Title
Binary pseudorandom test standard to determine the modulation transfer function of optical microscopes

ISBN
9781628417425

Authors
Lacey, Ian
Anderson, Erik H
Artemiev, Nikolay A
et al.

Publication Date
2015-09-01

DOI
10.1117/12.2185191

Peer reviewed

PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Binary pseudorandom test standard to determine the modulation transfer function of optical microscopes

Ian Lacey, Erik Anderson, Nikolay Artemiev, Sergey Babin, Stefano Cabrini, et al.

Ian Lacey, Erik H. Anderson, Nikolay A. Artemiev, Sergey Babin, Stefano Cabrini, Guiseppe Calafiore, Elaine R. Chan, Wayne R. McKinney, Christophe Peroz, Peter Z. Takacs, Valeriy V. Yashchuk, "Binary pseudorandom test standard to determine the modulation transfer function of optical microscopes," Proc. SPIE 9576, Applied Advanced Optical Metrology Solutions, 957608 (1 September 2015); doi: 10.1117/12.2185191

Event: SPIE Optical Engineering + Applications, 2015, San Diego, California, United States

Binary pseudorandom test standard to determine the modulation transfer function of optical microscopes

Ian Lacey*[a], Erik H. Anderson[a], Nikolay A. Artemiev[a], Sergey Babin[b], Stefano Cabrini[a], Guiseppe Calafiore[b], Elaine R. Chan[a], Wayne R. McKinney[a], Christophe Peroz[b], Peter Z. Takacs[c] and Valeriy V. Yashchuk[a]

[a] Lawrence Berkeley National Laboratory, Berkeley, California 94720; [b]aBeam Technologies, Inc., Hayward, CA, 94541; [c]Brookhaven National Laboratory, Upton, New York 11973

ABSTRACT

This work reports on the development of a binary pseudo-random test sample optimized to calibrate the MTF of optical microscopes. The sample consists of a number of 1-D and 2-D patterns, with different minimum sizes of spatial artifacts from 300 nm to 2 microns. We describe the mathematical background, fabrication process, data acquisition and analysis procedure to return spatial frequency based instrument calibration. We show that the developed samples satisfy the characteristics of a test standard: functionality, ease of specification and fabrication, reproducibility, and low sensitivity to manufacturing error.

Keywords: modulation transfer function, interferometric microscope, coded aperture imaging, calibration, test standard, correlation analysis, surface metrology, systematic error

1. INTRODUCTION

Following on the heels of fifty years of coded aperture imaging[1-4], we have developed a reproducible test pattern for use in determining the spatial frequency response or MTF of optical interferometric microscopes[5-8]. The pattern consists of a mathematically determined, binary pseudo-random (BPR), height sequences imprinted on a standard 1 inch diameter circular mirror substrate. The sequences are both 1-D gratings and 2-D arrays that have delta-function-like autocorrelation properties and white-noise-like PSDs. For application to a variety of objective magnifications, the binary pseudo-random sequences are repeated for a range of fundamental element sizes from 0.3 to 2 microns.

Unlike the 1951 USAF resolution test chart, a spoke pattern (Fig. 1a,b), or other test pattern standards with non-uniform frequency distribution across the field of view, using a binary pseudo-random array (BPRA), shown in Fig. 1c, provides a full instrument characterization without bias to a particular region of the objective lens or camera.

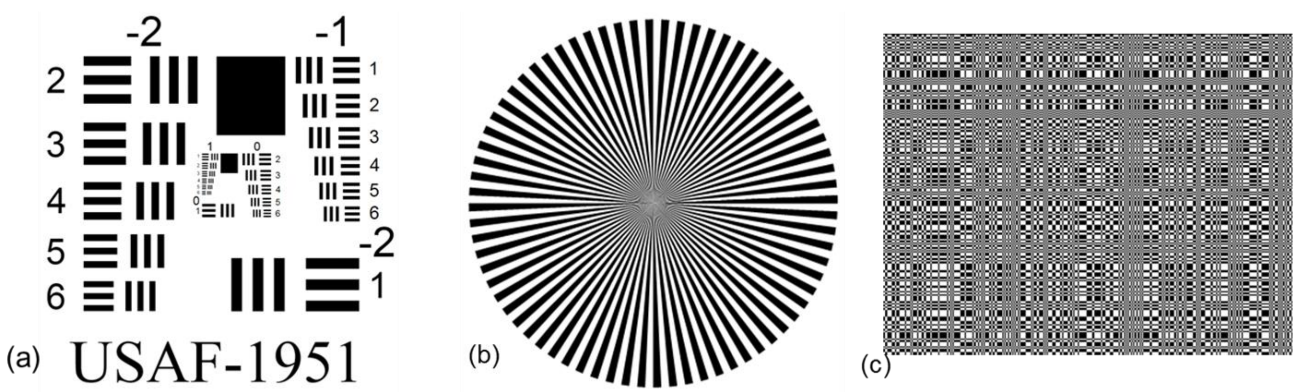

Figure1: (a) The 1951 United States Air Force resolution test chart with discrete spatial frequencies at discrete regions, (b) a Siemens star pattern with high spatial frequencies centrally located, (c) sub-aperture of the BPRA with nearly uniform spatial frequency distribution.

To determine the MTF[9] of an instrument, the measured frequencies of an image are compared against the intrinsic frequencies of the deterministic pseudo-random pattern. This is achieved via an algorithm of rotation, scaling and

*ilacey@lbl.gov; phone:510-495-2644, lbl.gov

Applied Advanced Optical Metrology Solutions, edited by Erik Novak, James D. Trolinger, Proc. of SPIE Vol. 9576, 957608 · © 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2185191

translational alignment between the measurement data and a sub-aperture of the ideal theoretical file that described the overall structure of the measured pattern.

2. BINARY RANDOM SEQUENCE AND ARRAY METHOD

The binary pseudo-random sequence consists of a prime number of unit sized elements[10]. In the cases of an array, the possible dimensions are twin primes, in this case 4129 x 4127 fundamental units. The fundamental unit size should be chosen such that it is below the resolution limit of the instrument, and that the entire instrument field of view is a sub-aperture of the test sample.

White noise like PSD

To provide a full characterization of the instrument optical path and detector, with uniform sensitivity to low and high spatial frequencies, a test sample will ideally be random. A truly random structure has an intrinsic flat PSD, which for a discrete number of steps, a pixelated measurement, can be expressed as (see e.g.[11, 12])

$$S_2(l,k) = M\ N\ \Delta x \Delta y \left| F_{l,k} \right|^2 \tag{1}$$

where

$$F_{l,k} = \frac{1}{M} \sum_{m=0}^{M-1} \left[\exp\left(\frac{-2\pi iml}{M} \right) \frac{1}{N} \sum_{n=0}^{N-1} h_{m,n} \exp\left(\frac{-2\pi ink}{N} \right) \right] \tag{2}$$

with M and N as the number of pixels in the respective directions, and with Δx and Δy as the unit dimensions of a single pixel. The term $F_{l,k}$, expanded in Eq. 2, represents the elements of the Fourier transform matrix. The one sided, positive frequency 1-D PSD may be evaluated from Eq. 1 as

$$S_1(k) = 2g(k) \sum_l S_2(l,k) \tag{3}$$

and

$$S_1(l) = 2g(l) \sum_k S_2(l,k) \tag{4}$$

with $0 \le l \le M/2$, $0 \le k \le N/2$ where $g(l) = 1/2 \quad at \quad l = 0, M/2$ and $g(\mathrm{k}) = 1/2 \quad at \quad k = 0, M/2$ and $g(l) = 1$ and $g(\mathrm{k}) = 1$ otherwise.[13]

For a limited spatial frequency bandwidth, such random structures may be approximated with "sandpaper" surfaces, or with the likes of un-treated magnetic tape, but such surfaces are not deterministic so the exact inherent PSD is unknown.

Delta function like autocorrelation

To avoid mis-alignment of the recorded image with the ideal pattern, a single strong cross-correlation between the experimental and theoretical data must be present. Such a delta-function-like correlation can be expressed from the sequence correlation function, $A_j = \sum_{i=0}^{N-1} a_i a_{i+j}$, and the "deconvolution" sequence, $b_k = \frac{2a_k - 1}{2^{n-1}}$ as,

$$\Delta_j = \sum_{i=0}^{N-1} a_i b_{i+j} = \frac{1}{2^{n-2}} \sum_{i=0}^{N-1} a_i a_{i+j} - 1 \tag{5}$$

For illustrative purposes, the alignment of the measured sub-aperture to the theoretical ideal is depicted in Fig. 2.

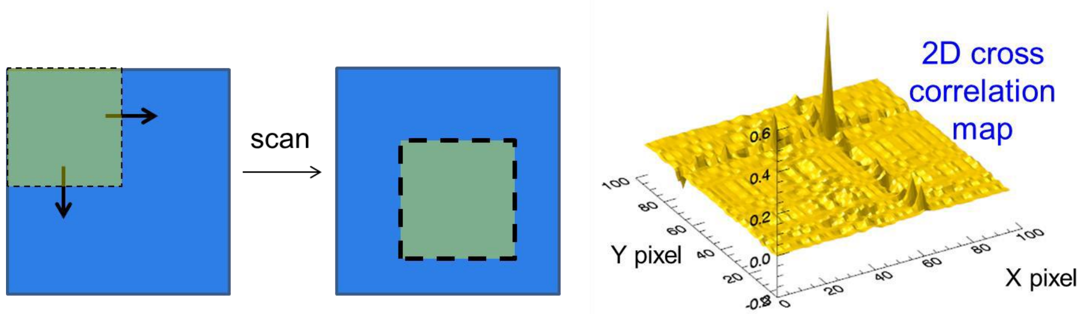

Figure 2: Diagram of the alignment of the measured region (represented as the small green box) to the theoretical file (represented as the large blue area), left and center. Right, the cross-correlation map used to determine mutual alignment.

From this alignment via cross-correlation, the theoretical region that matches the measured region is determined. From these two datasets, the MTF is determined, discussed in Sec. 4.

3. TEST STANDARD DESIGN FOR OPTICAL MICROSCOPES

While the method described above works to determine the instrument MTF, it is reliant upon the availability of a suitable test pattern. For extensibility to a variety of instruments at various labs around the world, we are developing reproducible test standards.

Multiple resolutions on a single sample

The base of the standard is a1 inch diameter circular Si substrate with multiple binary pseudo-random patterns and one step-height[14] etched on the surface. The frequency range is determined at the high end by the wavelength of light, and at the low end by half the pattern width.

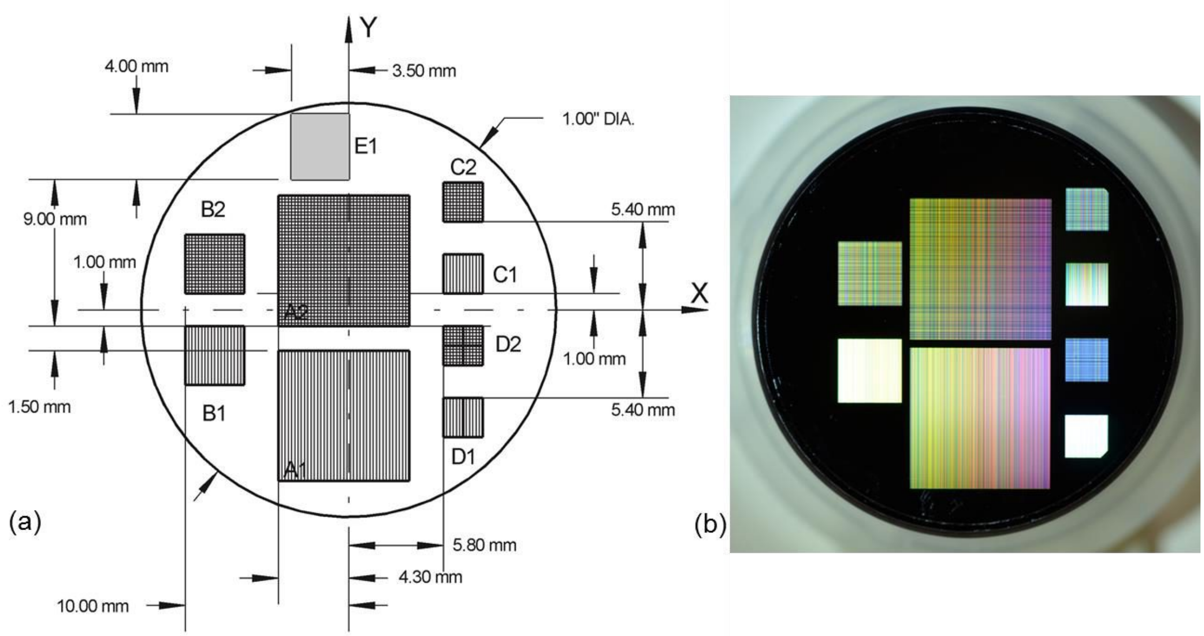

Figure 3: (a) Layout of the BRR patterns on a 1" Si substrate, (b) nano-fabricated MASTERMOLD test pattern.

The sample MASTERMOLD, Fig. 3b, is fabricated by electron beam lithography to the specifications in Table 1.

Table 1. Specification of the MASTERMOLD test pattern.

BPR Gratings			
	Elementary Size [nm]	Number of Elements, $N_X \times N_Y$	Total Size, $X \times Y$ [mm]
A1	2000	4095×1	8.19×8.2
B1	900	4095×1	3.69×3.7
C1	600	4095×1	2.56×2.6
D1	300	$2 \times 4095 \times 1$	$(2 \times 1.28) \times 2.6$
BPR Arrays			
	Elementary Size [nm]	Number of Elements, $N_X \times N_Y$	Total Size, $X \times Y$ [mm]
A2	2000	4129×4127	8.258×8.254
B2	900	4129×4127	3.716×3.714
C2	600	4129×4127	2.477×2.476
D2	300	$(2 \times 2)(4129 \times 4127)$	1.239×1.238
Single Step			
	Size [mm]	Number of Elements	Total Size, $X \times Y$ [mm]
E1	3.5×4	1	3.5×4

The grating, 1-D sequences can be used without advanced software to provide an estimate of noise. The PSD in the grating direction provides spatial frequency response. Where the PSD orthogonal to the grating direction differs from the expected zero, this gives an estimate of the noise cut-off.

The arrays may be used for a full 2D characterization of the instrument under test. The Hough transform of the lower frequency, readily resolved, array lines may be used to determine the optical aberration of the objectives.

From nanofabricated master to reproduction samples

Where electron beam lithography, used to produce the MASTERMOLD is time consuming and costly, the following reproduction technique is used to reproduce the same patterns onto Si substrates.

UV reactive material is poured onto the MASTERMOLD and pressed with a transparent quartz substrate that was spincoated and baked with a bonding agent. This mold is exposed for 110 seconds to 365 nm light with power density of 14 mW/cm^2.

Replication onto superflat 1 inch diameter Si substrates is performed with the Hyperbaric Imprint Tool, a home-made system to perform nano-imprinting with pressures greater than 8 bar. Final pattern transfer into Si is performed by reactive ion etching.

4. DATA PROCESSING SOFTWARE

Integral to the determination of the instrument MTF, is the comparison of the PSD of the measured BPRA, to the inherent PSD of deterministic pattern.

Data collection and processing

Multiple repeated measurements are averaged, with the number of frames to average determined from an instrument self-test measurement[15] such that the detector noise is effectively reduced below a threshold proportional to the step height.

Bad data points, either bad pixels in the detector, or surface contamination, are corrected by averaging over nearest neighbor points.

A Hough transform of Canny edge detection is used to determine any rotation of the sample image from the detector pixel coordinates. An inverse Hough transform, or backprojection, is used to rotate the image to the coordinates of the camera pixels. Prior to rotation, the pixel values are scaled by a factor of 10 to preserve intensities at each pixel. After rotation, the values are rescaled back to normal.

Polynomial detrending of the measured image is performed to compensate for low frequency height variation and to make the mean variation of intensity values equal to zero.

The theoretical file is scaled and resampled to the nominal effective pixel size of the measurement.

Determining the portion of the ideal BPRA contained in the field of view

The initial matching of the measured data and the scaled theoretical file is performed by determining the mutual position of the entire images that corresponds to the maximum cross correlation between the images. Ideally, the largest cross correlation value between the two images should indicate the region of best alignment between the measurement and the ideal pattern, and therefore reveal the area of interest on the theoretical sample. The upper left corners of both images are initially aligned, and the experimental image is shifted one pixel at a time horizontally and vertically over the entire theoretical image to determine the largest valued cross-correlation, see e.g. Fig.2.

Determination of the power spectral density (PSD) distributions and instrument MTF

The PSD of the measured data is divided by the PSD of the theoretical file to determine the MTF^2, according to

$$MTF^2 = \frac{PSD_{measured}}{PSD_{inherent}} \tag{6}$$

This squared MTF is then added to the measured PSD to provide the measurement correction.

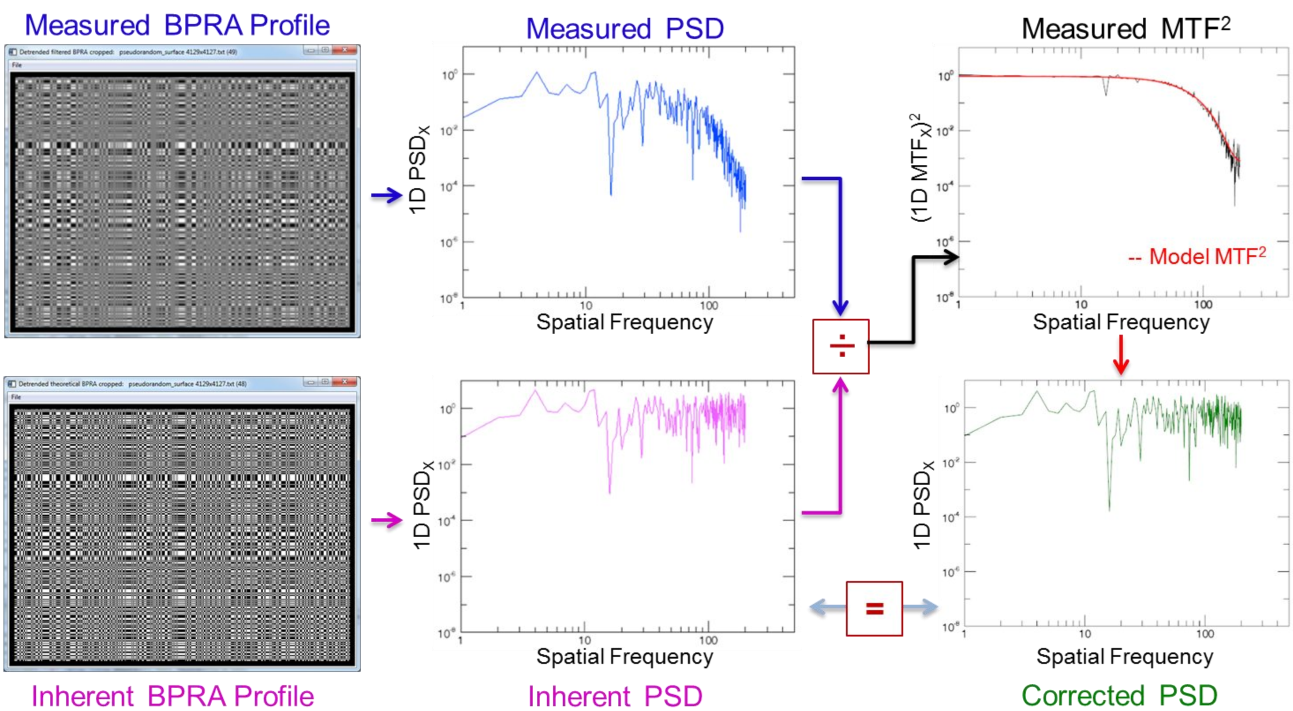

Figure4. Process diagram of the instrument correction showing both the measured and inherent surfaces, along with the associated PSDs. Dividing the PSDs normalizes the scale, and yields the MTF^2 which may then be used to correct both this and future measurements of unknown samples.

5. CONCLUSIONS

This patented innovation[16] is for improved calibration of the main metrology tools used for the characterization of high quality optical surfaces with sub-Angstrom roughness, and for imaging at the nanoscale, including interferometric microscopes.

Advantages of the BPRA samples and software are universality (applicability to the main metrology instrumentation), quantitative characterization (capability for precision calibration), high functionality (calibration over the entire dynamic range), ease of specification for a number of production processes, easily reproducible (low sensitivity to fabrication imperfections[8]), ease of interpretation (amenable to spectral simulation), and potential for development as certified standards.

Commercialization grant and work is in progress to optimize pattern reproducibility and improve software user experience and instrument integration.

ACKNOWLEDGMENTS

The Advanced Light Source is supported by the Director, Office of Science, Office of Basic Energy Sciences, Material Science Division, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231 at Lawrence Berkeley National Laboratory. DOE BES: STTR grant Phase I (2014) and Phase II (2015-2016) on "Development of pseudo-random binary array calibration artifacts for statistical functions of profilers used in measuring X-ray optics," under Award Number DE-SC0011352. University of California: Proof of Concept Commercialization Grant ID No. 268826 (2014) on "Test System for Calibration of High-Performance Microscopes"

REFERENCES

[1] Calabro, Domenick, "On the Synthesis of Two-Dimensional Arrays with Desirable Correlation Properties," Information and Control 11, 537-560 (1968).

[2] Fenimore, E. E., Cannon, T. M., "Coded aperture imaging with uniformly redundant arrays," Applied Optics Vol 17 No 3, 337-347 (1978).

[3] Chan, Y. K.,Siu, M. K., Tong, P., "Two-Dimensional Binary Arrays with Good Autocorrelation, " Information and Control 42, 125-130 (1979).

[4] Busboom, A., Elders-Boll, H., Schotten ,H. D., "Uniformly Redundant Arrays," Experimental Astronomy 8, 97-123 (1998).

[5] Yashchuk, Valeriy V., McKinney, Wayne R., Takacs Peter Z., "Binary pseudo-random grating as a standard test surface for measurement of modulation transfer function of interferometric microscopes" *Proc.* SPIE 6704-07 (2007).

[6] Yashchuk, Valeriy V., McKinney, Wayne R., Takacs Peter Z., "Binary pseudorandom grating standard for calibration of surface profilometers," Optical Engineering 47(7), 073602-1-5 (2008).

[7] Barber, Sam K., Soldate, Paul, Anderson, Erik. H., Cambie, Rossana, Marchesini, Stefano, McKinney, Wayne R., Takacs, Peter Z., Voronov, Dmitriy L., Yashchuk, Valeriy V. , "Binary pseudo-random gratings and arrays for calibration of the modulation transfer function of surface profilometers: recent developments,"Proc. SPIE 7448, 744803 (2009); doi: 10.1117/12.825389.

[8] Samuel K. Barber Erik H. Anderson Rossana Cambie Stefano Marchesini Wayne R. McKinney, “Stability of modulation transfer function calibration of surface profilometers using binary pseudo-random gratings and arrays with nonideal groove shapes,” Optical Engineering Vol. 49(5), 053606 (2010).
[9] Bracewell, Ronald, N., “The Fourier Transform and Its Applications,” McGraw-Hill Publishing Company, New York, (1986).
[10] Koleske, D. D., Sibener, S. J., “Generation of pseudorandom sequence for use in crosscorrelation modulation,” Rev. Sci. Instrum. 63(8), 3852-3855 (1992).
[11] Yashchuk, Valeriy. V., Franck, Andrew. D., Irick, Steve C., Howells, Malcolm R., MacDowell, Alastair A., McKinney, Wayne R., “Two dimensional power spectral density measurements of x-ray optics with the Micromap interferometric microscope,” SPIE Proceedings 5858, pp. 58580A-1-12.
[12] Yashchuk, Valeriy V., Irick, Steve. C., Gullikson, Eric. M., Howells, Malcolm. R., MacDowell, Alastair. A., W. R. McKinney, F. Salmassi, T. Warwick, “Cross-check of different techniques for two dimensional power spectral density measurements of x-ray optics”, *Proc.* SPIE 55921, pp. 59210G-1-12 (2005); doi: 10.1117/12.619892.
[13] Stover, J.C., “Optical Scattering: Measurement and Analysis,” Bellingham second edition, (1995)
[14] Takacs, Peter. Z., Li, Michelle X., Furenlid, Karen, Church, Eugene L. “Step-height standard for surface-profiler calibration”, *Proc.* SPIE 1995, 235-44 (1993).
[15] Lacey, I., Artemiev, N. A., McKinney, W. R., Merthe, D. J. and Yashchuk, V. V., “High precision surface metrology of x-ray optics with an interferometric microscope,” Proc. SPIE 8838, 883808-1-8 (2013).
[16] Yashchuk, Valeriy V., McKinney, Wayne R., Takacs, Peter Z., “Test surfaces useful for calibration of surface profilometers,” Patent No.: US 8,616,044, (Dec. 31 2013)