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Tutorial

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Practical aspects of modern interferometry for optical manufacturing quality control, Part 3

Abstract: Modern phase shifting interferometers enable the manufacture of optical systems that drive the global economy. Semiconductor chips, solid-state cameras, cell phone cameras, infrared imaging systems, space-based satellite imaging, and DVD and Blu-Ray disks are all enabled by phase-shifting interferometers. Theoretical treatments of data analysis and instrument design advance the technology but often are not helpful toward the practical use of interferometers. An understanding of the parameters that drive the system performance is critical to produce useful results. Any interferometer will produce a data map and results; this paper, in three parts, reviews some of the key issues to minimize error sources in that data and provide a valid measurement.

Keywords: cloud computing; interferometer; Internet of Things; partial coherence.

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1 Introduction to Part 3

Interferometers are enabling tools in high-technology manufacturing. Therefore, a practical understanding of interferometry, its application, and sense of future direction is required in the field of optics. This paper will focus on those aspects in three parts. Part 1 [1] covered the history and basic descriptions of interferometer systems. Part 2 covered the test configurations, data acquisition, and metrology.

This section, Part 3 concentrates on the software that, in many ways, is the main interface for the user, a primary driver to interferometer evolution and where many future improvements will emanate from. Part 3 also reviews the recent developments in partial coherent illumination systems, as well as potential developments in the near future.

2 Software

The electronics, computer, and photonics revolutions have driven the interferometer development, with software being the key-integrating element. Increased computing power and improved software have enabled new data acquisition methods, analysis, and results, and graphic displays for easy data interpretation.

2.1 Software modules

Each commercial interferometer software program is unique, yet they have common elements or modules. These modules might be implemented differently, but the basic functions exist. Depending on the software package, these modules and the controls within them might or might not be accessible to the user. Therefore, each particular software package needs to be learned to understand how to optimize its performance. Figure 1 shows the basic modules, followed by a general description of its function.

Interferometer control controls the physical and electronic systems of the interferometer to acquire raw intensity data. These include the fine mechanics (if they exist), the camera frame rate, pixel resolution, and shutter speed, plus illumination level, image magnification, and focus position read out and possibly the automatic setting of zoom and focus if under motorized software control. Some, none, or all of these might be settable by the user in any particular software package or system.

Data acquisition module grabs and prefilters the intensity data and converts the intensity data into the "unwrapped" phase data. This module is directly tied to the data acquisition method used, such as PSI or SPMI, described in Part 2 of this review [2]. Within the data acquisition method might be options to select a specific phase analysis algorithm and options to mask the data and minimize data noise by selecting minimum allowable contrast levels. Finally, the raw phase data must be unwrapped.

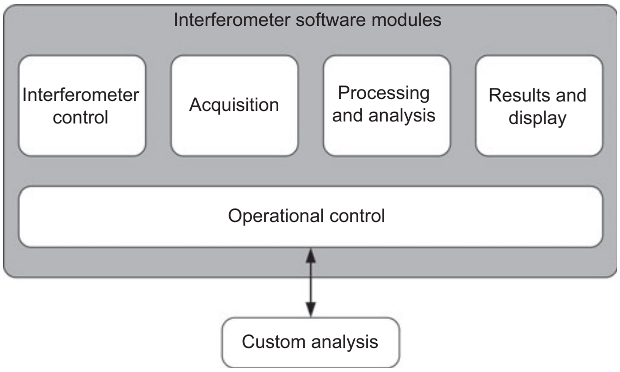

Figure 1 Basic interferometer software modules.

Interferometers can only measure in 2π increments of the phase. Therefore, the data appears to be a saw tooth with 2π jumps. To map the actual phase data, the 2π increments or discontinuities must be removed, this is called phase unwrapping [3–5].

Data processing and analysis scales the phase data and potentially converts the phase to height. It also filters the data for the spatial frequencies of interest, manually or automatically masks the data to focus on the areas of interest and often clips apparent noise (spikes) from the data. All these functions are performed under the control settings of the user. This module is where selected settings can lead to errors or noncorrelation between instruments, and great care must be used to confirm that the desired parameters are being measured.

Data results and display compute the results desired (RMS, PV, points measured, spatial frequencies displayed, etc.) and display them graphically for easy interpretation. Advanced results include process control statistics such as running averages, go/no go flags on results, standard deviation and run charts. Many systems allow the data results to be exported to a third party process control programs as desired by users.

Operational control is the underlying data flow control. No software package can anticipate all customer needs. Therefore, an operational control system is often included allowing users to control the sequence of operations during data analysis. This can also include calling on outside routines to analyze the data in a proprietary manner, then returning it to the interferometer software system for the final analysis and display. High-level scripting languages have been used, and now graphical approaches are available that allow a visual understanding of the data flow and how it affects the resulting data.

Figure 2 provides an example of this graphical approach. From the left side of the bottom row of the images, the data analysis sequence starts with a series of raw data acquisition single-frame Interferograms. The data is then masked using a variety of sources including composite intensity, a user-defined detector mask of arbitrary shape, and modulation depth (signal-to-noise). Then, the wrapped phase is computed using the interferograms plus some thresholding to suppress noise from entering the phase unwrap algorithm in the next step. The raw surface is computed by unwrapping the data, and various filters are applied to smooth out the spikes (filtered). Subtract ref, subtracts a reference or calibration file if available to improve measurement uncertainty. If desired, data fill is used to fill in the missing data points

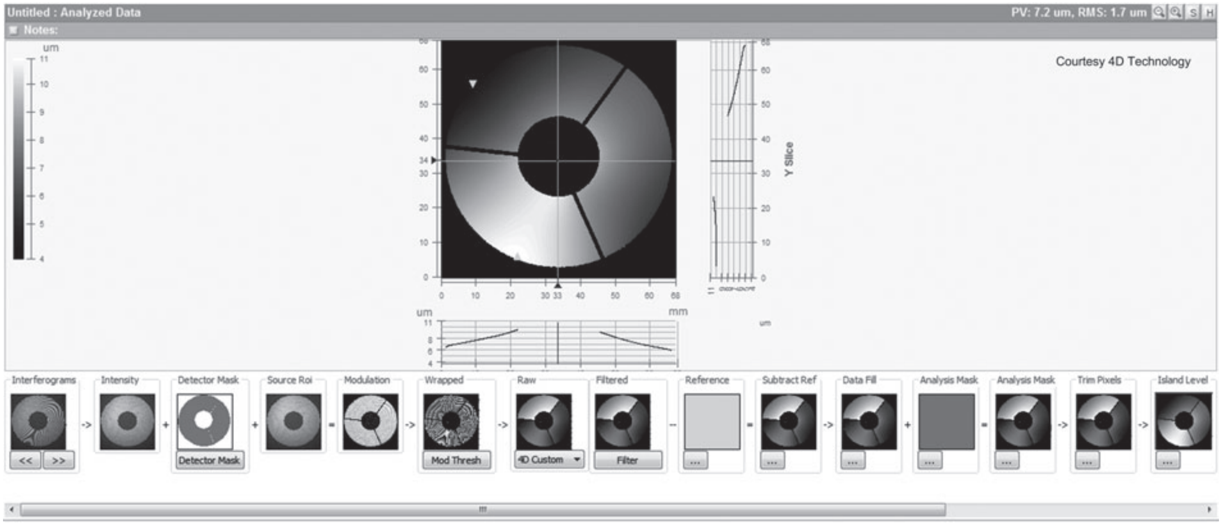

Figure 2 Commercial software graphical data flow management, courtesy of 4D Technology Corporation.

through interpolation. An analysis mask is used to analyze only a portion of the processed data, and the trim pixels removes the pixels at the edge of the aperture. In this case, an island leveling algorithm is used to resolve the 2π ambiguity between noncontiguous data regions. Not shown are the final processing steps that include the fitting and removal of the aberrations, e.g., Zernike polynomials; the final result is shown above the data analysis sequence.

2.2 Applications

Applications (APPs) are a powerful tool utilized by interferometer manufacturers. An application is a combination of preset controls, data acquisition and data processing settings, results, and displays under a particular operational control driven by a scripted sequence of steps that often prompt the user to make an adjustment and then continue. For example, an APP can be developed for calibration routines such as a three-flat test or two-sphere test. APPs improve testing efficiency, consistency, and make the use of an interferometer easier for less skilled or infrequent users.

A scripting language or graphical operational sequence control available in several commercial systems can be used to develop an APP. Several manufactures offer a learn mode where a series of measurements are made by the process or metrology engineer and the sequence and setup saved for future use by a technician. With the capability to access custom analysis (see Figure 1), these APPs can accommodate unique testing situations and desired results that are not possible with the standard software interface.

2.3 History

Today’s interferometer software is sophisticated and the result of over 35 years of development. Table 1 outlines a history of the primary software modules and indicates possible future developments.

From Table 1, the trend to use software to improve the measurement uncertainty is easily seen. More powerful computers enable interferometer and test setup error sources and potential operator errors to be minimized. This will be discussed in more detail regarding future trends in interferometry.

3 Illumination and imaging

Illumination and imaging improvements have been driven by high-end manufacturing processes used on advanced

Gen	Era	Acquisition	Operational control	Analysis/ results	Algorithm verification	Graphics	Operating system
1	1975	Fringe centers+PSI	Fixed controls and analysis	PV, RMS, Seidel, Zernike	Self verifying – little version control	Monochrome line maps	Proprietary
2	1985	PSI		Separated regions			
3	1990		+Scripting	+PSD, Zernike removes, better masks		Color filled plots	Unix and Dos
4	1995	+IPMI (direct measuring)	+Windows+APPs	+Fiducial, +process control statistics, MTF, spot diagrams, subaperture analysis	Internal regression analysis to establish version correlation	+User defined outputs	Windows 95
5	2000	+Multi surface+asphere (stitching)	+Custom linkable analysis+tool bars	New filtering+easy unit conversions		More color depth, solid models	
6	2005	+Asphere(scanning)+IPMI (dynamic)	+Graphical control	Subtract historic data maps +64 bit (some)		Dynamic controlled solid model	Vista+XP
7	2010	+PSI (vibration insensitive)	+Drop and drag	ISO 10110+64 bit (majority)	Comparison with 3rd party algorithms	+Simple ‘production’ screens	Windows 7
	Future	Autoselection on environment and goals	+Autosystem setup	+Autocorrection of interferometer errors+expert set up guidance	National standards institutes reference dataset comparisons – online	Measurement uncertainty with results	Latest Windows

Table 1 Interferometer software generations.

optical systems such as X-ray [6], EUV [7], and space optics [8]. These improvements have been evolving over the last 20 years and are now moving from proprietary to commercial systems (e.g., 4D Technology 'AccuFiz' and the Zygo Corporation 'Verifire™ ATZ'). Advanced surfaces demand tighter tolerances on form and also tolerances on higher spatial frequency features or waviness. These advanced surfaces are often aspheric in shape further complicating the measurement requirements again as discussed in Part 2 of this paper. The advanced manufacturing processes often include spot polishing that can naturally induce unwanted higher spatial frequency waviness in the optical surface [9–11]. These requirements have given rise to partial coherence illumination systems and higher optical resolution imaging systems.

3.1 Coherent noise

The high temporal and spatial coherence of the laser has enabled modern interferometry. Coherent illumination also produces interference patterns emanating from secondary sources including dust, scratches, and internal reflections. Furthermore, a background speckle pattern is developed from the residual roughness of all the lenses and prisms within the interferometer [12]. All these extraneous sources create coherent noise degrading the measurement.

The desire to increase the image resolution by increasing the imager pixel count and imaging system resolution exasperates the problem. Now the interferometer becomes more sensitive to small artifacts. Adding to this, the increased sensitivity of the data acquisition to finer phase steps and more artifacts are seen. The nominal efforts to measure finer features leads to degraded measurement performance.

3.2 Illumination: partial coherence

To overcome these problems, partial coherence sources are used. Partial coherence sources for interferometry have high temporal coherence, with decreased spatial coherence. The simplest approach is to change the laser point source into a small illumination disk [13, 14]. The illuminated disk creates many point sources of coherent illumination. The disk is rotated synchronously with the camera frames to average the individual point sources into a uniform illumination disk. The uniform disk decreases the coherence length limiting the path difference between the test and reference arms of the interferometer over which high contrast interference will occur. This is particularly limiting to a Fizeau. Practical implementation typically makes the disk size adjustable to maximize fringe contrast, while minimizing coherent noise. The down side is larger path differences between the test, and reference arms experience increased coherent noise.

An early approach was to use a single (spatially coherent) point source where the lateral position in the focal plane of the collimator could be virtually changed from phase map to phase map to average the phase results of several phase maps [12]. This virtual lateral position shift can be accomplished by means of one or two rotating wedges in the illuminating beam. The averaged phase map maintains both high- and mid-spatial frequencies in the data, but suppresses coherent noise. Furthermore, high fringe contrast is maintained over the large path differences between the test and reference arms, as a single point source is used for each phase map. The distance of this point source from the optical axis is only changed between the different phase maps, inducing time-variable phase offsets between the different phase-maps, but spatially constant over every phase map.

More recently, a similar concept was implemented at camera frame rates or in 'real time' [15–17]. This method creates a ring of off-axis coherent point sources of illumination. Each point source contributes a coherent interferogram with the same phase offset, as the radius is kept constant, and the ring is adjusted precisely symmetrical to the optical axis. The multiple interferograms are averaged into a single interferogram in real time at the camera minimizing the coherent noise but maintaining the full contrast. It will also be seen below that the multiple off-axis sources minimize phase errors due to focusing. Again, as these sources are coherent in real time, the test to reference path differences of several meters have been reported (Zygo Corporation sales information), coherent artifacts are minimized, and mid-spatial frequencies are maintained.

3.3 Instrument transfer function

How do you quantify an interferometer's imaging performance? For photographic and video systems, modulation transfer function (MTF) is the standard test; the image contrast or modulation of a sinusoidal object is reduced by the aberrations in the system and the normalized contrast reduction (image contrast/object contrast) is the MTF as shown in Figure 3A. This technique works well for cameras as the illumination is incoherent and acts in a linear fashion.

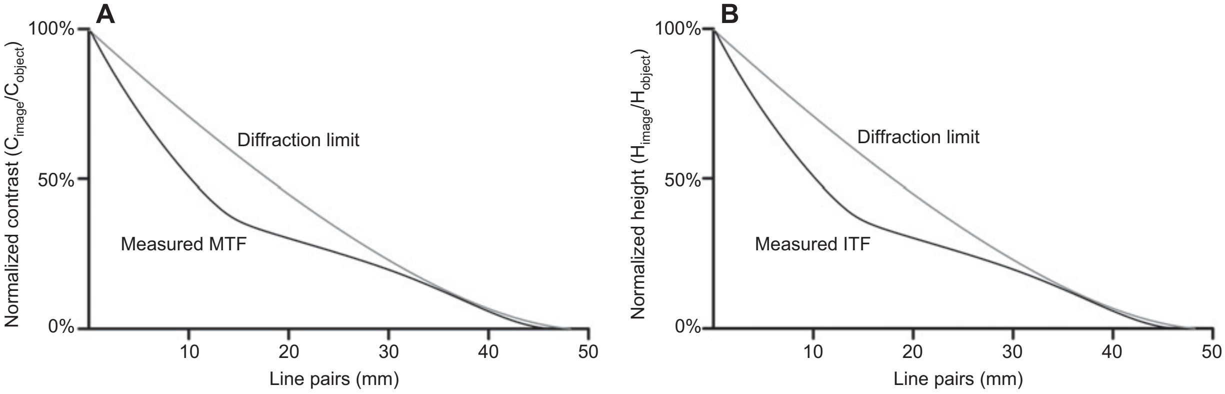

Figure 3 (A) MTF and (B) ITF ideal.

Interferometer manufacturers and users desire to measure smaller features and quantify the limits of resolution of their systems, and instrument transfer function (ITF) is targeted as a quantified test. There is a critical, and possibly fatal, difference in practice between MTF and ITF. An imaging system is rated as to whether a feature is detectable. An interferometer is rated on how accurately it measures a feature's height.

The y-axis of an ITF curve is a normalized surface height as in Figure 3B, which is the ideal sought in determining ITF for an interferometer. The ITF curve reports the ratio of the measured height to the actual test part height at a certain spatial frequency.

As simple as the concept is, there is much controversy in this area. Coherent imaging is nonlinear, and height reversals (a hill looking like a valley) for specific spatial frequencies can occur due to aberrations and even defocus, which as discussed in section 3.5 below, is not necessarily constant across the part. These phase reversals are seen in microscopy for the coherent imaging case where defocused structures for certain spatial frequencies reverse contrast [18]. The same occurs in interferometers.

Again, coherent imaging is nonlinear, and the image resolution performance is coupled to the part features being measured, and it has been shown that for a test target to behave in quasi-linear fashion, the phase heights must be $<<\lambda/4$ [19]. Therefore, the reference standards used to test the interferometer ITF must be constructed with features of heights $<<\lambda/4$ to respond linearly. Research into new target designs continues [20], as well as their application to interferometer systems [21], as do analyses of interferometer performance [22]. Unfortunately, in practice, optical surfaces have structures larger than $<<\lambda/4$; therefore, the applicability of the measured ITF to any practical surface is unknown.

There is a further complication with coherent imaging; the phase of the defocused features is a function of the amount of defocus. This can be seen at the edge of a tilted part. As the focus is changed, the fringes are seen to change. This is true of all defocused surfaces and objects; therefore, the phase across the image on a local level is changing as the focus is changed, and knowledge of where the 'best' focus is indeterminate for fine features. In other words, the ITF will vary with focus. The use of partial coherent illumination, described in section 3.2, eliminates this affect and converts coherent imaging into incoherent imaging (M. F. Küchel, private communication). This means there is a best focus position where measured RMS for the surface is maximized. Again a caution, repeatable results do not necessary mean the results are accurate, especially if the feature heights are not $<<\lambda/4$ or other aberrations are present.

This writer is not aware of any research demonstrating the practical application of ITF. At what spatial frequencies, surface height deviation, coherence, and magnitude of aberration do phase reversals occur; in other words, what are the practical limits of high spatial frequency coherent interferometry? Until such research is published and the practical limits demonstrated, ITF is at best an indication of a resolution for comparison purposes only, and not a measure of expected system performance on any particular part.

3.4 Consistent PV results regardless of ITF

A problem across the global optics industry is consistency of peak to valley (PV) results between systems. PV is a standard result and specified on most optical drawings without reference to the spatial domain of interest and is the measure of the highest to lowest pixel. Two pixels drive the result if data filtering is not employed. Depending on the imaging system, the results can vary tremendously. A 256×256 pixel imager is likely to give a different result than a 1000×1000 pixel imager. The main problem is form data, or the lower spatial frequencies are mixed with waviness, the higher spatial frequencies. Form data is reported as PV, whereas waviness is typically reported as RMS, so the mixing of data types causes inconsistencies in the PV result.

A solution to this has been the creation of PVr [23] or robust PV. PVr separates these two data types via filtering, analyzes them with PV for form and RMS for waviness, and recombines them for a final PVr. This is somewhat controversial, but the results are very consistent system-to-system regardless of the imaging system used. This is a good example of how new software analyses can overcome a hardware inconsistency.

3.5 Highly sloped surfaces focus error

A final note on imaging: in Part 2 of this paper, the importance of proper focusing [2] was discussed. At a deeper level, focus is a fundamental error source when measuring highly sloped surfaces. An interferometer images a curved test surface as a curved image unto a flat detector. Therefore, the focus varies across the image. For spherical surfaces, this is not a problem. For sloped surfaces, an error occurs that scales linearly with defocus and quadratically with surface slope [24]. An experimental test with a ‘mild’ asphere exhibited a 14-µm PV surface map error as a function of focus position [24]. This error must be considered when using a standard interferometer or sub-Nyquist interferometer when measuring highly sloped surfaces or aspheres. The focus error of highly sloped surfaces can be minimized by the use of null correctors or measuring only where the slopes are zero on the highly sloped surface [25].

4 Future directions

Interferometer performance will continue to improve toward the ideal of error-free measurements that faithfully map the test surface. The drivers will continue to be light sources, imagers and the computer, electronics, and software evolution [26].

4.1 Light sources

Solid-state light sources in recent years have enabled new systems as reported earlier. HB-LEDs, laser diodes, and new supercontinuum lasers are finding new application. Partial coherence illuminators will also continue to evolve to become less expensive and more broadly applied.

4.2 Imagers

Higher pixel density imagers will enable more spatial frequencies to be measured with one instrument. Faster frame rates (and brighter light sources) will enable new applications and environmental robustness with new algorithms. Lower prices for imagers from long-wave infrared (LWIR) to deep ultraviolet (DUV) will open new applications as price point barriers are overcome.

4.3 Moore’s law

In 5 years, computers will be 10× faster at the same price point, enabling many potential gains.

- Improved interferometer design, including modeling and simulation for decreased manufacturing and design-induced error, and increased modeling and correction of the part interaction with the interferometer.
- Fool proof controls that provide ‘Expert’ guidance during set up and catching and correcting operator errors.
- Maxwell equation level corrections for such error sources as thin film and edge effects, vibration and phase change on reflection, focus, and even coherent noise.
- Known measurement uncertainty that most likely uses the inputs of the Internet of Things (below), where higher-powered computers track and understand the sources of error in a measurement. This will result in the knowledge of the actual measurement uncertainty for each measurement.
- Handheld device apps running the metrology process on the cloud with Internet-connected devices.

4.4 Internet of things

The Internet of Things is sensors and actuators embedded in objects and connected via wired and wireless networks enabling. Potential applications include:

- Environmental monitoring and control with many remote sensors that feed into a model of interferometer performance to correct systematic errors.

- Field performance data that tracks all interferometer installations remotely for trends, potential failure modes, and system improvement opportunities. Will allow field software upgrades where system corrections are uploaded for improved metrology performance.

4.5 Cloud computing

Cloud computing is a shared pool of configurable computing resources. With a shared pool, less duplication and more standardization is possible. Two immediate benefits could be:

- Uniform analysis software code with results displayed locally but calculated remotely, even utilizing standardized algorithms accessed from standards labs (NIST, NPL, PTB...).
- Standards labs providing cloud-certification processes that are run in the field, but are controlled from the Standards laboratory. Whereby the results would be certified as traceable without the need for transfer artifacts.

Interferometer advancement will greatly benefit from the global economy's technology advancements. Leaders in the field will recognize how to utilize these advancements to provide better results with an easier to use product that ultimately lowers the cost of ownership.

5 Summary

Interferometry has rapidly evolved over the last 40 years. New computing technology and light sources have enabled new configurations and data processing methods. This, combined with a deeper understanding of the principles of instrument design, has led to a practical tool for optics manufacturing. Proper operation requires in-depth knowledge regarding how to optimize performance, but this knowledge is well within the capabilities of a technician. Future improvements will increase the range of applicability to new environments and wilder surfaces, as well as improve the fundamental performance while improving the ease of use. Interferometry will continue to be central to the modern optical fabrication facility and to be an enabling technology to the global economy.

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References

[1] R. A. Smythe, 'Practical aspects of modern interferometry for optical manufacturing quality control', Part 1, AOT 1, pp. 59–64 (2012).
[2] R. A. Smythe, 'Practical aspects of modern interferometry for optical manufacturing quality control', Part 2, AOT 2, pp. 203–212 (2012).
[3] D. Malacara, Ed., 'Optical Shop Testing' (John Wiley & Sons, Inc., Hoboken, NJ, USA, 2007), pp. 623–629.
[4] K. Itoh, Appl. Opt. 21, 2470 (1982).
[5] D. C. Ghiglia and M. D. Pritt, in: 'Two Dimensional Phase Unwrapping' (Wiley, Hoboken, NJ, USA, 1998).
[6] H. Mimura, H. Yumoto, S. Matsuyama, K. Yamamura, Y. Sano, et al., in 'Proc. SPIE 5921, Advances in Metrology for X-Ray and EUV Optics, 59210M (September 16, 2005); doi:10.1117/12.623103.
[7] P. Kuetz, T. Boehm, H. J. Mann, S. Muellender, W. Bollinger, et al., 'Optics for EUV Lithography', SEMI EUVL Symposium (2006). Available at http://www.ismi.sematech.org/meetings/archives/litho/7870/proceedings/oral/D2/D2%20Invites%20Speaker_Kuerz.pdf.
[8] J. E. Harvey, in: 'Lessons Learned Concerning Image Quality Criteria on Major NASA Programs', (The University of Central Florida, Tampa, FL, USA, 2010) OSE 5203.
[9] B. Braunecker, R. Hentschel and H. J. Tiziani, in: 'Advanced Optics Using Aspheric Elements', (SPIE Press, 2008), pp. 50–55.
[10] J. H. Campbell, R. Hawley-Fedder, C. J. Stolz, J. A. Menapace, M. R. Borden, et al., in: 'NIF Optical Materials and Fabrication Technologies: An Overview', (SPIE Photonics West, 2004).
[11] A. T. H Beaucamp, A. Matsumoto and Y. Namba, in: 'Ultra Precision Fluid Jet and Bonnet Polishing for Next Generation Hard X-Ray Telescope Application', (JSPE, Tokyo, Japan, 2010).
[12] M. Küchel, K-H. Schuster, K. Freischlad, "Method for Evaluating Interferograms and Interferometer Therefor", United States Patent Number 5,37,341.
[13] K. Freischlad, 'Interferometer Light Source', United States Patent Number 6,061,133 (2000).
[14] J. Biegen, 'Interferometer Surface Profiler for Spherical Surfaces', United States Patent Number 4,948,253 (1990).
[15] M. Kuechel, 'Vorrichtung und Verfahren zur Verminderung der Wirkungen kohärenter Bildfehler in einem Interferometer', Bundesrepublik Deutschland, Offenlegungsschrift DE 10121516A1, Anmeldetag: 3. 5.2001.
[16] M. Küchel, 'Apparatus and Method(s) for Reducing the Effects of Coherent Artifacts in an Interferometer', United States Patent 6,804,011 (2004).

[17] L. L. Deck, D. Stephenson, E. J. Gratix and C. A. Zanoni, 'Apparatus and method(s) for reducing the effects of coherent artifacts in an interferometer', United States Patent 6,643,024 (2003).

[18] R. Hild, 'Anwendung eines Siemenssterns als Kalibrinormal?', DGaO-Proceedings 2007 (figure 4).

[19] P. de Groot, X. Colonna de Lega, 'Interpreting interferometric height measurements using the instrument transfer function', Proc. of SPIE, FRINGE, Stuttgart (2005).

[20] V. V. Yashchuk, E. H. Anderson, S. K. Barber, N. Bouet, R. Cambié, et al., Opt. Eng. 50, 093604 (2011).

[21] D. Sykora and P. de Groot, 'Instantaneous measurement Fizeau interferometer with high spatial resolution', Proc. of SPIE 8126 (2011).

[22] B. Kimbrough and J. Millerd, 'The spatial frequency response and resolution limitations of pixelated mask spatial carrier based phase shifting interferometry', Proc SPIE 7790, 77900K (2010).

[23] C. J. Evans, Opt. Eng. 48, 043605 (2009).

[24] M. F. Küchel, 'Interferometric measurement of rotationally symmetric aspheric surfaces,' Proc. of SPIE 7389, section 4.4 (2007).

[25] M. F. Küchel, "Absolute Measurement of Rotationally Symmetric Aspheric Surfaces," in *Frontiers in Optics*, (OSA Technical Digest (CD), Washington, DC, USA, 2006), paper OFTuB5.

[26] R. Smythe, "Moore's Law, The Cloud, The Internet of Things and Precision Engineering", Proc. American Society for Precision Engineering (CD) (2011).

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