APPENDIX F

PUBLICATIONS BY THE AUTHOR

This appendix contains copies of papers published by the author, relevant to the thesis. These are:

Hughes E B, Jackson K, Lewis A J & Pugh D J
Recent advances in length measurement at the National Physical Laboratory, England
Metrology and Total Quality - Proceedings of the National Conference of Standard Laboratories, Washington DC (1990) 285-294

Lewis A J
Two-wavelength phase-stepping interferometry for absolute length measurement
Applied Optics Digest - Proceedings of Applied Optics & Opto-Electronics Conference, Nottingham (1990) 269-270

Lewis A J & Pugh D J
Design Note: Interferometer light source and alignment aid using single-mode optical fibres
Meas. Sci. Technol. **3** (1992) 929-930

Lewis A J
Three-wavelength phase-stepping interferometer for length measurement up to 1.5 m in a controlled environment
Proceedings of Applied Optics & Opto-Electronics Conference, Leeds (1992) 170-172

A paper entitled "Measurement of length, surface form and thermal expansion coefficient of length bars up to 1.5 m using multiple-wavelength phase-stepping interferometry" has been submitted for publication in a special issue of Measurement Science and Technology on Optical Techniques in Measurement, and is due for publication in June 1994.

RECENT ADVANCES IN LENGTH MEASUREMENT AT THE NATIONAL PHYSICAL LABORATORY, ENGLAND

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Division of Mechanical and Optical Metrology
National Physical Laboratory, Teddington, England.

ABSTRACT

Gauge blocks and length bars provide industry with practical secondary length standards. To provide traceability of these material standards to international standards, they are measured in terms of known wavelengths of frequency-stabilised lasers.

In the last five years NPL has been active in updating its facilities for the measurement of end standards. The main aims of the programme have been to simplify the process of measurement by interferometry so that relatively unskilled staff can operate the equipment and to reduce the time required for measurement.

The use of modem instrumentation and stabilised lasers has also meant that higher accuracy measurements can be made and that more information relating to the variations in length over the gauge measurement surfaces can be obtained

The NPL programme has concentrated on three main areas of work:

- the development of an automatic gauge block interferometer for the measurement of gauges between 0.1 and 100 mm in length,
- a white light interferometer for gauge block measurement,
- a phase stepping interferometer for length bar measurement in the range 100 mm to 1500 mm.

INTRODUCTION - GAUGE BLOCK INTERFEROMETRY

The method of gauge block measurement using multiple wavelength interferometry is well established [1,2]. Gauges to be measured are wrung vertically on to a reference flat and placed in an interferometer producing a set of interference fringes across the gauge and flat; see Figure 2. The fringe spacing corresponds to a height difference of half the wavelength of light used, approximately 300 nm. Having previously determined the approximate length of the gauge, an accurate value can be deduced by measuring the displacement of the fringes on the gauge relative to those on the flat at several wavelengths.

Accurate measurements of the air pressure, temperature and humidity are needed to correct for changes in the measurement wavelengths due to changes in the refractive index of air. Also because of the thermal expansion of the gauge it is necessary to measure accurately its temperature, so that the gauge length can be corrected for the specified operating temperature.

Until recently the interference fringe displacements were estimated visually by skilled operators who were also required to measure manually the pressure, temperatures and humidity. The process was tiring, slow and subject to errors. A new instrument was designed to overcome these deficiencies and to provide greater accuracy.

AUTOMATIC GAUGE BLOCK INTERFEROMETER

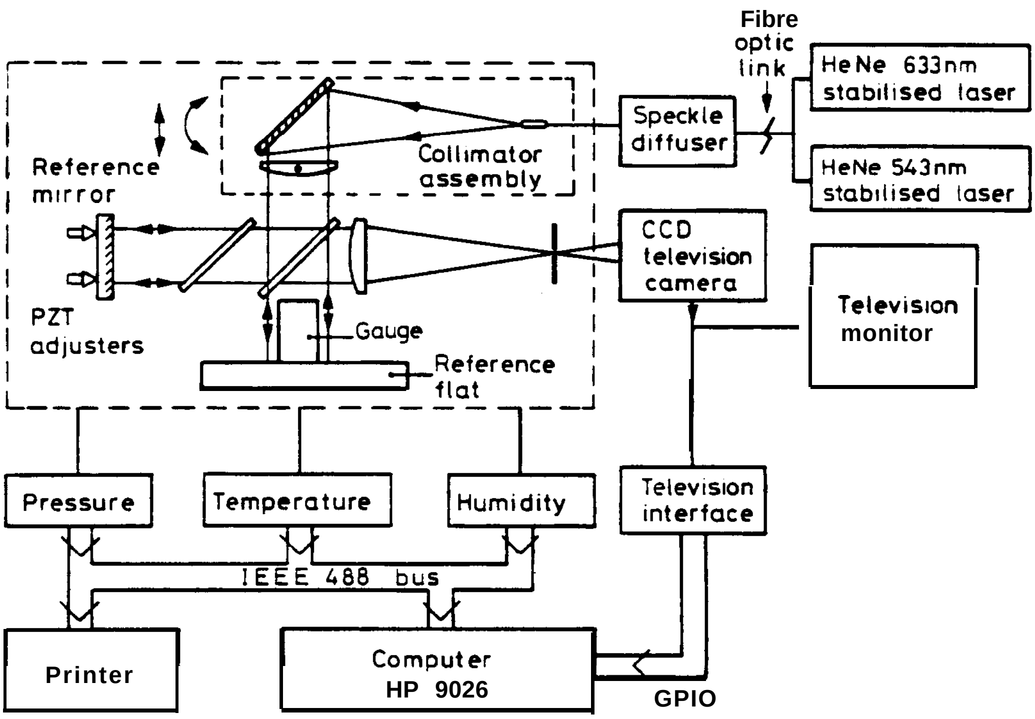

Figure 1. Schematic diagram of automatic gauge block interferometer

A Twyman-Green interferometer forms the basis of the new instrument [3], the high contrast sinusoidal interference fringes being well suited to computer analysis. Two He-Ne frequency stabilised lasers (633 and 543 nm) developed at NPL provide the measurement wavelengths. These lasers wavelengths are very stable and are traceable to international length standards with an uncertainty less than 1 part in 10^8. The brightness and spectral purity of these lasers allow the measurement of lengths up to several metres without loss of fringe contrast.

Automatic measurement of the fringe shifts at the two wavelengths is achieved by examining the fringes with a CCD television camera and calculating the fringe positions with a computer. A photograph of the fringes detected by the television camera is shown in Figure 2; the shift between the fringes on the gauge and reference flat can be seen clearly.

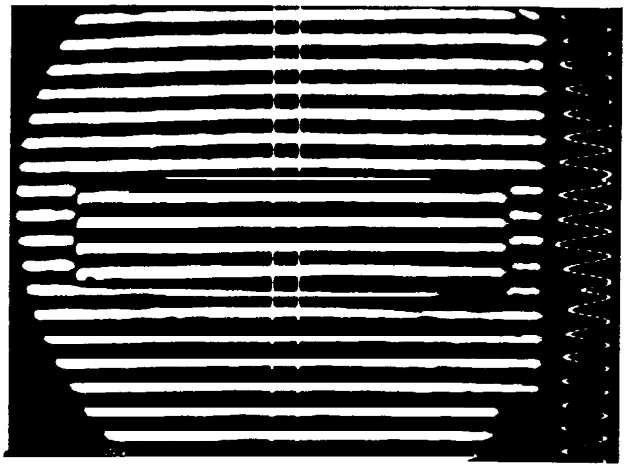

Figure 2. Interferometer output

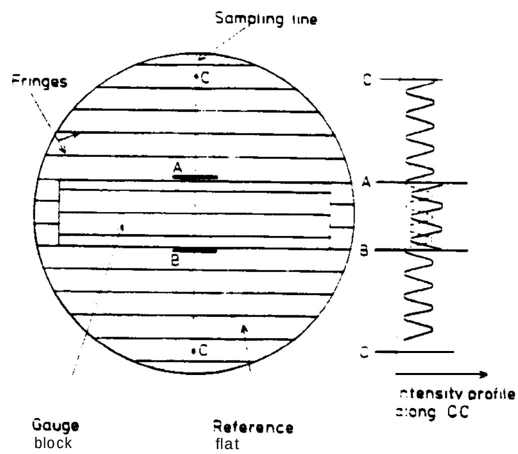

Figure 3. Fringe intensity profile

Figure 3 shows a drawing of the fringes on the gauge and flat with a plot of the intensity profile of the fringes along the line CC, on the right. By entering this profile into the computer and calculating the positions of the fringe minima, the fringe shift can be determined automatically. Because of the influence of pressure, temperature and humidity on the wavelength of light, frequent and accurate monitoring of these parameters is very important. This is achieved using an automatic resistance bridge with platinum resistance thermometers, a vibrating cylinder pressure transducer and a dew-point hydrometer, all interfaced to the computer. Wavelength corrections are applied automatically by the computer. The total uncertainty in the wavelength correction due to errors in this instrumentation and in the computer correction algorithm is typically 1 part in 10^7 ($\pm$ 10 nm for a 100 mm gauge).

Use of the instrument

In practice the instrument is very easy to use. Up to fourteen gauges are wrung on to a large circular reference flat, placed in the instrument, and allowed to reach thermal equilibrium over several hours.

To measure the length of a gauge, the operator views it in the interferometer on a television screen, positions the gauge between two bright line markers (see Figure 2) and adjusts the fringes by remote control of the interferometer reference mirror.

From this point on, the measurement is controlled by the computer. The operator is prompted to type in the gauge reference number, the thermal expansion coefficient and the nominal gauge length. The gauge temperature, air temperature, pressure and humidity are now read automatically by the computer. The two laser wavelengths are selected sequentially and the fringe shift for each wavelength measured. The gauge length is then calculated with all corrections applied automatically. The whole process takes about two minutes for each gauge. The length of each gauge measured is held in a data file and at the end of the measurement sequence a calibration certificate can be printed.

Flatness and surface topography

By measuring the gauge length at a number of points on the measurement surface the gauge flatness and topography can be calculated. This is achieved by moving the sampling line (Figure 3) to eleven positions along the gauge surface under computer control. Typical results of a gauge measured by this technique, over the whole of a gauge measurement face, are shown in Figure 4. Flatness, parallelism, and surface topography are calculated from the variations in length over the gauge surface.

Deviation from the nominal length (nm)

-22	-10	26	23	27	22	14	1	5	14	3	
-16	-2	26	20	30	25	17	7	8	16	25	
-15	6	27	33	38	30	20	13	8	20	40	
-13	10	27	30	36	31	21	13	5	15	49	
-13	10	27	39	39	32	20	11	-1	6	42	Y
-14	9	27	40	40	32	19	7	-6	-3	29	
-16	5	26	41	41	31	17	1	-17	-16	8	
-20	0	26	40	41	30	15	-7	-26	-33	-20	
-24	-7	26	39	41	26	11	-18	-41	-52	-55	
-29	-16	26	37	41	26	7	-30	-56	-74	-97	
					X						

Surface topography

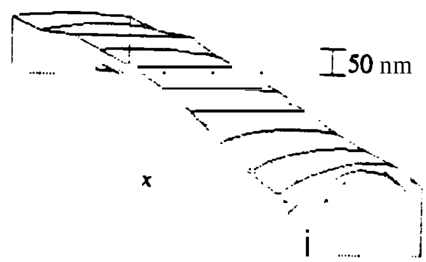

Figure 4. Flatness and topography results

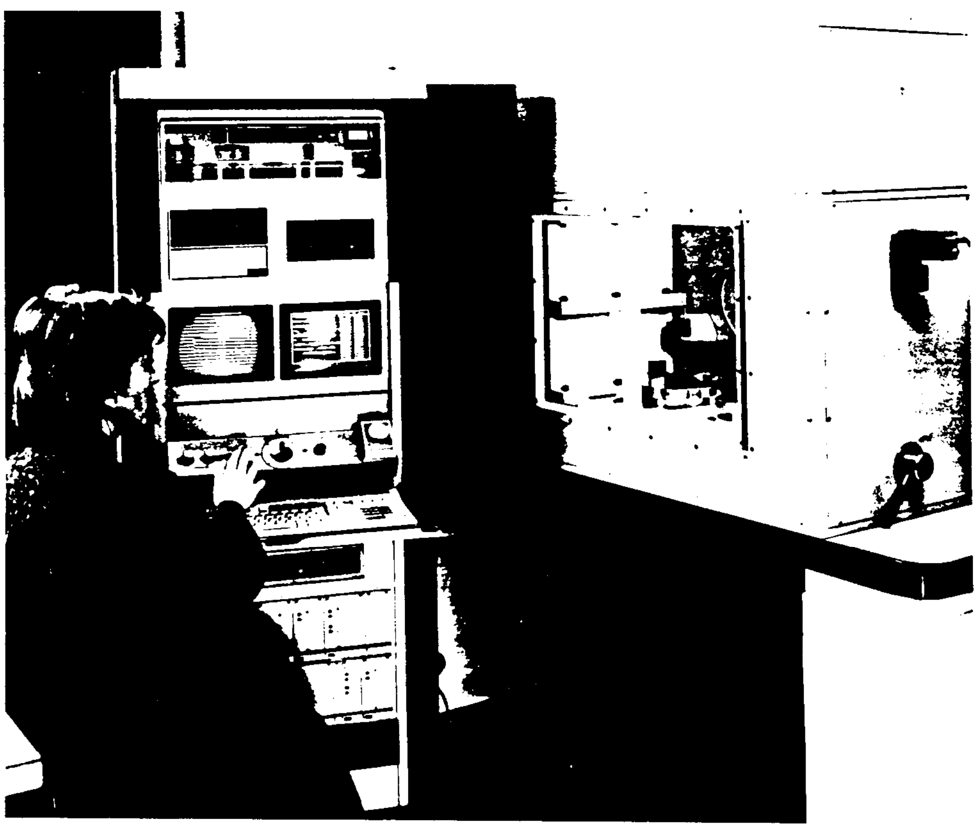

Figure 5. Interferometer and control console

Performance

As with all absolute measurement instruments the overall measurement uncertainty can only be determined by considering the errors in each part of the measurement process, and combining them by calculation. Major contributions to the overall uncertainty arise due to errors in the measurement of the gauge temperature, fringe displacement, and uncertainty in the gauge thermal expansivity. For this instrument the uncertainty of measurement has been calculated to be $\pm (0.02 + 0.2L)$ µm, where L is in metres, with a confidence level of 99% (eg ± 40 nm for a 100 mm gauge). Recent intercomparisons with other laboratories suggest that this is a conservative estimate.

Because of the demand from other international laboratories for an instrument of this type, the design for manufacture has been licensed to a company specialising in this type of equipment. (Tesa Metrology, Telford) [4]

A photograph of the interferometer and control console is shown in Figure 5.

WHITE LIGHT INTERFEROMETER

Introduction

To prevent ambiguity in the measurements made in the automatic gauge block interferometer described above, it is necessary to have prior knowledge of the gauge block length to better than ± 1 µm. This is usually achieved by separate and time consuming mechanical comparison techniques. To reduce the measurement time and to avoid the necessity to store a large number of calibrated gauges for measurement by mechanical comparison, the existing automatic gauge block interferometer at NPL has been modified.

The new instrument now uses two independent techniques to measure the length: white light interferometry to determine the approximate value, and two wavelength laser interferometry to give a more accurate measurement of the length of the gauge.

Principle of operation

The existing gauge block interferometer has been modified to allow the technique of white light interferometry to be used. A slideway to carry the reference mirror and a commercial plane mirror interferometer, to monitor its position, have been added. Photodetectors have been introduced in the image plane to detect the fringes and an optical compensation plate positioned between the reference mirror and beamsplitter. These are illustrated in Figure 6.

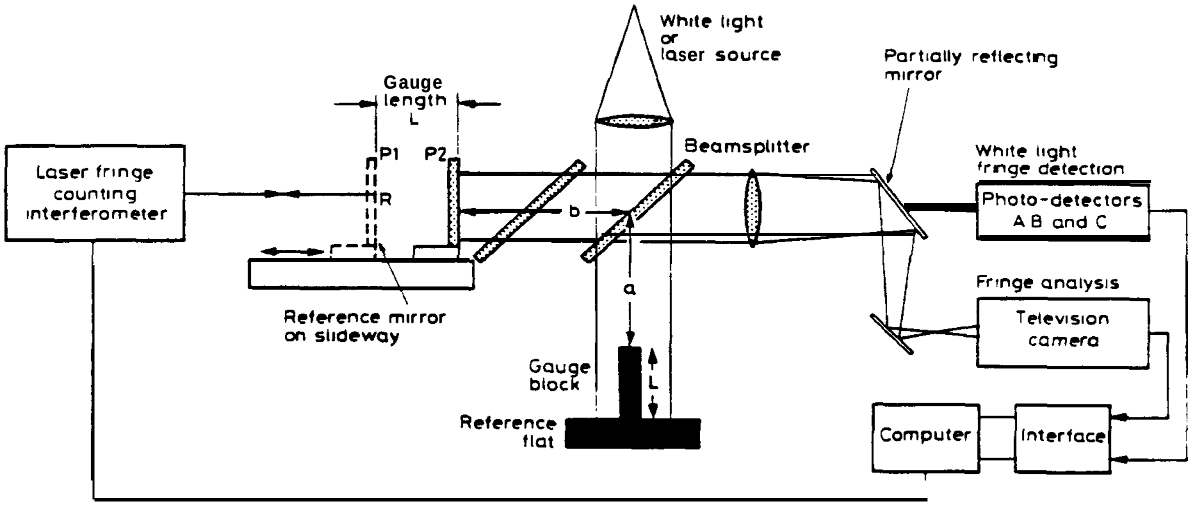

Figure 6. Schematic diagram of white light interferometer

When the laser source in the interferometer is replaced with a white light source, interference fringes will only be observed when the two optical path lengths of the interferometer are nearly equal, that is when b = a and when b = a + L. With a gauge wrung to a flat, fringes will only be visible for two positions of the reference mirror, **P1** and **P2,** corresponding to the top of the gauge and reference flat.respectively The gauge length can be determined by moving the reference mirror and measuring the distance between the positions at which the fringes are detected.

In operation the reference mirror is driven along a slideway, the distance continuously monitored by a fringe counting interferometer and the data entered into a computer. At the same time photodetectors in the image plane, also coupled to the computer, record the intensity of the fringes. By computing the mirror positions at which the central dark fringes occur, at the gauge and either side of reference flat, the gauge length can be calculated. Figure 7 shows the position of the photodetectors A, B and C in the image plane and their outputs as the reference mirror is moved along the slideway. The position of the reference flat is measured at either side of the gauge block by the photodetectors A and C; the mean of these two results provides the reference flat position in the central region of the gauge.

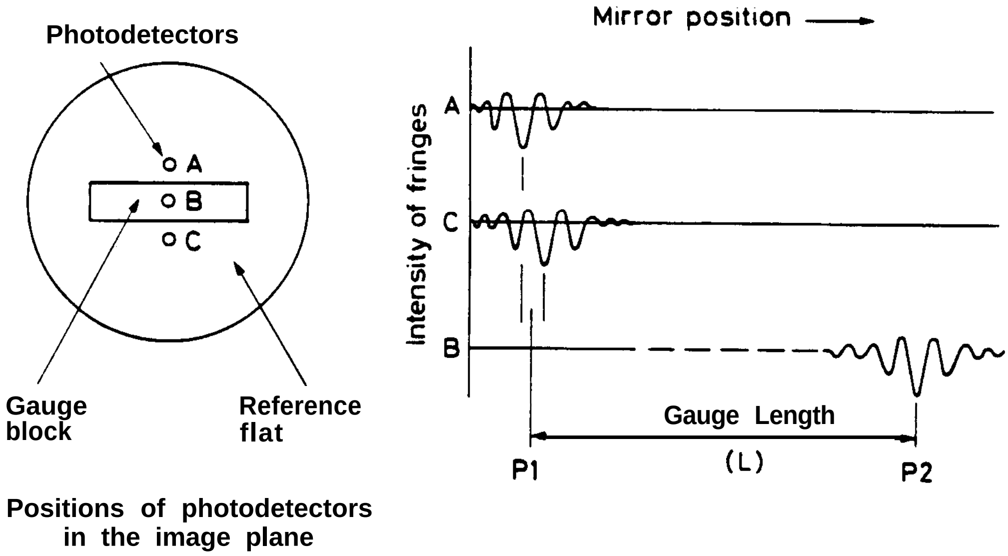

Figure 7. Operation of white light interferometer

Performance

In operation, the combined measurement of white light and two wavelength interferomeuy is totally automatic. Measurement and calculation of the data is treated separately so that two completely independent results are obtained. In practice the difference in the two measured lengths does not exceed ± 50 nm. The time taken for a dual measurement varies between 3 and 5 minutes, depending on the gauge length.

LENGTH BAR INTERFEROMETER

As machines for mechanical measurements improve in accuracy there is a need for higher accuracy length standards to validate their performance. To fulfil this requirement and a need for higher accuracy measurements in NPL, the development of a new facility has begun, which will enable length bars from 0.1 to 1.5 metres to be measured with a total uncertainty off 0.1 µm.

The interferometric technique which has been adopted is similar to that used for gauge block measurement but the need for control and measurement of the ambient conditions is much more stringent due to the long interference path length.

The most critical areas affecting the performance of the new instrument are the measurement of the refractive index of air, length bar temperature and the fringe shifts at the two wavelengths.

Length uncertainties due to errors in reading the bar temperature can be reduced to an acceptable level using high quality platinum resistance thermometers and a precision a.c. resistance bridge; an accuracy of ± 2 mK is achievable (equivalent to a length uncertainty of ± 30 nm in 1.5 metres).

The error in determining the fringe shifts using phase stepping interferometry can be reduced to a level equivalent to a length uncertainty of only ± 3 nm.

Because of the effect of the refractive index of air on the laser wavelengths, its accurate measurement is ***essential.*** This measurement provides the major problem in high accuracy length interferometry. The indirect determination of the refractive index of air using 'state-of the-art' instrumentation to measure air pressure, temperature and humidity in combination with a correction formulae [5] would not be sufficiently accurate for this application.

Our initial approach to the problem will be to operate the interferometer in a sealed chamber, filled with a gas of known composition. The refractive index of the gas will be determined in a separate experiment or with an independent refractometer linked to the chamber. With both of these options the uncertainties in the measured refractive index should be in the region of ± 2 parts in 108 (±20 nm in 1 metre). Frequency stabilised lasers similar to those in the gauge block instrument are used as a light source and these are sufficiently accurate for the measurement of bars up to 1.5 metres.

Description of the interferometer

The interferometer, which is similar to that used for gauge block measurement, is of a Twyman-Green design, but the optical components have been rearranged so that length bars can be measured in the horizontal position. Path folding mirrors are included to reduce the physical size of the instrument. This is illustrated in Figure 8.

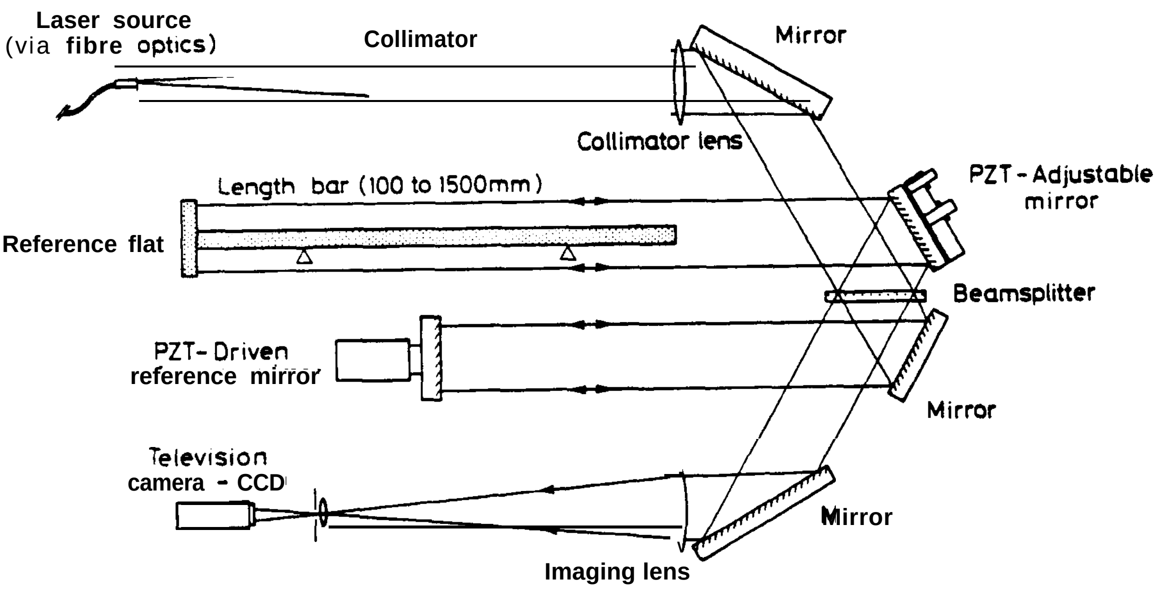

Figure 8. Optical layout of length bar interferometer

Bars are measured in a horizontal position, with a small reference flat wrung on to one end. They are supported near the Airy [6,7] points which provide the minimum deflection of the two end faces, from the free state. An adjustable mirror with remote PZT control is included to ensure that the interferometer beam runs parallel to the bar to avoid obliquity errors and also to allow adjustment of the fringe orientation.

Phase stepping interferometry [8] is being used to determine the phase shifts at the two wavelengths. In this technique the interferometer reference mirror is accurately moved by a PZT actuator in five nominally equal steps and at each step an image of the fringes is captured and stored in a TV frame store.

From the stored data of the five images the phase at any point in the image can be computed and a phase map of the whole image built up. Phase shifts between the length bar and reference flat can be determined to better than ± 3 nm using this technique and data relating to the surface flatness can be accurately determined. An example of the surface topography of a measurement face of a typical length bar is shown in Figure 9.

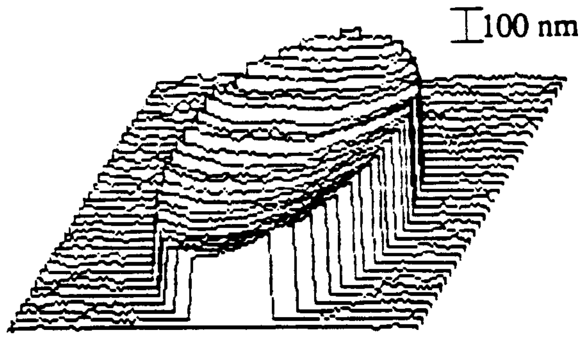

Figure 9. Measurement face surface topography

CONCLUSIONS

The NPL programme for updating its facilities for the absolute measurement of end standards is well under way. A fully automatic gauge block interferometer has been in regular service for four years and a modified version, for the measurement of gauge blocks without prior knowledge of the gauge length , is nearing completion. Our experience with these automatic techniques, is not only that they are faster and more accurate, but that the overall quality of the results has improved. This is mainly due to the ease of use of the instrument, encouraging the metrologist to repeat measurements whenever there is the slightest inconsistency in the results.

Specifications regarding the flatness of the gauge surfaces can be validated objectively rather than relying on subjective visual estimations, as currently used in manual interferometers.

The length bar interferometer programme has been running for one year and the initial results from a prototype instrument, using the phase stepping method, are being obtained. It is planned that this instrument will be fully operational by 1993.

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4 Tesa Metrology, P.O. Box 418, Halesfield, Telford, Shropshire, TF7 4QN, England.

5 Edlén, B., “The refractive Index of Air”, Metrologia Vol. 2.1966, pp 7 1.

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Two-Wavelength Phase-Stepping Interferometry For Absolute Length Measurement

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Introduction

Traceability of engineering measurements in the UK to national length standards requires the calibration of the highest grade of mechanical length standards at NPL. These standards, known as length bars, take the form of solid metal rods with polished ends ranging in size from 25 mm to 1500 mm in length, and are measured in a Twyman-Green, phase-stepping interferometer using light of known wavelengths. Phase-stepping interferometry has two distinct advantages over fringe interpolation techniques: reduced uncertainty in the measurement of fringe displacements and more detailed information about the measured surface.

1. Interferometry of Length Bars

The length of a bar is measured in terms of the wavelength of light emitted by a frequency-stabilised laser. A small reference flat is wrung† to one end of the bar, then the bar and flat are positioned in one arm of a Twyman-Green interferometer. After alignment, interference tilt fringes of a sinusoidal profile are visible on the bar. This image is viewed by a TV camera and stored in a computer framestore.

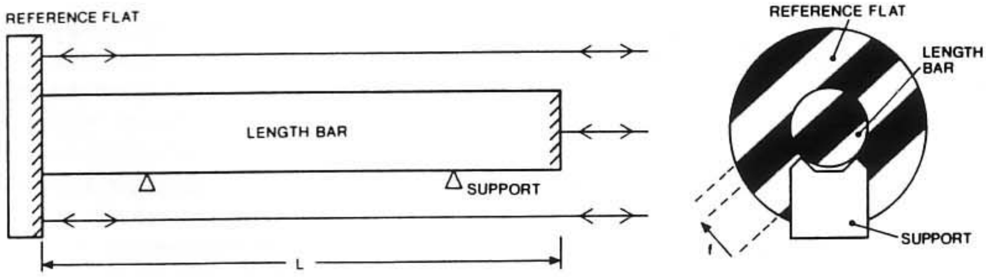

Figure 1. Length bar supported in interferometer, with image of fringes.

The displacement of the fringes on the bar with respect to those on the flat is due to the difference in the optical path length, 2L, between the light paths which strike the front of the bar and those which are reflected from the surface of the reference flat. The path difference can be expressed in terms of the wavelength of the light, λ:

$$2L = (n + f)\,\lambda \qquad 1.1$$

where n is an integer, or fringe order and f is the fringe fraction. It is the fractional shift of the fringes, f, which is visible and is measured.

2. Phase-Stepping

The 5-position technique, proposed by Hariharan (2), provides accurate measurement of these fringe fractions in terms of phase. In operation, the reference mirror in the reference arm of the interferometer is moved from an arbitrary start position, in 4 equal steps of 1/4 of a fringe. The images of the fringes at all 5 positions of the mirror are digitised into a framestore. The phase, ϕ, of the light reflected from the surfaces, with respect to some arbitrary value, taken to be zero, is given by:

$$\phi(x,y) = \arctan\left\{2\left(\frac{I_2 - I_4}{2I_3 - I_5 - I_1}\right)\right\} \qquad 2.1$$

where I_n represents the digitised intensity at a point (x,y) in image number n. This expression is able to return values of ϕ in the range 0 to 2π by using the signs of the numerator and denominator to determine the quadrant of the phase.

Discontinuities in the resultant phase map are removed by sequentially scanning through pixels, looking for phase differences larger than π between neighbouring pixels. Due to the discontinuity present around the circumference of the bar, a new 3-directional phase-unwrapping technique is used, the phase being corrected firstly in a downwards direction, then from left to right, and finally from right to left. A mathematical function is fitted to the now smooth phase map to remove tilt.

An initial estimate of the length of the bar is required before the technique of multiple-wavelength interferometry can be used. The length of the bar is measured initially in another instrument, to within the required uncertainty of ±0.9 µm. The bar is then measured in the interferometer using two wavelengths: 633 nm and 543 nm. Fringe fractions measured at the centre of the bar at these two wavelengths and the initial length measurement are used in the method of exact fractions (3) to calculate the accurate length of the bar.

3. Conclusions

The techniques of phase-stepping and multiple-wavelength interferometry have been successfully combined in a length measuring interferometer. Results from the prototype length bar interferometer indicate that this technique can be used to measure the lengths of mechanical length standards up to 1500 mm in length.

Two standards of lengths 4.5 mm and 400 mm have been measured; the spreads of measured lengths were ±1 nm and ±5 nm, and the standard errors of the means were ±0.3 nm and ±2.4 nm, respectively. These uncertainties represent the errors in the calculated length due to the spread in the fringe fractions, and do not include other errors associated with the measurement of temperature, humidity, and pressure of the air, as well as the temperature of the bar. Surface profiles of these objects were also determined as part of the length measuring process.

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† *'Wringing' takes place when two flat lapped surfaces are brought into contact in a sliding movement. It is generally accepted that a molecular adhesion results between the surfaces.*

Meas. Sci. Technol. 3 (1992) 929-930 Printed in the UK

DESIGN NOTE

Interferometer light source and alignment aid using single-mode optical fibres

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Received 9 April 1992, accepted for publication 8 June 1992

Abstract. A system has been developed using optical fibres to allow accurate positioning of a light source in the collimator of an interferometer. The design reduces the obliquity effect of the source by using single-mode fibres as the light source. Alignment of the interferometer is achieved using an autocollimation technique where one fibre detects the return spot. Up to three lasers can be launched into the collimator with no speckle in the image field

1. Introduction

When launching light into the collimator of a Twyman-Green length-measuring interferometer (Twyman and Green 1916, Dyson 1970) it is important to ensure that the light source is accurately positioned at the focus of the collimating lens and on the axis of the interferometer. An error in either the focus or off-axis adjustment will cause the wavefront to travel at an angle to the measurement axis. This causes an error in the length measured by the interferometer, termed an 'obliquity error', which is proportional to $s^2/2f^2$ where f is the focal length of the collimator and s is the distance by which the source is positioned off-axis (Bruce 1955). As an example, the obliquity error from a source positioned 1 µm off axis in a 1 m focal length collimator is approximately 5×10^{-7} or a length measurement error of 0.5 µm in 1 m. A similar error arises from the finite size of the source which also results in the wavefront travelling obliquely to the measurement axis. This error is proportional to $r^2/4f^2$ where r is the radius of the source (Bruce 1955).

To overcome these effects, a simple three-fibre system has been developed to launch up to three lasers into a collimator and to position them on axis and at the focus of the collimating lens.

2. Design

The system uses three single-mode optical fibres which have had the buffer coating removed from both ends. At one end the fibres are cemented into a tight bundle. The other end of each of the fibres is individually mounted and polished (see figure 1). Each fibre in the bundle can serve two functions: it can act as the light source for the collimator when light from a laser is focused into the fibre core and, secondly, the fibre can be used to detect the return spot, when used in an autocollimation arrangement, for which another fibre is used as the light source (see figure 2). The numerical aperture of the fibres can be matched with the focal length and diameter of the collimator lens to achieve efficient illumination of the collimator.

There are two advantages of single-mode over multi-mode fibre. Firstly, the effective source diameter is much smaller, typically 10 µm contributing to a smaller

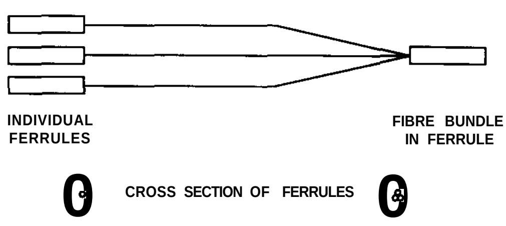

Figure 1. Three-fibre system

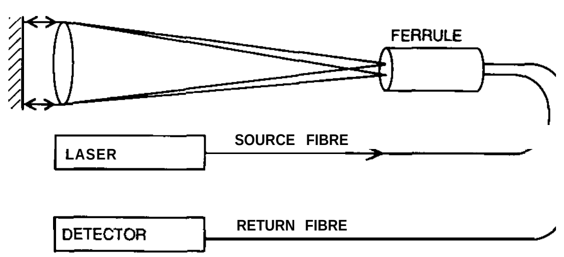

Figure 2. Autocollimation arrangement

* D J Pugh has now retired from NPL.

obliquity error, and secondly the problem of speckle in the image due to mode mixing in multimode fibre is eliminated since only one mode is transmitted by single-mode fibre.

In principle it is possible to use this technique with just one fibre acting as both source and detector though the extra optical components required, such as beam-splitters or couplers, could introduce losses which would make the detection of the return spot more difficult. Three fibres were used in this evaluation rather than two because a bundle of three fibres was easier to manufacture and mount, and there was a requirement to launch three lasers into the collimator.

3. Autocollimation

When used in the autocollimation arrangement of figure 2, the reference mirror of the interferometer is used to reflect the beam back to the source where one of the fibres in the bundle is used to detect the return spot. The fibre bundle is moved in three orthogonal directions and the intensity of the light incident on the detector fibre is monitored using a photodetector. When the detected intensity is maximized, the source and detector fibres are symmetrically positioned on either side of the axis of the interferometer, and at the principal focus. The off-axis position of the source is then half the separation of the fibres, which is typically less than 100 µm This technique aligns the collimator with the reference arm of the interferometer. The expected obliquity error from this system is less than 5×10^{-9} or 5 nm in 1 m. After alignment, the detector fibre may be used to launch a third laser source.

4. Measurements

Measurements were made using a collimator of focal length 1500 mm, illuminated by a laser operating at 633 nm. Figure 3 shows the peak in the detected intensity as the fibre bundle was positioned radially and axially. These results were repeatable after coarse adjustment over several millimetres of travel. Correct collimation was checked using a shearing interferometer (Melles Griot 09SPM003) placed in the collimated beam at various points along its length. Assuming the achromatic collimator lens to be diffraction limited, the expected central maximum (Airy disc) of the return spot diffraction pattern should be ~25 µm in diameter (Hecht 1987), and should result in a peak of width ~20 µm when a 10 µm diameter fibre is scanned across the moving diffraction pattern, as occurs when the fibre bundle undergoes radial motion. This can be seen in figure 3(a). It is thought that the non-symmetrical peaks in the observed data are due to cross-talk from the adjacent fibre which becomes partially illuminated. When diffraction theory is applied to an unaberrated circular pupil with defocus it predicts minima in the diffraction pattern, spaced at 1.1 mm along the focal axis. The results shown in figure 3(b) are consistent with the theory.

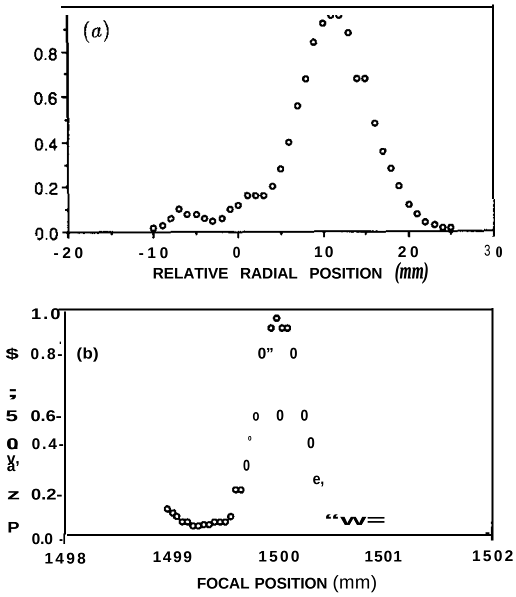

Figure 3. Detected intensity during (a) radial positioning and (b) axial positioning of the fibre bundle in normalized units.

5. Conclusion

The single-mode fibre system provides a simple, efficient, speckle-free light source for an interferometer. The auto-collimation arrangement using one fibre as a detector allows accurate repositioning of the light source, allowing the collimator beam to be aligned with the interferometer axis, whilst minimizing the obliquity effect due to the source.

Acknowledgments

The advice of Mr M Virdee on the design of the single-fibre ferrules and the polishing of the ferrules by the NPL Optical Workshop are gratefully acknowledged.

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Three wavelength phase-stepping interferometer for length measurement up to 1.5 m in a controlled environment

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1. Introduction

Length bars are widely used in industrial calibration laboratories as secondary length standards, and are becoming increasingly important as reference artefacts used to validate the performance of coordinate measuring machines. The highest grade length bars have their lengths calibrated at NPL in terms of the wavelengths of light emitted by calibrated frequency-stabilised lasers. A new interferometer is under construction at NPL to measure length bars up to 1.5 m in length to a target accuracy of 5 parts in 10^8 (50 nm in 1 m). The interferometer uses the techniques of three-wavelength phase-stepping interferometry in a sealed, temperature-controlled environment, see figure 1.

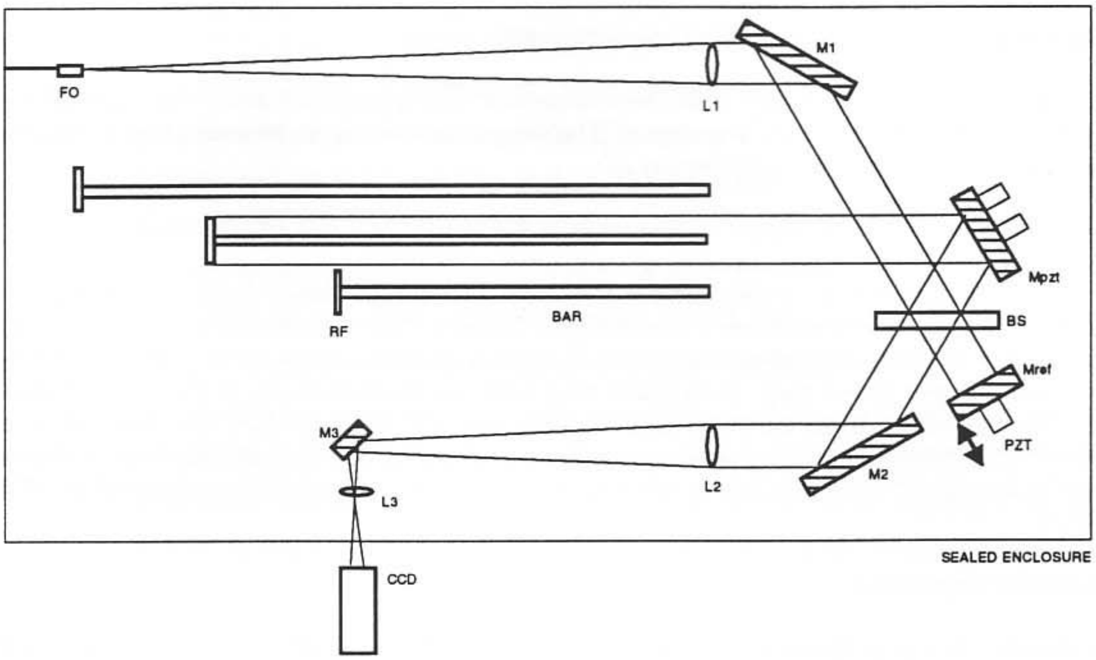

Figure 1 - optical layout of interferometer inside chamber
(L1, L2, L3 - lenses; M1, M2, M3, Mref, Mpzt - mirrors; RF - reference flat; BS - beamsplitter; FO - fibre optic source)

2. Refractive index

The refractive index along the optical path directly determines the laser wavelength. To minimise turbulence and drifts in refractive index, the interferometer has been constructed inside a sealed, temperature-controlled chamber. This ensures a uniform refractive index along the optical path which can be measured by sampling air from the chamber. The air is sampled using a PTFE pump which re-circulates the air back to the chamber. Measurements are made of the air temperature, pressure, humidity and carbon-dioxide content at the time each length measurement is made. The effect of each of these parameters is shown in table 1 for typical variations encountered in a temperature and humidity-controlled calibration laboratory.

Parameter	Typical value	Daily variation	Effect of variation on refractive index
temperature	20 °C	± 0.2 °C	$\pm 2 \times 10^{-7}$
pressure	1013.25 mbar	± 20 mbar	$\pm 5 \times 10^{-6}$
humidity	13 mbar	± 2 mbar	$\pm 1 \times 10^{-7}$
CO_2 content	300 ppm	± 100 ppm	$\pm 2 \times 10^{-8}$

Table 1 - effect of air parameters on refractive index

3. Thermal control

The temperature of the chamber is stabilised by controlling the temperature of water circulating in pipes in the lid and baseplate of the chamber. All heat sources such as lasers and CCD camera are external to the chamber, with the light brought into the interferometer using single-mode optical fibres. The temperature of the air inside the chamber is stabilised to 20 °C ± 0.05 °C and has a drift rate of less than 0.001 °C per hour. The temperature drift of the length bar is similar and the temperature gradient along the bar is less than 0.01 °C/m, at 20 °C.

4. Thermal expansion

Although each bar has a nominal thermal expansion coefficient, α, of 10.7 ppm/°C, in practice this may vary by up to 1 ppm/°C from bar to bar. The resulting uncertainty can cause an error if the bar is not measured or used at the standard temperature of 20 °C. To overcome this, each bar is measured in the interferometer at three temperatures over the range 15 °C to 30 °C and a value of α calculated.

5. Multiple-wavelength phase-stepping interferometry

Each bar is supported horizontally in the interferometer with a small reference flat attached to one end by 'wringing' (intra-surface attraction). The length of the bar is measured as a number of interference fringes at corrected wavelength λ'

$$L = (n + f)\lambda'$$

where n is an integer (fringe order) and f is a fraction of a fringe (fringe fraction). Values of f are measured by the interferometer for 3 wavelengths (633 nm, 543 nm and 612 nm) by using a five position phase-stepping algorithm (Hariharan *et al* 1987) to measure the surface from of the bar at each wavelength as a phase map. Each phase map contains measurements of the phase difference between light reflected from the surfaces of the bar and the reference flat. The method of exact fractions (Rolt 1929) is then used to combine the three phase measurements at the centre of the bar to calculate its length, based on an initial estimate to within ± 4.6 μm which is performed in another instrument.

6. Results and conclusions

Measurements have been made on bars ranging from 200 mm to 1000 mm in length. Repeatability of ± 1.9 x 10^{-8} has been achieved over periods of up to 2 days. Comparisons with other interferometric measurements (Pugh and Jackson 1986) on bars up to 300 mm in length shows agreement to within ± 5 x 10^{-8}. This departure is thought to be due to different accuracies in determining the bar temperatures and refractive indices in the two instruments and also due to the difference in surface roughnesses of the two reference flats used.

7. References

Hariharan P, Oreb B F and Eiju T 1987 *Digital phase-shifting interferometry: a simple error-compensating phase calculation algorithm* *Appl. Opt.* **26** 2504-2506

Pugh D J and Jackson K 1986 *Automatic gauge block measurement using multiple wavelength interferometry* *Proc. SPIE* **656** 244-250

Rolt F H 1929 *Gauges and Fine Measurement* (MacMillan & Co. : London) 49-50,212-213