Review Article

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Metrology for the production process of aspheric lenses

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Abstract: Metrology revealing the form deviation of an aspheric surface is a fundamental part of all different production processes of aspheric lenses. Different processing steps have different requirements for the production. A selection of measuring instruments commonly applied in these processes is presented. This contains tactile and optical pointwise measuring instruments and laser interferometer systems. The principle functionality and the properties are presented. An overview of the application of these systems in different production processes is given. In order to show comparability, measuring results of the different types of systems are presented.

Keywords: asphere; interferometer; measurement; metrology; profilometer; topography.

1 Introduction

Today aspheric lenses are found in a variety of optical systems. The basis for this success is a functioning process technology, which has continuously developed over the last years. New production equipment can produce even very low quantities of different types of aspheres in an affordable way. Extreme aspheric shapes with strong deviations from best-fit sphere and very steep flanks can be fabricated. These new options of the machining part of the production also pushed the development of new metrology equipment. In many cases, the process strongly depends on a closed-loop process between measurement and machining. This process is based on the measurement of the shape revealing the form deviation of the aspheric surface.

In this paper an overview of the technologies for the measurement of the form of an aspheric surface is presented. The first part describes the general requirements for the metrology for different production processes. In the following, different types of instruments commonly used in production are presented. The two major groups are pointwise measuring instruments and interferometer-based systems. The focus in this paper is the metrology necessary for the production of higher-quality lenses. Other measuring technologies may also be important in the future. These could be Shack-Hartmann sensors [1, 2] sometimes found in ophthalmic applications (see, e.g. [3–5]) or deflectometry systems, which have been significantly improved recently [6]. In order to show the comparability of the different types of instruments, measuring results of the different samples are presented and discussed. As a summary, a table correlates the basic groups of production processes with the different types of measuring instruments. The intention is to give the reader an overview of opportunities for the metrology equipment in production. The paper is based on the practical experience of the author obtained on various shop floors, from discussions with machine suppliers and lens manufacturers and from participation in different conferences over the last years.

1.1 Production processes

Aspheric lenses for different applications are fabricated with different methods. High-precision glass lenses are usually produced by material removal in grinding and polishing processes. Other glass lenses and most plastic lenses are molded. The molds are often produced by diamond turning and also by grinding and polishing. Lenses for infrared optics consisting of calcium fluoride, germanium, silicon, etc., are diamond turned. Emerging production technologies are based on ion beam finishing [7] or laser ablation and polishing [8–10]. These processes depend on metrology equipment, which provides information about the shape of the manufactured lenses. Owing to the increasing new markets and the variety of

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applications, a lot of effort has been put into the refinement of the production process.

The production processes have specific requirements on the metrology needed. In addition, there exists a demand for quality control in different production stages, for the final inspection and incoming goods inspection. For the quality control, the overall deviation of the form or shape, slope deviation, fine structure, roughness, or waviness has to be inspected. Of particular importance for the production of aspheric lenses is the measurement of the form because a measurement in between two production steps allows for the adjustment of the previous step or to correct the deviation in the following. Compared to a spherical lens, an aspheric lens has a contour, which is different from a circle but is otherwise rotationally symmetric. Thus, the major effort in the production is put into the generation of this contour. As an example, the process of the grinding and the polishing of high-precision lenses is demonstrated in principle in Figure 1. The goal of this production is to fabricate high-precision lenses. In order to obtain form deviations of a few hundred nanometers and below, the production machines have to be corrected all the time in a closed-loop process. In the first step, an aspheric contour is ground into a spherical blank. Owing to high material removal, the grinding process is much faster than the following polishing. Thus, the shape of the lens, which is closer to the finally desired shape after grinding, reduces the polishing time, i.e. lowers production costs. The grinding machines can only correct the shape of the contour. The rotational symmetry relies on the spindles in the grinding machines. Therefore, a measurement of the aspheric contour provides the necessary information for the closed-loop production. In addition, the measurement should be fast enough to fit into the cycle time of this process, which can be below 1 min. The rather rough surface from grinding has to be polished in order to obtain a smooth surface. In the following polishing process, remaining form deviations can be further reduced. A simple process can only correct for the contour and, thus, can make use of a contour profile. In addition, some polishing machines are capable of correcting form deviations over the whole topography. Thus, a measurement of the whole topography is necessary. This measurement requires a low measuring uncertainty determining the final shape. The measurement should be non-contact in order to avoid any damage to the surface of the almost finished lens.

Another important example is the diamond-turning process. Again, the challenge is to obtain a contour with sufficient quality. The spindle of a turning machine is good enough to provide a high rotational symmetry of the part. Thus, a measurement of the contour provides the basically necessary information for correction and quality control. In addition, a measurement of the whole topography is desired for the quality control of the final workpiece. In contrast to a grinding process, diamond turning creates a very smooth surface; no additional polishing is necessary. Also, the processed material is usually different from

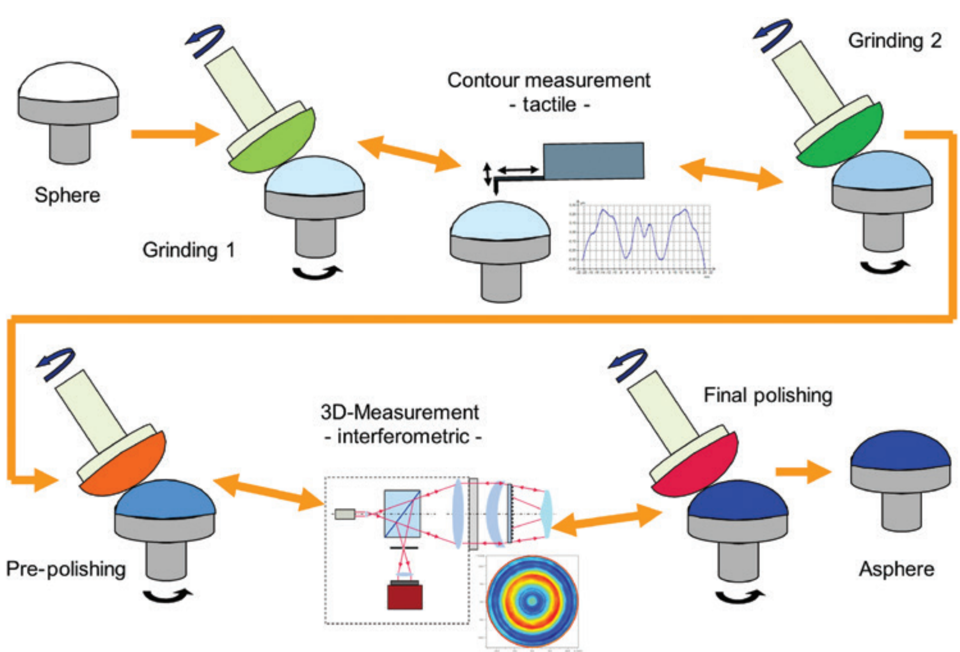

Figure 1: Principle production process for grinding and polishing.

the materials processed in grinding and polishing. Often, the rather soft metals, brass and aluminum, are processed in this way.

In the grinding, polishing, and turning processes, the number of workpieces of a single type produced can be thousands per year or just a single one, which can be a single mold. The continuous variation of the type of the asphere requires a very flexible metrology.

Other metrologies for investigating the fine structure or roughness measured in different processes are not discussed in this paper.

An overview of the basic requirements for the metrology is given in Table 1. It is distinguished between a measurement of the contour (2D) and the topography (3D) and between a contact and non-contact. There are columns for grinding, polishing, and diamond turning and 'QC/QA', which is a place holder for quality control, in general, or other production technologies such as ion beam finishing or laser polishing. An x indicates the standard requirement. Sometimes, other options are also sufficient and are indicated by (x).

2 Pointwise measuring instruments

The first group of instruments discussed measures the shape of the surface point by point. The instruments consist of a probe system, which obtains a single measuring point at a time and additional measuring axes moving the probe around the sample. In the following are presented two types. The first one is a contour measuring instrument, which can measure the contour of an aspheric lens. The second type can measure the whole topography of a lens.

2.1 2D contour measuring instruments

One of the basic instruments required for the production of aspheric lenses is the contour measuring instrument or the so-called profilometer. It can measure a single linear trace of a workpiece. Typically, the instrument consists of a linear axis (x-direction), a probe system with a probe arm, and a probe tip (Figure 2). A complete measuring station contains an additional manual or automatic supplementary axis in order to position the whole instrument in height (HZ) and a table for the positioning of the workpiece (Figure 2). The basic requirement of the linear axis is to perform a highly linear movement. It is the linear reference for the measurement, i.e. a measurement of a flat surface should create a straight line. In order to increase the straightness of the axis, the system can be calibrated via a measurement over a flat reference surface. This can reduce the remaining error to below 100 nm. The linear axis drags the probe tip connected via a probe arm to the probe system over the surface under examination. The probe system is a rocker setup with a probe arm with a probe tip on one side and a measuring system on the other rocker lever. By this, the displacement of the probe tip can be detected. The maximum measuring range, i.e. the vertical (z-direction) movement of the tip, is determined by the maximum rocker angle and the length of the probe arm. Typical probe tips are spherical-shaped diamonds with 2 to 10 µm radius or ruby balls about 1 mm in diameter. It is important that the probe is pushed with a constant well-defined force on the surface. The force can be created by taring the whole rocker and putting the weight necessary for the desired force on the probe tip lever. Another more flexible solution is an active force generator inside the probe system. The force should be adjusted considering the combination of the tip radius and the material of the surface under test. Diamond tips with small radii ≤10 µm in combination with soft material require low measuring forces down to 0.5 mN. Unfortunately, on very soft material, such as aluminum, scratches can still be found, but

Table 1: Overview of the requirements for different processes in the production of aspheric lenses.

	Grinding	Polishing	Diamond turning	QC/QA
2D	x	(x)	x	(x)
3D	(x)	x	(x)	x
Contact	x	(x)	(x)	(x)
Non-contact		x	(x)	x

x indicates the standard requirement. (x) may be a necessary or a useful option if nothing else is available.

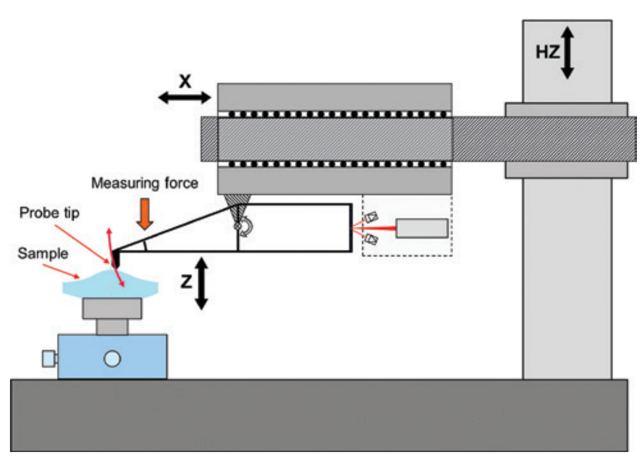

Figure 2: Principle setup of a contour measuring instrument.

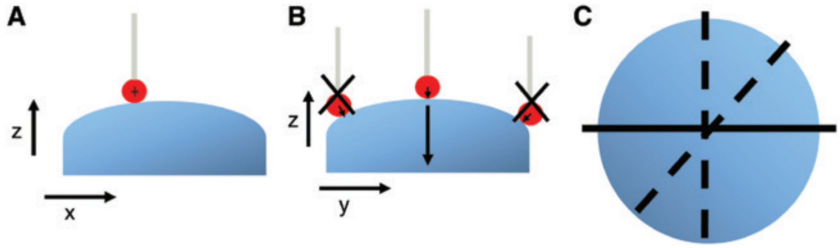

Figure 3: (A) Movement of the center point of the probe tip when scanning across an aspheric lens. (B) Correct and wrong positions of the probe tip for the scan. (C) Possible linear scans across the zenith.

to date, profilometers providing lower measuring forces are not available.

Actually, during the measurement, a profilometer can only track the center of the probe tip (Figure 3A). But the goal of the measurement is to detect the surface of the sample, i.e. the contact points of the sample. The software of the instrument can calculate the contact point with the knowledge of the probe tip radius and the assumption that the contact point is directly below the center point of the probe tip in the y-direction (Figure 3B). In practice, the scan has to be performed over the zenith of an aspheric lens (Figure 3C).

In testing aspheric lenses, a linear scan is performed, and in the subsequent analysis process, the measured profile is fit to the nominal aspheric shape. The differential profile (Figure 4) can then be used to correct the grinding or diamond-turning process. For quality control, peak-to-valley value (PV), root mean square value (RMS), or other surface parameters can be derived from the differential profile. Depending on the stability of the whole production process, these profiles may also be useful in polishing processes. Profilometers can measure flanks up to an angle of about 45°–50°. Even steeper-sided aspheres can be measured by tilting the lens or the instrument. In that process, profiles from both sides can be stitched together.

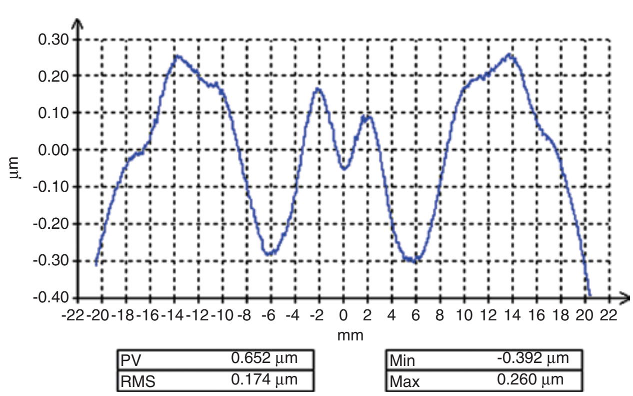

Figure 4: Example for the differential profile obtained from a measurement with a profilometer.

Profilometers are extremely flexible and, in principle, do not need any precognition about the sample. This is different from the other instruments, in particular, the laser interferometer system. These systems require a nominal description of the lens. The profilometer basically needs a start and a stop point. The probe will just follow the contour creating a profile. A description of an unknown lens may then be found by the fit of aspheric coefficients to this profile.

2.2 3D pointwise measuring instruments

A measuring system capable of measuring the topography of an aspheric lens consists of three measuring axes and a probe system. A standard setup, the so-called coordinate measuring instruments (CMM), is a Cartesian structure with a 1D or 3D tactile probe (Figure 5).

These systems can perform measurements of differently shaped samples in a very flexible way. Unfortunately,

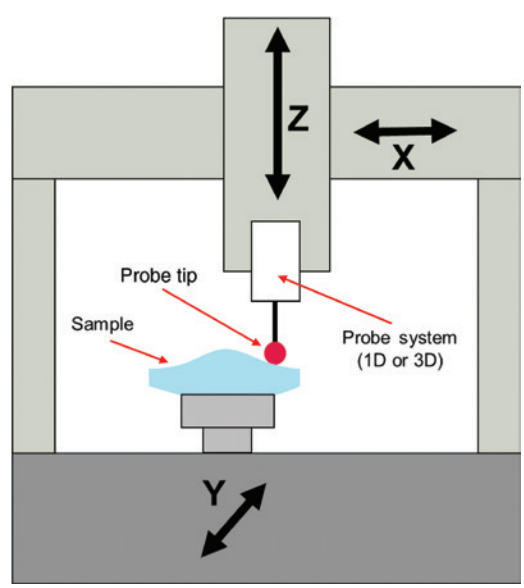

Figure 5: Principle of a coordinate measuring instrument (CMM) with a Cartesian setup.

standard systems are limited in accuracy, which may be sufficient for illumination optics but often not for projection systems. Some high-precision, but expensive, systems are also available and are used for the measurement of aspheric lenses (e.g. [11, 12]). These systems can achieve high accuracies because of a built-in metrology reference frame. A presentation of such a setup is found in Ref. [13]. In order to preserve the sensitive surface of a mold or a polished lens, these instruments include a specially designed probe system with very low measuring forces (0.15 mN [12], 0.07 mN [11]). As for all CMMs, limitations are the measuring speed, which limits the density of measuring points.

Naturally, a Cartesian setup is not ideal for the measurement of a rotationally symmetric sample such as an aspheric lens. Another solution is a system based on a cylindrical coordinate systems. These systems consist of a high-precision spindle with additional linear and rotational axes. A typical group of systems are the so-called form testers (see Figure 6), which are designed to measure features such as roundness, cylindricity, or flatness. A special setup of this type is a combination of a profilometer and a high-precision spindle (Figure 7) [14]. In addition to the linear scans, circular scans can also be performed describing the whole topography of the lens. Other commercially available cylindrical coordinate measuring instruments make use of an optical probe [15–20]. This prevents the surface from being damaged. Another advantage of the optical probe is that the measuring speed and, therefore, the density of the measuring points can be increased. Using a fast high-precision spindle, the speed of rotation can be on the order of one rotation per second. This is only possible with a fast optical probe. The mechanical dynamics of a tactile probe tip in contact with

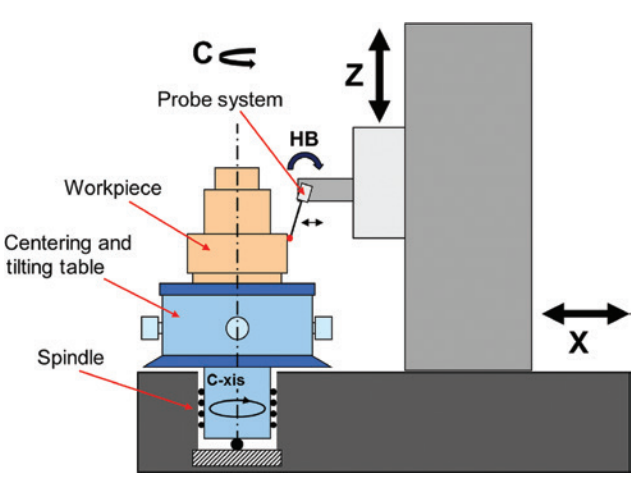

Figure 6: Principle setup of a form tester.

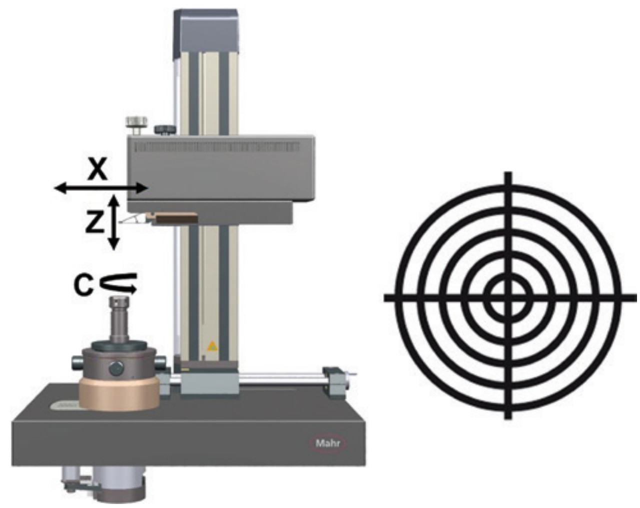

Figure 7: Combination of profilometer with high-precision spindle capable of measuring lines and circles.

the surface limits the velocities to usually about 10 mm/s depending on the actual probe system. At high rotational speeds, i.e. the velocity of the probe tip scanning over the surface is >100 mm/s, the probe tip would just vibrate and jump over the surface.

The measuring systems developed for high-accuracy applications [15–17] utilize an internal compensation system. It consists of sensors measuring distance changes to a reference metrology frame. With this compensation system, the measurement values are corrected for any nonsystematic movements of the axes, e.g. due to load changes or a nonrecurrent behavior of the guidings. One of those systems has a unique feature: it can be equipped with both a tactile and a new type of optical point sensor [15, 16]. This adds an additional amount of flexibility as the tactile and optical sensors have different advantages and limitations. One application is the measurement of the centricity of the aspheric axis measured with the optical probe and to the outer edge measured with the tactile probe.

The 3D pointwise measuring instruments are very flexible. They can measure all kinds of aspheric shapes. There are no limitations such as deviation from best-fit sphere. The type of aspheric lens can easily be changed from one measurement to the next as only different predefined measuring parameters are loaded. A limitation is the overall size of a lens defined by diameter and height. It has to fit into the measuring volume of the system. In order to obtain a sufficient number of measuring points, the measuring time increases with larger lenses.

In the analysis process, similar to the process for the profilometers, the measured 3D profile is fit to the nominal aspheric shape. The differential profile (Figure 8) can then

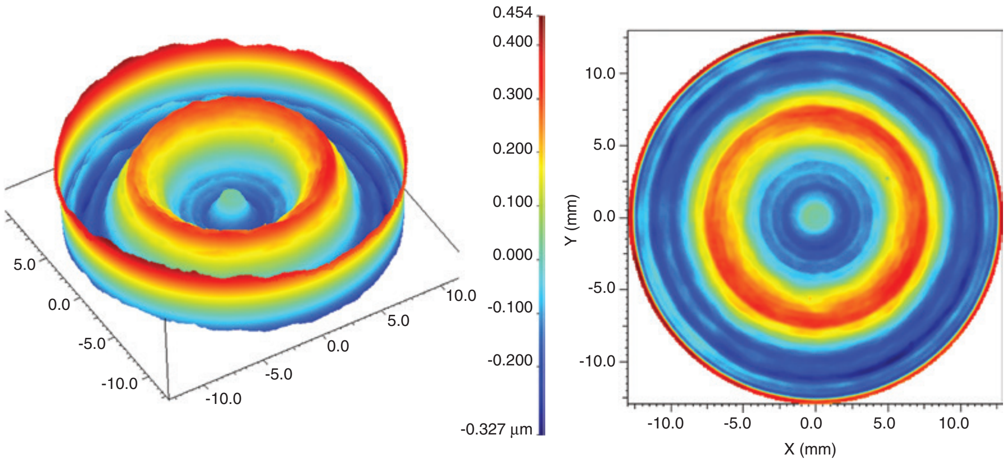

Figure 8: Example of a differential profile obtained from a 3D measurement.

be used for the final correction in the polishing process. For quality control, PV, RMS, or other surface parameters can be derived.

The 3D pointwise measuring systems can be used for many different applications. To start with an aspheric production with rather low investment, the profilometer combined with the high-precision spindle is a very flexible system [14]. It can perform the linear measurements on a rough ground surface and is also capable of measuring the topography of the polished surface for 3D corrections and quality control. The other systems (point3D) are optimized for high-accuracy measurements necessary for the polishing of high-quality aspheric lenses or molds. Usually, the forces of the probe tips are low enough to prevent the surfaces from scratches. Using a tactile probe, these systems can also perform the measurements for the grinding process. But the investment would be too high just for the grinding process.

3 Laser interferometer systems

Laser interferometers are the standard systems to test optical flats, spherical, and aspherical lenses. Commonly used are the Fizeau or Twynman-Green types [21]. As an example, Figure 9 shows a Fizeau interferometer. A collimated beam is combined with a removable transmission sphere available for different focal ratios [22]. With a spherical reference surface, a spherical lens under test can be positioned to have all light beams normal to the test and reference surface. The

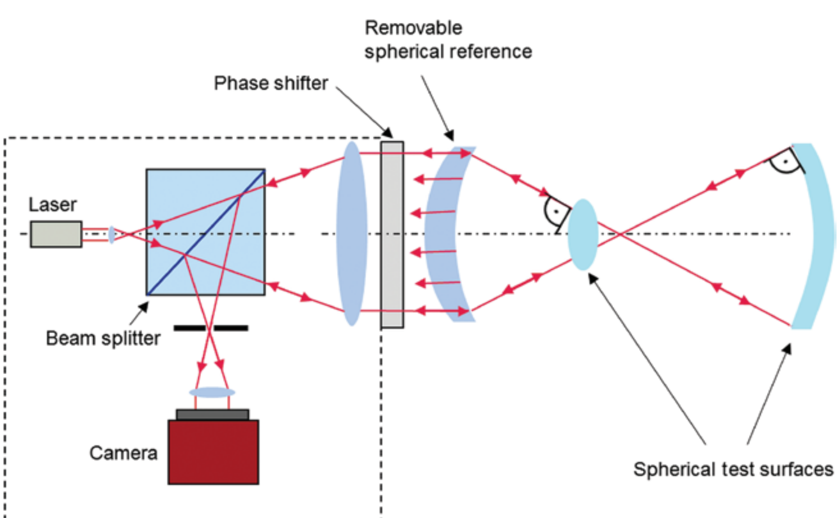

Figure 9: Fizeau interferometer setup for testing spherical lenses.

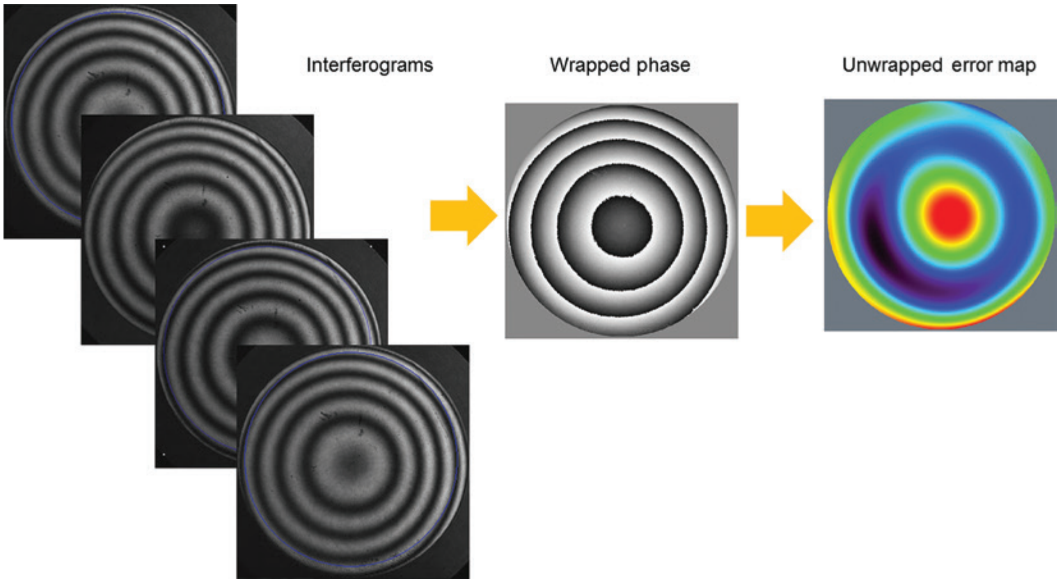

Figure 10: Interferograms of a spherical surface, wrapped phase, and unwrapped error map.

interference between the light reflected from the reference and the test surface creates a fringe pattern on the camera. Including piezo actuators at the transmission sphere for phase shifting, high-precision measurements of the wavefront deviation can be performed [23]. Each phase provides an interferogram, i.e. is the image obtained by the camera (Figure 10). The interferograms are used to calculated first the phase map, which is then unwrapped into the error map. The measurements reveal the differential topography between test and reference surface. The spatial resolution can be at the maximum the resolution of the camera, i.e. today typically 1k×1k or 2k×2k.

With increasing form deviation of the test surface, the density of the fringes on the camera increases, and at a certain slope, the fringes cannot be resolved anymore; the Nyquist limit of the camera is reached [24]. An aspheric test surface may be described with a best-fit sphere and a form deviation from that sphere. Thus, only aspheres with a form deviation creating resolvable fringes, i.e. a few micrometers, can be measured in this setup with a spherical reference surface (Figure 11). Thus, most aspheres produced today cannot be tested with this interferometer setup. An aspheric reference surface matching the asphere under test would be a solution. But in practice, the required high-quality reference aspheres are very difficult to fabricate, and there is no solution to test them, thus, are not available for each type of asphere. In the following different approaches to overcome the problem of the high density of fringes are presented.

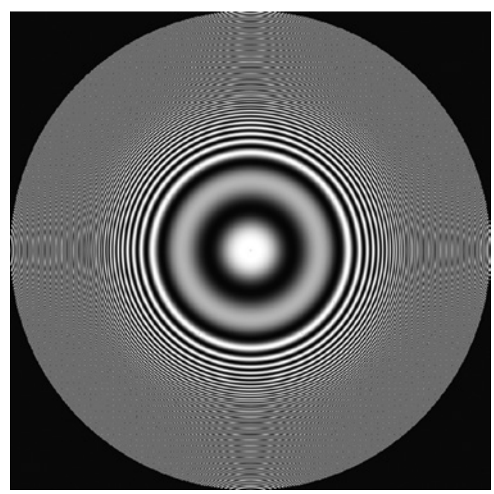

Figure 11: Fringes of an asphere obtained with a spherical reference.

3.1 Laser interferometer with CGH

A computer-generated hologram (CGH) is a binary grating, e.g. chromium on a glass substrate [25], which deforms the wavefront of an incoming wave. The CGH is inserted into the test arm of the interferometer acting as a null lens (Figure 12). For testing aspheric lenses, the CGH is a set of concentric rings. It is calculated to produce a test wavefront matching the nominal shape of the aspheric surface and to recollimate the wavefront from the asphere. The quality of the CGH allows one to perform measurements of aspheres with a measuring uncertainty of PV $\leq \lambda/20$ [26].

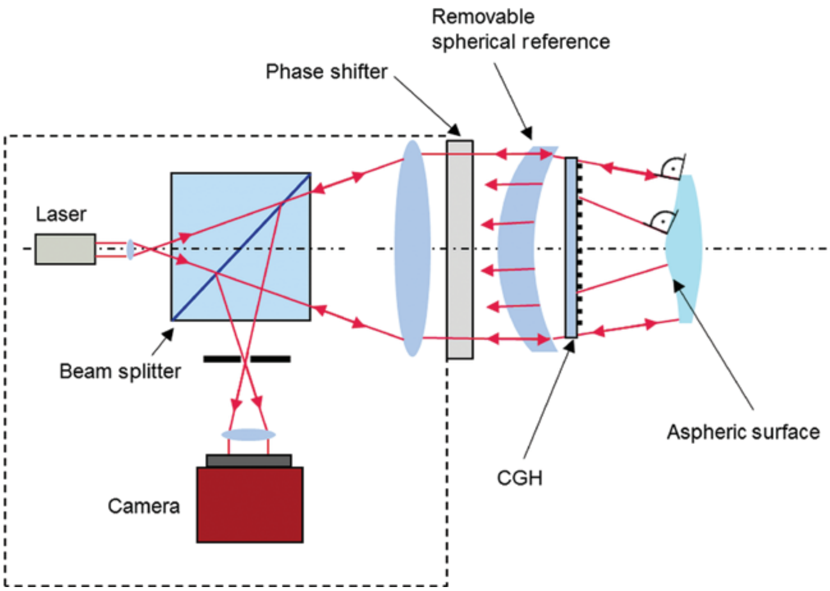

Figure 12: Fizeau interferometer with CGH.

The spatial resolution can be at the maximum the resolution of the camera.

CGHs in combination with a Fizeau laser interferometer have been used for many years to control the polishing process of aspheric lenses. The wavefront error topography can be used to correct the form deviation by local polishing. For a series production of one type of an aspheric lens, the application of CGHs is a robust, cost-efficient, and fast solution. A measurement with a few phase shifts takes only seconds and, thus, fits well into the production cycle. However, the major drawback is the very limited flexibility of this metrology approach. As it requires some effort to align a CGH in an interferometer setup, a frequent exchange of a CGH is inconvenient. Thus, additional interferometer systems for the different types of aspheres in production at a facility may be more efficient.

For low quantities of aspheres to be produced, the costs for the CGH necessary for each type of asphere are too high. In addition, the CGHs have some delivery time creating lead times in production. This prevents the flexible production necessary for prototyping or individual designs. This limited flexibility was the reason for the development of the other 3D metrology approaches discussed in this paper.

3.2 Subaperture stitching

With a decreasing size in the aperture of the measurement, the camera of the interferometer can locally resolve more fringes compared to a measurement of the whole surface of a lens. By making a lot of small aperture measurements with an overlapping range, the whole surface can be stitched together to obtain the whole topography (Figure 13). This method was first developed for convex spherical lenses or mirrors, which are too large or too steep to be measured within one aperture [27] but can also be used to measure mild aspheres (up to 200 waves departure from the best-fit sphere [28, 29]). A further development is the integration of a variable optical null (VON™) device [30, 31]. This generates an optical wavefront, which closely matches the asphere within each local subaperture. Aspheres with up to 1000 waves aspheric departure from the best-fit sphere can be measured with this setup.

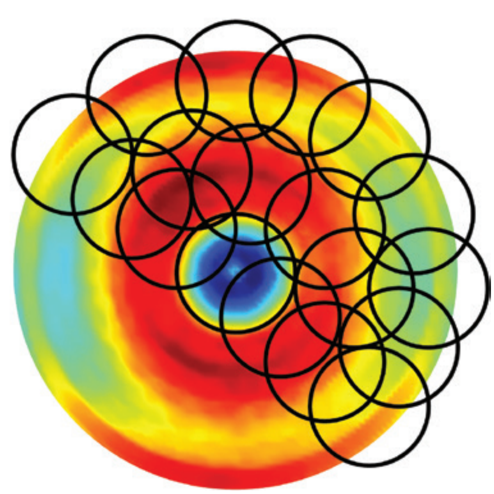

Figure 13: Subaperture stitching of a spherical or aspherical surface.

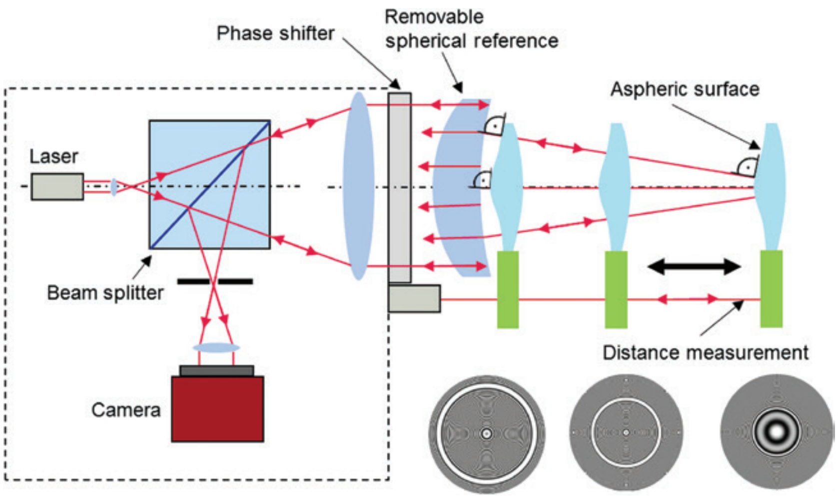

Figure 14: Multi-zone interferometry.

Compared to a CGH setup, an instrument based on this technology provides a very flexible solution with high lateral resolution for measuring aspheric surfaces but is much more complicated and, thus, is a much higher investment. A drawback is that the measurement of many subapertures takes much more time, which can be critical for an efficient production throughput.

3.3 Multi-zone interferometry

For the measurement of a spherical surface, the sample has to be positioned along the axis of the interferometer (Figure 9). For each radius, convex and concave, one position is found where the wavefront is normal to the spherical surface. If an asphere is cut into concentric rings, each ring may be approximated by a best-fit sphere. The asphere can be positioned along its axis in the interferometer so that the wavefront is normal to the surface for the best-fit sphere in that ring (Figure 14). Depending on the width of the ring or zone and the radius change of the asphere in the ring zone, the fringes inside the ring zone may be resolvable in a standard interferometer. In order to measure a complete asphere, a set of ring zones with resolvable fringes inside the zones has to be defined, and the asphere has to be moved along its axis to all the different positions necessary to measure the different zones. Including the precisely measured distance to the center point of the spherical reference surface and to the apex of the asphere, the measured ring zones can be but together into one topography [32, 33].

This is again a very flexible method to measure different types of aspheres. With a set of 6 to 200 zones, aspheres with a spherical departure up to 1 mm and 10 μm form deviation from the nominal design can be measured [33]. Compared to the application of CGH, a system based on the multi-zone interferometer is a much higher investment because of the higher complexity. But for many different types of aspheres, CGHs create high costs, and their application is not reasonable for low quantities. A drawback of the multi-zone interferometer setup is the measuring time, which depends on the asphericity of the sample and, thus, the number of zones required.

3.4 Sub-Nyquist interferometry

The application of a ‘sub-Nyquist camera’ provides the basis for another solution for the measurement of aspheric surfaces. The camera in this setup is covered with a mask of pinholes with diameters significantly smaller than the size of an individual pixel. Thus, smaller fringes below the Nyquist limit can be resolved (Figure 15), and even with

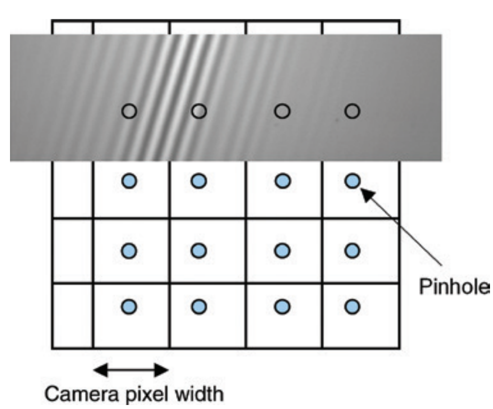

Figure 15: Principle of sub-Nyquist interferometry.

just a spherical reference surface in the interferometer, mild aspheres can be measured [24, 34–36]. For the measurement, the aspheric surface has to be well aligned to the optical axis of the interferometer. The measurement is a standard phase-shifting process. For further data processing, a theoretical fringe pattern [computer-generated reference fringes (CGR)] is calculated with the *a priori* knowledge of the nominal shape of the asphere. Combining the measured and theoretical data, the measured phase can be calculated. Unwrapping the phase creates the measured error topography of the surface (Figure 16).

A sub-Nyquist interferometer can be considered as an interferometer with a flexible CGH or null lens for a certain range of mild aspheres. In practice, measurements can be performed within seconds, and therefore, the system is rather well suited for the production floor fitting into any process chain. From the instrumental point of view, it is less complex than the other flexible interferometers presented here. But the system has limits as stronger aspheres create fringe densities that are too high.

3.5 Tilted wave interferometry

Another approach for a non-null interferometer is the use of several test beams with different tilts [37–40]. In the interferometer setup, each test beam has a certain area on the surface where the beam is rather normal to the surface, and the fringes can be resolved (Figures 17 and 18). The different beams necessary to cover the whole aspheric surface can be created with a lens array in the test arm of the interferometer. With a pinhole in front of the lens array, a single beam can be selected. In practice, it is more efficient to use a set of differently tilted beams

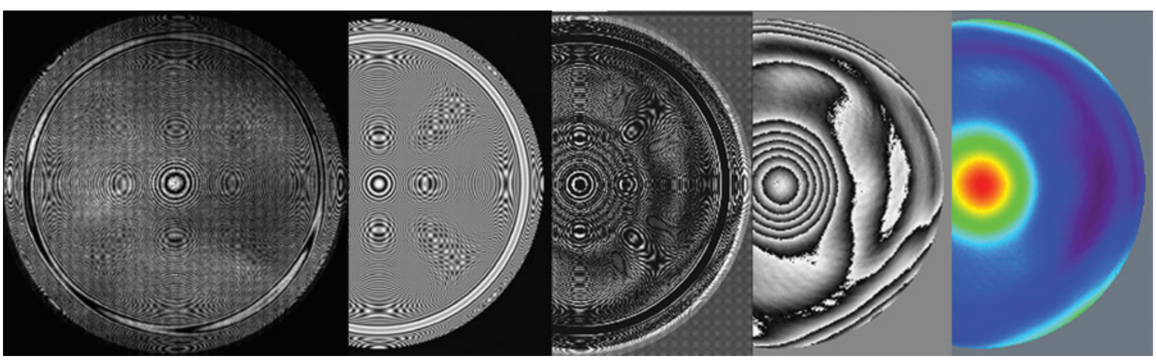

Figure 16: Measurement and data processing of a sub-Nyquist interferometer. From left to right: obtained fringes, CGR fringes, Moiré fringes, wrapped phase, unwrapped error map.

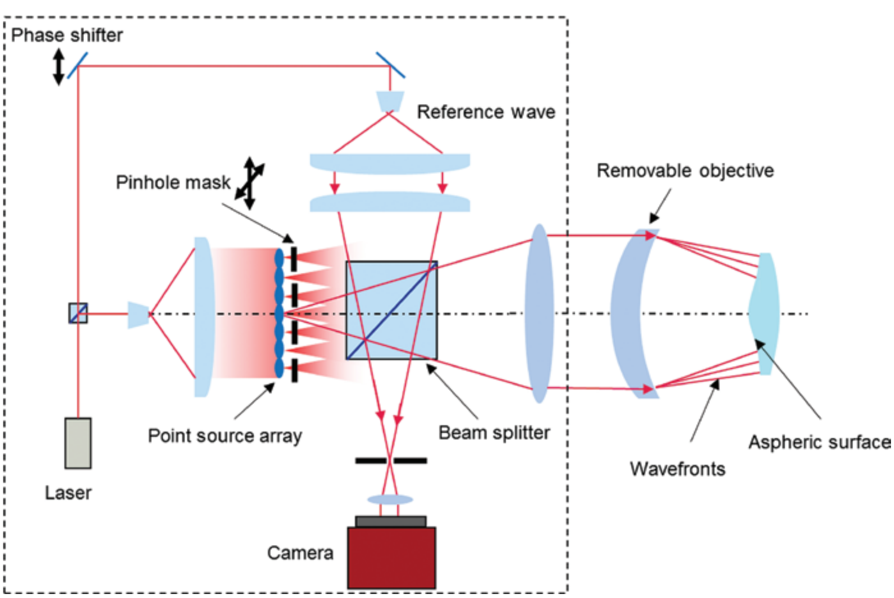

Figure 17: Tilted wave interferometer based on a modified Twynman-Green interferometer creating wavefronts with different tilts.

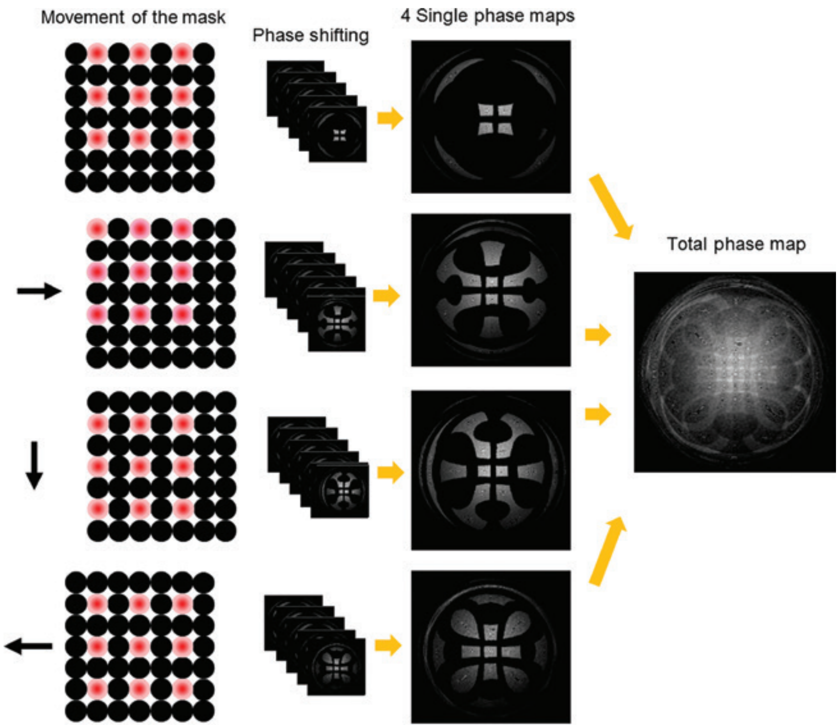

Figure 18: Measuring process of the tilted wave interferometer.

generated by a pinhole array placed in front of the lens array. In order to avoid any overlapping effects between the sources, the pinhole mask blocks every second source in each row and column. By moving the pinhole mask in front of the array, all point sources can be activated in four steps (Figure 18). The four single-phase maps obtained from each interferometric measurement can be combined into one phase map.

With a high dynamic range of up to 10° gradient deviation from the best-fit sphere [40], this technology is very flexible and covers a wide range of aspheric lenses. As only four measurements have to be performed, the process is rather fast. The measuring times below 1 min allow integration into different production processes. A drawback of this complicated system is the high investment cost.

4 Results

Each measuring instrument discussed above is suitable for a specific use in the production chain and can measure a certain range of aspheric shapes. Although the technologies of the measurements are very different, the results obtained from the aspheric surface should be comparable. For the measurement of flats or spheres, reference standards are available. For the measurement of aspheres, some work is ongoing for the development of reference artifacts [41]. But to date, nothing is available, which can be used to test very different systems. Pointwise measuring instruments can be traced back to spherical standards. For these instruments, the measuring process is, in principle, the same for a sphere and an asphere. Thus, a measurement of a sphere reveals a good impression of the capability of the measuring instrument. In Figure 19, the results of the measurements of a spherical reference standard are shown. The ball has a radius of ~22.5 mm and an overall form deviation of a few tens of nanometers.

The topography of Figure 19A is measured with the 3D profilometer-type system ‘MarSurf LD260 Aspheric 3D’ (LD) (Mahr GmbH, Göttingen, Germany). It is a contact measurement with a ruby ball of 1-mm diameter and a measuring force of 5 mN. The topography of Figure 19B is obtained from the cylindrical coordinate measuring instrument ‘MarForm MFU200’ (MFU) (Mahr GmbH, Göttingen, Germany) equipped with an optical point sensor [15, 16]. The high precision of the system is based on an internal compensation system consisting of a set of capacitive sensors measuring distance changes to a reference frame. The signals from the capacitive sensors are used to correct the measurement values for any nonsystematic movements of the axes. A unique feature of this instrument is that it is equipped with both an optical and a tactile probe. The sensor technology of the optical sensor is based on

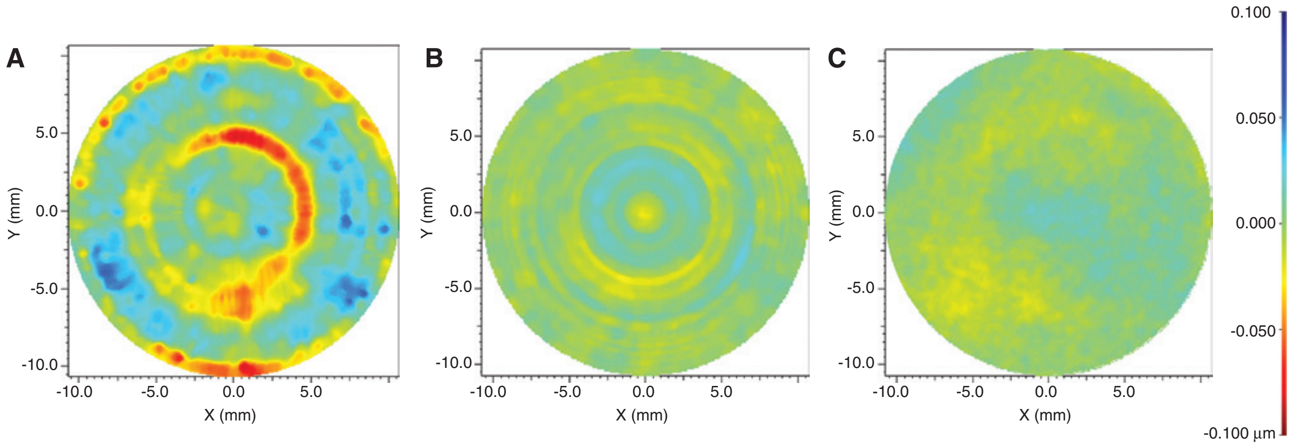

Figure 19: Measurements of a reference sphere performed with the LD (A) and the MFU (B) and a laser interferometer (C).

white light interferometry. For comparison (Figure 19C), the sphere is also measured with a standard Fizeau laser interferometer (MarSurf FI 1100 Z, Mahr GmbH, Göttingen, Germany). The result has a PV=43 nm and a RMS=6 nm. The topography from the LD has a PV=141 nm, a RMS=22 nm, and the best-fit radius is 22.48611 mm, i.e. a difference of 0.1 µm from the nominal calibrated radius of 22.462 mm. The results from the MFU are PV=54 nm, RMS=8 nm, r=22.48614 mm, i.e. a difference from the nominal radius of ~0.2 µm. The topographies measured with the pointwise measuring instruments are dominated by annular structures. This artifact is stronger for the LD measurements. The mechanical instrument setup guaranties a rather high stability for a single trace, bus is not designed for long-term stability, i.e. it shows drifts of position and tilt between the different circular scans. This effect is much smaller for the much more stable and compensated MFU. Actually, for the MFU, a small hysteresis effect is found, which should be reduced in the next developing stage. The circular scans of the LD setup show vibrations induced by the mechanical contact between probe tip and surface. This effect increased with increasing measuring speed and slope of the surface. The real shape of this sphere of a few 10 nm, as measured with the interferometer, cannot be determined with these two pointwise measuring instruments. The form deviations measured with those instruments are dominated by measuring artifacts demonstrating the limits of the instruments.

Measurements of an interesting structure are shown in Figure 20. It is a spherical surface with grooves of depths below 100 nm structured with ion beam finishing. For the topography measured with the LD, the deeper grooves are somehow visible, but become very noisy below ~50 nm depth. In the result from the MFU, structures even down to around 10 nm can be observed. Grooves of 20 nm are clearly measureable. In Figure 21, the

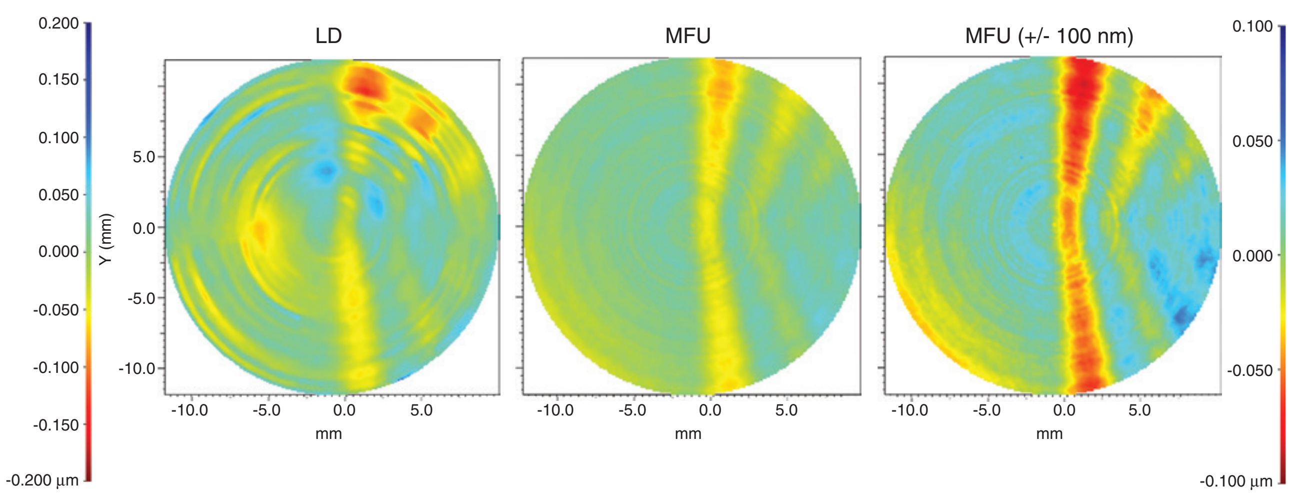

Figure 20: Measurements of the LD and MFU of a spherical surface structured with ion beam finishing. The base structure was fabricated by Schneider GmbH & Co. KG; the structure was processed by NTG Neue Technologien GmbH & Co. KG.

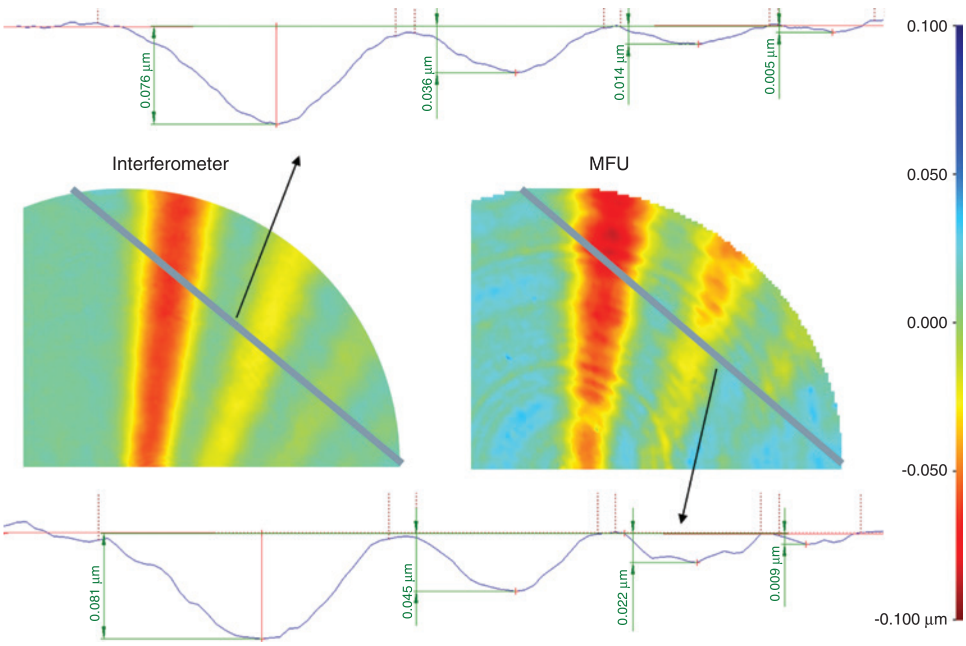

Figure 21: Comparison of a measurement of the structured sphere with a Fizeau laser interferometer (left) and MFU (right): topographies and linear profiles obtained from the topograhies.

measurement of the MFU is compared to a measurement of a Fizeau laser interferometer (Zygo Verifire™ AT+, Zygo Corporation, Middlefield, CT, USA). The groove depths are analyzed in the linear profiles obtained from the topographies. For both instruments, the depth agree within 10 nm. The depth of the grooves strongly depends on the position of the reference surface, which can be determined in different ways influencing the depths by a few nanometers. These results indicate how far local structures can be measured, i.e. for the LD ~50 nm and for the MFU ~20 nm, and may be correctable in a final polishing utilizing these measurements. Typically, both instruments collect the data with a point distance of 0.1° along the circular path. The number of circles can be varied. Usually, up to 40 circles are collected with the LD. More circular scans would take too much time exceeding the aim of ~10-min measuring time, which should fit into the production cycles. Owing to the optical sensor, the MFU is not limited by the dynamics of the tactile measurement. Up to 400 circles can be collected with up to 360°/s in a reasonable period of time. The measurements in Figure 20 were performed with 40 and 100 circular scans, respectively. The resulting lateral distances of the measuring points are 0.25 mm and 0.1 mm. In practice, structures ≥1 mm are examined with the MFU. Smaller structures are not considered because polishing tools are also limited in size and can usually not correct smaller deformations. However, mid-spatial frequency errors can hardly be measured with these instruments.

As there are no traceable aspheric standards available, comparing measurements of an asphere with different instruments should give some information about the individual performance of the instruments.

In Figure 22, the measuring results of an aspheric surface are presented. It has an aspheric departure from the best-fit sphere of ~75 µm. The maximum measured slope is ~30°. The measurements were performed with two pointwise measuring instruments [LD (contact) and MFU (non-contact)] and the ‘multi-zone’ interferometer Zygo Verifire™ Asphere (VA, Zygo Corporation, Middlefield, CT, USA) [42]. The PV values are 1.42 µm (LD), 1.34 µm (MFU), and 1.31 µm (VA). The RMS values are 0.39 µm (LD), 0.33 µm (MFU), and 0.31 µm (VA). These values are rather similar and may be slightly influenced by the exact evaluation range. The topographies are dominated by a rotationally symmetric contour deviation. This contour deviation is shown by the linear profiles cut out of the topographies. The profiles shown in the figure are obtained from a cut at y=0 mm in the x-direction. Any differences between the measurements of the different instruments are hardly observable. Clearly, the measurement of an aspheric lens with form deviations in this dimension is not challenging for these three instruments. The measurements do not reveal any substantial differences between the systems. As demonstrated by this sample, the form deviation of aspheres with decreasing quality is often increasingly dominated by the contour deviation, which can just be measured with one linear

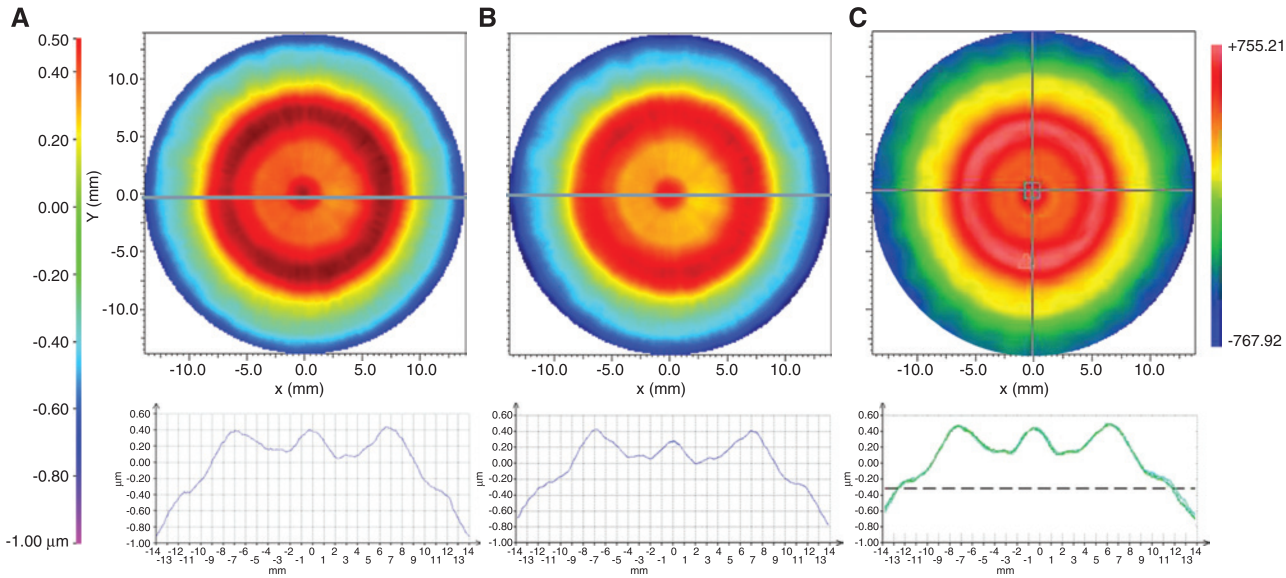

Figure 22: Measurements of an asphere performed with the LD (A), the MFU (B), and the Zygo Verifire™ Asphere (C).

scan of a profilometer. Actually, in this case, the topography map does not provide much information. It only demonstrates that the error is rotationally symmetric.

The next example is an asphere with ~0.1 mm departure from the best-fit sphere and an aperture of about 25 mm. The maximum slope of the surface is ~25°. The asphere is rather precise with a form deviation of PV ~400 nm. The present sample can either be considered as a precise asphere, which has to have a PV of let us say <500 nm and has to be tested if that tolerance can be achieved, or it is a sample from the production process, which has to be measured to provide the topography for a final polishing step.

On the left-hand side of Figure 23, the result of a measurement with the 3D profilometer-type system LD is shown. It is a contact measurement with a ruby ball

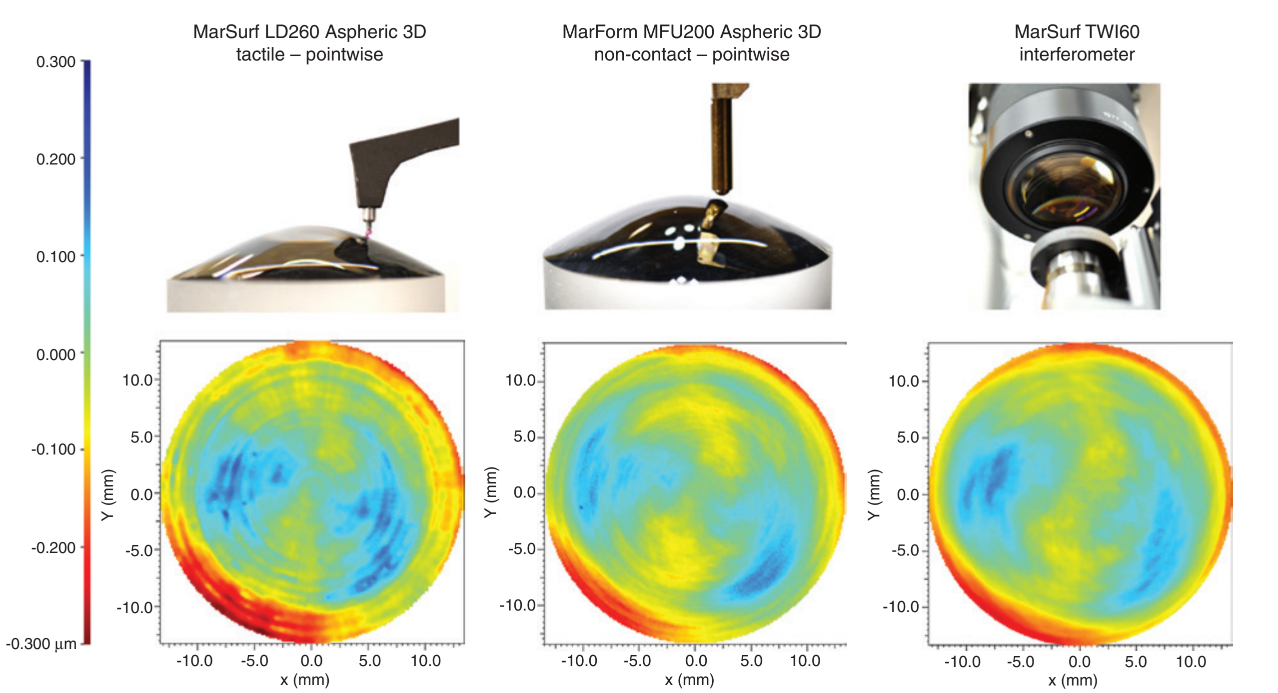

Figure 23: Measuring results of an aspheric lens measured with three different types of systems. The lens was provided by Schneider GmbH & Co. KG.

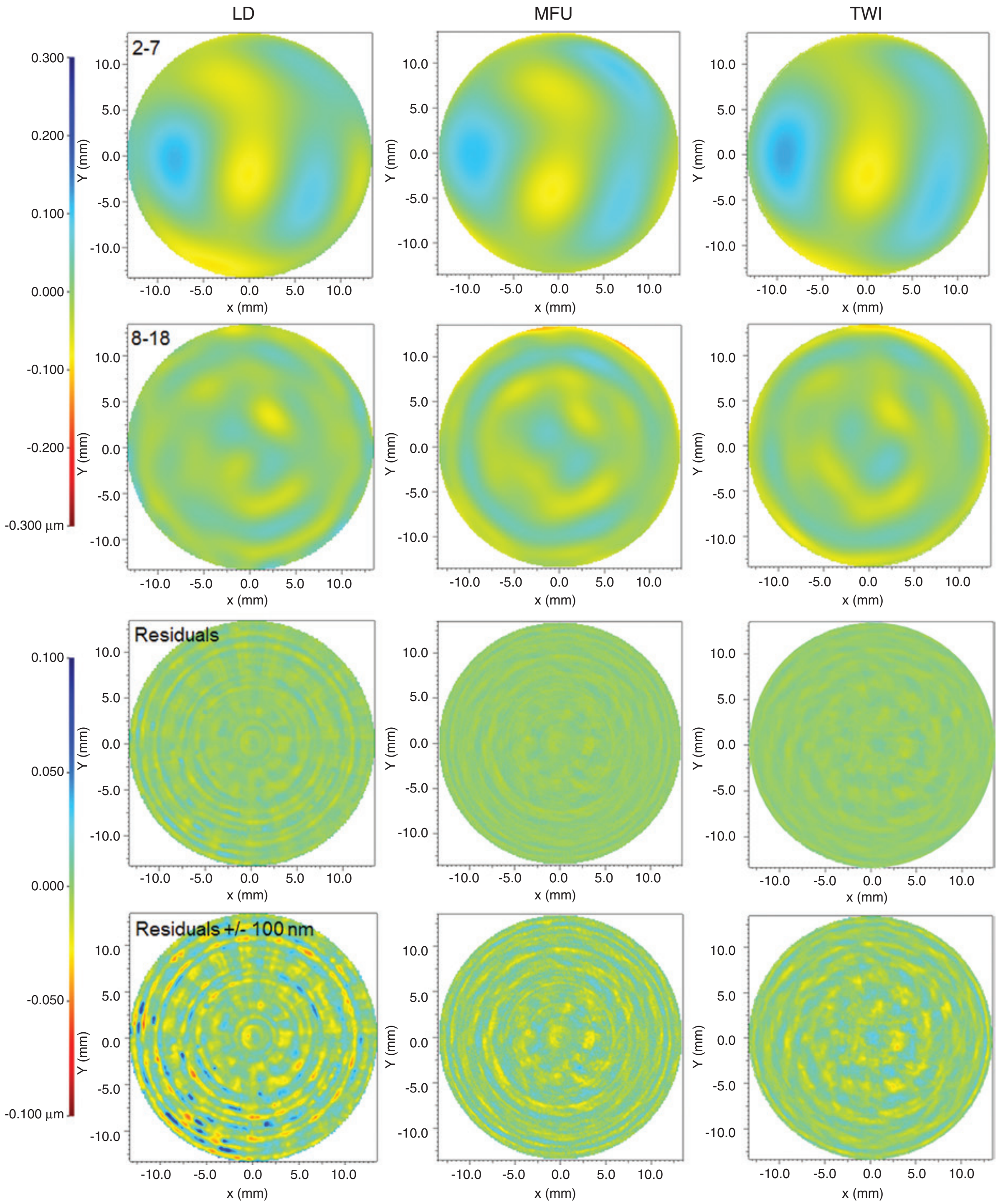

Figure 24: Results of the fit of Zernike polynomials and the residuals of the measuring results from Figure 23.

of 1 mm in diameter and a measuring force of 5 mN. It is measured with 40 circles providing a topography with about 80×80 points. The measuring time was ~10 min.

In the center of Figure 23, a measurement with the MFU, a high precision pointwise measuring instrument with an optical probe, is shown. For the measurement of the aspheric sample, 100 circular measurements were performed. Thus, an array of about 200×200 points was collected. The measuring time was ~6 min.

On the right-hand side of Figure 23, the result obtained from a flexible interferometer, a prototype of the tilted wave interferometer 'MarSurf TWI60' (TWI, Mahr GmbH, Göttingen, Germany), is presented. The data are collected with a 2k×2k camera. The measuring time was ~30 s.

The presented results show the error topography of the surface, i.e. the difference between the nominal and the measured profile. The overall form deviation PV obtained from the 3D profilometer LD is 487 nm, from the cylindrical coordinate measuring instrument MFU, 377 nm, and from the tilted wave interferometer, 405 nm. The RMS values are 91 nm (LD), 83 nm (MFU), and 76 nm (TWI). The observed structure appears to be rather similar in all cases. Differences between the profiles can be explained by the measuring artifacts from the instruments (see above: comments to Figure 19). In particular, the topography from the LD seems to be noisier as is also indicated by the higher PV value. For the demonstrated results, a radius fit was performed. The maximum radius difference obtained from the fit is 0.8 µm.

For a more detailed comparison, Zernike polynomials were fitted to the differential topographies (Figure 24). The top row shows a fit for the polynomials n=2–7 after removal of the best-fit sphere. The PV values are 206 nm (LD), 205 nm (MFU), and 242 nm (TWI). The overall appearance is similar. The structures are pronounced slightly different. The second row shows the fit for n=8–18. The PV values are 144 nm (LD), 203 nm (MFU), and 164 nm (TWI). Again, the structures look rather similar. The higher PV of the MFU is induced by a structure at the edge.

The lower two rows show the residuals of the topographies after subtracting the polynomials up to n=18. The PV values are 133 nm (LD), 87 nm (MFU), and 77 nm (TWI). The residuals from the LD measurement are clearly dominated by circular structures and annular oscillations. As discussed above, these features are created by movements of the system between the different circular scans and the vibrations induced on the circular path increasing at high slopes and higher velocities. However, these higher-frequency structures are usually not corrected in a deterministic polishing process. Thus, using the lower frequency structures obtained from the Zernike fit, the measurements from the LD can be used with a somehow similar potential for a corrective polishing as the similar results from the MFU and TWI in this case. The residuals of the TWI have the appearance of a typical mid-spatial frequency structure induced by polishing. However, the residuals probably also contain some measuring artifacts. The MFU residuals show some similarities to the TWI but are disturbed by ring structures.

5 Summary and conclusions

In this paper, an overview of the metrology commonly used for the production of aspheric lenses is given. As indicated in Table 2, different types of instruments are necessary for different process steps. For a grinding process, a linear scan is usually sufficient and can be performed rather fast within a few seconds with a profilometer (prof, 3Dprof). For most optical technologies, in particular for the laser interferometer systems, a ground surface is too rough to obtain any reliable measuring data; thus, a good choice is the contact probe of the profilometer. The high-precision coordinate measuring instruments can also perform these measurements but are usually too oversized for this application considering the investment costs. In the first polishing step, a linear profile may also supply sufficient information for the first correction. At this stage, a contact measurement is still not too critical. Therefore, a profilometer can be a fast and efficient solution. In particular, to start with an aspheric production, a solution for a topography measurement for the polishing can be the 3D profilometer (3Dprof). It is possible to produce aspheres with a few hundred nanometers surface form deviation. However, the standard method is a laser interferometer performing high-precision measurements without any danger of damaging the surface. If a lens is produced over months or years, the investment of a CGH (int-CGH) will be a good solution for a fast and robust measurement. For varying types of aspheres, the flexible interferometer systems (int-flex) are

Table 2: Overview of the requirements for different processes in the production of aspheric lenses.

	Grinding	Polishing	Diamond turning	QC/QA
2D	x prof 3Dprof	(x) (prof) (3Dpoint)	x prof (3Dpoint)	(x) prof (3Dpoint)
3D	(x) 3Dprof (3Dpoint)	x (3Dprof) 3Dpoint int-CGH int-flex	(x) 3Dpoint int-flex	x (3Dprof) 3Dpoint int-flex
Contact	x prof 3Dprof	(x) (3Dprof) (3Dpoint-t)	(x) prof 3Dpoint-t	(x) (prof) (3Dpoint-t)
Non-contact		x 3Dpoint-o int-CGH int-flex	(x) 3Dpoint-o int-flex	x 3Dpoint-o int-flex

x indicates the standard requirement. (x) may be necessary or a useful option. In addition, there are assigned different types of metrology systems to the different requirements; brackets indicate an option in particular if nothing else is available: 2Dprof, Contour measuring instrument/profilometer; 3Dprof, Combination of profilometer with spindle; 3Dpoint, High precision 3D pointwise measuring instruments (-t tactile option, -o non-contact option); int-CGH, Laser interferometer with CGH; int-flex, Flexible laser interferometer.

usually a better choice. To be even more flexible, the non-contact coordinate measuring instruments (3Dpoint-o) are found on the production floor.

In order to control a diamond-turning process a linear profile is required for a closed loop process. A fast solution is a profilometer (prof) or the more expensive high-precision coordinate measuring instrument (3Dpoint). Often, soft materials are processed so a non-contact method is preferred. Unfortunately, for a lot of applications like very steep-sided aspheres, no optical sensor-based systems are available. Even the tactile methods are at the limit at very steep flanks. So interferometers are only useful in certain cases.

For quality control in the production or incoming goods inspection, a flexible and non-contact method is preferred. Of course, non-contact methods are the choice but may involve too high investments or are not flexible enough.

With the increase in applications of aspheric lenses over the last years, more aspheres are produced in lower quantities requiring more flexible metrology solutions. The result is the development of the flexible interferometers (int-flex) and the high-accuracy coordinate measuring instruments (3Dpoint). With different potentials and limitations, such as range of aspheric shapes, measuring time, lateral resolution, all systems have their justification for a certain application.

To date, there are no reference standards available to control the quality of the measuring results. But, as demonstrated, measuring results of an aspheric sample obtained from different instruments, if available, can be compared directly. In practice, this can show the limitations of the systems and will at least reveal if the instruments perform correctly.

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