

CHAPTER 2

REVIEW OF LENGTH MEASURING INTERFEROMETERS

“Lux, etsi per immunda transeat, non inquinatur.”
(*“Light, even though it passes through pollution, is not polluted.”*)
St. Augustine

2.1 THEORY OF INTERFEROMETRIC LENGTH MEASUREMENT

The basic principles of length measurement using interferometry were demonstrated in the reverse sense by Michelson in 1892 when he measured the wavelength of the red light from cadmium in terms of the International Prototype Metre.

The principle of length measurement by interferometry is straightforward - it is the comparison of a mechanical length (or a distance in space) against a known wavelength of light. This may be expressed in a simple equation

$$L = (N + f)\lambda \quad (2.1)$$

where L is the length being measured, λ is the wavelength, N is an integer and f is a fraction ($0 < f < 1$). Commonly the optics are arranged such that the light beam measures exactly double the required length (*i.e.* it is a double-pass system), in which case the measurement units, ‘fringes’, are half-wavelengths.

$$L = (N + f)\frac{\lambda}{2} \quad (2.2)$$

i.e. one interference fringe corresponds to a distance or length equal to $\lambda / 2$. By using a light source for which λ is known (*e.g.* laser, gas discharge lamp), measurement of N and f leads directly to a value for L .

When using sources of visible light the wavelength of the light is small, typically 400 - 700 nm and hence the basic ‘unit’ of measurement, one fringe, is 200 - 350 nm in size. Hence knowledge of N alone provides a measurement resolution of 200 - 350 nm. For

comparison, a typical atomic spacing is of the order of 0.5 nm, so the tick marks on an ‘interferometric ruler’ are spaced 400 - 700 atoms apart.

By careful analysis of these interference fringes, it is possible to sub-divide them (and hence measure f) to a resolution of 1/100 to 1/1000 of a fringe - the minor tick marks on the ‘ruler’ are represented by single atoms.

By using sources with much smaller wavelengths (*e.g.* x-rays), the size of each fringe can be reduced to 0.2 nm, and fringe sub-division yields a measurement resolution in the picometre range [1]. Alternatively, the complications of x-ray optics and fringe detection may be avoided by using a ‘many-pass’ arrangement of optics in which the measurement beam traverses the object length many times, by multiple reflection from slightly tilted mirrors. (This should not be confused with multiple-beam interferometers such as the Fabry-Perot design. In the former, each point in the interference pattern is the summation of two beams, which have travelled in many passes, whereas in the latter (Fabry-Perot), each point is the summation of many beams, which have travelled different path lengths - see § 2.4.2).

2.2 BASIC INTERFEROMETER TYPES

There are many types of interferometer using a variety of techniques, mostly using lasers as their light source. Each design of interferometer is suited to a particular situation and has certain advantages and disadvantages for interferometry of length bars. These will now be examined.

The first distinction that can be made between interferometer types is whether they are dynamic or static. Dynamic interferometers are usually fringe counting interferometers, often with a small beam diameter. Static interferometer designs, on the other hand, are often large field, and are typically used for optical testing.

2.3 REVIEW OF SMALL FIELD, DYNAMIC INTERFEROMETERS

2.3.1 Fringe counting interferometry

In the simplest type of fringe counting interferometer, one of the mirrors is moved whilst the other remains stationary. As the interference fringes cross a detector, typically a photodiode, the number of maxima or minima in the signal are counted by a simple circuit. No attempt is made to sub-divide the fringe count. The resolution of this

type of interferometer is thus limited to the size of one interference fringe, typically 300 nm.

In fringe counting interferometers with interpolation, the output beam of a laser is split into two. After travelling along the reference and measurement paths the beams interfere with each other and are split again. One beam is given an extra phase difference of $\pi/4$ to produce two orthogonal outputs for example by using a quarter-wave plate, as in figure 2.1, or by using a specially coated beamsplitter [2]. Two detectors view these two outputs which are in phase quadrature and the signals from these two detectors, after suitable processing, are used to drive a bi-directional counter. By using a fringe interpolator using look-up tables or computer processing, each fringe can be sub-divided to the 1/1000 fringe level to provide the potential for more accurate measurement.

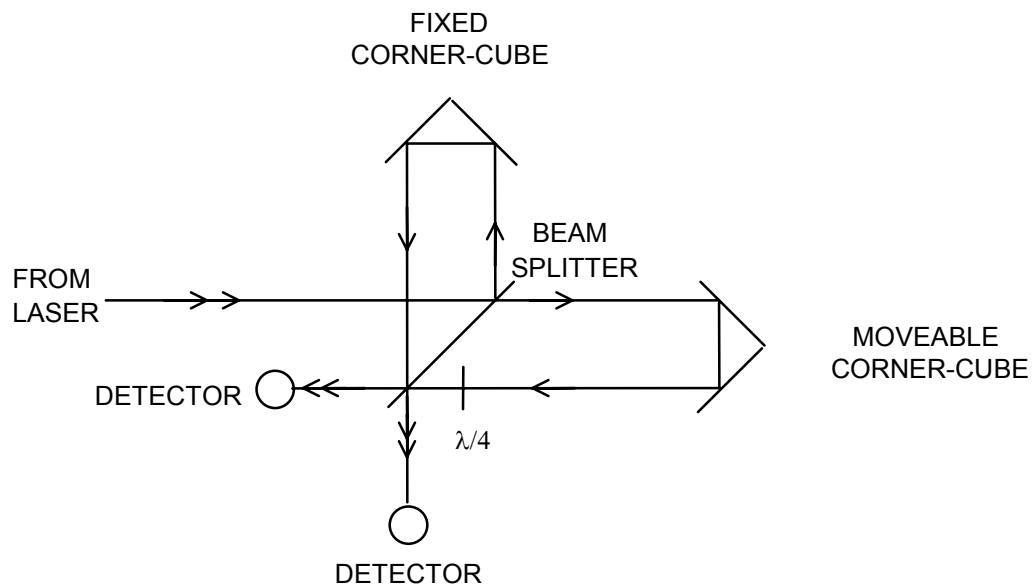


Figure 2.1 - Schematic diagram of a fringe counting interferometer

The main disadvantage of using a fringe counting system is that it provides only relative measurements of distance and requires accurate setting at two defined points to define a length. In the measurement of absolute lengths, the optical path difference of the fringe counting interferometer must be increased by a distance equal to the length of the object to be measured. This can be done by traversing a mirror on a linear stage between two points coincident with the two ends of the object to be measured, see figure 2.2, or by using the interferometer to monitor the position of the probe of a coordinate measuring machine.

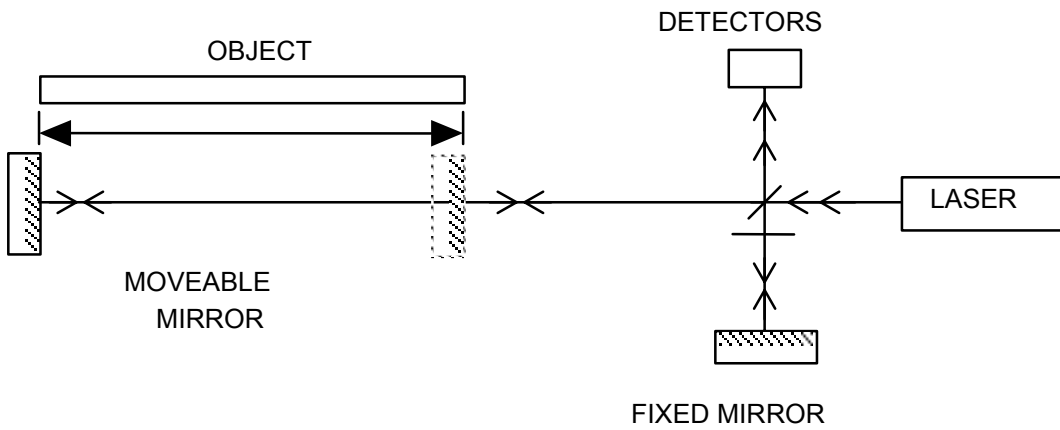


Figure 2.2 - Use of fringe counting to measure the length of an object

This system is then prone to alignment errors. There are three axes which must be coincident: the central axis of the object, the axis of the linear stage and the axis of the interferometer beam. Any mis-alignment of one of these will lead to a length dependent error.

The fringe interpolation is also prone to errors. If the amplitudes of the two orthogonal signals are not equal or their phase difference is not exactly $\pi/2$, then the interpolation will be incorrect. Table 2.1 gives typical values for fringe interpolations errors for a commercial fringe counter with 1/1000 fringe interpolation. Use of a computer curve fitting algorithm to fit an ellipse to the intensity data can sometimes be used to increase the accuracy [3].

Parameter	Error in parameter	Error in fringe fraction
Gain mis-match	5 %	0.004
DC offset	10 mV	0.001
Phase difference	5 °	0.010

Table 2.1 - Typical fringe interpolation errors (FT Technologies FT612AS)

The speed of measurement is also important to the overall accuracy. Any fringe counting system which relies on the translation of a moveable mirror or mechanical probe will require a finite amount of time for the probe to move between the two ends of the object. The speed of movement is not usually limited by the ability of the fringe counter to track the fringes as the probe is moved since fringe counting rates up to 20 MHz may be easily achieved, corresponding to a velocity of 6 m s^{-1} . However it takes a few seconds to accelerate and decelerate the probe and mount. With a settling time of a few seconds before the fringe interpolation can be made accurately this requires a total

of approximately 10 seconds during which any movement in the bar or optical components, any drift in refractive index or thermal expansion of the bar will cause an error in the measurement.

2.3.2 Heterodyne fringe counting interferometry

The field of heterodyne interferometry has been made accessible due to the very narrow linewidths of lasers which allows the observation of beats between two laser frequencies. The technique has resulted in a commercial design of interferometer (Hewlett-Packard 5528A) which can be used for distance measurement of path lengths up to 60 metres [4]. The instrument contains a He-Ne laser in which a longitudinal magnetic field splits the output beam into two components (Zeeman splitting) which are separated in frequency by 2 MHz. These two components have opposite circular polarisations which are converted into orthogonal linear polarisations after passage through a quarter wave plate. A polarising beamsplitter directs one polarisation to a fixed corner-cube which acts as a reference whilst the other beam is directed to the moveable corner-cube, see figure 2.3. The beat frequency between the two beams is detected and combined with a reference frequency in a differential counter. When the mirrors are stationary these two frequencies are equal, however if one of the corner-cubes is moved there is a frequency difference signal which can be used to monitor the change in path length between the two arms.

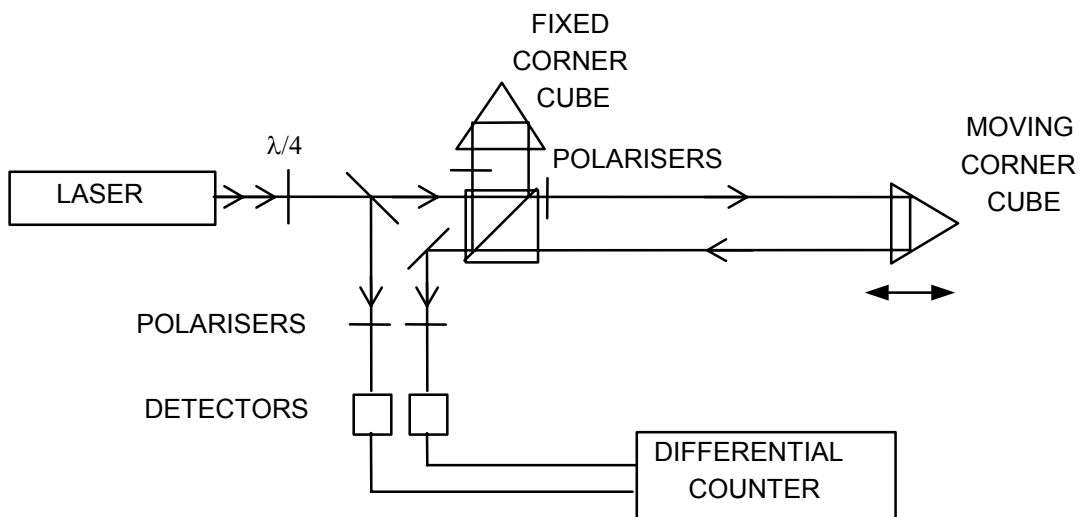


Figure 2.3 - Schematic diagram of a heterodyne fringe counter

The conventional arrangement of the Hewlett-Packard system offers a resolution of 10 nm, though this can be improved by using multiple-pass interferometry where the beam traverses the measurement path many times.

The drawbacks with this system are similar to those of the simple fringe counting system above. This type of interferometer is used in many industrial calibration laboratories where the wavelength of the laser is calibrated to provide traceability.

2.3.3 Two-wavelength fringe counting interferometry

By illuminating an interferometer sequentially with two wavelengths λ_1 and λ_2 , the effective range is that which would be obtained with an effective wavelength λ_e

$$\lambda_e = \frac{\lambda_1 \lambda_2}{|\lambda_1 - \lambda_2|} \quad (2.3)$$

Measurements have been made with carbon dioxide lasers [5] where the laser output wavelength is switched rapidly between two wavelengths as one of the mirrors of the interferometer is moved. Matsumoto [6] has investigated measurement of distances up to 100 m to an accuracy of 1 part in 10^7 . Error sources for this technique include the alignment of the paths, the accuracy of the laser wavelengths (including refractive index effects) and the accuracy of the fringe interpolation performed in the computer.

2.3.4 Other fringe counting systems

Kubota [7] employed a frequency modulating interferometer using semiconductor lasers where polarised beams were combined to produce fringe patterns with intensities in phase quadrature. The absolute measurement of distance was performed by sweeping the frequency of the laser by ramping the supply current. Detection of the beat frequency provided information about the path difference between the two arms of the interferometer. The accuracy of the system is limited by the accuracy of the wavelength measurement whilst sweeping.

Other authors have used direct modulation of the laser output intensity using feedback. In this scheme the moveable mirror reflects the beam back into the laser cavity and thus acts as an extended external cavity [8,9,10]. The drawback with this scheme is that the feedback affects the ability of the laser to stabilise at a single mode and hence the absolute value of the laser wavelength cannot be maintained.

In order to overcome the limitations described above, a system for the measurement of length bars must be static, *i.e.* the measurements must be performed with little or no

movement of the optical components or mechanical parts of the system including the object or length bar to be measured. A drawback of using a dynamic fringe counting interferometer is that it does not directly measure the positions of the end faces of the bar, rather it measures the positions of the interferometer mirrors, which require accurate setting at the opposite ends of the bar. Better accuracy can be achieved by measuring the bar directly and using its flat polished end faces as the optical mirrors in the interferometer.

The system must therefore be able to detect, image or otherwise measure the positions of the two ends of the bar simultaneously. The laser source must operate at an accurately known wavelength such that the distance between the ends of the bar can be measured in terms of interference fringes of a known, fixed size. The interference pattern generated by the interferometer must be amenable to analysis to allow fringe sub-division to the nanometre level. These conditions are satisfied by using a large aperture interferometer. The effect of laser beam diffraction is also minimised by increasing the aperture of the interferometer.

2.3.5 The effect of laser beam diffraction on measured length

Due to the spread of wavevectors in a gaussian laser beam, there is a slight alteration to the longitudinal propagation speed of parts of the wavefront. This can be estimated as follows.

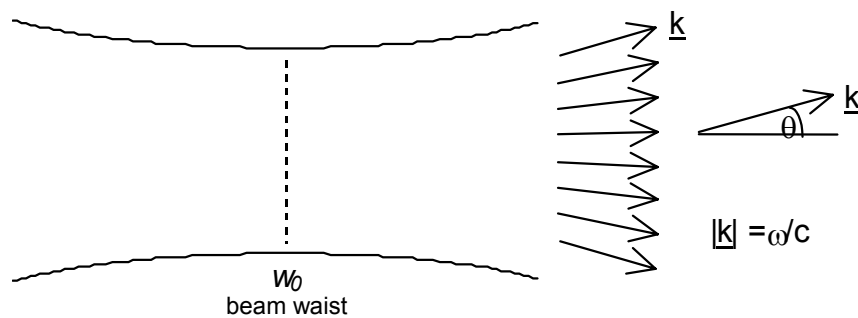


Figure 2.4 - Laser beam waist - alteration of effective propagation speed

The effective propagation speed is reduced by

$$\approx |\mathbf{k}|(1 - \cos \theta) \quad (2.4)$$

with

$$\theta \approx \frac{\lambda}{w_0} \quad (2.5)$$

where λ is the wavelength and w_0 is the minimum beam diameter (waist). Therefore the correction to the measured distance is approximately

$$\frac{\theta^2}{2} \quad \text{or} \quad \frac{\lambda^2}{2w_0^2}$$

For an expanded laser beam used in an interferometer with aperture 80 mm, this evaluates to $\sim 3 \times 10^{-11}$, and is thus negligible. A more detailed derivation is given by Rowley [11] and is reproduced here, to confirm the approximate estimate. The combined effect of the wavefront curvature and the propagation phase shift on D , the distance measured by the interferometer, is given by

$$D' = D - \frac{\lambda}{2\pi} \arctan\left(\frac{D\lambda}{2\pi w_0^2}\right) \quad (2.6)$$

$$D' \approx D \left(1 - \frac{\lambda^2}{4\pi^2 w_0^2}\right) \quad (2.7)$$

Substituting $\lambda = 633 \text{ nm}$, $w_0 = 80 \text{ mm}$ (beam diameter), the result is

$$D' = D(1 - 1.6 \times 10^{-12})$$

i.e. negligible. This is the same result as that of Dorenwendt and Bönsch [12]. Mana [13] obtained the result

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda^2}{2} \frac{\pi^2}{w^2} \quad (2.8)$$

which is approximately 10^{-10} . Thus by using an expanded beam in the interferometer, rather than the conventional unexpanded laser beam size of 1 - 2 mm diameter, diffraction effects due to the beam waist can be made negligible.

2.4 REVIEW OF LARGE-FIELD INTERFEROMETER DESIGNS

2.4.1 The Fizeau interferometer

The most common large field interferometer is the Fizeau interferometer. This requires the minimum of optical components: a light source, collimating lens, reference flat and test surface, see figure 2.5. The source and return beams are coincident unless the

source is positioned slightly off-axis which then leads to an obliquity effect (see § 4.1.3). The profile of the fringes in a Fizeau interferometer with tilt is determined by the reflection and transmission coefficients of the optical surfaces used.

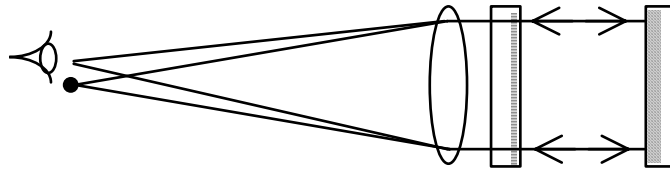


Figure 2.5 - Standard Fizeau interferometer

To overcome the problem of separating the source and return beams it is common to use an extra beamsplitter in the collimator path to re-direct the output beam, figure 2.6.

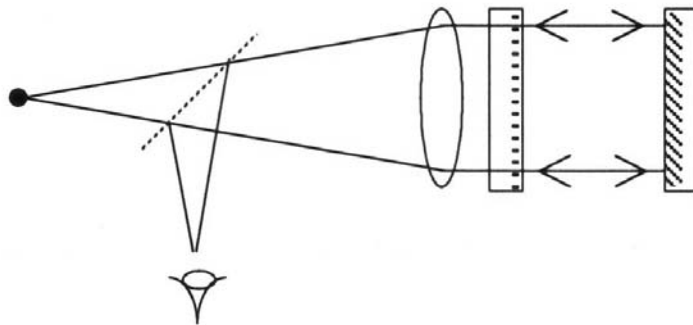


Figure 2.6 - Modification to Fizeau interferometer

Care has to be taken to minimise extra reflections from the beamsplitter secondary surface, *e.g.* by using an anti-reflection coating. Typical fringe intensity profiles can be seen in figure 2.7. These were calculated from equation 2.9, for values of R from 0.1 to 0.9, where $R = R_1 R_2$, and $R_1 = R_2$.

$$I = 1 - \frac{(1 - R_1)^2 (1 - R_2)^2}{1 + (R_1 R_2)^2 - 2 R_1 R_2 \cos(2m\pi)} \quad (2.9)$$

R_1 and R_2 are the reflectivities of the two surfaces and m is the order of interference.

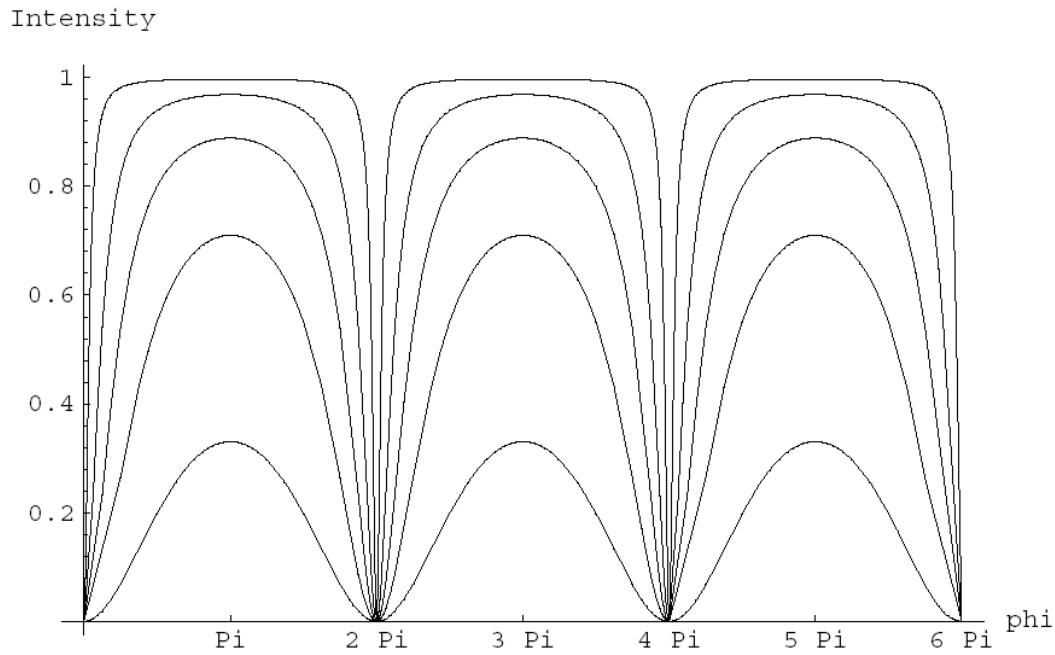


Figure 2.7 - Normalised intensity profiles of fringes in a Fizeau interferometer for values of the reflectivity (R) ranging from 0.1 (lowest curve) to 0.9 (uppermost curve), according to equation 2.9

2.4.2 The Fabry-Perot interferometer

In fact the Fizeau interferometer may be regarded as a version of the Fabry-Perot interferometer which uses multiple reflection to achieve narrow profile fringes especially suited to spectroscopic work.

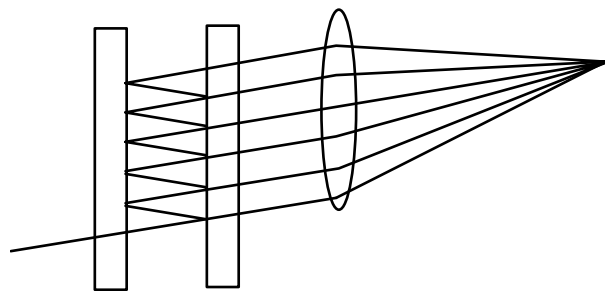


Figure 2.8 - Fabry-Perot interferometer

2.4.3 The Michelson interferometer

By introducing the extra beamsplitter to the Fizeau interferometer, the number of optical components has equalled that found in another common interferometer, the Michelson interferometer. Here a beamsplitter at 45° is used to split the incoming beam into two (amplitude division) which are directed to two mirrors: the reference mirror and the test mirror, and then recombined.

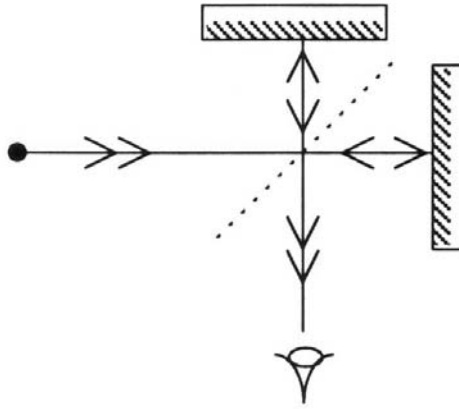


Figure 2.9 - Michelson interferometer

The Michelson interferometer produces different types of fringes according to the path difference between the two arms and whether or not any tilt has been introduced. It is common to use a compensating plate in the Michelson interferometer to account for the path difference between the two beams since one of them passes through the glass of the beamsplitter 3 times whereas the other passes through only once.

2.4.4 The Twyman-Green interferometer

When the Michelson interferometer is used with a collimated beam of light the arrangement is called the Twyman-Green interferometer [14].

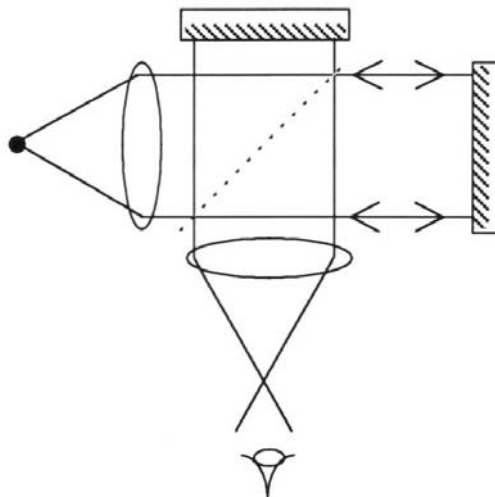


Figure 2.10 - Twyman-Green interferometer

The Twyman-Green interferometer is ideal for measurements of surface shape and surface texture as it offers a large field with sinusoidal fringes of good contrast and has the added advantage that by careful positioning of the reference mirror, twice the coherence range of the Fizeau interferometer can be obtained when imaging extended

objects, *i.e.* by positioning the reference mirror at an optical path equal to half the length of the extended object to be imaged, the useable coherence is doubled, see figure 2.11.

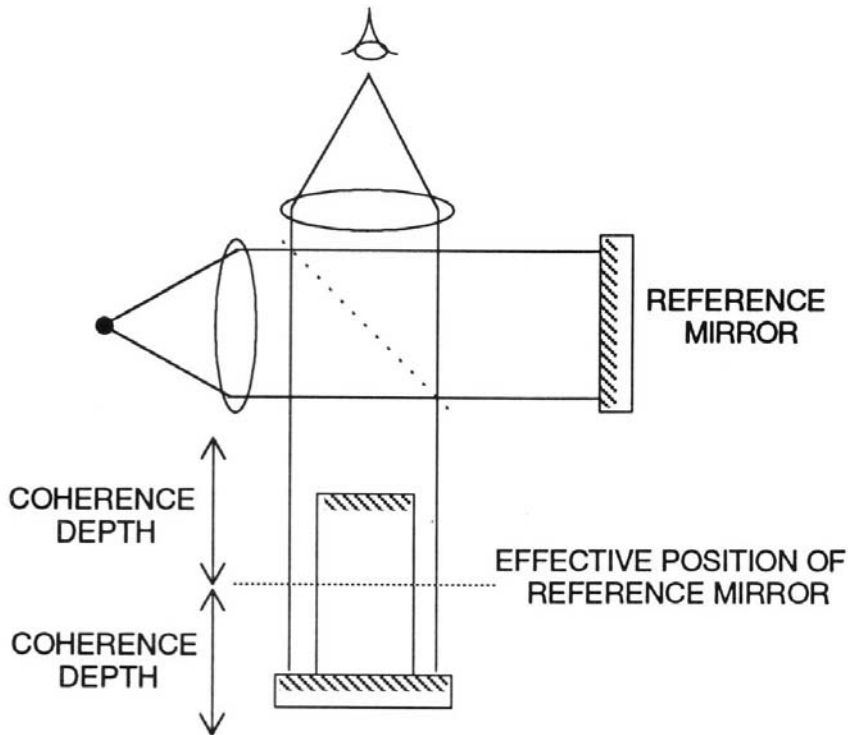


Figure 2.11 - Coherence depth doubling by positioning of reference mirror

Thus for a source of coherence length 50 mm, by using a Twyman-Green arrangement as opposed to a Fizeau system, objects up to 100 mm can be measured.

Whilst the narrow fringes of the Fizeau/Fabry-Perot interferometer are ideal for fringe locating and tracking algorithms, the sinusoidal nature of the fringes in a Twyman-Green interferometer are ideal for analysis by phase-stepping techniques which offer potentially greater accuracy of fringe interpolation approaching 1/100 to 1/1000 fringe (see chapter 5). Although it is possible to use phase-stepping with a Fizeau interferometer (see § 5.3.7.3), the analysis is more complex and requires symmetrical fringe profiles.

2.4.5 Other designs of length measuring interferometer

Previous interferometers for the measurement of end standards of length have included the NPL Automatic Gauge Block Interferometer (Twyman-Green), NPL-Hilger interferometer (Fizeau) and the Kösters-Zeiss interference comparator which used a precision Kösters prism as the beamsplitter/combiner, shown in figure 2.12.

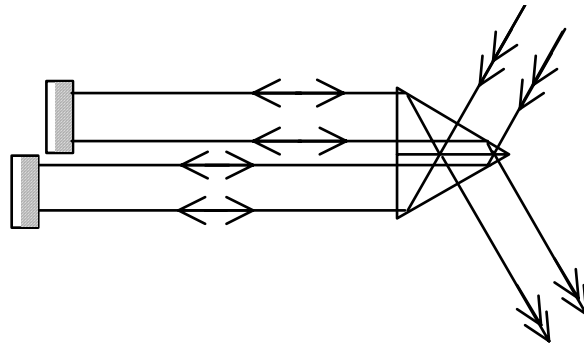


Figure 2.12 - Kösters-Zeiss interference comparator

2.5 PRIMARY LENGTH BAR INTERFEROMETER - BASIC INTERFEROMETER TYPE

Of the designs investigated, the Twyman-Green design was chosen as the basis for the Primary Length Bar Interferometer. The large field makes it possible to view interference fringes over the whole of the surface of the bar and hence measure surface form. The sinusoidal fringe intensity is ideal for analysis by phase-stepping interferometry (see chapter 5), the alignment is straightforward and the coherence-depth sufficient (given a relatively small source).

To measure the length of the bar, it is attached to a reference flat or platen, as shown in figure 2.13.

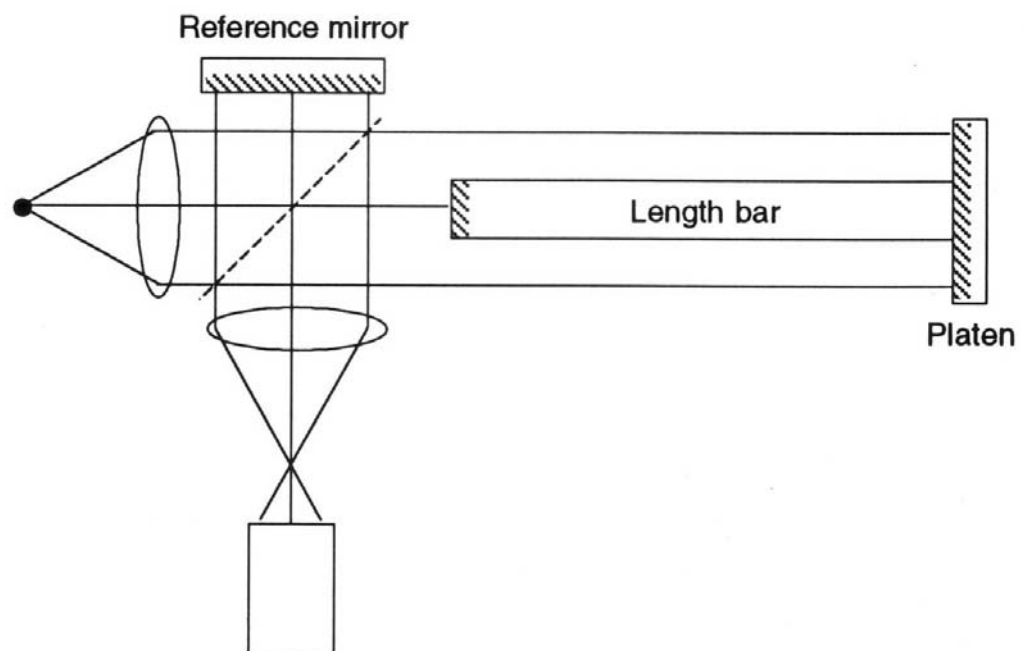


Figure 2.13 - Twyman-Green interferometer for the measurement of length bars

2.5.1 The technique of ‘wringing’

The platen is attached to the bar by the process of ‘wringing’. In this process the surfaces of the bar and platen are thoroughly cleaned using acetone to remove all presence of oils, dirt and dust. A small drop of a solution of ‘wringing fluid’ (liquid paraffin diluted 1:50 in Arklone (1,1,2 Trichloro-1,2,2 Trifluoro-Ethane)), is smeared over the surface of the platen and polished off with a tissue until none can be seen by the naked eye. The platen is then slid onto the end of the bar whilst the two are in plane contact. During this process, the bar rests on temporary supports to allow access to the end of the bar.

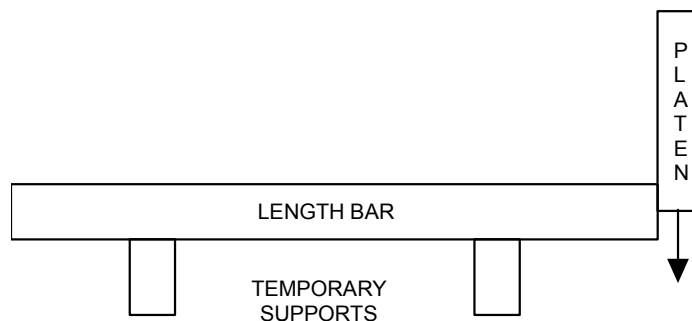


Figure 2.14 - Wringing a platen onto the end of a length bar

If the surfaces of the bar and platen are sufficiently flat and polished/lapped, molecular attraction takes place between the two surfaces and the molecular layer of paraffin between them. This attraction is strong enough to support the weight of the platen. Previous work [15] has shown that the ‘wringing thickness’ - the apparent separation between the two surfaces, is typically 7 nm (± 5 nm), and is not dependent on the amount of wringing fluid or its composition. The wringing was also proved to be a definite attraction rather than the effects of air pressure holding the two surfaces together (wringing can take place in a vacuum). The effects of surface tension have also been shown to be minimal in this situation. The wringing is much stronger when a wringing fluid is used on slightly rough surfaces, *i.e.* surfaces which are macroscopically flat, but not highly polished. It is thought that this is due to penetration of the wringing fluid into the sub-microscopic interstices of the platen leading to a larger surface area in good contact with the bar.

The size of the wringing film layer is taken into account when defining the length represented by a length bar. BS 5317 states:

Length ... is defined, with the bar mounted horizontally and referred to the standard reference temperature of 20 °C ... as the distance from the centre of one of its faces to a flat surface in wringing contact with the opposite face, measured normal to the surface.

There is an advantage in using a wrung length standard in that the length can be represented by a step height which allows measurement by probing in one direction; the probes can be optical, capacitive, linear variable differential transformers (LVDTs) or touch-trigger probes of CMMs. The penetration of the probe into the surface of the bar and platen due to phase effects (optical probes) or material compression (mechanical probes) is then accounted for, if the platen and bar are of the same material. This is not true if the object is probed from different directions.

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