Effect of the number of fringes on the measurement of Gauge Blocks using an interference pattern.

Speaker/Author: Jorge Luis Galvis Arroyave, National Metrology Institute of Colombia, Av. Carrera 50 No 26 - 55, +57 310577172, jlugalvis@inm.gov.co.

Author: William A. Gomez, Mayerlin Nuñez, Laboratorio de Óptica Cuántica, Universidad de los Andes de Colombia, A.A. 4976, Bogotá, D.C., Colombia

Abstract:

The National Metrology Institute of Colombia and the metrology laboratories in charge of providing traceability to industry have been challenged by the exponential growth of new technologies and the improvement of the measurement systems of industry in Colombia. As a result, the National Institute of Metrology of Colombia (INM) has adapted and modified its technologies to ensure the traceability chain for the latest and most innovative measurement systems. In a joint effort with the Universidad de los Andes, we present preliminary results for a 2 mm grade 0 gauge block length measurement using a Twyman-Green interferometer and the use of phase stepping as a technique to verify the laser beam wavefront. We also present the suitability of the interferometer for gauge block length measurements and the effect of the number of fringes on the length measurement results and uncertainty. This apparatus is intended to be the first prototype of an interferometer for gauge block measurement and calibration in Colombia.

1. Introduction

The digital revolution in manufacturing techniques has led to the adoption of new measurement and inspection tools with ever-stricter accuracy requirements. This imposes stringent demands on the measurements and length standards used to fulfil traceability requirements set out by the BIPM, particularly for lengths below one metre. The traceability chain from the practical realization of the meter to the industry is ensured by gauge-blocks. These blocks are widely used since they are robust, made from relatively cheap material and provide a convenient way to calibrate different length measuring instruments [1]. The gauge-block calibration is one of the most important tasks of national metrology institutes. There are two main techniques employed for gauge-block calibrations, the mechanical comparison between gauge-blocks and interferometric measurements [2] [3]. The uncertainty for the mechanical comparison is defined by the contribution associated to thermal expansion of the gauge block, deviations on the measurement system and the mechanical conditions of the gauge-block comparator [4]. On another hand, the uncertainty for interferometric measurements is associated with the air refractive index correction, thermal expansion, and wavefront aberrations caused by the pass of the light through the interferometer [5].

Gauge-block length measurements using interferometric techniques have been reported the use of multiple light sources and interferometers such as the Michelson interferometer [6], the Twyman Green interferometer [7], the Kösters interferometer [8], and the Fizeau interferometer [9] among others. Interferograms are analyzed by the estimation of the fringe separation between the patterns from the gauge-block and from a reference surface using the excess fraction method. This method has variations in order to improve the accuracy of the length measurement from interferograms. The variations include the analysis of the interferograms using curve fitting [10], phase stepping [11]–[13] and Fourier transform [14]–[17].

In order to reduce the uncertainty in length measurement, the phase stepping technique has been improved by studying the influence of the wavelength of the different light sources [16], [18]–[20], by changing the optical path of one of the light beams in the interferometer[21] and by improving the filtering algorithms for image processing [22] .

In this work, a Twyman-Green interferometer is set up for the measurement of the length of gauge blocks. The wavefront of the light is characterized using the phase stepping technique implemented by changing the optical path in combination with a non-continuous path algorithm for image processing [23]. The setup presented here is intended to serve as a guide for the first prototype of an interferometer for the automatic measurement and calibration of gauge blocks in Colombia, with the aim of expanding the capabilities of the National Institute of Metrology (INM) [2].

2. Gauge Block Length Measurement Method

From interferometric techniques the length of a gauge-block is determined by the excess fractions method. Figure 1 illustrates the principle behind the method. The fraction F_i can be calculated from the static interference pattern by measuring the fringe relative shift between patterns from the gauge block surface and from the reference surface.

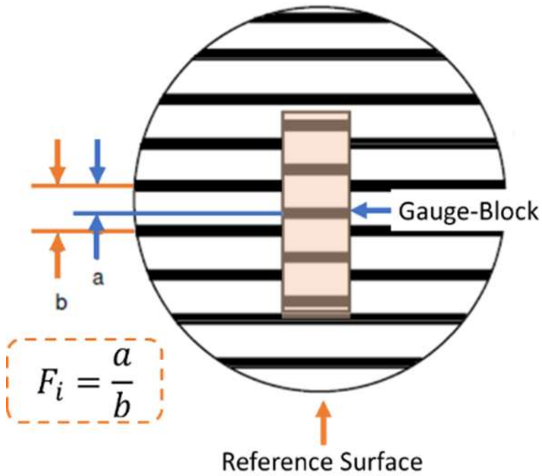


Figure 1. Illustration for the extraction of the fraction $\boldsymbol{F_i}$

According to the method, the length of the gauge-block, l_{fit} can be written as [24], [25]

$$l_{fit} = (m_i + F_i)\frac{\lambda_i}{2} \tag{1}$$

Where λ_i is the wavelength of the light, m_i and F_i are the integer and fractional part of the number of light waves required to span the length of the gauge block [Decker]. When a single laser is used for the measurements of gauge blocks is very practical use the nominal length of the gauge-block l_p to obtain the theoretical values for m_i and F_i in order to validate the experimental results for l_{fit}. Due to the value l_p is obtained from mechanical calibrations of the gauge-blocks, l_p has a coverage interval Δl_p given by the expanded uncertainty (U_{lp}) reported in the calibration certificates, as a consequence, for the nominal length of the gauge block exist a set of possible values between the limits of the coverage interval given by $\Delta l_p = \{l_p - U_{lp} \leq l_p \leq l_p + U_{lp}\}$. Therefore, the theoretical fraction F_p also has an interval of possible values denominated as the error range $\Delta\varepsilon_F$ and is defined by the Eq. 1 and Δl_p as

$$\Delta\varepsilon_{Fp} = \left\{\frac{2}{\lambda_i}\left(l_p - U_{lp}\right) - m_i \leq F_p \leq \frac{2}{\lambda_i}\left(l_p + U_{lp}\right) - m_i\right\} \tag{2}$$

From Eq. 2, $\Delta\varepsilon_{Fp}$ is a useful tool to determine if the measured fringe fraction F_i is suitable for the estimation of l_{fit}.

3. Experimental Setup

In order to determine the fraction F_i and to calculate l_{fit} for a gauge-block a Twyman Green interferometer is set up. The light source is a Helium Neon (He-Ne) laser with a central wavelength of $\lambda = 632.991 \pm 0.001$ nm measured with a wavelength meter (High-Finesse WS6-200). The laser light is directed to the interferometer from the bare end of the laser housing as shown in Fig. 2. Lenses L_1 and L_2 form a Keplerian beam expander that collimates and doubles the diameter of the laser beam (1 mm), L_3 and L_4 form a Galilean beam expander that expands the laser beam to 25 mm. The expanded light beam is divided using a beam splitter. One of the beams is reflected by the reference surface where the gauge block is wrung. The second beam is sent to a reference tilted mirror mounted on a piezo-electric (PZT) translational stage (Thorlabs NFL5DP20/M). The fringe pattern produced by the interferometer varies form concentric rings to parallel straight lines depending on the tilt (θ) of the reference mirror. The interference pattern resulting from the combination of the two beams is imaged into a monochromatic CCD camera (Thorlabs DCU224M) through a plane convex lens L_5. The flatness of the mirrors inside the interferometer are in the order of $\lambda/10$. The measurand is a grade 0 gauge-block with nominal length $l_p = 2.00000 \pm 0.00005$ mm with a calibration certificate issued by INM and wrung to a reference surface which is a Karl Frank precision parallel gauge block. The length of the measurand is measured for different tilt angles (θ_i) (different number of fringes). The interferometer was adjusted to guarantee the wavefronts are plane and perpendicular to the direction of propagation of the beam. These conditions are verified with the phase stepping technique.

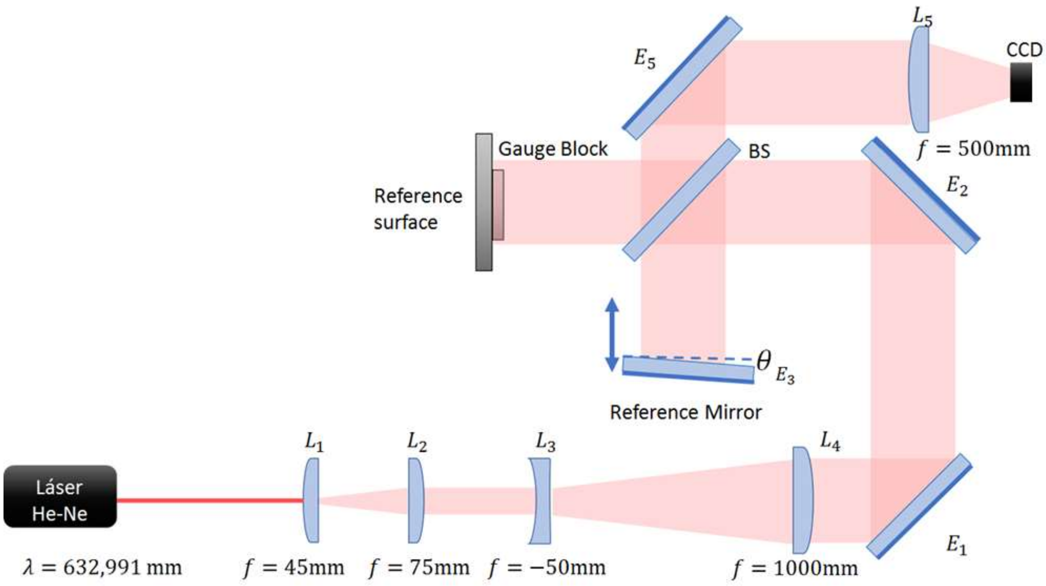


Figure 2. Twyman Green interferometer built for the gauge block length measurement.

4. Wavefront characterization and phase stepping technique

The phase stepping technique enables the evaluation of the phase distribution of the wavefront and the noise produced by problems of collimation, misalignment of the optical components and errors in the displacement of the reference mirror [24], [26].

A 5-step phase stepping technique was implemented due the low sensibility to the low order detector nonlinearities and the low phase step errors [27]. The phase shift is generated by the linear displacement of the reference mirror using the PZT in Fig.2. The translation stage moved the reference mirror by phase steps of $\alpha = \pi/2$ from $-\pi$ to π obtaining 5 images of the interference patterns. Each phase step corresponds to a movement of the mirror of $d = 79.2 \pm 0.6$ nm. The phase map ϕ of the wavefront can be calculated from the images as

$$\phi = tan^{-1}\left(\frac{I_2 - I_4}{-I_1 + 2I_3 - I_5}\right) \tag{3}$$

$$cos(\alpha) = \left(\frac{I_5 - I_1}{2(I_4 - I_2)}\right) \tag{4}$$

if α is uniform over the measurement surface, the phase stepping is performed correctly and there are no step errors (Lewis p159). Figure 3 shows the phase map ϕ and the phase step α obtained from 5 images of the 2 mm gauge-block according to Eq. 4 and Eq. 5 respectively. Care is taken to wait for the conditions of the interferometer to be stable after the movement of the PZT. The Fig. 3a shows the acquired phase map from the reference and gauge-block surfaces with 2π discontinuities due to the technique. Additional discontinuities are presented in some regions of the phase map due to the optical noise from different sources [16] and to the errors in the steps made by the PZT. To quantify the phase step error, the deviations of α from the expected value (90°) are shown in Fig. 3b from which the maximum phase step error is estimated to be $\pm$ 6.43° , so the maximum error for the phase ϕ is $\pm$ 0.18° , calculated according to Hariharan et al. [27]. This phase error guarantees that the wavefront in the experiment is suitable for gauge-block length measurements [12], [27].

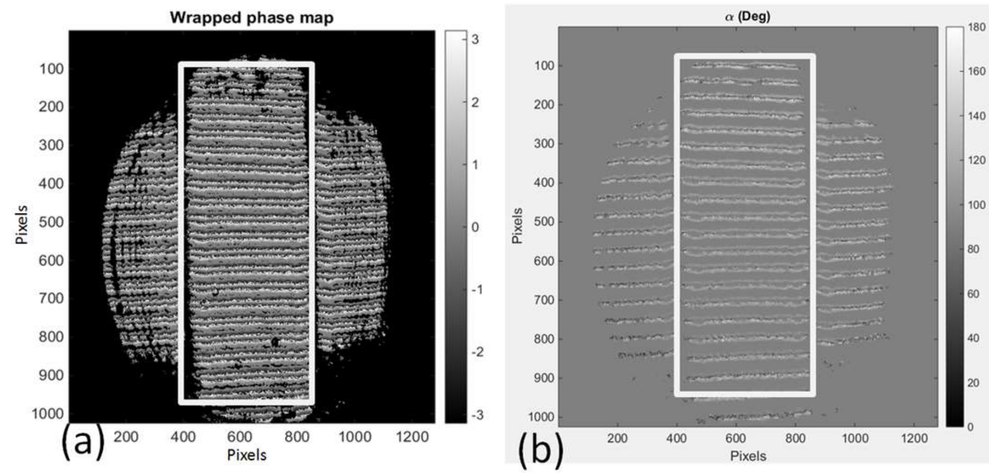


Figure 3: a) phase map. b) α Phase step image.

Information from Fig. 3a is used to obtain the unwrapped phase applying the Herráez algorithm [23]. The algorithm is capable of properly extracting the phase reflected from the reference surface and the gauge block surface [21]. Figure 4 shows the unwrapped phase. The homogeneous color pattern in Fig. 4 corroborates the phase distribution over the gauge-block and over the reference surface. The color scale indicates the different phases from both surfaces.

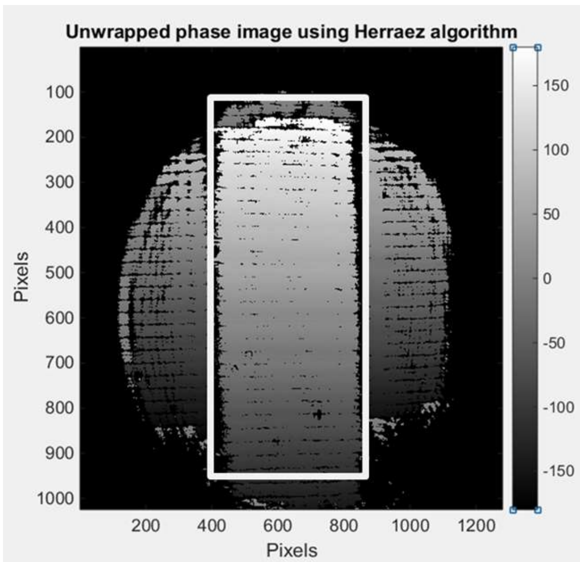
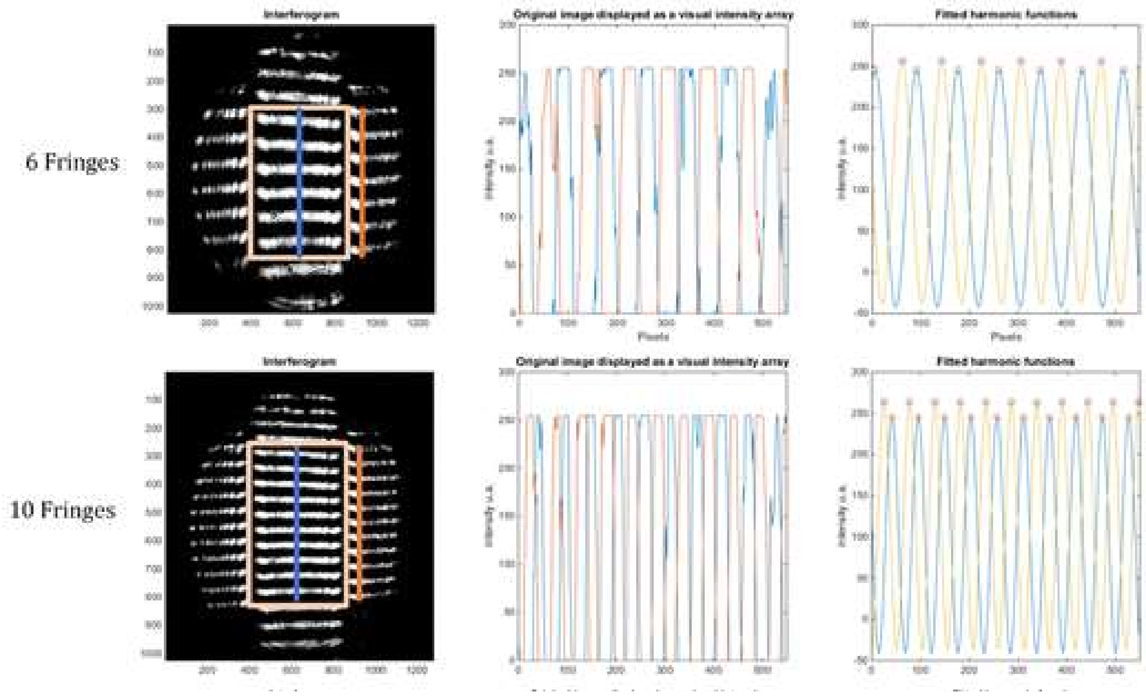


Figure 4: Unwrapped phase map.

5. Length measurement results

After validating the phase error in the setup of Fig. 2, the fringe fraction F_i for the gauge-block is measured as a function of the number of fringes in the interference pattern. Five different numbers of fringes (6, 10, 12, 14, and 20) are considered by changing the tilt of the reference mirror θ. Figure 5a shows the interference patterns obtained for the different numbers of fringes. The intensity profiles are obtained from the average of 10 pixels represented by the vertical lines in the interferograms. Figure 5b shows two curves obtained from the interference patterns from the gauge-block and from the reference surface. The intensity of the light saturates the camera creating rectangular functions making it difficult to identify the real center of each peak affecting the measurement of F_i . Using the Levenverg Marquardt algorithm [28] the rectangular function can be fitted to a harmonic function that represents the intensity profiles from the interferometer images. The fitted functions, in Fig. 5c, enables the estimation for the parameters α and b required for the calculation of the fringe fraction F_i (Fig.1). The uncertainty in the fraction $u(F_i)$ is calculated from the uncertainty in the parameters α and b from the measurements.



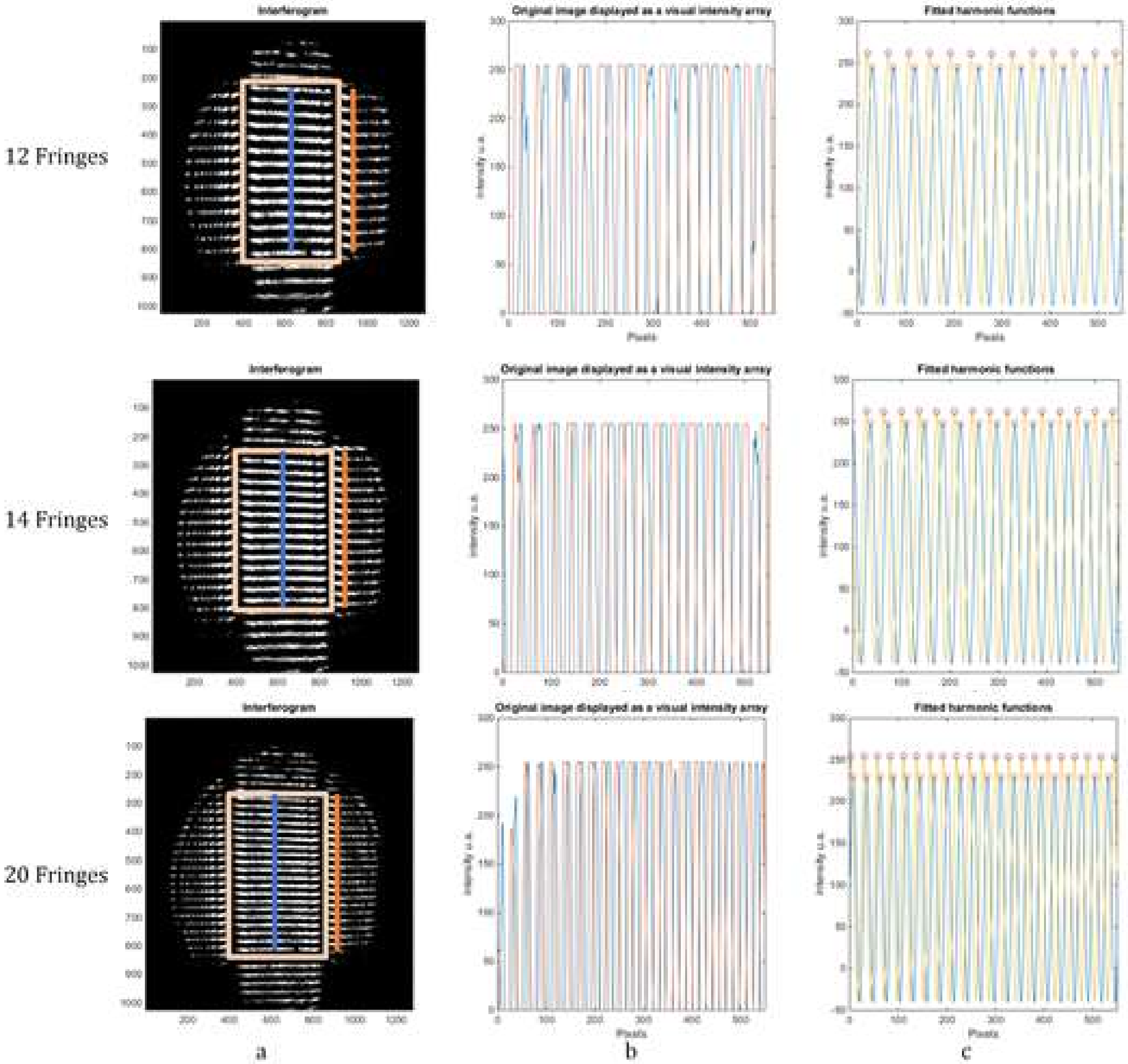


Figure 5: a) the image of the fringe pattern over the gauge block and the reference surface; b) the intensity profile from the gauge block and the reference surface: c) the best fitted functions for the intensity profile.

6. Uncertainty Evaluation

Since this work aims to evaluate the influence of the number of fringes of the interferograms for the mathematical model, only the main parameters for fitting the gauge block length have been considered. According to the Guide for the Expression of Uncertainty in Measurement (GUM), the model can be expressed as

$$l_{fit} = (m_i + F_i)\frac{\lambda_i}{2} \tag{5}$$

From Eq. 3 the standard combined uncertainty is expressed as

$$u_c^2(l_{fit}) = \left(\frac{\lambda}{2}\right)^2 u^2(m) + \left(\frac{\lambda}{2}\right)^2 u^2(F_i) + \left(\frac{m+F}{2}\right)^2 u^2(\lambda) \quad (6)$$

The uncertainty for λ is defined by the wavelength meter uncertainty (Δν), the laser wavelength (λ) and frequency (ν).

$$u(\lambda) = \sqrt{\left(\frac{\Delta\nu}{\nu}\lambda\right)^2} = 5{,}4 \times 10^{-7}\ \text{nm} \quad (7)$$

The uncertainty for the integer m is defined by the uncertainty of the gauge block from calibration certificate $u(l_p) = 25$ nm and the uncertainty of the laser wavelength $u(\lambda)$.

$$u(m) = \sqrt{\left(\frac{2}{\lambda}\right)^2 u^2(l_p) + \left(\frac{2}{\lambda^2}\right)^2 u^2(\lambda)} = 0{,}16\ \text{nm} \quad (8)$$

For the fringe fraction uncertainty, the mean values calculated for a and b from Fig.5 have to be used as part of the sensitivity coefficients $(1/b)$ and (a/b^2) with their respective uncertainties $u(a) = u(b) = 0{,}29$. Because of the above, the repeatability uncertainty has to be considered for each parameter $u(r_a)$ and $u(r_b)$.

$$u(F_i) = \sqrt{\left(\frac{1}{b}\right)^2 u^2(a) + \left(\frac{a}{b^2}\right)^2 u^2(b) + u^2(r_a) + u^2(r_b)}$$

Table 1 shows the results for the gauge-block length, l_{fit}, obtained by measuring the fringe fraction F_i for the different interferograms in Fig. 5. According to Eq. 1, for the 2 mm gauge-block, $m_i = 6319$ and $F_p = 0.219 \pm 0.011$. In order to validate the obtained length measurements, the F_i should be less than the maximum acceptable error for F_i, defined as $\varepsilon_{Fmax} = F_{max} - F_p = 0.158$ [29], where the maximum value for the fraction is $F_{max} = 0.377$ (Eq. 2). Table 1 shows the different values obtained for the fraction F_i and the error in the fraction defined as $\varepsilon_{F_i} = F_i - F_p$. For the interferogram with 6 fringes where $\varepsilon_{F_i} > \varepsilon_{Fmax}$, therefore the length of the gauge-block cannot be determined from this image. For the other 4 images, the uncertainty $u(F_i)$ for the measured fraction decreases when the number of fringes in the interferogram increases, affecting the total uncertainty for the l_{fit}. This suggests that a proper number of fringes has to be considered in order to improve the measurements made with the interferometer. The last two columns in Table 1 report the lengths measured for l_{fit} and its uncertainty calculated from Eq. 1 where the uncertainty in the wavelength λ is given by the wavelength meter as $u(\lambda) = 5.4 \times 10^{-7}$ nm.

Table 1: Fringe fractions estimated, Fringe Error and lengths fitted

N Fringe	$\boldsymbol{F_i}$	$\boldsymbol{\varepsilon_{F_i}}$	$\boldsymbol{u(F_i)}$	$\boldsymbol{l_{fit}}$ (mm)	$\boldsymbol{u(l_{fit})}$ (mm)
6	0,39	0,16	-	-	-
10	0,33	0,11	0.46	2.00004	0.00031
12	0,25	0.03	0.22	2.00001	0.00017
14	0,23	0.02	0.19	2.00001	0.00016
20	0,222	0.003	0.051	2.00001	0.00011

From the results in Table 1, the lower uncertainty for the length measurement is $u(l_{fit}) =$ 110 nm for the interferogram with 20 fringes. In comparison with uncertainty reported by the calibration certificate for the nominal length ($u(l_p) = 50$ nm), the uncertainty reported here is overestimated. In order to reduce the uncertainty, $u\left(l_{fit}\right)$, the optical noise and external influences over the measurement system must be considered carefully.

In order to have an absolute length measurement for the gauge-block, the values for the fitted length l_{fit} in Table 1 must be corrected considering the influence of the optical instruments, the mechanical characteristics of the gauge block and environmental conditions over the length measurements [13][30]. A future study must be performed in order to estimate these corrections and the error of the measurements here reported with respect to the nominal length l_p.

7. Conclusions

In this paper we report the first setup of a Twyman-Green interferometer for the measurement of gauge blocks in Colombia. The phase stepping technique is used to evaluate the phase error of the wavefront. The suitability of the interferometer for length measurements is demonstrated by estimating the phase of the wavefront with an error of $\pm$ 0.18° using updated algorithms [23]. Using this apparatus, the first results are presented for a length measurement of a gauge block of 2 mm in size. Using the excess fraction technique, the best length measurement has an uncertainty of 110 nm. All the corrections necessary to validate our measurements from a metrological point of view will be considered in future work. The results presented are first steps towards interferometric calibration of gauge blocks in Colombia.

8. References

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