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Modernization of the Hilger and Watts Guage-block Interferometer

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Modernization of the Hilger & Watts gauge-block interferometer

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Abstract. The Hilger & Watts gauge-block interferometer was designed and manufactured commercially in the 1950s. The instrument uses isotope lamps as wavelength standards to perform absolute length calibration of gauge blocks (slip gauges) up to 100 mm in length, to an accuracy of approximately 1 ppm. It is entirely manually operated. In order to make the instrument more suitable for the modern laboratory, new hardware has been added, and a customized software package developed to automate the measurement process. This paper shows how interferograms may be imaged successfully at each of the eight available wavelengths, and the critical fringe fraction measurement automated, ensuring an accuracy better than ±0.05 fringe. To demonstrate the validity of the new system, representative data are presented alongside data obtained using the traditional method and from an external accredited laboratory.
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Subject terms: metrology; fringe analysis; interferometry; computer vision; image enhancement.

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1 Introduction

Gauge blocks are secondary standards of length used extensively in engineering and metrology laboratories for dimensional calibration and inspection. They are currently specified under ISO3650,[1] which requires the highest grade (grade K) of gauge blocks to be calibrated interferometrically against a primary wavelength standard.[2] Many instruments have been developed over the to perform this task, one of the most popular being the Hilger & Watts interferometer (Fig. 1)[3–5] manufactured during the 1950s.

This instrument realizes the meter[2] using two isotope lamps (^{114}Cd, ^{198}Hg), which produce eight standard wavelengths in total. The method then requires manual reading of each variable together with slide rules and printed correction tables for computation of the final calibration result, a process that demands considerable time and skill.

During calibration, each gauge block is wrung radially to a circular steel or quartz platen, which is then mounted underneath an optical flat, so that the entire assembly becomes a Fizeau interferometer. The interferometer is then illuminated by each standard wavelength in turn. The resultant interferograms appear discontinuous, showing a phase difference between fringes along the face of the gauge (Fig. 2) and those along the platen, which is termed the fringe fraction *f*. The length of the gauge, *L*, is related to this quantity by the following series of equations, for each wavelength λ_n and each observed fraction f_n:

$$L=(M_1+f_1)\frac{\lambda_1}{2}=(M_2+f_2)\frac{\lambda_2}{2}=\cdots=(M_n+f_n)\frac{\lambda_n}{2}. \quad (1)$$

Here M_n is an integer term, corresponding to the order of interference at each wavelength. Equation (1) contains n unknowns and $n+1$ equations; hence there is no unique solution. However, if two or more wavelengths are used, the length tolerance of a gauge block is so small that all but one solution will be acceptable, a technique known as the *method of exact fractions*. These equations were originally solved using slide rules and tables. Alongside the length calculation, other corrections for thermal dilatation of the gauge, obliquity, phase change, and the refractive index of air[6–8] are added to produce the final mechanical length value at 20°C, in accordance with ISO3650.[1]

Since the advent of affordable microelectronics and reliable stabilized lasers in the 1980s, numerous automated gauge-block interferometers have been developed.[9–12] Instead of adding a laser source[13] to the existing interferometer, the current research sought to retain each of the eight isotope-lamp wavelengths for calibration, with a system able to accommodate these and any future laser wavelengths. This paper describes how a high-quality gauge-block interferometer may be significantly upgraded at a fraction of the cost of a newer instrument.

2 Experimental

2.1 *Imaging*

A major drawback of the original system was that interferograms must be observed and the fringe fraction estimated visually, increasing measurement uncertainty and reducing repeatability. To eliminate this subjective measurement, a conventional CCD camera (JAI, M50IR) was mounted in place of the eyepiece. This camera was in turn linked to a computer-mounted framegrabber (National Instruments, PCI-1407), which converts analog camera signals to monochrome digital images, suitable for software-based measurement.

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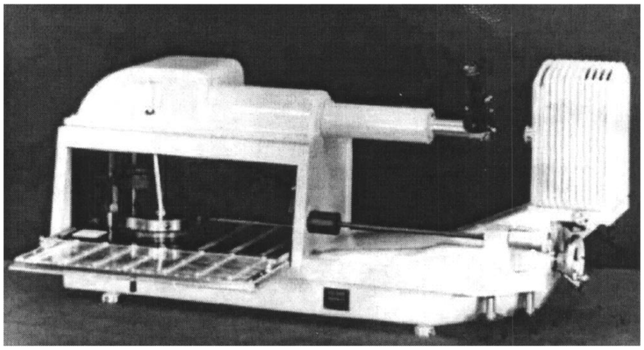


Fig. 1 Hilger & Watts gauge-block interferometer.

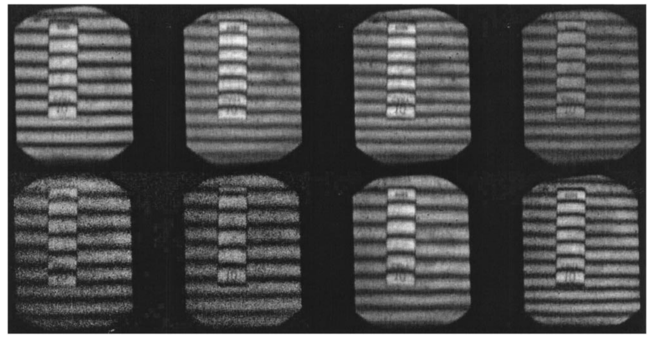


Fig. 2 Enhanced images at each wavelength.

The principal experimental problem was the extremely low light level provided by the isotope lamps. The aperture and image size were first optimized to yield discernible images from the camera. These images were still too poor for quantitative analysis; therefore preprocessing was required. Firstly, a sample of fixed pattern noise is subtracted from incoming images. Subsequently, a sequence of these corrected images (12–20) are added, yielding images with a high enough signal-to-noise ratio for accurate measurements. This process is successful across all eight wavelengths; samples from a 10-mm gauge are shown in Fig. 2.

2.2 *Transducers*

Three digital transducers were added into the measurement chamber to precisely monitor the gauge and air temperatures, atmospheric pressure, and relative humidity. Each transducer was linked to a computer through the RS-232 ports. This arrangement allowed each variable to be recorded digitally in real time; the data are subsequently used in length and refractive index computation.

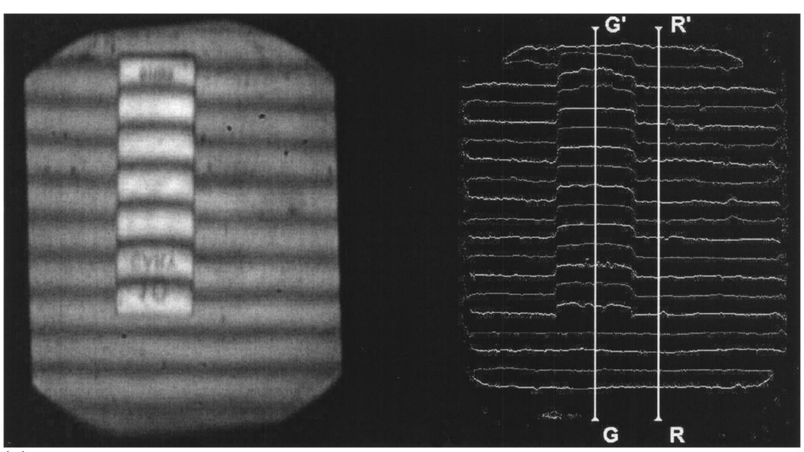
2.3 *Calibration Software*

In order to control all the new hardware and produce the required calibration data, a customized software package was developed using the LabVIEW™ development environment. The main tasks it must accomplish are to extract a fraction data value from processed images, apply the method of exact fractions, add all required corrections, and finally store and retrieve all data.

The length of a gauge block is defined[1] as the vertical distance from the reference plane to the center of the gauge face. Therefore, the fringe fraction must be measured precisely at the center of the gauge. In order to measure the fringe fraction from each of the enhanced images (Fig. 2), the peaks and troughs of the fringes must first be detected. This *skeletonizing* process is depicted in Fig. 3.

These skeletonized images yield both position and phase (i.e., the orders of each fringe) information. Data are then extracted from along the centerline $(G-G')$ of the gauge and along the reference surface $(R-R')$. A third-order polynomial is fitted to each data set, and the curves generated from Fig. 3 are shown in Fig. 4. Each curve interpolates the phase at each point along the interferogram. The relative phase (the horizontal distance between the curves) corresponds to the fringe fraction across the face of the gauge. Evaluating at the center of the block (Fig. 4) yields the correct fraction value. This calculation is repeated at additional reference lines $(R-R')$ to check the repeatability of the calculation and ensure inconsistent data are rejected.

This algorithm has also been tested extensively using simulated interferograms, to assess the accuracy and repeatability of the method, with noisy and unevenly illuminated



(a) (b)

Fig. 3 (a) Enhanced and (b) skeletal images.

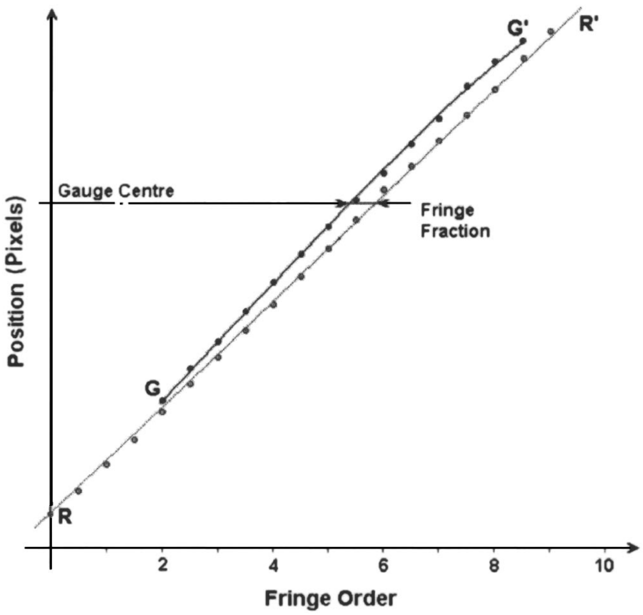


Fig. 4 Fringe fraction interpolation (diagrammatic).

inputs. Despite the low image resolution combined with the inherent noise, the measurement is accurate to better than ±0.05 fringe. This uncertainty figure depends on the noise level, pixel resolution, and fringe visibility. The best results are obtained for short gauge blocks, illuminated with the brighter wavelengths (480, 508, and 546 nm).

While fraction data are obtained at each wavelength, data are acquired periodically from each transducer. Using the fraction and environmental data, the software constantly applies an iterative algorithm to solve the exact fraction equations [Eq. (1)] for whichever wavelength combination the user specifies. All corrections are automatically applied, and the final result presented to the user.

All this information is presented to the user on a Windows-style control panel, a sample of which is presented in Fig. 5. This panel also allows the user to implement all the typical tasks required to administer the calibration, for example, initiation and monitoring of fraction measurements, switching between the results obtained for each gauge, and the adjustment of relevant hardware settings.

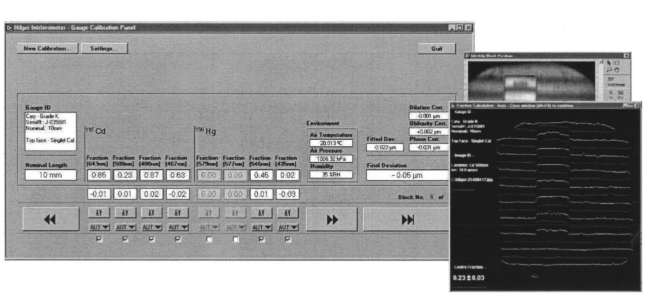


Fig. 5 Calibration software: main window, processed gauge image (top roght), and analysis window (bottom right).

Table 1 Principal uncertainty components.

Component	Value (nm)
Fraction measurement	5.3
Thermal dilatation	0.629(L/mm)
Phase correction	30

3 Results

3.1 *System Performance*

The key advantage of the new system is speed. Image processing and analysis takes less than 10 s. Therefore, using all eight available wavelengths, a calibrated length value may be obtained in as little as 2 min. The original manual method of measurement required about 10 min of observation, together with all the subsequent manual computation and correction to obtain the final value.

In terms of the overall measurement uncertainty, the chief benefits stem from an objective and more accurate measurement of the fringe fraction (within 0.05 fringe) and a reduction in the gauge temperature drift, as the calibration time is reduced. However, some large uncertainty contributors remain; for instance, thermal drift is still large, due in part to the heat dissipated from the isotope lamps. Other factors, such as the phase and obliquity corrections, are unavoidable in high-accuracy interferometric measurements. A summary of the principal uncertainty components is presented in Table 1. Note that the length L should be expressed in millimeters.

Other, more practical benefits include increased traceability, as each interferogram is saved together with each atmospheric measurement taken during the calibration period. Data are also stored and retrieved digitally, making it easy to cross-reference results and compile calibration data for a given set of gauge blocks.

3.2 *Calibration Data*

To assess the validity of the new system, sets of grade K (Ref. 1) gauge blocks were repeatedly calibrated. Results were obtained using the traditional manual method and the new automated system. A representative sample of the data is presented in Table 2, alongside certified (1 month previously) values for each gauge.

The results show clearly that there is no consistent or significant offset present in the data, suggesting that the

Table 2 Gauge calibration results.

Nominal length (mm)	Deviation from nominal (μm)		
	Certified	Manual	New system
25	−0.06	−0.09	−0.07
10	−0.01	+0.01	+0.01
5	+0.00	+0.01	+0.02
2	−0.04	−0.03	−0.03
1	−0.02	−0.04	−0.03
0.5	+0.00	+0.00	−0.01

lamp wavelengths and all the various interferometric corrections are accurate. Each result also falls within the ±30 nm uncertainty band of the certified results. The estimated measurement uncertainty of the new system is ±40 nm, which again is consistent with the data obtained and the certified values.

4 Conclusions

The original aim of this research was to modernize the Hilger & Watts gauge interferometer while maintaining the integrity of an excellent instrument. This paper has demonstrated for the first time how gauge interferograms may be imaged successfully at each of the eight available isotope-lamp wavelengths, and a fringe fraction measurement extracted reliably from each one. Along with other hardware and software, these improvements allow automatic fringe-fraction estimation at each of the eight available wavelengths; environmental readings are recorded constantly, and the data are processed and corrected instantaneously. Calibrations can therefore be completed reliably and in a fraction of the time required by the traditional method.

The system is also designed to be extensible, accommodating any laser sources that may be added in the future. The fringe-fraction methodology may also be adapted to the calibration of Hoke and cylindrical gauges, and enhanced images can also be used to tackle additional dimensional calibration problems, such as optical flats and angle gauges.

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Michael O’Hora graduated from the University of Dublin with a first-class BSc (Hons) in 2000, and later that year joined the Centre for Industrial and Engineering Optics (CIEO) as a postgraduate researcher. His research work has concentrated on optical metrology in collaboration with the Irish National Metrology Laboratory, Dublin. He is currently completing a PhD in physics at the Dublin Institute of Technology (DIT).

Brian Bowe graduated from DIT with a Technician Diploma in applied science (physics), and also a first-class honors BSc in physics and mathematics from Trinity College Dublin (TCD), in 1995. He spent four years as a postgraduate student at DIT School of Physics, and submitted a PhD dissertation to TCD in June 1999. During this time he worked at the European Commission Joint Research Centre, Ispra, Italy for eleven months. He joined the CIEO as head optical engineer in May 1999, and was appointed lecturer in the School of Physics in August 1999. He was awarded his PhD by TCD in August 1999. As well as being a researcher at the CIEO, he is also head of the Physics Education Research Group, set up in 2001 to undertake research into student learning, curriculum development, and pedagogical approaches.

Vincent Toal, BSc, MSc, PhD, FInstP is head of the school of physics at DIT, and director of the CIEO at the institute. He has more than thirty years’ research and teaching experience, mainly in experiment design and the development of courses in applied optics, holography, Fourier optics, and optical metrology. He has published more than 40 papers on these subjects.

Sean Peyton has worked at the Irish National Metrology Laboratory since it was founded in the 1960s. He has more than thirty years of experience in mass, electrical, temperature, and dimensional metrology. Since 1994, he has worked on mass metrology, and is the Euromet contact for mass in Ireland. He was involved in the initial proposal for the modernization of the Hilger & Watts interferometer, and has participated in the project through to completion.