Measurement of gauge blocks by interferometry: an investigation into the variability in the wringing film thickness

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Abstract

According to the British Standard on gauge block calibration (BS 4311), when measuring the length of a gauge block by optical interferometry it is necessary to wring the gauge to an auxiliary surface or platen. Consequently, the measured length of the gauge block includes any physical length associated with the wringing. It is thus essential that a repeatable winging contact between a gauge block and a platen is achieved during routine gauge block calibration. Due to the use of a finite amount of fluid to aid the wringing process, the length associated with wringing a gauge to a platen is known as the wringing film thickness. This report describes a number of experiments designed to quantify the variability in the wringing film thickness. No attempt has been made to determine the absolute wringing film thickness, only its variability when wringing is repeated.

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1 INTRODUCTION

The unit of length is the metre. The definition of the metre based upon a bar of platinum-iridium was replaced at the 17th meeting of the CGPM (1983) by the following:

The metre is the length of the path travelled by light in vacuum during a time interval 1/299 792 458 of a second.

At NPL the metre is realised through the wavelength of the 633 nm radiation from an iodine-stabilised helium-neon laser. Through the use of interferometry, using lasers that have been calibrated against the stabilised lasers mentioned above, a gauge can have its length measured - a measurement that is directly traceable to the definition of the metre.

To give traceability to the definition of the metre in industry, gauge blocks are widely used as convenient, robust and relatively cheap material length standards in the range 0.5 mm to 1000 mm. They are usually made of steel, tungsten carbide and, more recently, ceramic. NPL offers a measurement service for the calibration of the highest quality gauge blocks by optical interferometry. The measurements are made using NPL Gauge Block Interferometers, the details of which are outlined elsewhere (Pugh and Jackson 1986, Hughes, Jackson, *et. al.* 1990).

The length of the highest quality gauge blocks (grade K) is defined in BS 4311 (1993) as follows:

"The mean value of two interferometric measurements of the central length, first with one measuring face of the gauge block wrung to the horizontal plane surface of a rigid auxiliary body and then with the other measuring face similarly wrung."

From the above definition it can be seen that the length of a gauge block includes the physical length associated with one wringing or one wringing film thickness. The process of wringing occurs when two optically polished, flat surfaces are placed in contact, with a sliding, twisting motion, until the two surfaces adhere. It is commonly accepted that forces are at work at the molecular level, although the matter is far from settled. Figure 1 illustrates the combined effects of wringing and phase change at reflection (Leach 1998) on the length of a gauge block when measured interferometrically. It is worth noting that even when lower quality gauge blocks are measured using a mechanical comparator the wringing film thickness must still be taken into account in the definition of the length of the standard gauge block, which has been measured interferometrically. The effect of wringing is, therefore, present throughout the entire gauge block hierarchy.

This report describes a series of experiments undertaken to quantify the variability in the wringing film thickness.

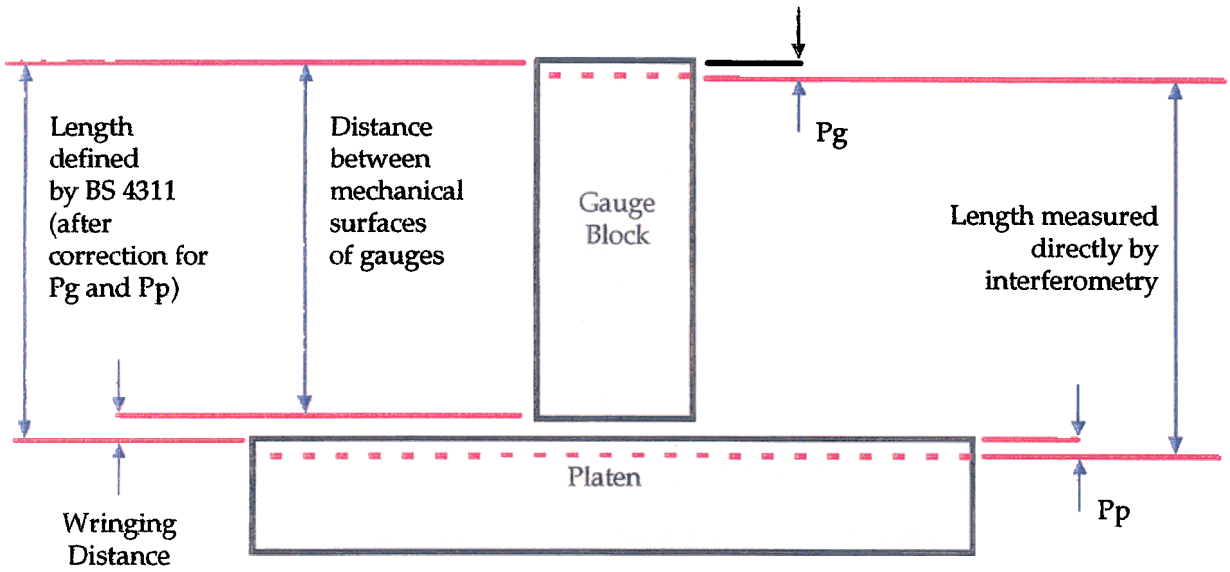

Figure 1 The effect of wringing and phase shift at reflection on length measurement, where P_g and P_p are the phase shifts off the gauge block and platen respectively

2 THE WRINGING FILM THICKNESS

2.1 PREVIOUS WORK

It is commonly accepted (see references given below) that the adherence of two surfaces to each other during wringing is due to a thin film of liquid between the two surfaces being brought into contact. The length associated with this film is therefore known as the 'wringing film thickness'.

The wringing effect has been exploited in the field of length metrology for over 100 years. For wringing to take place between two surfaces they must be brought into contact by applying a force normal to their surface plane along with a tangential combination of sliding and twisting forces. The process normally involves the presence of a fluid film - possibly just due to such molecules being present in the atmosphere. The result is that the two surfaces adhere to each other with a force of attraction of about 200 to 300 N for a typical gauge block surface (Budgett 1911). This force is far too large to be due to atmospheric pressure alone and experiments in *vacuo* have confirmed this. Rolt (1929) and Budgett (1911) suggest that the force of attraction is mainly due to the tensile strength and molecular cohesion of the wringing film (in this case the term tensile strength can be used to describe a property of the fluid film because the film has essentially undergone a change of state brought about by the lack of other fluid molecules in its surrounding area). Rolt and Barrel (1927) suggest that if the two solid surfaces are close enough together so that the molecules of the liquid film experience forces of attraction from both surfaces, the liquid becomes a quasi-solid and loses its fluidity. Subsequent measurements have shown the film thickness to be about twice the molecular radius of attraction (about 0.8 nm for most atoms). Some contact must, however, exist between the two metal surfaces, even if only in isolated areas, to account for the wear observed upon repeated wringing (surface debris would also be a factor). McFarlane and Tabor (1950) suggest that the force of attraction is mainly due to the surface tension of the film. Experiments by Bruce and Thornton (1956) give values for the wringing force which are an order of magnitude lower than those expected due to surface tension alone. Denisov (1958) also attributes most of the adhesive force to a liquid film and suggests that the film increases the total area of contact between the two surfaces.

The effect of the surface roughness has been investigated by Siddall and Willey (1970). They took two surface roughness profiles of gauge blocks, measured with a stylus instrument, inverted one profile and mathematically fitted the profiles to each other. Their theoretical results for the wringing film thickness, based on the assumption that high points on the surface are in physical contact, were consistent with the experimental work by other authors. They also found there is a limit in the reduction of the film thickness between two surfaces, if only one surface is continually polished, and that the magnitude of the film thickness rises with the viscosity of the fluid used in the wringing process.

Some workers have measured a negative wringing film thickness and attributed it to mutual crushing of the metal surfaces (Pérard and Maudet 1921 and Bölöni 1982). Many of the experiments described in the literature involve wringing a gauge block to an optical flat, the resulting wringing film thickness being smaller due to the relatively small surface roughness of the optical flat. Historical methods for measuring wringing film thickness are discussed in Appendix A. Table 1 summarises the results of some authors.

Author	Date	Wringing film thickness (nm)
Pérard and Maudet	1921	-60
Rolt and Barrel	1927	17
Rolt	1929	8 ± 2
Bruce and Thornton	1954	-13 to +15
Denisov	1958	5 to 10
Bölöni	1982	-17 ± 11

Table 1 Experimental results from studies on the wringing film thickness

The variation in wringing film thickness was investigated by Thwaite and Leslie (1963) by repeatedly wringing steel gauge blocks to a steel platen under controlled conditions. No attempt was made to determine the magnitude of the film thickness. The limits for its variability were found to be ± 15 nm at the 95% confidence level.

The explanation behind the wringing process varies from author to author and it appears that there are more physical processes at work than just the effect of a liquid film.

2.2 METHOD USED AT NPL TO WRING A GAUGE BLOCK TO A PLATEN

Experience at NPL has shown that steel and ceramic gauges wring to a platen more firmly and evenly when a thin layer of wringing fluid is present between the gauge and platen surfaces. A suitable fluid has been found to be liquid paraffin diluted with a suitable solvent, for example Opticlear S, in the ratio of 1 part paraffin to 10 parts of solvent. The technique used requires the operator to apply the fluid very sparingly to the platen using a cotton bud, or similar applicator. A dry paper tissue is used to remove almost all of the fluid and to spread it evenly across the platen surface before wringing down the gauge. Tungsten carbide gauge blocks wring more firmly without the use of any wringing fluid.

Currently, the variability of the wringing film thickness, based on an analysis of the literature, contributes ± 10 nm at the 95% confidence level to the total uncertainty budget for gauge blocks measured by interferometry at NPL .

3 MEASUREMENT PROCEDURES AND RESULTS

A number of experiments were devised to quantify the variability in the wringing film thickness when a gauge block is wrung to a platen. Most of these involved using steel gauge blocks, as experience has shown that it is easier to judge if a firm wringing has been obtained with gauge blocks of this material. Repeated measurements of length were made by interferometry. In order to minimise uncertainties from other sources, for example platen flatness, a special steel platen and jig were made (see figure 2). The diameter of the platen was 70 mm, and it had a flatness of 100 nm with an average surface roughness, Ra = 11 nm. Three supporting pads on the base of the platen were lapped so that the top surface of the platen was co-planar with the wave front of the interferometer when the platen rested on the pads within the interferometer. The jig was made from a low expansion ceramic material and ensured that the platen kinematically relocated in the same position each time in the interferometer. A plastic template was used to ensure that any gauge was wrung in the same place on the platen each time.

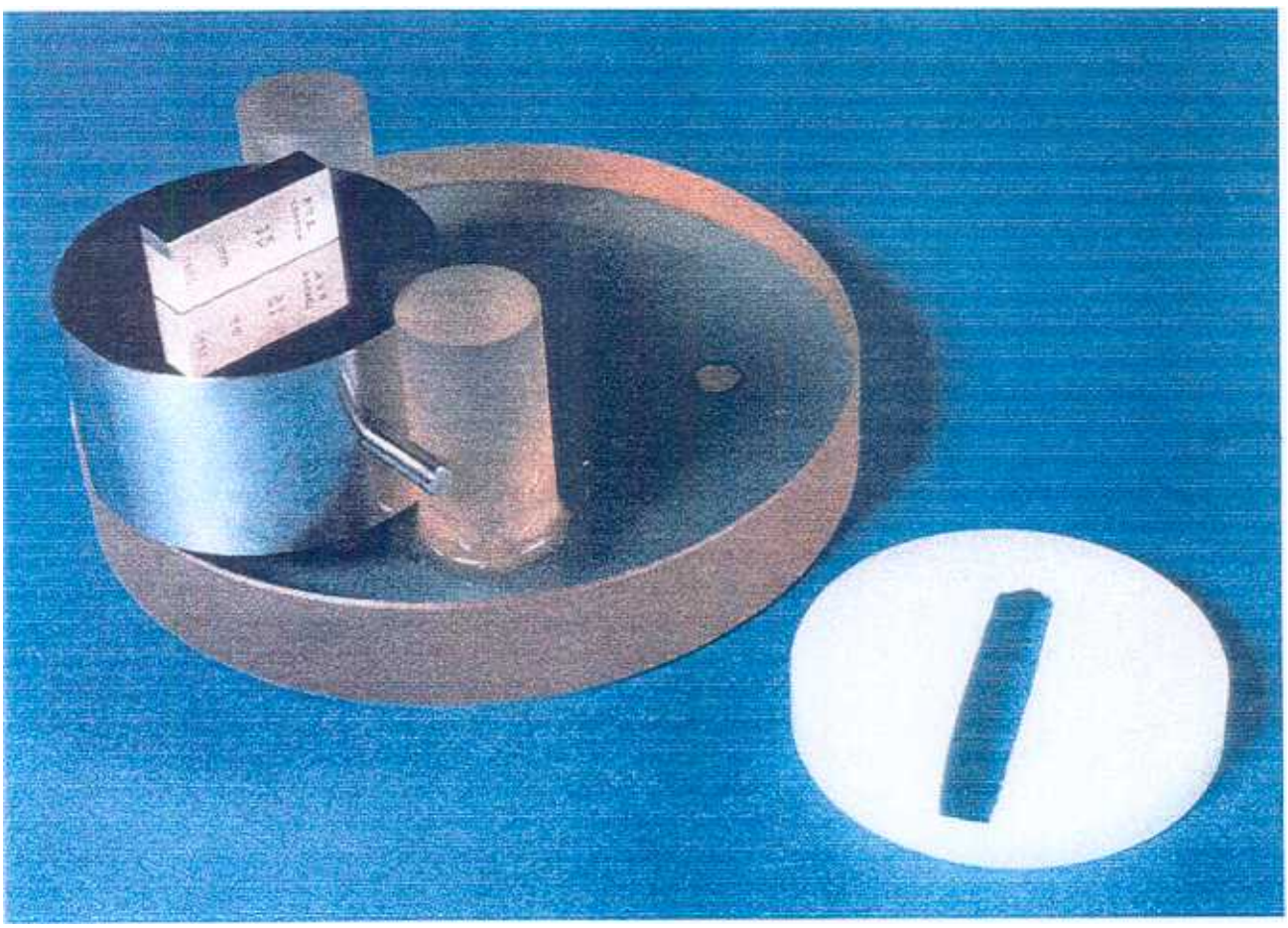

Figure 2 The wringing film variability jig

A number of repeated length measurements were also made on tungsten carbide and ceramic gauge blocks. These were wrung to individual tungsten carbide and ceramic rectangular platens,

50 mm x 35 mm in size. Guides were used to ensure that gauge blocks were positioned in the same place on the same platen, and in the same position in the interferometer for each set of measurements.

The measurement technique ensures that any systematic uncertainties in the length measurement are common to length measurements of the same gauge on the same platen. Random uncertainties will be the dominant factors affecting the uncertainty in the variability of the wringing film thickness. The following random uncertainties affect the length measurements using the NPL Gauge Block Interferometer (GBI):

(a) the short-term variability of the wavelength of the laser source gives rise to a 1σ uncertainty of $\pm 1 \times 10^{-9} L$ nm, where L is the length of the gauge in metres;

(b) the random uncertainty associated with the fringe fraction measurement depends on the accuracy of digitisation and datafitting, and gives rise to a 1σ uncertainty of ± 0.0032 of a fringe, at a wavelength of $\lambda = 633$ nm. This is equivalent to a length uncertainty of ± 1.0 nm;

(c) the gauge temperature is measured using a calibrated platinum-resistance thermometer. The estimated difference between the actual and the measured temperatures of the gauge gives rise to a 1σ uncertainty of $\pm 1.1 \times 10^{-8} L$ nm;

(d) a random uncertainty will arise due to the finite resolutions of the instruments that measure air temperature, air pressure and humidity to correct for the refractive index of air. Adding the three terms in quadrature gives a total 1σ uncertainty of $\pm 3.2 \times 10^{-8} L$ nm.

The standard uncertainty is found by adding contributions (a) to (d) in quadrature. Multiplying by a coverage factor k = 1.96 to give the combined uncertainty, U, at 95% confidence gives the following expression:

$$U = \pm k\sqrt{1+(34L)^2}$$

For example, for a 5 mm gauge the measurement uncertainty is ± 4 nm.

In experiments 3.1 to 3.3 the gauge blocks and platens were left to stabilise thermally and mechanically for a minimum of one hour in the GBI before measurements were made. At least ten repeat length measurements were taken for each gauge at one minute intervals and all measurements were carried out at 20 °C ± 0.12 °C. After measuring the length of the gauge blocks, they were removed from the platens, and the gauge block and platen surfaces were cleaned with ethanol before repeating the wringing process. Each gauge block was wrung to its

respective platen ten times and its length was measured. None of the gauge blocks needed to be deburred during the experiments.

3.1 VARIABILITY OF THE WRINGING FILM THICKNESS USING DIFFERENT WRINGING FLUIDS

Measurement procedure

A 5 mm steel gauge block was wrung to the steel platen using normal wringing fluid. The process was repeated using:

(i) a diluted solution of wringing fluid (1 part wringing fluid, already diluted 1:10, diluted further with 10 parts of Opticlear S);
(ii) Vaseline.

Between each set of wringings with a different fluid the gauge block was wrung down using normal wringing fluid and its length was measured as a check.

Results

Figure 3 displays the results in graphical format. With dilute wringing fluid, the mean and the distribution of the results showed a small increase (table 2). However, a simple statistical test (*t*-test) showed that at 95% confidence there is no significant difference between the normal and the dilute samples and between the Vaseline and the dilute samples. There may, however, be a difference between the normal and the dilute samples, but considering a measurement uncertainty of ± 4 nm, this seems highly unlikely.

In order to ensure that a firm wringing was obtained, the wringing technique was varied slightly for each fluid used. When using diluted wringing fluid there were some problems in obtaining a "tight" wringing and it was found that more fluid needed to be left on the platen surface. With Vaseline the technique was to rub a very small amount over a wide area of the platen and remove most of it with a dry tissue. The gauge block was slid across the platen surface, removed and any Vaseline present was wiped from contacting surface of the gauge. This process was repeated until a firm wringing was obtained.

The gauge block was repeatedly wrung to the steel platen thirty times and there was no significant change in its measured length when measured at the end of an experiment with a particular wringing fluid (table 3).

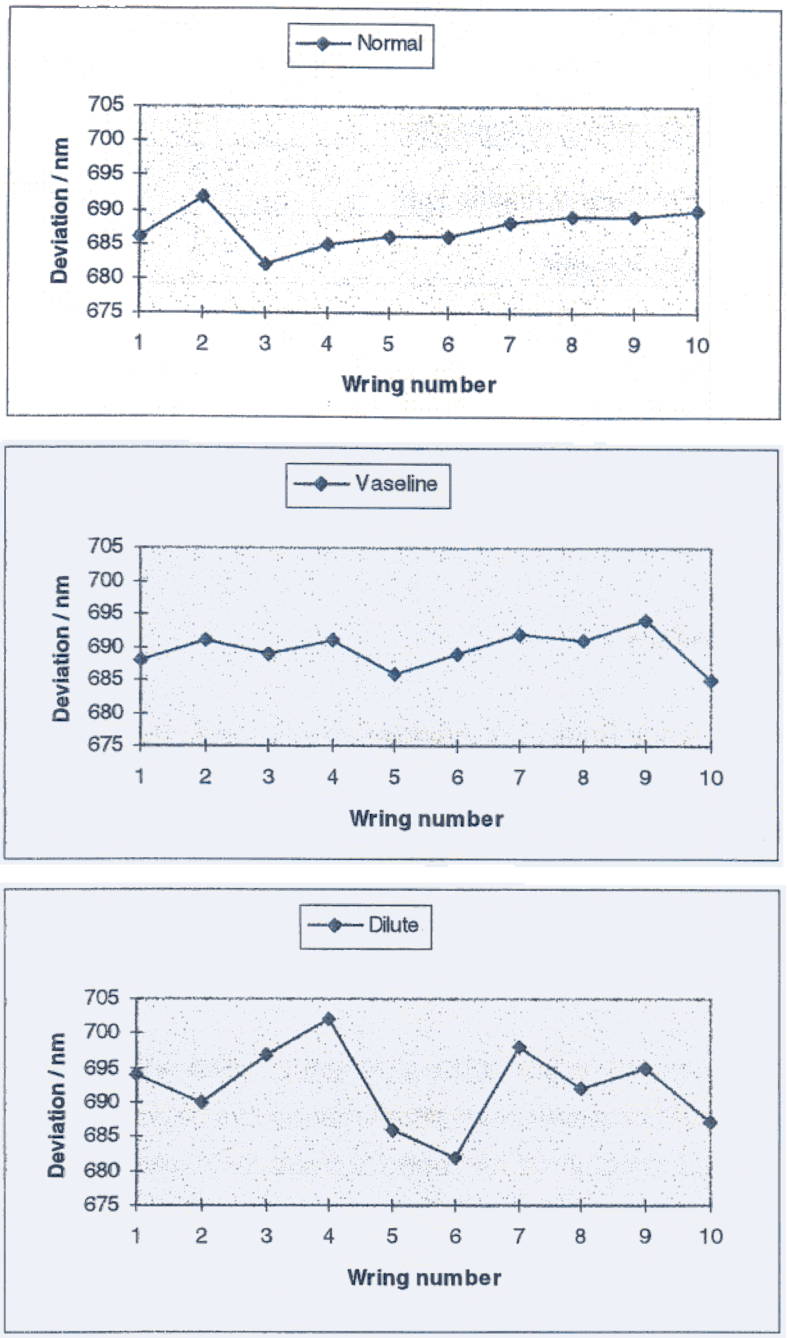

Figure 3 Variation in measured length of a steel gauge block using different wringing fluids

Wringing fluid	Mean deviation from nominal length (nm)	Standard deviation (nm)
1:10 paraffin in Opticlear S	687	3
1:100 paraffin in Opticlear S	693	6
Vaseline	690	3

Table 2 Summary of results for a steel gauge block after repeated wringing using different wringing fluids

	Deviation from nominal length (nm)
After 10 wringings with normal wringing fluid	687
After 10 wringings with dilute wringing fluid	689
After 10 wringings with Vaseline	687

Table 3 Repeatability check on the 5 mm steel gauge block

3.2 VARIABILITY OF THE WRINGING FILM THICKNESS USING GAUGE BLOCKS OF DIFFERENT MATERIALS

Measurement procedure

Three 5 mm gauge blocks made from steel, tungsten carbide and zirconia ceramic were wrung to individual steel, tungsten carbide and ceramic platens respectively. Normal wringing fluid was used to wring the steel and ceramic gauge blocks, the tungsten carbide gauge was wrung without wringing fluid.

Results

Table 4 shows that the measured length of the steel gauge block was repeatable within ± 5 nm. The repeatability of the tungsten carbide and ceramic gauge blocks was worse. This may be due to differences in the wringing properties of the three materials. With a steel gauge block it is easier to feel when a firm wringing has been achieved. There is a point at which the gauge block no longer

Gauge material	Deviation from nominal length (nm)		Standard deviation (nm)
	Mean	Range	
Steel	687	682 to 692	3
Tungsten carbide	-135	-123 to -141	6
Ceramic	27	21 to 51	9

Table 4 Summary of results for ten repeated wringings of gauge blocks of different materials

slips across the platen surface but adheres strongly to it. Tungsten carbide gauge blocks tend to grip firmly to the platen surface on contact and are often difficult to slide into position. Although the wringing is very strong there may be some parts of the gauge surface that are not in close contact with the platen and consequently may be difficult to repeat. Conversely, when ceramic gauge blocks are wrung down to a platen the wringing feels quite loose. This often makes it difficult to judge a good wringing with a ceramic gauge block.

3.3 VARIABILITY OF THE WRINGING FILM THICKNESS DUE TO WRINGING IN A FOUR GAUGE STACK

3.3.1 Measurement procedure

The phase correction for a set of gauge blocks can be determined by wringing four gauges together in a stack and applying a formula which involves subtracting the combined individual lengths of the gauge blocks from the measured length of the stack. The individual lengths of four 5 mm steel gauge blocks were measured twice on the steel platen to ensure repeatability of the wringing. The gauge blocks were then wrung together in a stack and the length of the stack was measured. Normal wringing fluid was used on each contacting surface. The stack was dismantled, the gauge blocks were wrung together in the same order and the measurement was repeated. Thermal settling times allowed for a stack were between two and two and a half hours.

3.3.2 Results

The variability of the wringing film thickness in a stack of four gauge blocks is clearly much higher than that of a single gauge (table 5). Figure 4 shows the deviation from the nominal length of the stack for each repeatedly wrung stack. The standard deviation is four times that expected for a single gauge. These results have a profound implication for the use of a stack of gauge blocks to measure a phase correction. To this end, NPL has developed an alternative method to measure a phase correction for a metal gauge block on a given platen that uses the technique of total integrated scatter (Leach 1998). However, the stack method still has to be used to measure a phase correction for ceramic gauge blocks.

Deviation from nominal length (nm)		Standard deviation (nm)
Mean	Range	
- 18	-76 to +39	24

Table 5 Summary of results for ten repeated wringings of a stack of four steel gauge blocks

In order to minimise the problem of the high spread in repeatability for wringing a stack of gauges during calibration, gauge blocks are wrung to a platen in a stack and measured; the stack is dismantled and the gauge blocks are wrung together in the same order as before but with the measuring faces turned the other way up. The stack is re-measured and agreement between the length measurements for the two wringings must be within 10 nm otherwise the process is repeated until agreement is reached.

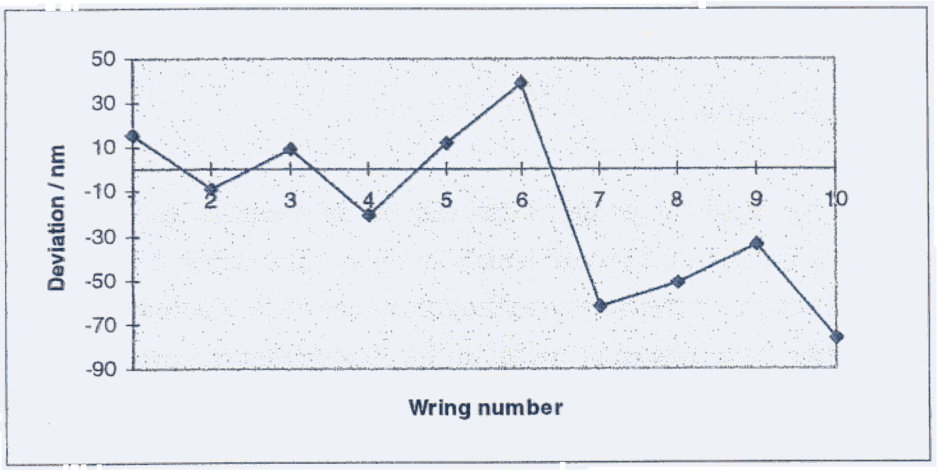

Figure 4 Results for the four gauge stack experiment

3.4 VARIABILITY IN TWO WRINGINGS FOR A NUMBER OF STEEL GAUGE BLOCKS

3.4.1 **Measurement procedure**

A further set of experiments was carried out to determine the repeatability of wringing gauge blocks under conditions that apply during calibration at NPL. When repeat measurements are made of gauge blocks during routine calibrations, the gauges are not necessarily wrung onto the same area of a large platen each time they are measured. A number of steel gauge blocks were wrung onto a large steel platen, using normal wringing fluid, and length measurements were made. The gauge blocks were removed from the platen and the contacting surfaces were cleaned with ethanol. The same face of each gauge block was wrung to the platen, without the use of templates or guides to position the gauge blocks, and the length was measured again. A total of 41 gauge blocks were measured in this way. Both measurements on any one gauge were made by the same operator. As is standard practice at NPL, if the two measured lengths of each gauge were not within ± 30 nm of each other, the wringing was repeated.

3.4.2 Results

Length measurements on the gauge blocks were made under normal operating conditions that apply during calibration. Table 6 and figure 5 present the results. The standard deviation is twice that obtained in section 3.3 under more rigorously controlled conditions. The increase in the standard deviation under normal calibration conditions is because there are higher uncertainties involved in the measurements plus each of the 41 gauges has a different surface structure.

Mean difference between 2 wringings (nm)	Standard deviation (nm)
8	6

Table 6 Summary of results for measured differences between two repeated wrings for 41 steel gauge blocks

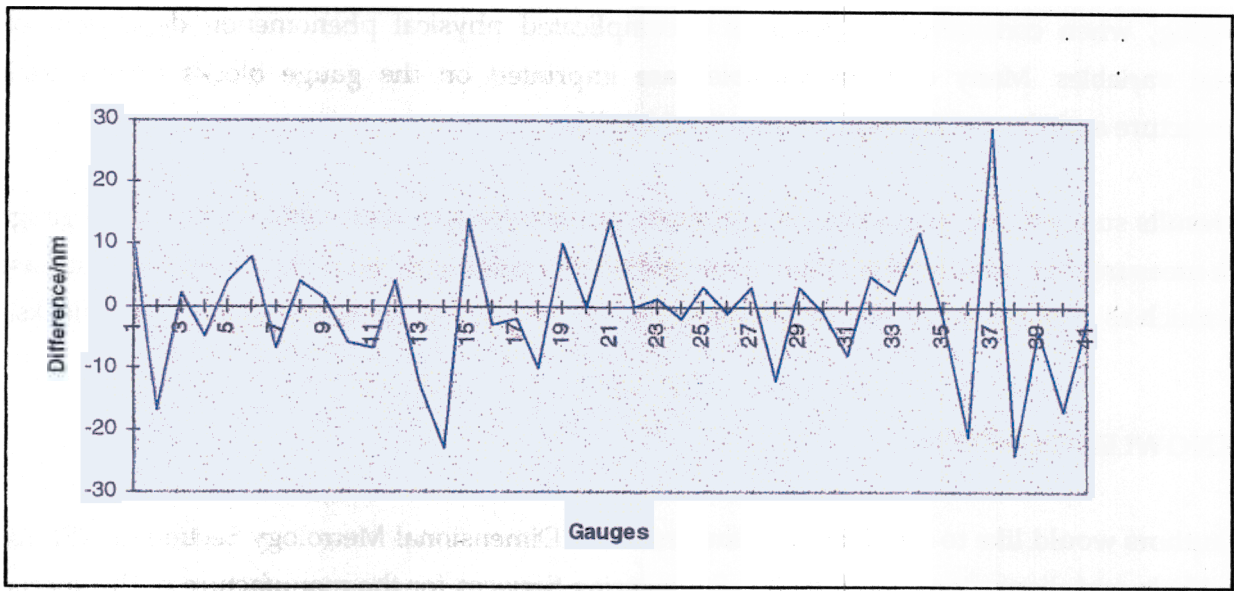

Figure 5 Results for repeated wringings of steel gauge blocks under normal wringing conditions

4 CONCLUSIONS

This study has highlighted a number of factors which contribute to the repeatability of the wringing film thickness. Wringing technique appears to be the most important factor in obtaining a firm wringing. Different wringing fluids appear to have little effects on the variability of wringing film thickness, although normal NPL wringing fluid does appear to give a smaller variation. A possible explanation for this may be that the peaks on the metal surfaces of the platen and gauge are in direct contact when wrung. The use of wringing fluid increases the contacting area by evening out irregularities between the two contacting surfaces.

The material of the gauge block also appears to have some influence on wringing. The most consistent results were obtained with steel gauge blocks. However, a firm wringing, especially with a difficult material such as ceramic, is based as much on the judgement of the operator as on the appearance of the fringes in the interferometer. Operator experience may play a significant role in achieving reproducible results although looking back at historical data at NPL does not back this statement up.

Wringing, when considered in detail, is a complicated physical phenomenon dependent on several variables. Many of these variables are imprinted on the gauge blocks during their manufacture and change throughout their working life.

The results suggest that in general the variability in the wringing film thickness for a steel gauge block measured by interferometry is ± 6 nm at the 95% confidence level. This value may increase to as much as ± 18 nm at the 95% confidence level for ceramic and tungsten carbide gauge blocks.

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APPENDIX A - MEASUREMENT OF THE WRINGING FILM THICKNESS

Two methods of measuring the length error introduced by the wringing effect have been employed in the past both of which give results agreeing with the limited theory. These methods are absolute, but usually involve experimental uncertainties of the same order of magnitude as the values of the measurand. Both methods are discussed by Rolt (1927 and 1929).

A.1 AREA METHOD

In the area method, a known volume of wringing fluid, determined by weighing, is used when wringing together an optically polished glass flat and the lapped surface of a gauge block (see figure 5). After allowing the film to attain its maximum area (or minimum thickness) the area of the fluid can be measured using a travelling microscope or planimeter and the average wringing film thickness calculated. Results do not vary significantly when using different liquids. With another glass flat used in place of the gauge a lower value of the film thickness and a higher value of the force of cohesion between the two surfaces is measured (Budgett 1911). This is probably due to the scratches and sleeks caused by the lapping process not allowing such intimate contact.

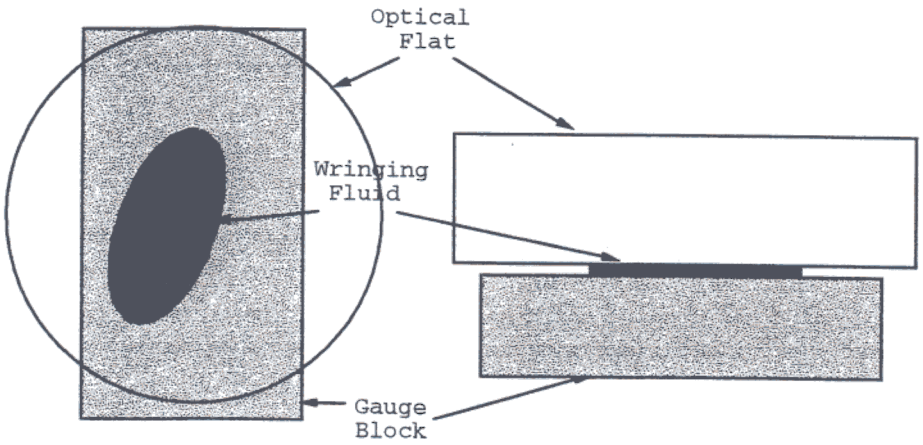

Figure 6 The area method of measuring wringing film thickness (with highly exaggerated wringing film thickness)

The area method is the only traceable method for determining wringing film thickness, but it has high measurement uncertainties. It is difficult to produce a consistent weight of the film so as to allow a proper averaging process to be carried out and the resulting film geometry, after wringing, is far from homogeneous. The method does not take into account the fact that the molecular cohesion between a lapped steel surface, or a polished glass surface, and steel surface is not the same. The method would be very time consuming to perform and does not give the wringing film thickness of a particular gauge wrung to a particular platen.

A.2 INTERFEROMETER METHOD

In the interferometer method the lengths of a number of gauge blocks are measured using interferometric techniques and their combined length is measured when they are wrung together as a stack (see figure 7). The interferometric method usually involves sandwiching the gauge block, or stack of gauges, between two semi-transparent, optical flats to produce a Fabry-Pérot étalon which can then be used in conjunction with a monochromatic light source to measure the optical displacement between the glass plates. From measurements of individual gauge blocks and the stack, a number of equations can be produced, the solution of which gives a value which is a combination between the wringing effect at the glass-gauge interface and that between the gauge-gauge interface. These thicknesses are assumed to be equal and a single value is obtained.

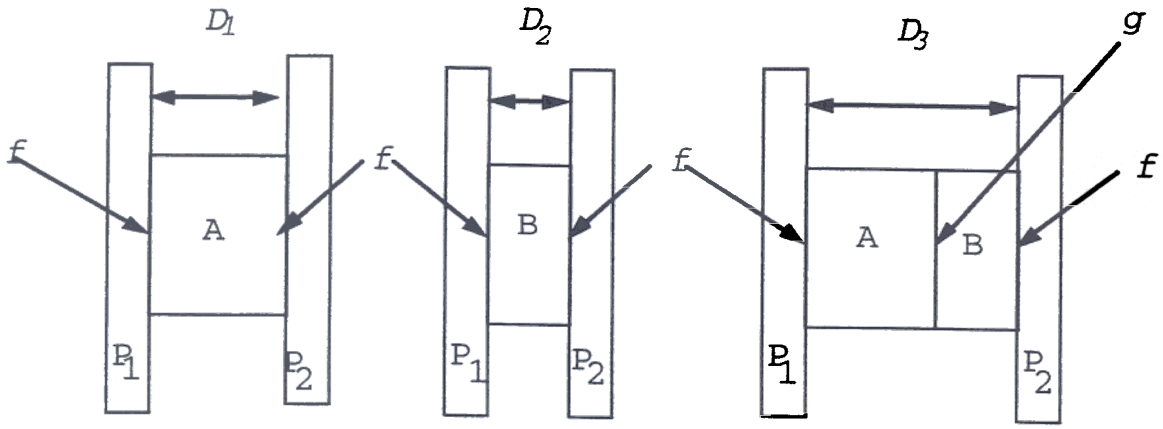

Figure 7 The interferometric method of measuring wringing film thickness. A and B are gauge blocks and P_i are glass flats. The method gives the result that $2f - g = (N_1 + N_2 - N_3)\lambda$; where f is the wringing film thickness between a plate and a gauge, g is the wringing film thickness between the two gauge blocks, λ is the wavelength of the light used and $D_i = N_i\lambda$ are the distances between the glass faces as measured interferometrically

This method is subject to a number of problems. First, the wringing effects between the steel and glass interfaces are not the same. Also, there is a phase shift on reflection from the semi-transparent, glass plates which changes the effective optical displacement between them. In the past this method has only been used to check the results obtained using the area method.