Development of traceability methodology for optical coherence tomography (OCT) using step height standard as calibration reference.

Iakyra B. Couceiro[a], Thiago Ferreira da Silva[a] , Luiz V.G. Tarelho*[a], Carlos L. S. Azeredo[a],
Igor Malinovski[a] , Hans P. H. Grieneisen[a] , Wellington S. Barros[a],
Giancarlo V. Faria[b], Jean P. Von der Weid[b] ,
Marcello M. Amaral[c] , Marcus P. Raele[c], Anderson Z. de Freitas[c]
[a]INMETRO, Av. N. Sra. Das Graças, 50, Duque de Caxias, RJ, Brazil 25250-020
[b]PUC-RJ, ,R. Marques de S. Vicente, 225, Rio de Janeiro, RJ, Brazil 22451-900
[c]IPEN-SP, Av. Prof. Lineu Prestes, 2042 , São Paulo, SP, Brazil 05508-900

ABSTRACT

This paper presents a methodology for providing traceability to OCT measurements linked to Length SI unit. The link to primary length standard is provided by an interference microscope (IM). The chosen transfer standard was a step height gauge block. The results for IM and OCT showed good agreement for step height standards, such that the OCT will be able to perform reliable measurements of complex surface topographies and to ensure traceability to the length scale. The main uncertainty components were evaluated for the OCT system. In addition, OCT also was used for measuring a surface roughness standard -a depth standard - in order to test this methodology for round groove profiles. Results were found to be in good agreement with the calibration certificate.

Keywords: interferometry measurements, depth standard, step height standard, interference microscope, optical coherence tomography, optical transfer device.

1. INTRODUCTION

OCT (Optical Coherence Tomography) is an imaging technique developed originally for tomography of biological microstructures [1] but soon found applications in other areas. For instance, OCT measurements have found broad medical and industrial applications ranging from dermatological characterization [2] to material analysis [3].

OCT allows reconstructing 3D images of the internal microstructure of a sample, using a Michelson interferometer with a broadband spectrum light as a source and a high speed optical detector. The axial resolution of OCT images is governed by the coherence length of the illumination source. The penetration depth depends on both, the wavelength of the source and sample optical properties.

The particular features of this technique are the controlled penetration depth, non contact measurement and potential high speed data acquisition. OCT technology is experiencing a fast growth due to high resolution achievement of about 1 μm, improving the conventional technical limit of 10 μm [4]. The high speed data acquisition (~25000scans/s) was possible due to FD-OCT technique (Fourier Domain – OCT) developed in 2006 and some companies achieved higher speed for their systems compared to TD-OCT (Time Domain OCT - ~400 scans/s)[5]. This technology change allowed reduction of speckle and motion artifacts during the image processing [6].

Despite of its widespread applications, OCT is still lacking a calibration method for axial scale measurements. We propose in this paper a methodology to provide traceability to OCT measurements using step height gauge blocks as transfer standards. In order to achieve SI traceability, an interference microscope of Linnik type illuminated by a stabilized He-Ne laser source was used to measure this transfer standard. The He-Ne laser is traceable to Inmetro´s primary length standard [7].

Optical Measurement Systems for Industrial Inspection VII, edited by Peter H. Lehmann,
Wolfgang Osten, Kay Gastinger, Proc. of SPIE Vol. 8082, 80822P · © 2011 SPIE
CCC code: 0277-786X/11/$18 · doi: 10.1117/12.889404

2. BACKGROUND INFORMATION

2.1 TD-OCT system

In the beginning of the 90´s a great diversity of OCT methods was developed. There are two main types TD-OCT (Time Domain) and FD-OCT (Fourier Domain), whose main difference is related to interferogram analysis in the time or frequency domain. The FD-OCT can be classified as SD-OCT (Spectral Domain) and SS-OCT (Swept Source), latter depending whether the illumination source is a broadband or tunable source, respectively [8]. In spite of the differences between these techniques, the calibration procedure proposed here - focused in depth scale calibration - can be applied to all of them. Calibration of lateral displacements (XY directions) can be done interferometrically with fringe counting method.

OCT differs from ultrasound imaging by interfering the back reflected infrared light with a reference beam in the interferometer arms. The tomographic measurements presented here are based on optical low-coherence reflectometry (OLCR) [9]. It is based on a broad spectral width optical source with low coherence length. A continuous wave (CW) signal is divided into two arms with equal lengths, reflected back at the end of these arms and combined again at a photo detector. By changing the optical path of one arm relative to the other by a distance smaller than the coherence length, an interference pattern can be recorded. From the temporal locus of the damped envelope of the interferogram, which only occurs within the coherence length of the source and with the optical path of both arms matched, distance information is extracted. Each mirror scan provides axial information (a-scan) and the transversal translation of the sample after each axial scan provides a spatial tomographic image (b-scan).

The axial and transversal resolution for this technique are independent and their limits depend on the source bandwidth and wavelength for axial resolution limit while the transversal resolution is determined by the focusing properties of the probe beam [10].

2.2 Linnik interferometer

A Linnik interferometer is a modified Michelson interferometer with an objective lens in each arm. The sample lens allows one to observe a small sample area, typically in the micrometer scale, and the other lens is placed into the reference path. No fringes are observed when the optical paths from both arms are identical [11]. Fringes are observed when the conjugation points between the reference plane and the object have different optical path lengths giving rise to an interference pattern. If both reference and object are plane surfaces and slightly tilted to each other, the interference pattern produced is a set of parallel interference fringes. At Inmetro, this kind of interferometer was assembled and characterized for traceability transfer between the practical realization of the length and materialized artifacts in the sub-micron scale. The data acquisition and analysis are performed by an in- house developed software in Visual Basic [12].

3. EXPERIMENTAL SETUP

3.1 TD-OCT system

Figure 1 shows an experimental setup of TD-OCT. A fibered super luminescent light-emitting diode (SLED with 90 nm spectral width centered at 1320 nm) was used as the broadband light source. This device was operated under temperature and current control. After passing through a 50/50 fiber coupler the light beam emerging is launched onto the sample under test. Part of the back reflected beam from the sample and from the single mode fiber tip is collected and guided by the same fiber and injected into a Michelson interferometer after passing through the same coupler. This interferometer contains movable and stationary mirrors in perpendicular arms and a detector in the third arm. The fourth arm is a bended fiber for avoiding undesired back reflection. The envelope of the interferogram is obtained in each scanning cycle (inset in Figure 1). The data is processed and analyzed by an in- house developed software in MATLAB.

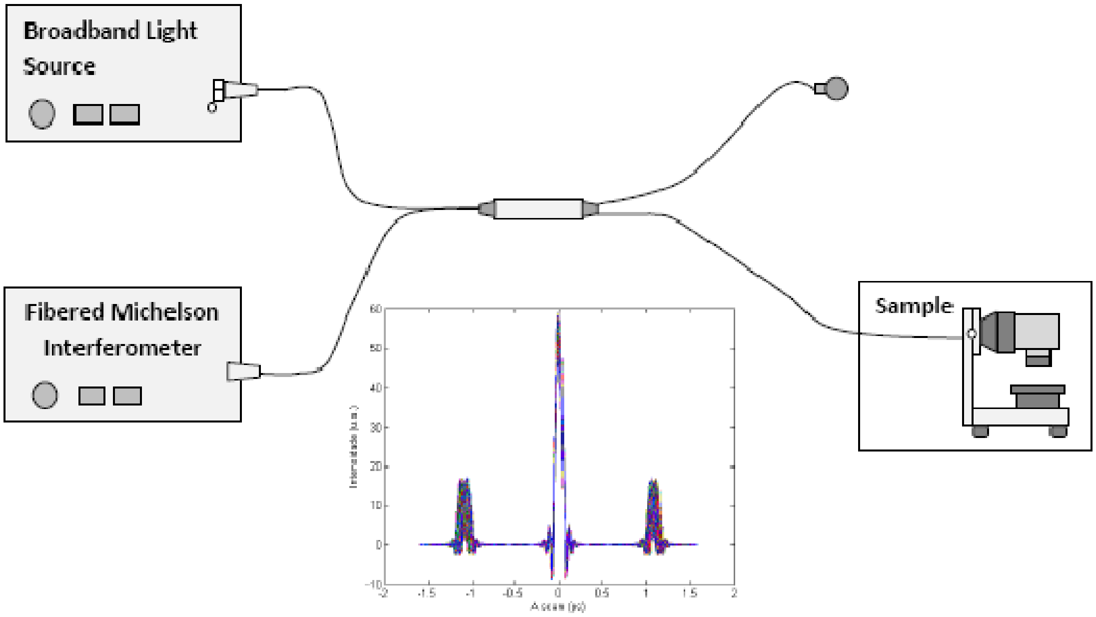

Figure 1 – TD-OCT experimental setup.

3.2 Interference microscope – Linnik interferometer

Inmetro´s Linnik interferometer was mounted on top of an optical breadboard as shown in Figure 2. The light source used in this setup is a frequency stabilized He-Ne laser. The laser beam is directed through a speckle removal device consisting of two lenses with 100 mm focal length and a rotating diffuser plate. The emerging light is divided by a 50/50 beam splitter and directed into the object and reference arms. Two identical microscope objectives are placed at the same distance from the step height block object and the flat reference mirror (λ/20). The reflected beams from object and reference are recombined at the image plane of the CCD camera where they generate the fringe pattern (inset at Figure 2)

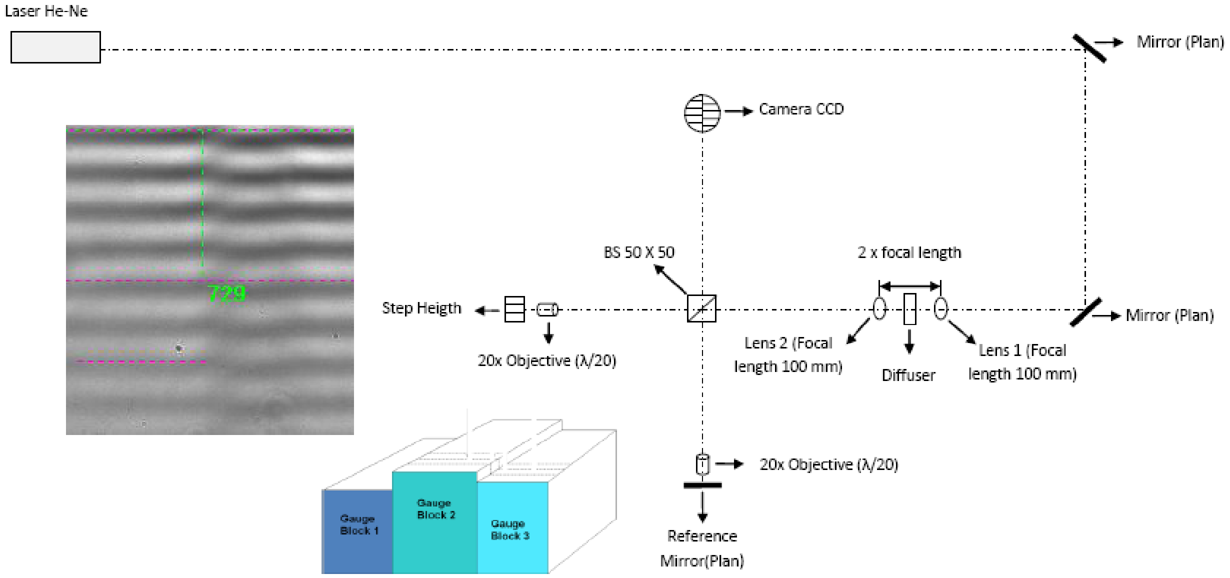

Figure 2 – Linnik interferometer setup

4. RESULTS AND DISCUSSIONS

The materialized artifact used as transfer standard for length realization consisted of a step height standard made up from three different gauge blocks joined together with nominal step heights of 2 and 10 μm, as shown in the inset of Figure 2. The surface flatness was better than λ/20 as specified by the manufacturer. This standard was first measured with the Interference Microscope (IM) and then it was measured by TD-OCT technique. The measurement procedures on both systems were adapted from SIM-Euramet L-K8 surface roughness technical protocol [15].

The correction results for the nominal height agreed very well with the manufacturer calibration in an IM similar to the Brazilian Linnik type, as can be seen in Table 1a. One should observe that with the Linnik interferometer the deviation from the nominal step height is measured, while with the OCT system the actual step height is determined, as shown in Table 1b.

Table 1a – Deviation of nominal depth and uncertainty for step height gauge blocks measured by interference microscopy

Nominal Step Heigth h_0 (μm)	Manufacturer		Inmetro Linnik	
	Δh (nm)	U(h) (nm)	Δh (nm)	U(h) (nm)
2	-50	50	-43	23.3
10	+50	50	+67	23.3

Table 1b – Measured step height and uncertainty for step height gauge blocks measured by TD-OCT and Linnik.

Nominal Step Heigth	TD-OCT		Linnik	
h_0 (μm)	h (μm)	U(h) (μm)	h (μm)	U(h) (μm)
2	2.09	0.68	1.957	0.023
10	10.30	0.68	10.067	0.023

5. UNCERTAINTY BUDGET

The uncertainty components have been estimated and the uncertainty budget for measurements at Inmetro for both systems (IM and OCT) was evaluated.

The uncertainty budget for Linnik interferometer (Table 2) can be evaluated taking into account some predominant components and those which appear in other interferometers for length measurements, such as Koesters [16] or Twyman Green [17]. The environmental influences have not been considered due to small length measurements which are expected to be insignificant. They will be characterized in a future work with a proposal for minimization of these systematic errors.

Table 2 - Uncertainty Budget for Primary Transfer Device – Interference Microscope (Linnik)

	Standard Uncertainty Component	Source of uncertainty	Value of standard uncertainty $u(x_i)$	$C_i=\left\|\frac{\partial f}{\partial x_i}\right\|$	$u_i(l)=C_i\ u(x_i)$ (nm)	Degrees of freedom ν_i
a	$u(t_1)$	Sample-Objective distance	$\frac{0.001}{\sqrt{3}}$ mm	473.5 nm/mm	0.273	3
b	$u(l_2)$	Source Spot Size	$\frac{0.001}{\sqrt{3}}$ mm	1.92 nm/mm	0.001	4
c	$u(l_1)$	Source Alignment	$\frac{0.001}{\sqrt{3}}$ mm	1701.7nm/mm	0.982	4
d	$u(\varepsilon)$	Fringe fraction	0.01	$\lambda/2$ *	3.16	∞
e	u(s)	Interferometer alignment	1.62	1	1.62	5
f	u(repe)	Repeatability	8.81	1	8.81	5
g	u(repro)	Reproducibility	0.83	1	0.83	12
h	$u(\lambda)$	Laser Wavelength	0.009	1	0.009	∞
Combined standard uncertainty u_C					9.6	
Effective degree of freedom						7
k (95.45%; 7.00) = 2.43						
Expanded Uncertainty $U=k\ u_C$					23.3	

Materialized Standard for primary transfer – Step height

*λ=633.99 nm

In the absence of a mathematical model one has to determine a sensitivity coefficient experimentally as can be observed in Figure 3.

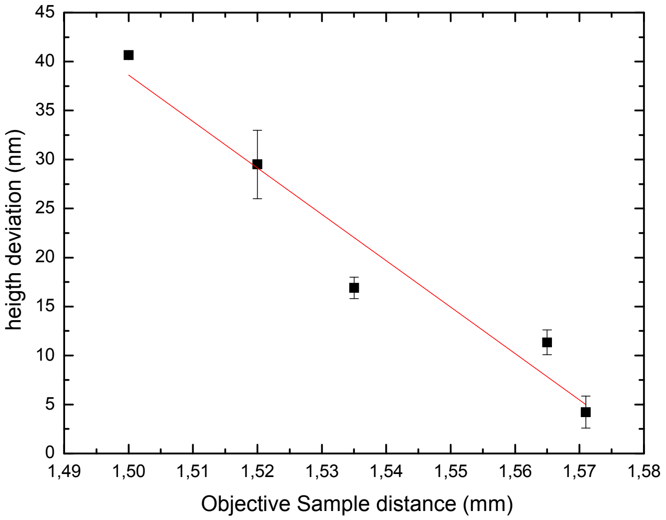

Figure 3- Experimental Sensitivity Coefficient for Linnik interferometer.

The uncertainty budget for TD-OCT (Table 3) can be evaluated taking into account the transfer standard and statistical analysis of the system. The spectral bandwidth of broadband light source was measured and found to be stable during the measurements such that the uncertainty component was not necessary to be evaluated.

Table 3 - Uncertainty Budget for Secondary Transfer Device – TD - OCT

	Standard Uncertainty Component	Source of uncertainty	Value of standard uncertainty $u(x_i)$ µm	$C_i=\left\|\frac{\partial f}{\partial x_i}\right\|$	$u_i(l)=C_i\,u(x_i)$ (µm)	Degrees of freedom ν_i
a	u(h)	Step heigth uncertainty	0.0096	1	0.0096	7
f	u(repe)	Repeatability	0.040	1	0.040	330
g	u(repro)	Reproducibility	0.300	1	0.300	660
Combined standard uncertainty u_C					0.303	
Effective degree of freedom						11
k (95.45%; 11) = 2.25						
Expanded Uncertainty $U=k\,u_C$					0.683	

Materialized standard for secondary transfer –Step height standard.

In order to prove that OCT system works for another different topography, a depth standard was measured, consisting of a flat surface with 6 grooves depths ranging from 0.264±0.008 to 9.457±0.020 µm according to its calibration certificate from German NMI – PTB (Physikalische Technische Bundesanstalt).

OCT measurements were performed with good agreement to the calibrated depth values as can be seen in Table 4 and the surface profile can be seen in Figure 4.

Table 4 – Depth standard calibration results.

Index	Nominal Depth d_0 (µm)	PTB		TD-OCT	
		d(µm)	U(d) (µm)	d(µm)	U(d) (µm)
1	10	9.457	0.02	9.47	0.71
2	6	6.191	0.15	6.13	0.71
3	3	3.075	0.013	3.01	0.71
4	1	0.979	0.010	1.42	0.71
5	0.6	0.624	0.009	0.96	0.71
6	0.2	0.264	0.008	0.53	0.71

The slope baseline for Figure 4 is due to a slight tilt angle of approximately 10^{-4} rad between the translation axis and the surface of depth standard. The fitted depths were presented in the inset of Figure 4.

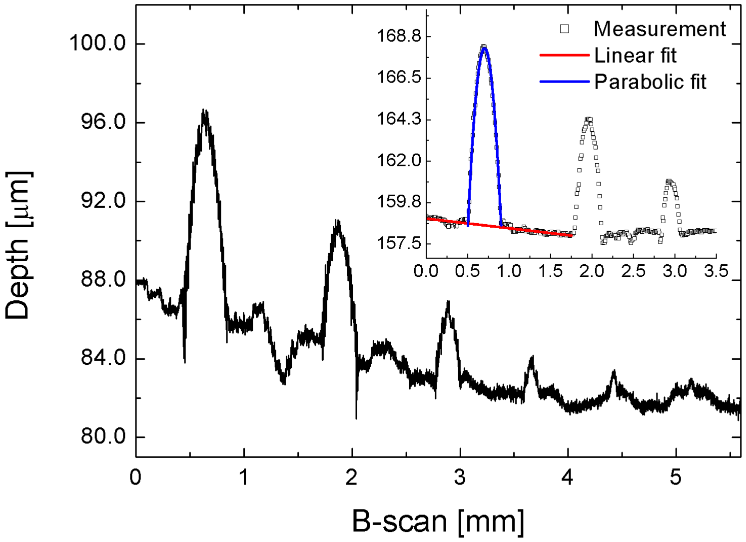

Figure 4 – Sample Profile for depth standard

Experimental measurements were compared to the calibration certificate values and the results were in good agreement to each other according to the uncertainty for both systems, as shown in Figure 5.

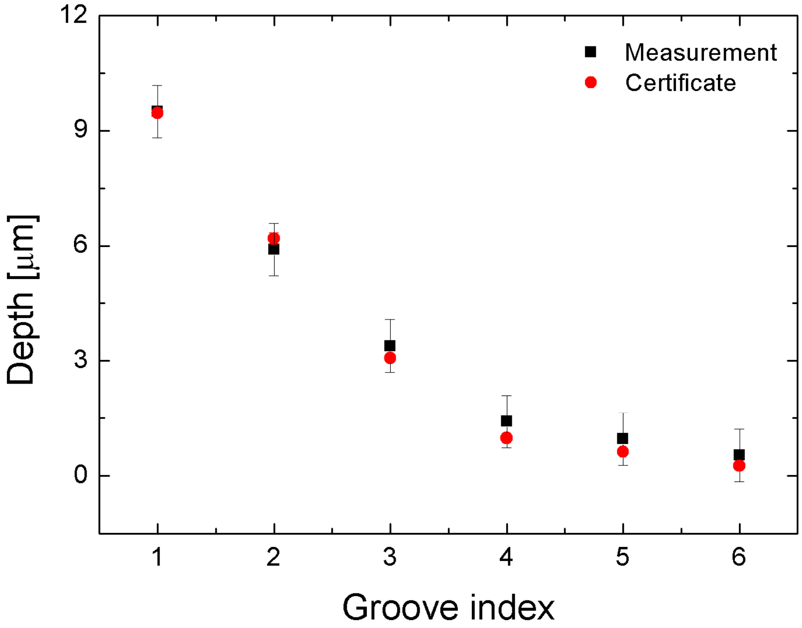

Figure 5 – Results comparison between the depth measurements performed by TD-OCT and the calibration certificate.

6. CONCLUSIONS

In this paper we implemented a methodology for providing traceability to OCT measurements. These first results show good agreement for step height standards, such that the OCT will be able to perform reliable measurements of complex surface topographies and to ensure traceability to the length scale. The uncertainty budget for the measurements was determined to be smaller than 1 μm.

7. REFERENCES

[1] J.G. Fujimoto, "Biomedical Imaging Using Optical Coherence Tomography", Winter College On Spectroscopy And Applications, 1133/18, (1999) And "Optical Coherence Tomography", Winter College On Ultrafast Non-Linear Optics, 1397/12, (2002).

[2] Marcello M. Amaral Et Al, "Roughness Measurement Methodology According To Din 4768 Using Optical Coherence Tomography (Oct)" , Proc. Spie 7391, 7390OZ 1-8 (2009).

[3] Marcello M. Amaral Et Al, "Laser Induced Breakdown Spectroscopy(Libs) Applied To Stratigraphic Elemental Analysis And Optical Coherence Tomography (Oct) To Damage Determination Of Cultural Heritage Brazilian Coins", Proc. Spie 7391, 7391OI 1-12 (2009).

[4]Arnaud Dubois Et Al, "Ultra-High Resolution Full-Field Optical Coherence Tomography", App. Opt.43(14), 2874-2883 (2004).

[5] G. Smolka, [Optical Coherence Tomography: Technology, Markets, And Applications 2008-2012], Pennwell Corp., (2010)Www.Bioopticsworld.Com/Resourcecenter/Octreport.Html

[6] Delphine Sacchet Et Al, "Motion Artifact Suppression In Full Field Optical Coherence Tomography", App. Opt. 49(9), 1480-1488 (2010).

[7] Matus, Michael "Final report for the period 2007–2009 on the CCL-K11 ongoing key comparison",Metrologia 47, 04009 (2010).

[8] Mark Brezinski, [Optical Coherence Tomography- Principles And Applications], Elsevier, Burlington (2006).

[9] D. Huang Et Al, "Optical Coherence Tomography", Science 254, 1178-Xxx (1991).

[10] W. Drexler And J.G. Fujimoto, [Optical Coherence Tomography: Technology And Applications], Springer, Berlin (2008).

[11] Linnik, W.P., "Ein Apparat Für Mikroskopisch-Interferometrische Untersuchungen Reflektierender Objekte (Mikrointerferometer)." , C. R. Dokl. Acad. Sci. Urss 5, 210 (1933), Cited In: Harris, W., Mrowka, S., Speer, R.J., " Linnik Interferometer: Its Use At Short Wavelengths", App. Opt. 21(7), 1155-1155 (1982).

[12] Igor Malinovski, “Development Of The Interference Microscope For Traceable Step Height Standard Measurements And Afm Calibration”, Proc. Spie 8036, 8036-34 (2011)

[13] International Standard, Iso 5436-1 – Geometrical Product Specifications (Gps) - Surface Texture: Profile Method; Method Standards – Part 1 – Material Measures (2000).

[14] International Standard, Iso 4287 – Geometrical Product Specifications (Gps) - Surface Texture: Profile Method– Terms, Definitions And Surface Texture Parameters (1997).

[15] Euramet L-K8 Surface Roughness Comparison- Technical Protocol (2009).

[16] H. Darnedde , “High Precision Calibration Of Long Gauge Blocks Using The Vacuum Wavelength Comparator”, Metrologia 29, 349-359 (1992).

[17] J.E. Decker, J.R. Pekelsky, “Uncertainty Evaluation For The Measurement Of Gauge Blocks By Optical Interferometry”, Metrologia, 34, 479-493 (1997).