Deflectometric Acquisition of Large Optical Surfaces DaOS

Using a new physical measurement principle: vignetting field stop procedure

Engelbert Hofbauer and Rolf Rascher

The vignetting field stop procedure uses a deflectometric approach to acquire big optical surfaces (DaOS) and it offers the possibility to measure nearly any shape or form by using a scanning routine. The basic physical measurement principle in DaOS is the vignetting of a quasi-parallel light beam emitted by an expanded light source in auto-collimation arrangement with a reflecting element. Thereby, nearly any curvature of the specimen is measurable. Due to the fact that even sign changes in the curvature can be detected, aspheres and freeform surfaces of any size can be evaluated. Actual results of test measurements with calculated absolute deviation with larger lateral dimensions on flat and spherical specimen with diameter of 300 mm are examined. These measurements are compared critically to reference results which are recorded by interferometry and the DFR method.

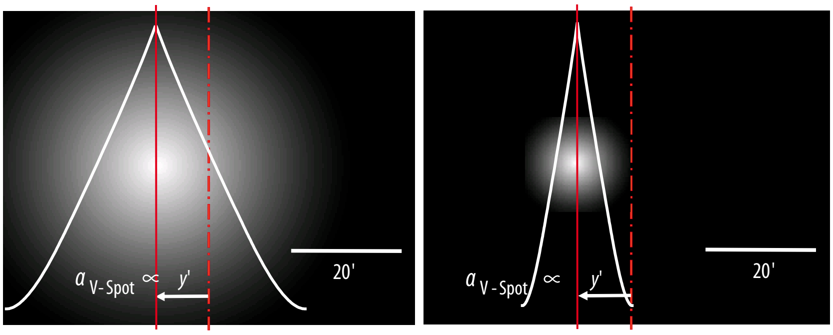

Fig. 1 Image and intensity distribution on an image sensor with 1/2" CCD-camera and focal length f' = 140 mm F / 5

In the field of precision optics, interferometry is mostly used to determine shape errors of spherical or flat surfaces. However, especially for large convex optics or aspheres, its functionality is strongly limited. Very large collimator optics and also large reference surfaces are necessary so the costs are growing dramatically. The principle of deflectometric flatness reference DFR is well known by using a scanning pentaprism [1] or pentamirror. This works very well at flat surfaces down to the sub-nanometer scale [2, 3]. However, the problem is the measurement on strongly curved optical surfaces like spheres, aspheres or freeforms with slope changes larger than for example ± 1,000 arcsec. The additional effect of vignetting by classical autocollimator with crosshair in the object field as a point (e.g. on the optical axis) is not successful for such measurement because reflected beams do not fit the aperture of the optic of the autocollimator.

Company

HOFBAUER OPTIK Mess- & Prüftechnik

Munich, Germany

HOFBAUER OPTIK Mess- & Prüftechnik develops and manufactures angle measurement sensors for straightness, flatness and alignment, as well as 3-D measurement technology for mechanical engineering and optical production measurement technology. It advises companies in technical optics, optical metrology, assembly and manufacturing technology of precision optical, optomechanical components and systems and carries out calibration services.

www.hofbauer-optik.de

DaOS for large curved surfaces

Combining the deflectometric flatness reference with vignetting field stop procedure VFS [4] leads to the deflectometric acquisition of optical surface DaOS. Therefore, another data acquisition system is necessary. The vignetting field stop or so called V-SPOT procedure [4 – 6] is able to solve the problems of the classical autocollimator and gives further innovative solutions and options. Instead of a sharp picture, a mathematically clearly describable and defocused light spot is determined. The following image processing method calculates the value of the lateral offset corresponding to the angle of reflected beams.

Vignetting field stop procedure VFS

The vignetting field stop VFS is a special autocollimation principle developed by Dr. Hofbauer, using vignetting of the small aperture of the collimating optics. Instead of a fixed crosshair in the object field of the optical axis at the classical autocollimator, the larger emitting area allows varying the path of light, corre-

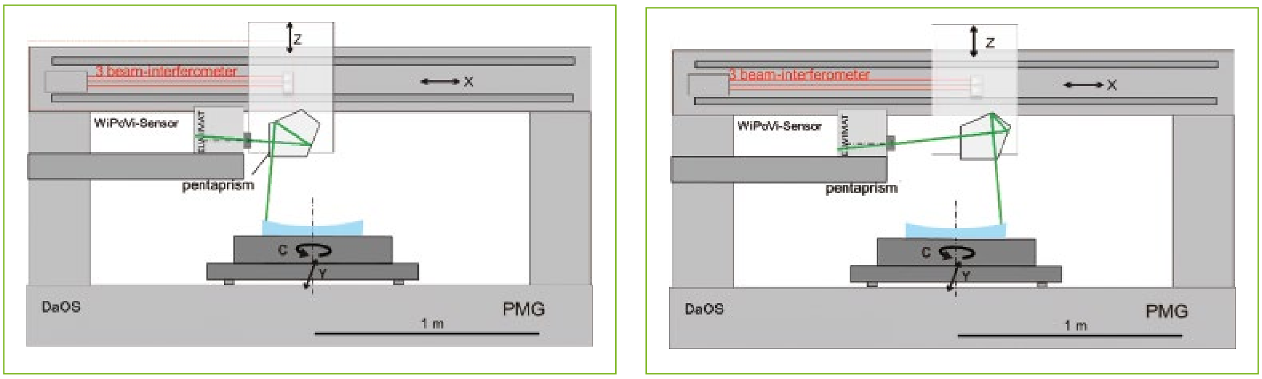

Fig. 2 Setup of DaOS in two edge positions. One of the emitted beams within the measurement range will always be perpendicular to the surface under test SUT. It will be reflected directly back to the sensor and fit the aperture of the optics of the V-SPOT-sensor.

sponding to perpendicularity of surface at specimen under test and illuminating of full entrance pupil.

Fig. 1 shows the image on a ½" CCD sensor using a focal length of 140 mm with F / 5 at mirror distance of 500 (left) and 2000 mm (right). The lateral shift of V-SPOT (image height y') is proportional linearly to the mirror tilt α by

$$\tan\alpha = y'_{\text{V-SPOT}} / f' \qquad (1)$$

This also means that the measurement range of equivalent sensors (same camera format and focal length) is two times larger than at the classical autocollimator. In practice, a focal length of 46 mm at F / 5 with 1,2 MP camera format of about ½" is used. The physical resolution for the movement detection in lateral displacement for the single binary V-SPOT detection is given by [7]

$$\Delta\alpha, \Delta\beta = 1/\pi \cdot \sqrt{r_{\text{V-SPOT}}} \qquad (2)$$

with $r_{\text{V-SPOT}}$ as radius of the binarized V-SPOT (= BLOB) in range of several pixels to several hundred pixels.

Even for a non-binarised V-SPOT, the resolution will increase. The accuracy (linearity) over the range of ± 2,8° is smaller than 0,001° (3,6 arcsec) with an average rms-value of < 0,00045° (1,6 arcsec) over a mirror distance range from 300 to 2,400 mm.

Deflectometric acquisition of DaOS with VFS

In order to detect also reflected light from the edge of specimen under test, the VFS sensor has to have an angular measurement range up to a maximum slope on the edge. Then measurements can be done as seen in Fig. 2.

Reconstruction of optical surface by line scan methods

In order to reconstruct the surface of a substrate, several radial sections will be measured, using scans at azimuthal directions (e.g. 0°, 45°, 90° and 135°, Fig. 3). More scans allow better reconstruction. In addition to these radial sections, measurements in one or more circular sections are necessary to get correct reconstruction including all information about aberrations of third and higher order like Coma, Trefoil, and others.

To reconstruct the complete surface out of the small amount of data points of the measured traces along the surface, several approaches were created and due to a program routine in our laboratory, the measured traces along the surface were converted into mod-format. The results were saved as x-y-z files to enable an alignment of the PV, rms- and power-values with the analysis software MetroPro. For our own approach the development environment MATLAB is used. The main part of all developed analysis algorithms is the use of a Zernike polynomial expansion.

Measurement results

Single line scan with absolute accuracy for radius measurement

Very first results as shown in SPIE Proceedings [6, 7] are done with the sensor ELWIMAT 45-46 SN.#14, a sensor with focal length of 46 mm by F / 4.8. A

Institute

Technology Campus Teisnach
Teisnach, Germany

The Technology Campus Teisnach bundles Deggendorf Institute of Technology's know-how in the field of optical technologies with process development and optimization, measurement engineering and manufacturing engineering. The research group "Optical engineering" at the DIT has worked on these competencies for many years. TC-Teisnach works as research and manufacturing partner in funded projects and for industrial customers.

www.th-deg.de/de/tc-teisnach

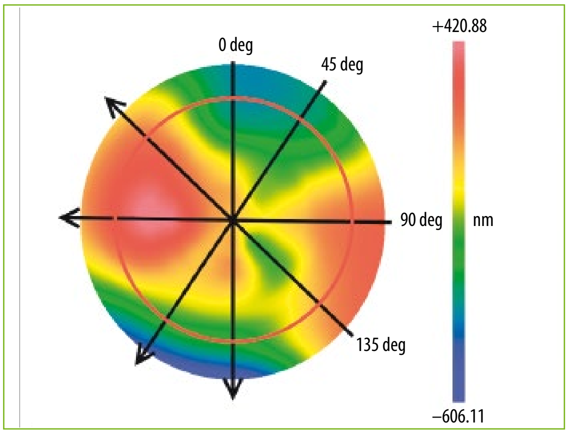

Fig. 3 Lines and optional ring segments of future DaOS-surface evaluation of large optics

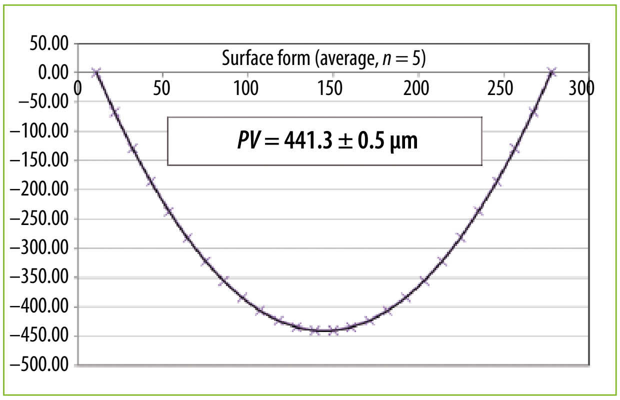

Fig. 4 Average result of surface form deviation on mirror with radius 20 m.

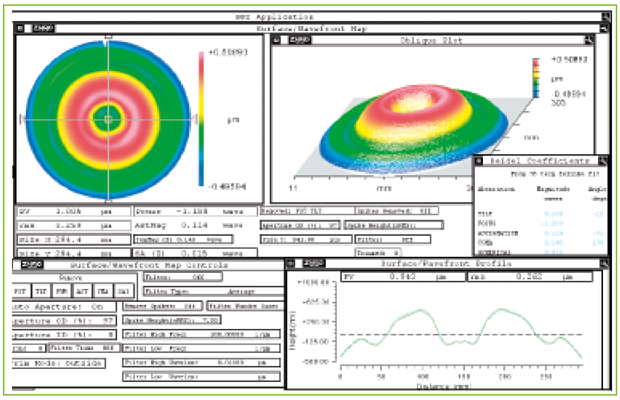

Fig. 5 Interferometric measurement result at plano-double-sombrero, diameter 300, with long term and mid-frequency aberrations with 12" interferometer.

mirror (sample one) with a smooth radius of radius R about 20 m, Ø 300 mm, coated with aluminum has been measured according DaOS with this sensor (Fig. 4). The sagitta height of 441.3 µm with an evaluated and calculated uncertainty of ± 0.5 µm at the measured diameter of 270 mm ± 0.7 mm enables to calculate the radius of curvature to 20.280 mm with uncertainty of 140 mm (k = 2). This means a relative error of radius of 0,69 % and a SAG error according to ISO 10110-5 of about eleven fringes (3/ 11 (-,-).

There are some influences in measurement errors which have to be considered to get highest accuracy better than $\lambda/10$ @ 633 nm. On the one hand, there are systematic errors like geometrical deviations, pentaprism adjustment, wavefront aberrations, linearity, and distance depending linearity effects of V-SPOT sensor. On the other hand, several random errors like temperature variations in measurement environment and on DUT, vibrations and air turbulences, random errors of sensor signal processing (signal-to-noise ratio), non-reproducible roll angel, and others may influence the measurement. The error budget can reach up to 1.5 µm [8] per line scan if errors will not be considered and eliminated or reduced.

Validation of long term and higher order aberrations

In order to validate the measurement principle of new DaOS, a special "plano-aspheric" geometry with "double-sombrero" was measured by a round robin test. Ø = 308 mm, thickness = 50 mm $Ø_e$ = 300 mm / 294 mm.

We used interferometry at the one hand and DFR on the other hand for evaluation. For interferometric measurements, a QED SSI-A instrument with a 4"-TF and a 6"-TF – both calibrated with tree flat test at TC Teisnach – was used. Another evaluation is given by a 12" Fizeau interferometer from Zygo Corp. in vertical position at the cooperating company Berliner Glas. The DFR setup at PMG in Teisnach was done with three different classical electronic autocollimators: ELCOMAT 2000 (f = 300, Möller-Wedel,), Triangle (f = 500, Trioptics) and ELWIMAT_AKF 46/40-19 (f = 46, Hofbauer Optik). The surface was reconstructed according to Fig. 3.

Reference measurements with interferometry and DFR-measurements

First, we measured the plano-double-sombrero at SSI-A with 4" TF transmission flat which was calibrated using the tree flat test in 2012. Second and after some deviations on DFR measurements, we made a three flat test on 4" TF and also at a 6" TF. Fig. 5 shows the result of the 12" interferometer measurement at Berliner Glas and table 1 includes the summarized PV, rms and SAG error (power) for all interferometric measurements.

The results showed in table 1 offer an average PV Value of 985 nm with a maximum deviation of 50 nm at all three measurements in two different laboratories and two different types of interferometers. The absolute deviation of 3D-fitted power (SAG error) is at maximum 66 nm. The standard deviation of the average of the three measurement results is 39 nm. The larger deviation of power at the instrument of Berliner Glas is a gravity induced effect because, due

Interferometric	PV [µm]	RMS [µm]	SAG [µm]	DFR	PV [µm]	RMS [µm]	SAG [µm]
SSI-A 4"	0.955	0.249	−0.717	ELCOMAT 2000	0.965	0.253	−0.752
SSI-A 6"	0.973	0.244	−0.686	Trioptics AKF 500	1.039	0.266	−0.793
BG 12"-Vertical	1.005	0.259	−0.752	ELWIMAT_AKF46	0.910	0.232	−0.640
Average	0.985	0.251	−0.723	Average	0.974	0.250	−0.729
Std. Dev.	0.037	0.008	0.039	Std. Dev.	0.061	0.017	0.079
Max. Difference	0.050	0.015	0.066	Max. Difference	0.129	0.024	0.153

Table 1 Results in interferometric and DFR-measurements of the "plano-double-sombrero" ($Ø_e$ 294 mm)

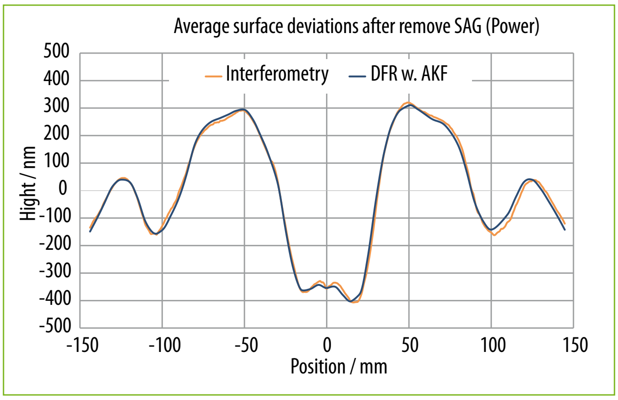

Fig. 6 Averages of Interferometric and auto collimator DFR measurements at azimuth 0° after removing SAG error.

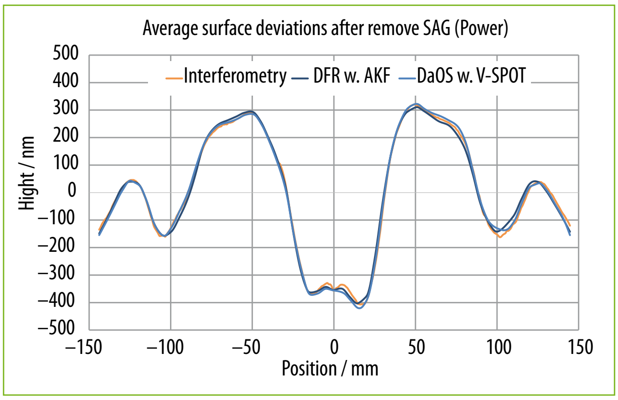

Fig. 7 Interferometric, DFR- and DaOS- measurements of plano-double-sombrero at azimuth 0°.

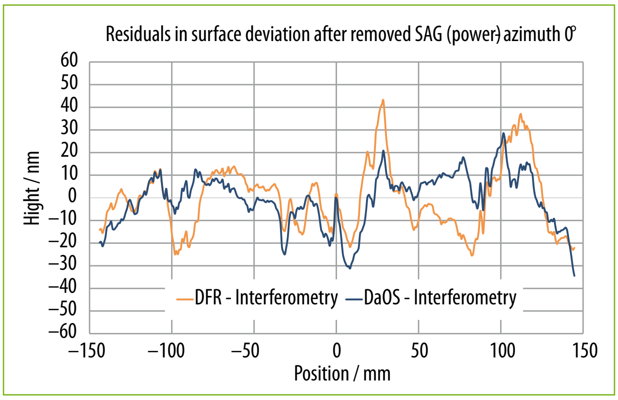

Fig. 8 Residuals of DFR- and DaOS- measurements against Interferometric results of plano-double-sombrero at azimuth 0°

to the vertical orientation, the transmission reference flat shows deformation of about 50 nm in the power term.

The deflectometric measurements with classical electronic autocollimators (crosshair) were done in four sections at 0°, 45°, 90° and 135 degrees. A stop was applied near to the surface under test with an area of 14 × 20 mm for ELCOMAT 2000 (step 10 mm) and a diameter of 5 mm for Triangle 500 and ELWIMAT_AKF 46 mm. At that position, the distance of measurement steps has been 5 mm. The scans are used to reconstruct the surface by software. The results in PV, rms and power are seen on the right part of table 1. Significantly, we can see the PV values, which correspond strongly with the influence of power in table 1. Considering the range of PV value up to 129 nm and power (SAG) up to 153 nm at DFR-measurements, we can realize a time and temperature depending influence, which is about 2.5 times bigger than at the results of the interferometric measurements. To eliminate these effects influenced by temperature on not stable material we subtracted the power-term (SAG) at all measurements and analysed the irregularity IRR corresponding to the DIN-ISO 10110-5 to get a better comparison for our measurement principle. Fig. 6 shows the average surface measurement of the two SSI-A interferometric measurements and the average of all three autocollimators.

DaOS-measurements on double sombrero with V-SPOT sensor

At last, measurements are done with the modified and contrast enhanced Vignetting V-SPOT sensor ELWIMAT

	Interferometry	DFR w. AKF	DaOS w. V-SPOT	Maximum dev.
IRR [nm]	727	714	743	29
rms [nm]	214	213.2	217.9	4.6

Table 2 Results in irregularity IRR after removal of SAG for all types of measurements at the "plano-double-sombrero"

45-4,8#17-K in order to validate also non coated substrates with small reflectivity. Measurements are done in line scans at 0° of plano-double-sombrero eliminating most of the systematic errors like pentaprism wavefront error and distance dependence error of the whole setup of DaOS by reversal measurements [8]. The measuring result of the irregularity IRR is seen in addition to results of reference measurements with interferometry and DFR in Fig. 7.

Table 2 shows the very good agreement of all three measurement types including interferometry, DFR with auto collimator and DaOS with the Vignetting V-SPOT Sensor.

By interpolating the different measurement data, we are able to take the residual curves of the measurements for a direct comparison. Therefore, we take the difference of averaged DFR and also DaOS-measurement to interferometry. The result shows that there are residual errors of about 69 nm PV with 14,5 nm rms at DFR and 63 nm PV with 11,5 rms at DaOS with V-SPOT sensor.

There are some effects in the results in Fig. 8 visible, e.g. the large "peaks" at position 30 mm. A better adjustment of centration or a transformation of coordinates after measurement may help to get better results than IRR < 60 nm according to $\lambda/10$ and rmsi < 11 nm according to $\lambda/50$ @ 633 nm even on large optics.

Summary and Outlook

We showed that it is possible to measure very large radiuses up to 20 m at large optics with more than 300 mm diameter. The relative accuracy of $\Delta R < 0{,}69$ % will be reduced in further developments and future tasks.

Considering the sagitta error (SAG) we can see some temperature effects and influences on the quality of V-SPOT sensor calibration. Further on, and considering the irregularity of spherical optics, we showed the measurements compared with interferometric stitching results at SSI-A and a 12" Fizeau interferometer at Berliner Glas, hence, it is possible to compensate systematical errors of higher order (nonlinearity and penta prism wavefront error) of the setup of DaOS. Good geometrical adjustments and also centration and compensation of mechanical deviations before surface reconstruction may help to get better results than IRR < 60 nm according to $\lambda/10$ and rmsi < 11 nm according to $\lambda/50$ @633 nm even on large optics. This will be a good starting position even without a precision measurement room but measuring in a manufacturing environment.

DOI: 10.1002/opph.201600036

[1] *E. Debler, K. Zander:* „Ebenheitsmessung an optischen Planflächen mit Autokollimationsfernrohr und Pentagonprisma", PTB Mitteilungen Forschen + Prüfen, 89. Jahrgang (1997).

[2] *I. Weingärtner, C. Elster:* System of four distance sensors for high- accuracy measurement of topography, Precision Engineering **28** (2004) 164-170.

[3] *H. Lammert, T. Noll, T. Schlegel, F. Siewert, T. Zeschke:* Details XUV-Optik – Neue unkonventionelle Bestimmung ihrer Flächenformen bei BESSY mit der NOM, DgAO 105. Tagung (2004).

[4] *E. Hofbauer, M. Lenz:* Vignettierung als physikalisches Messprinzip, Technisches Messen **75** (2008) 3.

[5] *E. Hofbauer:* Optisches Verfahren zur zweidimensionalen Messung von Winkeln und Winkeländerungen bei großen Messabständen, Dissertation (2007).

[6] *E. Hofbauer* et al.: 3D-optical measurement system using vignetting aperture procedure, Proc. of SPIE **9132** (2014) 913206-14.

[7] *T. Zellner:* Programmierung, Simulation und Optimierung des videogestützten optischen Winkelmesssystems ELWIMAT, Diplomarbeit Hochschule München (2005).

[8] *E. Hofbauer, R. Rascher, M. Schilke, J. Liebl, P.-P. Richters:* Deflectometric…SPIE-Proceeding POM100-33, Juli 2016.

Authors

Engelbert Hofbauer graduated in precision engineering at University of Applied Sciences in Munich as Dipl.-Ing. (FH) he promoted 2008 at TU Ilmenau, Department of Technical Optics. From 2009, he set up and supervised the measurement room for production measurement technology at TC Teisnach of DIT. Since 2013, he has been working as a research associate and consultant, researching the optical production measurement technology. For more than 30 years, he has been working on the techniques of industrial angle measurement technology.

Rolf Rascher graduated in mechanical engineering at TU Munich he is Professor at the Deggendorf Institute of Technology since 2001 and today in the faculty natural sciences and industrial engineering. Focus of his teaching is production technology and technology management. Since October 2009, he leads the Technology Campus Teisnach and the research group Optical Engineering at the DIT. He takes care of a variety of industrial R&D projects in the area of the manufacturing, process development in optics and measuring technology for optics.

Dr. Ing. Engelbert Hofbauer, Hofbauer Optik Mess- & Prüftechnik, Petzetstraße 8, 81245 Munich, Germany, Phone: +49 89 89669088, e.hofbauer@hofbauer-optik.de, www.hofbauer-optik.de