpha_3X^6+\alpha_4X^8+\alpha_5X^{10}$ $\quad C_x=\frac{1}{R_x}$ Where k=-1	
Equation based freeforms	Zernike Polynomials, XY Polynomials, Etc.	 *Figure 1. A representative freeform optical surface. This particular shape is classified as a Zernike trefoil overlay, often encountered in the mounting of mirrors in large telescopes. P and V denote where the surface error is a peak or a valley, respectively. λ: Wavelength.* **Kyle Fuerschbach, Jannick Rolland, and Kevin Thompson,** Extending nodal aberration theory to freeform surfaces
XYZ freeforms	Freeform: Surface created from point cloud	

Table 1: Common equations used to define freeform surfaces

2. CURRENT FREEFORM OPTICAL MANUFACTURING AND TESTING PROCESSES

The optical manufacturing process for a freeform is similar to that of a highly complex asphere. One way to describe asphere complexity is to examine the departure from the best fit sphere increases.[6, 7] Departure from a best fit sphere can determine the manufacturing process used to make the asphere. Table 2 depicts in general terms how the manufacturing process changes for an asphere as the departure increases. For example, aspheres with mild departure allow the manufacturer the ability to generate a sphere and polish in the aspheric profile.

Departure From Sphere	Generate	Fine Grind	Polish	Relative Cost
<10µm	Sphere	Sphere	Asphere	$
<50µm	Sphere	Asphere		$$
>50µm	Asphere			$$$

Table 2: General optical manufacturing processes for aspheres as a function of departure from best fit sphere. [Departure values are guidelines not rules.]

Aspheric departure from a best fit sphere is only one aspect of asphere complexity. Surface form and local slope change are also factors that influence asphere complexity. In general terms, a convex asphere is easier to manufacture than a concave asphere due to grinding/polishing tool geometry limitations, yet concave aspheres are easier to measure than convex aspheres. Figure 2 shows a graphic that simply portrays the increase complexity of aspheres comparing concave and convex aspheres and increasing complexity to a category of aspheres referred to as "gullwings". Gullwing aspheres include inflections on the optical surface or change in slope on the optical surface; these complex aspheres essentially contain both concave and convex aspheres on the same surface.[8]

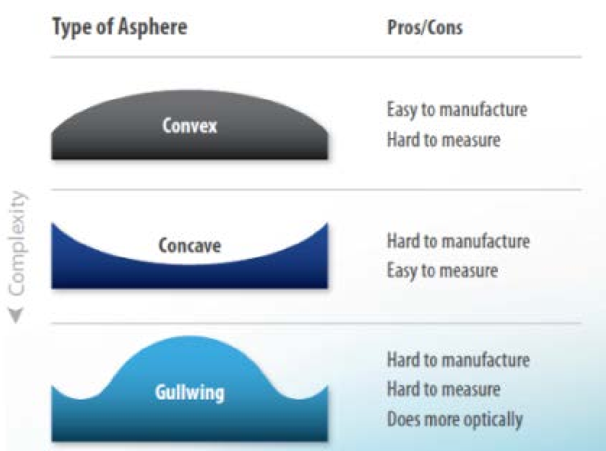


Figure 2: Graphical representation of increasing complexity of aspheric surfaces

All of the aspheres mentioned above have the advantage of rotational symmetry. The biggest distinguishing feature of a freeform surface over an asphere is a lack of symmetry. Non-rotational symmetry increases the demands placed on the manufacturing and testing process.

The freeform optical manufacturing and testing process presented here introduces the freeform surface profile in the initial surface generation. Figure 3 shows a general freeform manufacturing and testing process. Depending on the surface shape and tolerances, all or some of these steps are required. For the example, for the freeform surface shown in Figure 4, only the first three steps of the process were necessary due to the surface specifications (< 10µm PV form error). Generation of the shape was necessary. Figure 4 shows a photograph of the freeform being generated and the associated full aperture form error measured on a scanning probe coordinate measuring machine (CMM) after generation. Figure 5 contains a photograph of the same optic being pre-polished using the VIBE polishing along with the form error over the clear aperture of the surface after VIBE polishing. The general form was held while smoothing the higher frequency noise. Two of the main benefits of the VIBE process are the high speed associated with the process and the ability to maintain the form introduced during generation.[9, 10]

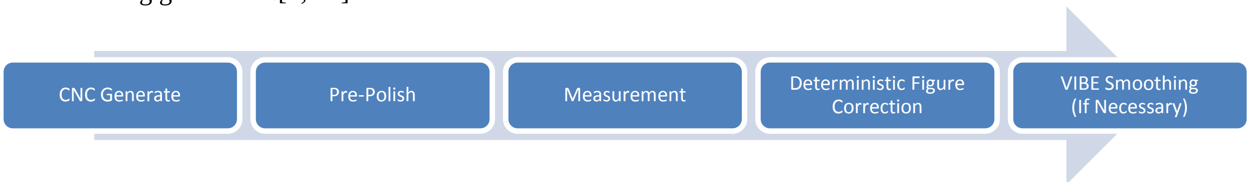


Figure 3: Freeform optical manufacturing and testing process

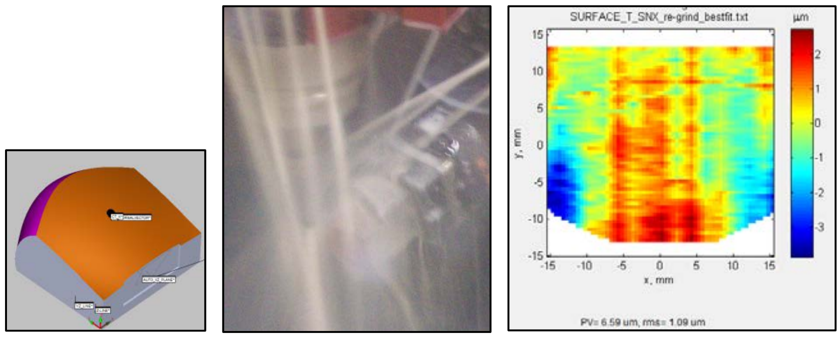


Figure 4: Computer model of the freeform optic (left), photograph of the freeform surface being generated (center) and the resulting surface form after generation (right)

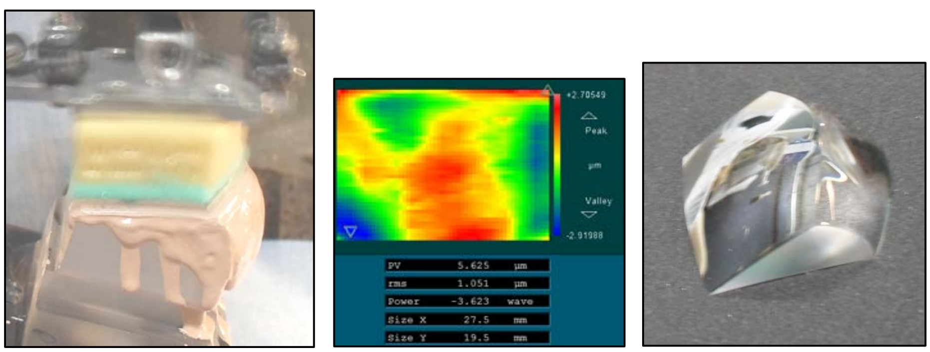


Figure 5: Photograph of the VIBE polishing process (left), the resulting surface form after polishing (center) and a photograph of the final polished surface (right)

The form error after the VIBE polishing process is limited to the form accuracy of the generation process. In order to achieve higher precision freeform surface, sub-aperture deterministic polishing processes are necessary.[11, 12] Deterministic polishing processes are dependent on the metrology method used to measure the initial figure error. The area of freeform metrology is currently under investigation by a number of different research groups.[13-15] Achievable surface form error of freeform surfaces is a function of the complexity of the shape and the uncertainty of the measurement method. A typical scanning probe coordinate measuring machine is limited to approximately ±1 µm PV form error.[15]

Surface smoothing may or may not be necessary based on the application and the severity of resulting mid-spatial frequency errors on the surface. Smoothing can be done implementing the VIBE smoothing process.[16]

3. LIMITATIONS, SPECIFICATIONS AND TOLERANCING SUGGESTIONS FOR FREEFORMS

There are currently three major freeform manufacturing and testing limitations to consider when designing a freeform optical surface; measurement method, local concave radius and maximum sag. The measurement method dictates achievable form error, two main paths include interferometry and profilometry [17-20]. Interferometry is applicable to select surfaces and can measure freeforms to fractional wave surface irregularities. In order to implement traditional interferometric techniques, use of a computer generated hologram (CGH) or stitching if possible. Figure 6 shows an illustration of how a CGH is used with a spherical wavefront to measure a freeform surface. Figure 7 is an example of an off-axis parabola measured interferometrically to a λ/40 peak-to-valley (PV) surface irregularity. Profilometry typically using a coordinate measuring machine (CMM) is applicable to most surfaces and is good for form errors down to one micron surface irregularity. Figure 8 is photograph of a CMM measuring a surface and Figure 9 is a photograph of an anamorphic freeform and corresponding data measured with a CMM to 5 μm surface irregularity. In general a measurement method guideline to determine possible form error is that if a surface can be measured interferometrically, it is possible to achieve interferometric form error > λ/40 PV, and if interferometric measurement is not possible, a CMM can be used to measure form error to greater than +/- 0.5 μm PV.

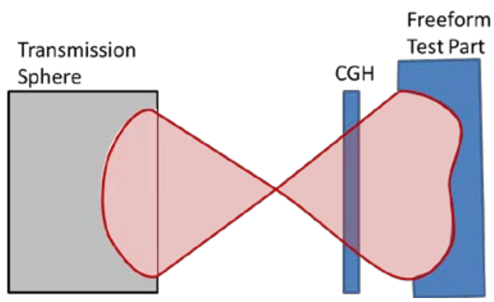


Figure 6: Illustration of using a computer generated hologram (CGH) to interferometrically measure a freeform surface.

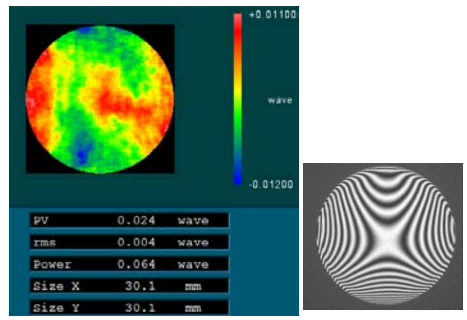


Figure 7: Example data from of a 30 mm clear aperture off-axis parabola that was finished to λ/40 PV irregularity

Figure 8: Photograph of a coordinate measuring machine (CMM) measuring a freeform surface.

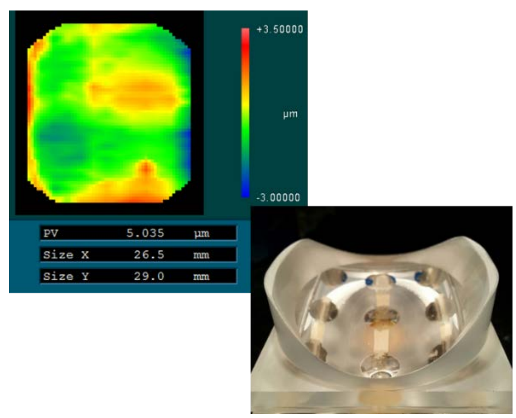


Figure 9: Example data from a 26 x 29 mm clear aperture anamophic freeform surface that was finished to 5 μm PV irregularity.

The local concave radius of a freeform surface dictates what process/tool and measurement method can be used. A sketch illustrating a local concave radius is shown in Figure 10. Please note that this condition this may occur outside the clear aperture which is one major reason it is important to extend the surface form outside the clear aperture to ensure it is well-behaved. A general guideline for possible local concave radius is to ensure that it is greater than 8 mm.

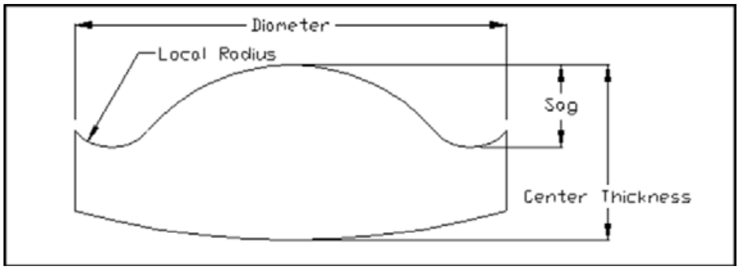


Figure 10: Sketch of an aspheric surface with a local concave radius.

The maximum sag dictates if there is tool clearance. A sketch of a concave surface where the maximum sag conflicts with the tool is shown in Figure 11. The maximum sag possible is highly dependent on the size or diameter of the optic. A general guideline for maximum sag to keep it less than 50 mm for optics with diameters on the order of 200 mm.

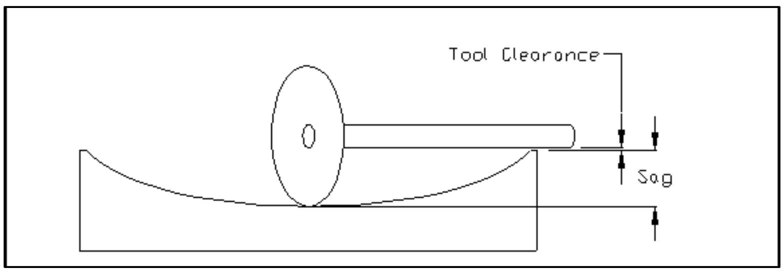


Figure 11: Sketch of a concave surface with possible tool clearance conflict due to a large sag condition.

Freeform tolerance limitations are similar to aspheres. Table 3 compares current asphere tolerance limits to freeform tolerance limits, which can be used as a guideline for determining feasibility of including freeforms in optical designs. This table also highlights key areas of room for future work, such as better definition and control of (center) thickness and wedge. Irregularity or form error is also highly dependent on the measurement method available, improvements in this area can be made for both manufacturing and testing to allow for fractional wave freeforms.

Attribute	Asphere Tolerancing Limit	Freeform Tolerancing Limit
Glass Quality (n_d, v_d)	Melt Rebalanced and Controlled	Melt Rebalanced and Controlled
Perimeter (mm)	+0, -0.010	+0, -0.010
~~Center~~ Thickness (mm)	± 0.010	± 0.050
Clear Aperture	95%	95%
Vertex Radius	± 0.1%	NA
Irregularity – Interferometry (HeNe waves)	0.020	0.025
Irregularity – Profilometry (µm)	± 0.5	± 0.5
Wedge Lens – ETD (mm)	0.002	TBD
Bevels – Face Width @ 45° (mm)	± 0.05	± 0.05
Scratch – Dig (MIL-PRF-13830B)	10 – 5	10 – 5
Surface Roughness (Å RMS)	5	5

Table 3: General list of soft tolerance limits for glass aspheric and freeform optics

As mentioned earlier, freeform optical manufacturing is similar to high departure and complex aspheres, which implies that many of the same challenges apply, such as a minimum local concave radius and maximum sag to allow for tool clearances. Also similar to aspheres, during manufacturing the freeform surface is oversized in diameter/aperture. It is important that the surface continues to be "well behaved" outside the clear aperture to avoid exotic or undefined surface changes just beyond final aperture.

Measurement is a gating item. Initial work shows that various measurement platforms correlate, but discrepancies at low orders remain.[15] Although significant progress has been made in this area, additional research is required in order to ensure the capability of fractional wave freeform surfaces.

In addition to reducing freeform measurement uncertainty, questions have arisen around specifying and controlling the surface form. A few of these questions include: How is radius error separated from irregularity? How is alignment error separated from irregularity? How is wedge defined for a freeform? How is thickness measured and defined? One key lesson learned while encountering these questions is the importance of physical datums to help control and minimize alignment and machine registration errors.

4. CONCLUSION

Freeform manufacturing and testing methods continue to evolve. Achievable surface quality of freeform optics depend on available measurement methods and every freeform is its own unique case and it is recommended to consult an optical fabricator early in the design process to ensure manufacturability. A complete freeform specification should contain physical datums (fiducials) with well-defined XY orientation and an equation or solid model with wedge and thickness defined. New advances are made every day to improve fabrication and testing methods to push limits for fractional wave surfaces that include topics such as novel measurement techniques, and researching better ways to use datums and fiducials.

REFERENCES

[1] A. W. Greynolds, "Battle of the Biconics: Comparison and Application of Various Anamorphic Optical Surfaces," in *Imaging and Applied Optics 2015*, OSA Technical Digest (online) (Optical Society of America, 2015), paper FT2B.1.

[2] E. Goodwin, U. Fuchs, S. Gangadhara, S. Kiontke, V. Smagley, and A. Yates, "Design and Implementation of a New Freeform Surface Based on Chebyshev Polynomials," in *Imaging and Applied Optics 2015*, OSA Technical Digest (online) (Optical Society of America, 2015), paper FT2B.3.

[3] M. Chrisp and B. Primeau, "Imaging with NURBS Freeform Surfaces," in *Imaging and Applied Optics 2015*, OSA Technical Digest (online) (Optical Society of America, 2015), paper FW2B.1.

[4] C. Menke, "Optical Design with Orthogonal Freeform Representations," in *Imaging and Applied Optics 2015*, OSA Technical Digest (online) (Optical Society of America, 2015), paper FW2B.3.

[5] K. Fuerschbach, J. P. Rolland, and K. P. Rolland-Thompson, "Realizing Freeform: A LWIR Imager in a Spherical Package," in *Renewable Energy and the Environment*, OSA Technical Digest (online) (Optical Society of America, 2013), paper FW1B.2.

[6] R.H. Wilson, R.C. Brost, D.R. Strip, R.J. Sudol, R.N. Youngworth, P.O. McLaughlin, Considerations for tolerancing aspheric optical components, Applied Optics, 43 (2004) 10.

[7] G.W. Forbes, Shape specification for axially symmetric optical surfaces, Opt Express, 15 (2007) 5218-5226.

[8] G. Forbes, P.E. Murphy, Simple Manufacturabilty Estimates for Optical Aspheres, in: Frontiers in Optics, OSA, Rochester, NY, 2010.

[9] J.D. Nelson, A. Gould, C. Klinger, M. Mandina, Incorporating VIBE into the precision optics manufacturing process, in: J.H. Burge, O.W. Fahnle, R. Williamson (Eds.) Optical Manufacturing and Testing IX, SPIE, 2011.

[10] J.D. Nelson, A. Gould, N. Smith, K. Medicus, M. Mandina, Advances in freeform optics fabrication for conformal window and dome applications, in: R.W. Tustison (Ed.) Window and Dome Technologies and Materials XIII, SPIE, Baltimore, MD, 2013.

[11] N.E. Smith, A. Gould, T. Hordin, K. Medicus, M. Walters, M. Brophy, J.D. Nelson, Conformal window manufacturing process development and demonstration for polycrystalline materials, in: J. Bentley, M. Pfaff (Eds.) Optifab SPIE, 2013.

[12] C. Supranowitz, P. Dumas, T. Nitzsche, J.D. Nelson, B. Light, K. Medicus, N. Smith, Fabrication and metrology of high-precision freeform surfaces, in: J. Bentley, M. Pfaff (Eds.) Optifab, SPIE, 2013.

[13] S. DeFisher, E. Fess, Non-contact metrology of aspheres and windows of large departure, in: Optical Manufacturing and Testing X, SPIE, 2013.

[14] M. Gutin, O. Gutin, X.-M. Wang, A. Gutin, Interferometric tomography metrology of conformal optics, in: Window and Dome Technologies and Materials XIII, SPIE, 2013.

[15] K. Medicus, S. DeFisher, M. Bauza, P. Dumas, Round-Robin measurements of toroidal window, in: J. Bentley, M. Pfaff (Eds.) Optifab, SPIE, 2013.

[16] J.D. Nelson, B. Light, D.E. Savage, R.A. Wiederhold, M.P. Mandina, VIBE finishing to remove mid-spatial frequency ripple, in: Inernational Optical Design Conference and Optical Fabrication and Testing 2010, OSA, Jackson Hole, WY, 2010, pp. OWE2.

[17] C. J. Evans and A. D. Davies, "Freeform Optical Surface Metrology: Challenges and Capabilities," in *Imaging and Applied Optics 2015*, OSA Technical Digest (online) (Optical Society of America, 2015), paper FT3B.1.

[18] M. Beier, D. Stumpf, U. D. Zeitner, A. Gebhardt, J. Hartung, S. Risse, R. Eberhardt, H. Gross, and A. Tünnermann, "Measuring position and figure deviation of freeform mirrors with computer generated holograms," in *Imaging and Applied Optics 2015*, OSA Technical Digest (online) (Optical Society of America, 2015), paper FT3B.2.

[19] P. R. Dumas, "How MRF and SSI can benefit Freeform Manufacturing," in *Imaging and Applied Optics 2015*, OSA Technical Digest (presentation only online) (Optical Society of America, 2015), paper FTh1B.1.

[20] S. Defisher, "Metrology for Manufacturing of Freeform Optical Surfaces with UltraSurf," in *Imaging and Applied Optics 2015*, OSA Technical Digest (online) (Optical Society of America, 2015), paper JT5A.6.