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A new approach for establishing a reference plane for absolute measurement of shape and flatness with nanometre precision

by

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ABSTRACT

An alternative optical method to interferometry has been developed to measure form of flat and of shallow curvature optical surfaces to nanometre accuracy without reference to a master surface. The method consists of measuring the surface slopes at points along a line with a resolution of 1/100 of a second of arc. Slope values are integrated with respect to distance to obtain profile height. The surface is scanned with a laser beam whose direction and straightness can be maintained to a high degree of accuracy by using enclosures that insulate the acoustic noise and improve the thermal stability to better than 0.1 °C. The line profiles measured in X and Y directions are combined using a least-squares solution to obtain a complete surface map and reference plane. The calculated reference surface is further corrected for twist by measuring the diagonal profiles. Recent measurements using a new two-dimensional profilometer system have shown that it can repeatably measure shape over an area of 120 x 120 mm to within ± 2 nanometres with angular deviations from flatness of up to 5 minutes of arc. This profilometer has a capability of readily examining surfaces with specular reflectivities varying from 4% to 100% up to 200 mm in diameter. Recently an assessment of systematic uncertainties of the two-dimensional instrument has been made by comparing flatness results with those obtained by Fizeau and Zygo interferometry, and the two sets of measurements agree to within ± 5 nanometres. The slope integration method has the potential to be developed further to characterise non-specular diffusing and specular surfaces over an area of at least 400 x 400 mm.

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1. INTRODUCTION

To characterise test flats it is necessary to calibrate them against master surfaces which are in turn calibrated against a reference plane in the form of a liquid surface [BUNNAGEL 1956]. The flatness comparison is made using a Fizeau interferometer. There are other methods for calibrating test flats which do not require a reference surface. Whitworth's method for example compares unknown surfaces by employing a suitable combination of tests to provide absolute information of all the surfaces being compared. The Whitworth method can however only give planeness in one dimension, e.g. along one diameter at a time. Nonetheless, this method can provide partial information about a surface in horizontal and vertical azimuths.

The above techniques measure absolute shape of surfaces as departures from a mathematically defined surface or plane [WOLF 1976]. They are of fundamental importance and form the basis of other tests for quality control in the optical industry. However, the real surfaces must not deviate too far from an ideal shape, or else the accuracy of measurement may be reduced significantly [WOLF 1976]. It is recommended that when performing calibrations on optical surfaces their shape should ideally be within 1/10 of a fringe of the reference surface to obtain reliable measurements. This also applies when spherical or aspherical components are characterised. It is not an easy task to produce and maintain large flats to the above requirement. Other factors which can influence the accuracy of measurements of the liquid reference standard are: mechanical vibrations, temperature variations, evaporation, electric charges, capillary effects at the boundary, dust particles on the liquid, disturbances caused by unevenness of the bottom of the vessel when the layer of liquid is too thin, the effect of the curvature of the earth and sagging of the test surface by gravitation on account of the horizontal position required.

Other effects which are not related to the liquid standard can also introduce significant errors. These can be in the form of spurious interference between the surfaces being compared and secondary reflections from back surfaces together with the flare spots which are inherent in interferometric methods. The anomalous phase effects due to material inhomogeneities are considered to be small when polished glass surfaces are considered for accurate metrology [RAINE and FRANKS 1985], i.e. less than a nanometre. If phase stepping techniques [CREATH 1988] are considered for shape measurements instead of using electronic sub-division of fringes [DEW 1966a], then the above problems are compounded further. For example, due to the increased coherent length of laser sources and very sensitive electronic digitizers that are employed. Therefore it would not be prudent to assume that one could claim flatness measurements accurately to a nanometre with absolute certainty.

Although interferometric methods are widely employed for quality control and can give surface shape information in real time, the procedures involved to obtain a reference plane seem to be unnecessarily complicated and time consuming. So far an uncertainty of 1/10 of a fringe seems to have satisfied most users in the optical industry, but it does not seem to be the case in the X-ray imaging field [FRANKS *et al* 1980] and in the electro-optical industry, where metrology in the nanometre region is sought. Furthermore, adequately trained staff are required to perform visual techniques [BUSCH 1965] to determine the correct shape of every test flat that needs to be characterised (i.e. concave or convex). The visual methods may not work reliably if an optical surface exhibits hills and valleys of very small amplitudes, and if its shape is extremely close to the reference plane as well.

An alternative simple method which is not prone to most of the above adverse effects has been developed and is based on the slope integration method [ENNOS and VIRDEE 1982]. An instrument based on this principle was initially developed to scan surfaces using a laser beam in conjunction with a constant deviation (pentagonal) prism in a linear direction, to satisfy an internal requirement at the National Physical Laboratory. The requirement was to monitor the performance of the precision lapping and polishing techniques applied to correct the residual errors due to imperfect machining [FRANKS *et al* 1980]. The measured shape is then only related to the direction of a laser beam employed to scan a surface. If the beam can be made directionally stable by using insulation to prevent changes in the refractive index of air due to thermal gradients, then comparison against a master surface or slide is unnecessary.

2. TWO-DIMENSIONAL LASER PROFILOMETER

The initial 1-D laser profilometer verified that it is possible to measure shape along a line repeatably to an accuracy of ± 1 nm, and consistent results are obtained when the flat specimen is rotated by 180° [VIRDEE 1988] from end to end and remeasured. The method employed in this instrument has been developed further to measure form of optical surfaces in two dimensions, and is shown in Figure 1. It consists of a scanning laser beam which is fed via a monomode optical fibre to isolate the profilometer system from heat generated by the laser tube. Another major advantage of using an optical fibre is that increased directional stability of the interrogating beam is achieved [VIRDEE 1992] because it maintains its position on the output side even if there are instabilities on the input side due to airborne vibrations. The optical micrometer (a parallel-sided glass plate) is rotated in two orthogonal directions by using the out-of-balance signal from all four quadrants of the photodiode (UDT type PIN SPOT 4/D). The amplified signals from the position sensitive detector drive the two tangent arms attached to the glass tilt plate to null the readings using geared-down servo-motors linked via two off-set circular cams [VIRDEE 1986]. Although the tilt of the glass plate can be measured in two directions, only the slope in the vertical direction is required, which is read by an MT30 Heidenhain micrometer. The null position of the glass plate is maintained all the time in both the axes by using closed loop circuitry. Nulling in both axes is desirable to make the initial adjustment of the beam normal to the surface being examined easier and eliminate the need for critical alignment of the quadrant detector in the horizontal plane [VIRDEE 1988].

The stability of the 2-D profilometer system and the specimen to be measured, are obtained by constructing enclosures shown in the photograph (Figure 2(a)). Also shown in the photograph is the ancillary equipment such as the control computer, interfaces for stepper slides and a rotary stage, Heidenhain transducer readout box and a laser with an optical fibre feed. This equipment for obvious reasons is placed as far as is practically possible outside the main enclosure to prevent the distortion and bending of the laser beam due to heat. The main enclosure is constructed using an aluminium frame, toughened glass and chipboard panels. Figure 2(b) is a photograph showing an optical flat in position for scanning together with the translation stages and the servo-controlled autocollimator which is mounted on a separate metal platform.

3. AUTOMATION AND SCANNING PROCEDURE

The 2-D flatness measurement system has been completely automated [VIRDEE 1986], and the control device for the profilometer system is an Acorn Archimedes A440 microcomputer that scans the surface using the classical "Union Jack" configuration using a square grid as shown in Figure 3. The grid size can be varied and results in two

dimensions for 2N(N+1) data points recorded for analysis [BUSCH 1965], where N is the number of rows and columns.

To carry out the two-dimensional scan, software has been written to step the scanning beam by nearly half its diameter on the surface in equal increments along a line. The distance between the line generators is also equal to the incremental step length which is important and maintained accordingly. The vertical component of surface slope is then read at each increment by the Heidenhain micrometer [VIRDEE 1986] to obtain profile height. The measurement of unrelated line profiles in the two orthogonal directions are made in a raster fashion by incrementally stepping the optical flat across at right angles to the scan direction of the pentagonal prism. The positional relationship between the diagonal and X/Y direction profiles can be achieved to better than 5 μm by using a precise rotary table and two linear stepper motor slides, supplied by Ealing Electro-Optics plc.

The sequence of operation which is employed for automatic recording of data of an optical flat is shown in Figure 4, and it consists of four steps. Starting from position *d* in step 1, using point by point raster scanning, *n* number of rows are measured as indicated. Similarly, after rotation of the flat by 90°, *n* number columns are catered for but in the reverse direction from position *a* in step 2. Line scans for rows and columns are then manipulated, as shown on a regular grid in Figure 3, so that the profiles in X and Y directions with the correct sign can be calculated using the integration method. The first diagonal *a-c* is measured when the flat has been rotated by 45° in an anticlockwise direction and the scanning beam spot has been moved to position *c* in step 3. For this diagonal, the readings are reversed before they are stored. In the final step, the second diagonal is measured after the flat is rotated by 90° in the clockwise direction. For the last two steps the incremental step length is multiplied by $\sqrt{2}$ before scanning to maintain the positional relationship on the grid. Time taken for the scanning sequence is about 16 minutes for 2N(N+1) data points, if N is equal to 21. Over this time period, the flat specimen must remain stable to achieve the highest measurement accuracy, which is ± 2 nm. However, the instrumental stability is only required for each generator because the profiles calculated along all the generators have no relevant relationship to one another.

4. ANALYSIS

The analysis of the recorded data can be performed immediately after it has been saved on a hard or floppy disk. The following evaluation methods require that the grid of generators should have an equal and odd number of generators in the two orthogonal directions. These generators shall intersect on the diagonals, and therefore there are an equal number of measurement stations along each generator, including the diagonal generators. This has been fully satisfied by developing a scanning method in which the test specimen is moved [VIRDEE 1988] instead of moving the measuring instrument [MOORE 1970; EL SAYED and HUME 1974].

Usually, the analysis of nominally flat surfaces such as surface tables and plates, has been and to some extent is still being carried out, by using a method of calculation that combines the profiles of the individual generators so that they constitute a grid of heights referred to a selected plane [HUME and SHARP 1959]. This plane is defined by the vertices of the triangle formed by the two adjacent boundary generators and the closing diagonal. In such a solution the vertices of the triangle, three of the corners of the surface, are arranged at zero height. The fourth point is obtained by intersection of the other boundary generators and the remaining diagonal when this diagonal is

positioned in space by adjusting it to be in the plane of the established triangle. All the generators are then adjusted to conform with the three defining generators. One might object to this method due to the fact that where the two adjusted generators meet and if their values do not agree, then an arithmetical compromise has to be made. This compromise can be considered invalid if the initial three defining generators exhibit experimental or systematic errors. This criterion may not be applicable to laser profilometry results because an individual generator profile can be measured to an accuracy of ± 1 nm. Even if there were an error, a least squares solution can be applied, after establishing the respective relationship in terms of profile heights in X and Y directions using the above method to reassess the overall distribution of experimental errors. This may provide some evidence or cause of the existence of systematic uncertainties.

In the process of verifying the assumptions relating to a liquid surface that initially lead to a flatness standard at NPL [DEW 1966a], computer programs were written, in which all the generators are weighted equally in combining them to evaluate a surface [BIRCH and COX 1973]. The outcome of the result is still referred to the evaluated surface or a reference plane that passes through three corners. Alternatively, the evaluated surface may refer to a mean plane. The definition of such a plane is that the sum of the squared residual differences between the evaluated surface and the mean plane is a minimum.

At the National Physical Laboratory, computer software is available to evaluate the departure from flatness of the surface, making use of the method of least-squares to solve the large system of over-determined simultaneous equations that describe the observations. For N^2 measurement stations or points on the evaluated surface, where $N \geq 3$, there will be $2N(N+1)$ observations (N^2 along each set of parallel generators and N along each diagonal generator). Therefore $(N+2)^2$ unknowns are evaluated in conjunction with the above.

In the above solution, the method of solving the simultaneous equations is further controlled by the relevant set of conditional equations included with the observational equations that gives a reference plane or is representative of the evaluated surface. For example, height and orientation of the surface have a particular relationship to the minor departures from flatness of the surface. The first conditional equation that is most frequently used is the least-squares plane and its definition has already been given earlier. The second produces a surface with zero values at the three corners, and the third or final makes the central value of the surface to be at zero height and residual values balanced or made equal at selected positions on either side of the centre for the two orthogonal generators [BIRCH and COX 1973].

Although the above method is the most rigorous and is preferred, its main limitation has been that it requires a lot of computer memory even for a small number of arrays, e.g. 7 x 7. With an IBM 2900 series mainframe computer the memory criterion cannot be fully satisfied and the analysis time can be unnecessarily long. A recent development in the microcomputer technology, the Acorn's Archimedes Risc computer system can more than satisfy the above needs, apart from fulfilling its main role as the control device in terms of automation of the profilometer system. The total memory, that is the Random Access Memory (RAM) can be up to 8 Megabytes and it costs below £3K. Using the NPL software or programs which were converted from Algol to Basic language on this Risc machine, the analysis time is still a few tens of seconds instead of several minutes when compared with other types of machines. If the programs can be converted into Assembly Language, an increase in speed by a further factor of 5

would be possible. Therefore larger arrays for extended surfaces can then be catered for. Previously, only a small sub-set of larger set of arrays could be analysed and then appropriate adjustments for the whole surface were made accordingly for flatness. However, a reliable residual error assessment for the whole surface due to using the sub-set data for analysis may not give valid information.

If a surface has to be analysed by scanning it with a small beam diameter, say 100 μm, taking measurements over an area of 10 x 10 mm using an incremental step of nearly half the beam size would mean that arrays of over 200 x 200 would have to be catered for. It may not be possible even for the Risc computer to cope with task of performing calculations using the over-determined solution to obtain shape. Furthermore, it would take several hours for the computer to perform such a task.

Apart from the previous method, another alternative approach which can satisfy the requirement to analyse a large number of arrays relies entirely on the diagonals to apply a correction for the twist information, but the analysis time is reduced to a few seconds instead of several hours. Again, this approach initially makes the use of the method of least-squares to combine unrelated profiles along horizontal rows and vertical columns obtained from slope measurements. The least-squares process determines the surface shape uniquely except for the amount of twist, which does not alter the fit of the profiles. The twist is determined by measurement of profiles along the diagonals. Using the average surface profile for the adjustment, the height values along each diagonal are subtracted from the corresponding surface heights. A least-squares quadratic function is fitted to the two sets of height differences, and the mean of the two quadratic terms is used correct the profile heights. It is assumed here that the differences along the diagonals will be of the quadratic form and not cubic.

The latter two methods of determining shape when applied to data obtained by using the two-dimensional profilometer system gave identical height values for every measurement station. The advantage of using the third or final method is that the differences between the calculated and measured height values specially along the diagonals can give an indication whether a flat specimen under test distorts during scanning. The scan period can be up to two hours, but usually it is no more than 20 minutes. The residual uncertainty in the two orthogonal directions is mostly under 2 nm. However, small differences of the order of 0.1 nm in height values were observed when data from an interferometric instrument [BIRCH and COX 1973] were used for determining flatness by employing the latter two analysis methods. This seems to suggest that the stability and repeatability of measurement of the laser profilometer system is very good. Systematic uncertainties can be assessed, if present, by comparing the laser profilometry results with those obtained by interferometric methods which so far have been and still are used to produce a reference standard.

5. VERIFICATION OF MEASUREMENTS

To check the stability and the measurement accuracy of the new two-dimensional laser profilometer system, a float glass test flat whose profile along two orthogonal diameters was previously obtained with the single-axis instrument was examined over an area of 14 x 14 mm with a step length of 1 mm. The departure from flatness is as shown in Figure 5(a). This verified the sense of the profiles in the X and Y directions (i.e. concave or convex) and the magnitude of the height values. The residuals or differences between the regressed or adjusted X and Y direction profiles were random and below 2 nm. This means the inherent accuracy of this profilometer is very high and absolute flatness calibration can be realised provided the effects of thermal gradients together with

airborne vibrations can be reduced and maintained to an acceptable level. The residual uncertainty is shown in Figure 5(b) and is of the order of 1 nm for the float glass test flat. In this case the standard deviation of the residuals is below 1 nm.

A high repeatability of measurements is achieved because of the precautions taken against environmental noise. The profilometer's performance has been checked by rotating a specimen by 180° and remeasuring over the same area. Measurements confirm that the scanning stages and the pentaprism slide give results that are repeatable to ± 2 nm. However, this gives very little indication whether systematic errors are present or not. Systematic errors can be present due to static thermal gradients and also can occur if the position sensitive detector in the autocollimator is not positioned in the correct focal plane. Correct positioning has been achieved by using a glass shear plate which is tilted in front of the telescope or collimating lens until the signal from the position sensitive detector is minimised. This critical alignment has been checked by generating known angles by using a small angle generator [BUSCH 1965]. The statistical uncertainties associated with the integration process employed to obtain profile heights [EL SAYED and HUME 1974] may be ignored since they are very small because of the inherent high resolution of the measurement system [VIRDEE 1988] in relation to the electronic position sensitive detector which measures the surface slopes.

In order to verify the existence of systematic errors, it is convenient to compare the profilometry results against those obtained by standard methods [DEW 1966a] based on interference of wavefronts. Measurements made on a fused-silica 100 mm diameter flat along two orthogonal diameters by Fizeau and Zygo interferometers together with those obtained by the 2-D profilometer are shown in Figures 6(a) & (b). The estimated uncertainty of Fizeau [DEW 1966a] and Zygo interferometers is ± 5.5 nm and ± 2 nm respectively. The accuracy of measurement of the laser profilometer is ± 2 nm and the results are shown by continuously drawn lines; Fizeau measurements are shown by dotted lines and the Zygo ones by dashed lines. Curves along diameter C-D are within ± 5 nm and the results along diameter A-B show large variations on the left hand side of the diagram. A point to note is that the laser profilometry and Zygo measurements are in good agreement. Although the general trend of the profiles is similar, the surface waviness between 1 and 20 mm differs slightly outside the error limits in one or two places. Nevertheless, the profilometry measurements made on another surface agree very well when compared with those obtained by a stylus profilometer [PALMER 1990], and the surface waviness present is confirmed to a nanometre or so.

6. INITIAL ASSESSMENT OF SYSTEMATIC UNCERTAINTIES

There are three main aspects concerning the laser profilometer system that can give or result in erroneous measurements apart from the alignment and other factors which have already been mentioned in the previous section. These relate to the constant deviation prism, the scanning slide and atmospheric effects.

6.1 THE CONSTANT DEVIATION PRISM

The constant deviation prism employed is a pentagonal prism which bends a beam of light through a right angle by means of two reflections. The important property of this prism is that the magnitude of the deviation angle is almost independent of small misalignments in terms of translations and rotations. Lateral translations in x, y and z coordinates should not alter the 90° angle provided the reflecting surfaces of the penta-prism are adequately polished flat. The roof surfaces of the penta-prism employed were polished to better than 1/20 of a fringe and an uncertainty of a similar value was

detected by using double pass interferometry. Consequently, for example, if a curvature or sag of 1/15 of a fringe is present, then a measurement uncertainty of less than a nanometre in profile height over a 300 mm scan length can occur due to translation of the laser beam spot caused by the parasitic pitch motion of the slide. The penta-prism is not affected by small angular rotations about the x-axis perpendicular to the scan direction: the nominal 90° angle is maintained for scanning and reflected beams even if the 300 mm slide exhibits a pitch uncertainty of 100 μrad. This design value was found to be slightly larger than the actual value when its performance was assessed by using the detection method of the laser profilometer.

A number of high quality prisms were specially produced and two of the prisms were tested using the laser profilometer system; the resulting measurements compared very well. However, if the scanning prism is constrained in any way in its traversing mount then a good prism can give anomalous measurements. To avoid this, a kinematic method of support is essential and associated uncertainties are less than the resolution of the detection method employed for the chosen penta-prism.

6.2 SCANNING SLIDE

Another source from which uncertainties in the profile height measurement can arise is due to the other parasitic motions such as roll and yaw of a scanning slide employed to traverse the constant deviation prism. These are always present in slideways and the question is to what degree. The roll and yaw motions will alter the nominal 90° angle and will produce an uncertainty which will be equal to the square of yaw error [WILLIAMS 1983]. In actual practice, the total uncertainty due to yaw motion will be 4 times the average value of these motions because the input and reflected beams will be similarly affected. Here the roll motion becomes the yaw motion for the return and input beams. The design values provided by the manufacturer (Ealing Electro-Optics plc) for roll and yaw motions are 100 μrad and 125 μrad respectively. This means that the scanning errors of the slide can introduce an uncertainty of 2.5 nm in profile height measurement over 300 mm scan length. This profile height uncertainty nearly corresponds to the resolution of the detection method of the laser profilometer. However, the scanning slide will not normally be used to assess surface profiles over 250 mm in a linear direction and over 200 x 200 mm in two dimensions. Therefore the slide and penta-prism related uncertainties will be reduced significantly by avoiding excessive errors which occur at the two extreme ends.

6.3 ATMOSPHERIC EFFECTS

The accuracy of an optical measurement instrument or system is often limited by the surrounding atmosphere. The effect of variations in temperature, pressure and air can result in large errors [EDLEN 1966]. Presence of turbulence in air produces a small random and spatial variation in the refractive index [STROBEHN 1978]. For a propagating laser beam, its diameter or spot in the far field will deviate randomly from its mean position if the movement due to air turbulence is larger than the beam diameter. These random uncertainties are considered to be small in a laboratory type environment, and have been effectively eliminated by using efficient insulating enclosures. However, only the systematic changes in the refractive index of air along any scanning direction due to thermal gradients need to be considered which can cause bending of a laser beam and are difficult to overcome.

6.4 CUMULATIVE UNCERTAINTY

The assessment of systematic uncertainty concerning the pentagonal prism (Y_1) due to slide motions can be made by using the sagittal formula

$$R = \frac{\ell^2}{2d}$$

where **R** is the radius of curvature, ℓ is the half chord length and **d** is the sagittal error. In order to relate the sagittal error into an angular one, the following expression can be applied provided **R** is very much greater than **d**.

$$\theta = \frac{4d}{\ell}.$$

Considering uncertainties associated with slide motions, namely roll and yaw, the previous expression becomes

$$d = \frac{\theta^2 \ell}{4}.$$

The nominal 90° angle is very slightly affected by the square of these errors (See section 6.2). Therefore, the uncertainties Y_2, Y_3, Y_4 **and** Y_5 for the input/return beams can be calculated.

The remaining major source of systematic uncertainty which bends the interrogating laser beam into a radius of curvature Y_6 can be determined [HARRISON *et al* 1972] by

$$Y_6 = \frac{\ell^2}{2} \frac{\partial n}{\partial y}$$

where ∂**n** is the change in the refractive index of air due to temperature variation [EDLEN 1966] across the air path in the vertical direction: and ∂**y** is the distance over which the index gradient occurs. The refractive index value at sea level changes approximately by 1 part in a million per degree Celsius or when the pressure increases by 400 pascals. The pressure is almost constant at a particular location; the variations in pressure are likely to give an uncertainty of about 0.5 nm over the maximum scan length of 300 mm. Quite a large variation of relative humidity has to occur (50%) to cause a similar difference in the value of refractive index of air.

However, the sensitivity of the laser profilometer is such that it can also detect very small bending or sag of test specimens again due to thermal gradients. This uncertainty (Y_*) is not related to the measurement system and can be assessed by using

$$Y_* = \frac{\ell^2}{2} \frac{\partial t}{\partial y} \alpha.$$

The previous expression takes into account the coefficient of expansion α of a test flat and ∂t is the change in temperature across the air path or the specimen. Nevertheless, this uncertainty cannot be ignored if measurements of the highest calibre are required.

There is no rigorous method of combining the above uncertainties, but one way is to combine them by arithmetic addition ΔY [CAMPION *et al* 1973]:

$$\Delta Y = (\Delta Y)_1 + (\Delta Y)_2 + (\Delta Y)_3 + (\Delta Y)_4 + (\Delta Y)_5 + (\Delta Y)_6 + (\Delta Y)_*.$$

The above method will tend to give an indication of the maximum possible limit or uncertainty. Another method is to take a statistical approach concerning the systematic uncertainties caused by the scanning slide. To combine uncertainties Y_1 to Y_6 in quadrature, the following expression can be used with a proviso to cater for the bending of a test surface Y_* due to thermal gradients.

$$(\Delta Y)^2 = (\Delta Y)_1^2 + (\Delta Y)_2^2 + (\Delta Y)_3^2 + (\Delta Y)_4^2 + (\Delta Y)_5^2 + (\Delta Y)_6^2 + (\Delta Y)_*^2.$$

This method at present is not particularly suitable in the case of laser profilometry because one of the uncertainties (Y_6) is significantly larger than the others [CAMPION *et al* 1973] due to high values of the parasitic thermal gradient and will tend to underestimate the total systematic uncertainty.

For example, over a scan length of 0.3 m, a gradient of 0.1 °C/0.3 m can cause a displacement of the scanning beam in the middle or sag of 3.8 nm. In the case of normal incidence profilometry, the scanning beam is folded back and therefore the uncertainty is doubled. In practice the thermal gradients have been reduced to a level of 0.05 °C/0.3 m with an appropriate air conditioning system. The following table gives the magnitude of this uncertainty, over the full scanning range (300 mm) of the system in a linear direction, for different values of thermal gradients that can occur in a laboratory type environment.

Temp. gradients in °C/0.3 m	*Uncertainty or sag in nm*
0.5	18.8
0.1	3.8
0.05	1.9
0.01	0.38
0.005	0.19

The criterion applied to assess the bending of a laser beam is particularly relevant to determine the bending of test flats due to thermal gradients provided the materials do not exhibit unknown and random internal strain. Here the cause of bending, as previously stated, is related to the coefficient of thermal expansion of the material used to produce test flats. For example, if fused-silica is chosen as a test surface and a temperature gradient of 0.1 °C/0.3 m exists, the profile height uncertainty in terms of sag (Y_*) over 0.3 m would approximately be 2 nm.

Ignoring the uncertainty relating to the test specimen (Y_s), the total arithmetic uncertainty ΔY over 300 mm scan length is ± 5.5 nm and over a shorter scan length (e.g. 10 mm) is reduced by a factor of 900: which is about ± 6 pm. If a statistical approach is considered, the uncertainty over 300 mm is ± 3.9 nm and over 10 mm it will again be insignificant when compared with the resolution of the measurement system. As seen from these estimates, the main source of uncertainty is due to the naturally occurring thermal gradients. If the thermal gradients can controlled to below 0.05 °C/0.3 m, then the statistical method of combining various uncertainties will give a better estimate. If changes in thermal gradients can be ascertained or recorded while scanning, the effect of this uncertainty can be calculated and appropriate correction can then be made to each line profile before calculating the complete surface shape. What this actually means is that Y_s uncertainty need not be considered as a systematic error when calculating the total arithmetic or statistical uncertainty.

At the nanometre level any claim about accuracy of a measurement system can be meaningless if the artefacts exhibit instabilities at nominal room temperature (i.e. 20 °C). The existence of strain can give an error which is very much more than the total systematic uncertainty of the laser profilometer for small temperature fluctuations around the stated nominal value. This suggests that most of the time the instrument performance cannot be used to its full potential. This also pertinently applies to measurement systems where two or more surfaces are compared to obtain relevant shape information.

7. APPLICATIONS

7.1 ASSESSMENT OF A GOLD COATED SURFACE

Examination of flatness of highly reflecting mirror surfaces with interferometry presents severe problems in that the intensity of both the reflected beams have to be equalised to obtain high contrast fringes for analysis. This is either achieved by inserting a colloidion sheet or wire gauge in between the two surfaces being compared or by depositing a metallic film on the reference surface to lower the reflectance [CLAPHAM and DEW 1967] in order to achieve accurate measurements. The application of a coating after calibration may deform the substrate, thereby reducing the accuracy of the calibrated surface. If the reference surface is considered for calibration after coating against the liquid surface, the formation of low contrast fringes becomes a problem. This criterion does not apply to laser profilometry, if one uses an optical fibre feed. Here one has only to attenuate or misalign the fibre end slightly at the input side to reduce the intensity at the reflecting surface to prevent the position sensitive detector from saturating. This process does not alter the alignment of the measurement system at the output end of the fibre.

For example, a gold film deposited on to a thick carbon fibre substrate which in turn was bonded to a glass blank was examined to detect surface wavelengths below 5 mm. It was thought that these types of wavelengths occurred due to the curing process when a resin type of glue is used for bonding. Detection of these is difficult when a stylus instrument is used because its probe digs into the surface due to softness of the gold film; and the interferometric methods were unable to give accurate height values of the amplitudes present. However, profilometer values for flatness are typically as seen in Figure 7 over 10 x 10 mm which were obtained with a step length of 0.5 mm. Surface wavelengths between 3 and 6 mm with amplitudes up to 35 nm can easily be distinguished. Use of the above results led to improvements being made to the production method and surfaces without this type of undulations were subsequently obtained.

7.2 MEASUREMENT OF FUSED-SILICA FLATS

A number of fused-silica flats produced by the NPL Optical Workshop, Engineering Services were measured for intercomparison purposes to assess systematic uncertainties of the new profilometer. One of the flats examined was 125 mm in diameter and had a thickness of 25 mm. It was scanned with a step length of 4 mm over an area of 80 x 80 mm. Measurements on this flat are as shown in Figure 8(a) could be repeated to within ± 2 nm over an interval of many months. However, when the flatness values were compared with those obtained by a standard interferometric method, a significant difference in the overall curvature was apparent together with a surface anomaly of 20 nm at one of the corners. This anomaly moved with the specimen when it was rotated through 90° increments and remeasured. The anomaly was not detected when this flat was measured by an interferometric method used for producing a reference plane or standard [DEW 1966a]. One possible reason for this may be due to the poor spatial resolution of the Fizeau instrument, which at best is 10 mm. However, the anomaly was detectable with a Zygo interferometer. The curvature and erroneous height differences can also occur if the master surface is calibrated against the liquid reference using tilt fringes at nominal 20 mm spacing, and then using this to test other surfaces at 10 mm spacing or vice-versa.

To check if the curvature difference is due to the various measurement instruments and different environments, it is necessary to measure larger surfaces to see if the trend of the curvature increases or reverses. Also to check or confirm whether the stability of large flats can be maintained during longer scan periods. Figure 8(b) again shows a contour map with 3 nm intervals over an area of 120 x 120 mm and still repeatable measurements to ± 2 nm could still be made. If one closely examines the contour map, a three lobe deformation pattern can be observed which relates to the method of support using three points on the periphery of the flat.

7.3 MEASUREMENT OF A ZERODUR FLAT

It was thought that a flat made of Zerodur would be ideal to assess the performance of the profilometer system. A 125 mm diameter and 25 mm thick specimen flat was produced by using standard lapping/polishing machines and methods. It was first measured 24 hours after it had had its final lapping. The measurements indicated that its overall flatness was well below 30 nm (convex) and it was remeasured under identical environmental conditions after 5 days. The shape of the flat became more convex by about 30 nm. After about a month the shape had stabilised over 80 x 80 mm to that shown in Figure 9. The initial movement or distortion may be attributed to releasing of thermal strain that may have been induced at the time of polishing or due to inherent instability of the material [JACOBS 1990]. The contour map also shows that a pimple or hill is present over the middle region over 30 mm which sometimes occurs due to imperfect lapping motions, i.e. at dead centre.

8. NEW SCANNING SCHEMES

In normal incidence interferometry or laser profilometry when carried out with coherent laser sources, erroneous measurements can result if transparent parallel-sided components need to be characterised, particularly if the second surface is polished as well. The beam reflected back from the second surface will find its way to the detector and superimpose on the signal beam. These two signals beams will then produce a random interference pattern as the main surface is scanned because perfect parallelism between the two surfaces cannot be assured. The energy reflected back from the second

surface can be reduced considerably by contacting an absorbing surface with an index matching oil. However, the matching of refractive indices is bound to be imperfect, and the residual reflected energy may still be sufficient to cause significant errors when highest accuracy is sought.

This problem can be eliminated completely by means of the two following schemes. The first scheme is to scan a surface at grazing incident angle as shown in Figure 10. Scanning of a surface is achieved by employing two pentagonal prisms. One of the prisms is used to scan the surface and the other is moved by the same amount in the opposite direction to receive the beam before it is directed to the detection system. In this system de-sensitising of the profile height values does not occur, when compared with interferometric methods, as the small angular deviations are measured from the initial grazing incidence condition. If a circular beam is considered for scanning purposes, then an elongated beam spot will result on the surface at this high angle. Therefore there will a deterioration in the spatial resolution. It can be enhanced slightly by employing a smaller elliptical beam which will form a circular spot on the surface. This is the only disadvantage with this method of scanning. Nonetheless, specular-and non-specular surfaces up to 400 x 400 mm can be scanned very quickly because fewer number of steps will be needed. This is because of the large beam spot and the translation stages stepping the prisms will travel short distances in this new mode of operation, and the beam spot will move by the step length divided by the sine of the grazing incident angle. Under these conditions the interrogating beam will be only that reflected from the main surface and hence the problem due to secondary reflections does not arise.

The second scheme as shown in Figure 11 will work only with reflecting surfaces, but with improved spatial resolution. It consists of two air spaced pentagonal prisms in a back to back configuration. The deviation angle is more than 90° and the direction of the output beam is in line with the input beam to the opposite side of the specimen. As indicated, the secondary reflection from the parallel sided specimen is physically separated from the outgoing signal beam. Therefore this can easily be suppressed with a black absorber before it reaches the detection system.

9. CONCLUSIONS

It has already been shown that the method of slope integration can be applied successfully to measure optical shape or flatness of specularly reflecting surfaces along a line to nanometre accuracy [VIRDEE 1986]. The recent pertinent development of the integration method has been to characterise surfaces in 3-D to high accuracy and also over significantly larger distances or areas. Measurements made over 120 x 120 mm area for flatness can be repeated to ± 2 nm provided thermal stability and airborne vibrations can be maintained to an acceptable level. The spatial resolution of this new instrument can be varied from 0.2 to 8 mm by choosing a suitable focal length lens for collimating a diverging laser beam from an optical fibre. Apart from achieving an improved measurement accuracy, the main advantage of laser profilometry over interferometry is that the need for a mechanical reference plane or surface can be eliminated by using or establishing a laser beam to define a datum direction.

The curvature difference as shown in Figures 6(a) & (b), when Fizeau results are compared against the Zygo and laser profilometry measurements, is nevertheless quite distinct and as stated previously is within the quoted uncertainty of the Fizeau interferometer that is used to determine a reference plane or flatness standard. In contrast, the curvature difference between the Zygo and laser profilometry results is

negligible. This seems to suggest that the curvature error associated with the Fizeau instrument is perhaps due to the use of tilt fringes which are introduced in order to determine profile heights on predefined grid lines. One possible reason for the disagreement between the two similar, Fizeau and Zygo, instruments is that the latter is used in a null mode, i.e. virtually without fringes.

Although the comparison of line scans verifies that the overall curvature uncertainty is within ± 5.5 nm, the interferometric measurements when compared over the full field of view in 3-D failed to detect surface features such as cylindricity and correct profile height values where large surface slopes exist due to edge roll off. For an example, an anomaly of 20 nm was not picked up. The cause of this anomaly has so far remained unresolved and it is thought that it is due to anomalous phase variations of the surfaces being compared or due to imperfect collimating optics of the Fizeau interferometer. It is unlikely that it is a systematic error related to the 2-D laser profilometer. This has been verified by rotating the particular specimen by 90° increments and when remeasured the anomaly moved with the specimen.

Differences of up to 10 nm were found between measurements made by two similar interferometric instruments. The cause of these differences is most likely to be multiple reflections that occur between surfaces being compared and possibly due to the distortions of the wavefront due to imperfect collimating optics. Uncertainties can also arise from reflections from secondary surfaces which would be difficult to overcome, and if this occurs then it may not be appropriate to rely completely on interferometric measurements to obtain nanometre accurate results.

The laser autocollimation method has the advantage of giving a digital output of the surface height, provided care is taken to ensure that the laser beam direction is maintained for each line scan during the measurement run period. Nevertheless, it is of paramount importance that a specimen remains stable for the duration of the 2-D scanning. In practice, stability of the specimen has been achieved not only while scanning, but also over many months and this has been verified by performing measurements at appropriate time intervals. Construction of appropriate thermal enclosures has been the main factor in achieving highly repeatable and accurate measurements.

The measurement range of the new laser profilometer in a linear direction is 300 mm. Therefore shape of optical surfaces in two dimensions over an area of 200 x 200 mm can be measured. The angular range is of the profilometer is 5 minutes of arc, which means that a surface with a sag of a few tens of micrometres over a scan length of 200 mm can be catered for with high precision, which in this case is about ± 2 nm. If one compares this with interferometric methods, surfaces which depart by more than 1/10 of a fringe from flatness cannot be measured accurately to ± 5.5 nm [DEW 1966a and WOLF 1976]. Furthermore, if a small diameter beam (say less than 0.1 mm) is considered for evaluating a surface and the slope values can be measured to 0.05 μrad accuracy, then the height variations below 5 pm could be detected. This could then form the basis of assessing the performance or calibration of atomic force microscopes [BARRETT and QUATE 1991].

To overcome the uncertainties due to second surface reflections, two schemes are proposed as shown in Figures 10 and 11. If these are developed, they can enhance the accuracy of measurement of non-specularly reflecting flat components and of transparent parallel-sided surfaces. The oblique incidence scheme can also be employed to assess the straightness of machine beds, rollers and float glass sheets over at least 2 m distances.

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The construction of the 2-D profilometer was aided considerably by the NPL Mechanical and Optical Workshops, Engineering Services. In particular, it was due to the efforts of Mr G Ashton who produced stable and adjustable mechanical structures for mounting test flats and scanning stages or slides.

Finally, the skills of glass workers, Messrs Benson and Hammond, need to be acknowledged for producing various precision optical components without which it would have been difficult to assess the performance of the measurement method.

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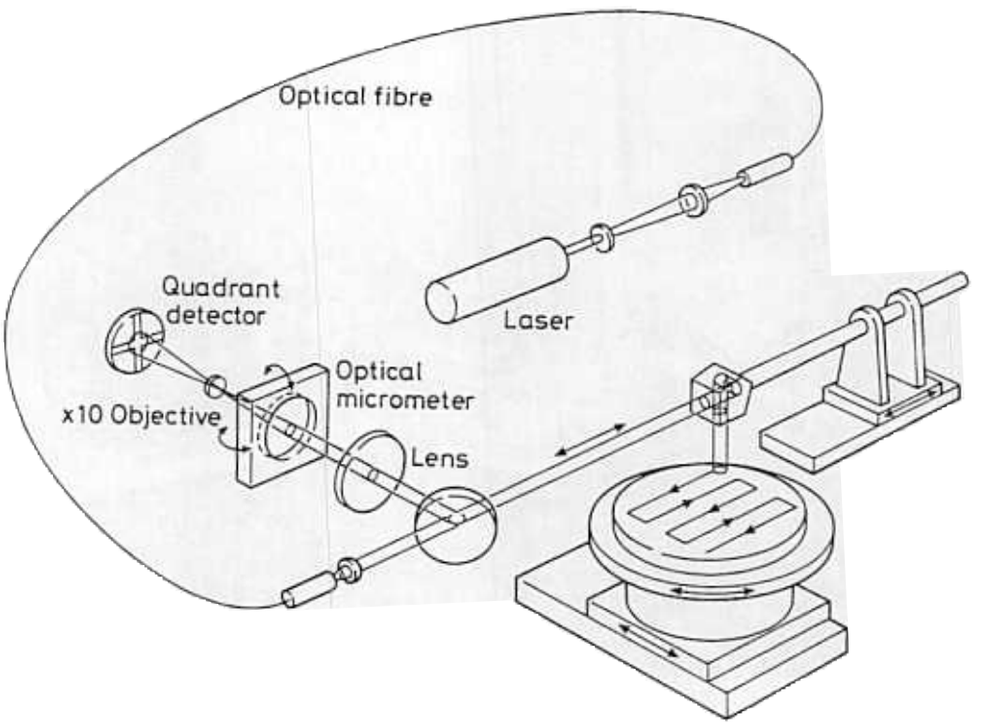

Figure 1. Two-dimensional profilometer for flatness measurement.

Figure 2(a). Shows enclosures to overcome acoustic noise and temperature instability. Ancillary control equipment is placed outside the main enclosure.

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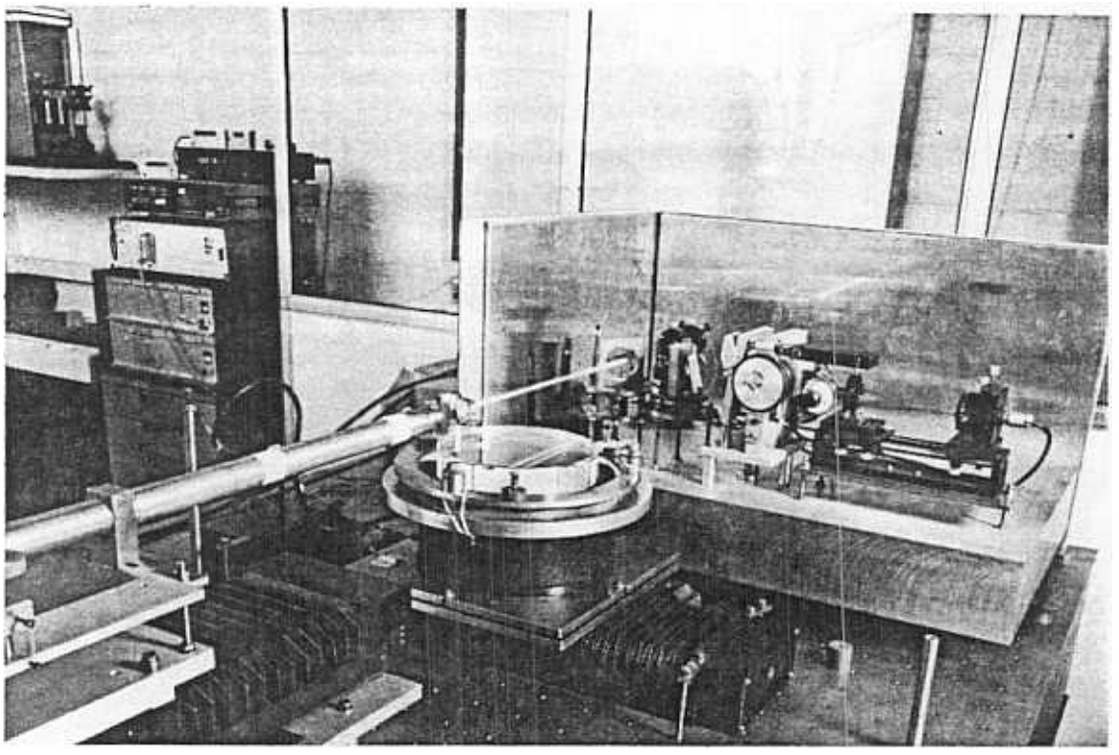


Figure 2(b). Two-dimensional profilometer with an optical flat, scanning stages and the autocollimator with servo-controlled two-dimensional optical micrometer.

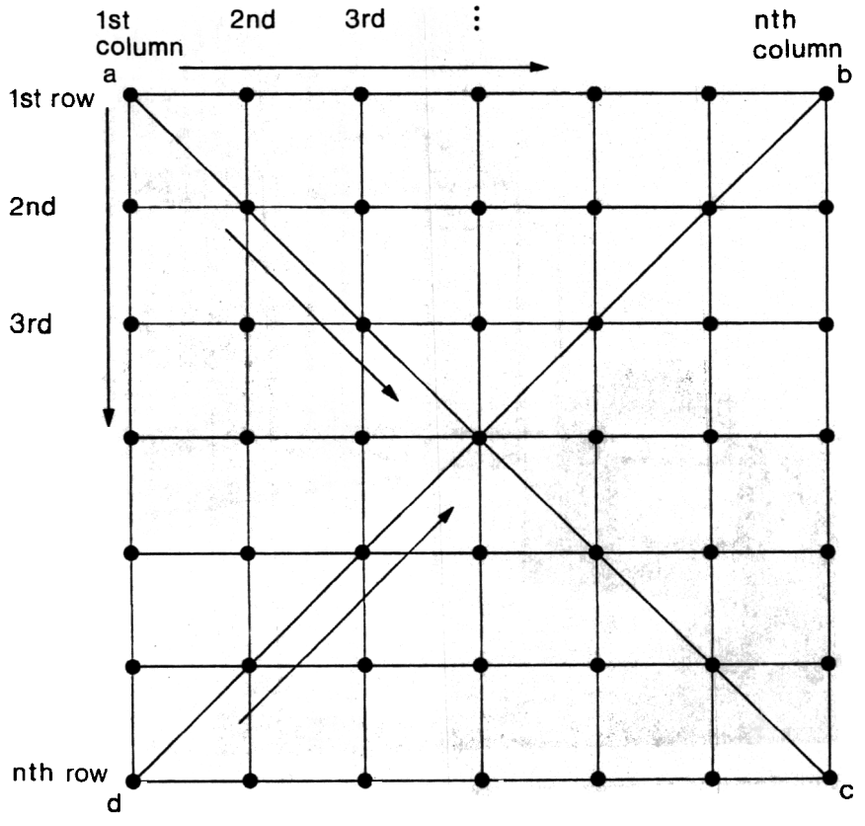
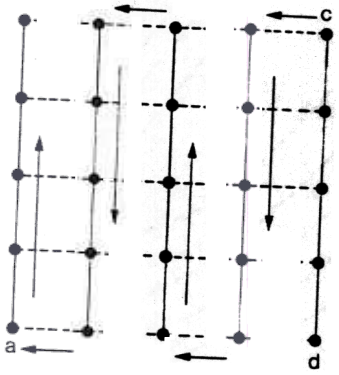
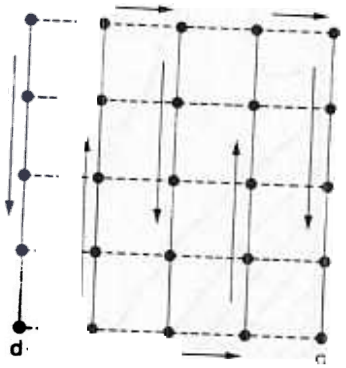


Figure 3. Variable scanning grid for a surface in two dimensions.



Raster scan n rows starting from position (d) rotate flat clockwise by 90°



Step Raster scan columns starting from position (a); rotate flat anti clockwise by 45°

Scan first diagonal from (c) rotate flat clockwise by 90°

Step Scan second diagor

Figure Sequence of scanning using linear and rotary stages.

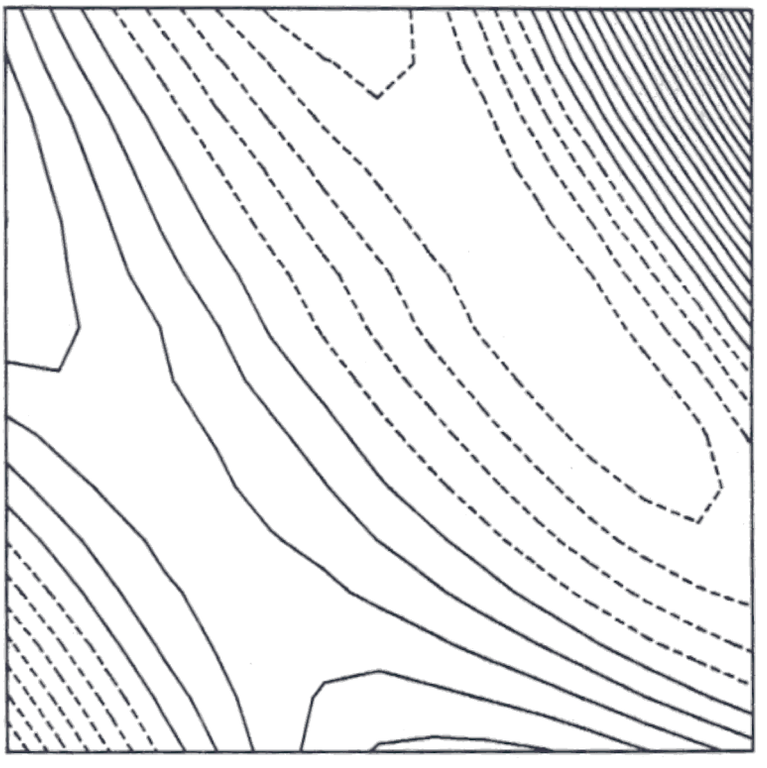


Figure 5(a). Flatness measurement for a float glass test flat over an area of 14 x 14 mm; scan or step length is 1 mm; contour interval is 5 nm; - - - - -, indicate negative values.

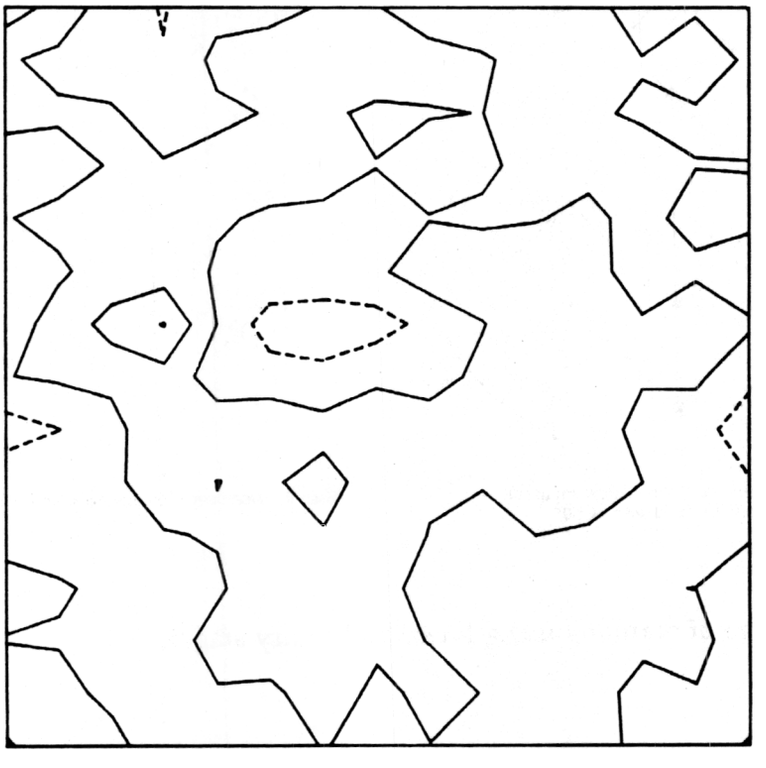


Figure 5(b). Residuals for the float glass test flat. Each contour is 1 nm.

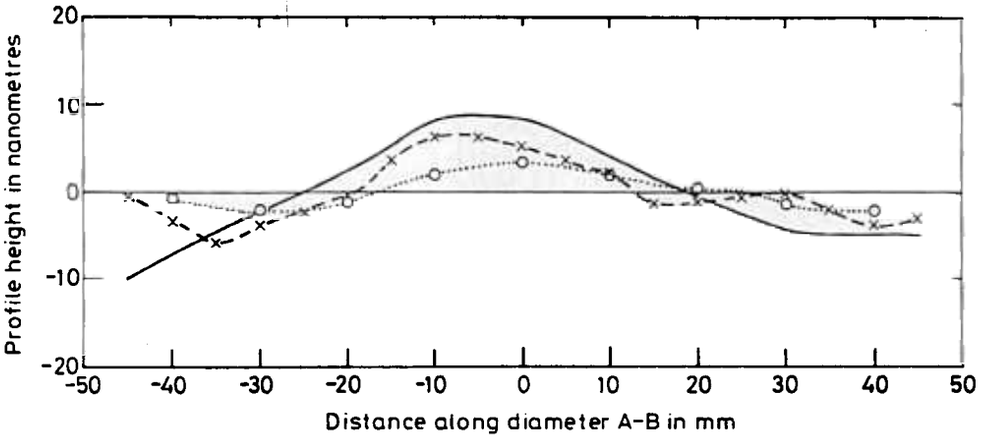


Figure 6(a). Intercomparison of flatness measurements along diameter A-B; ·····, Fizeau interferometer; - - - - -, Zygo interferometer; ——, laser profilometry.

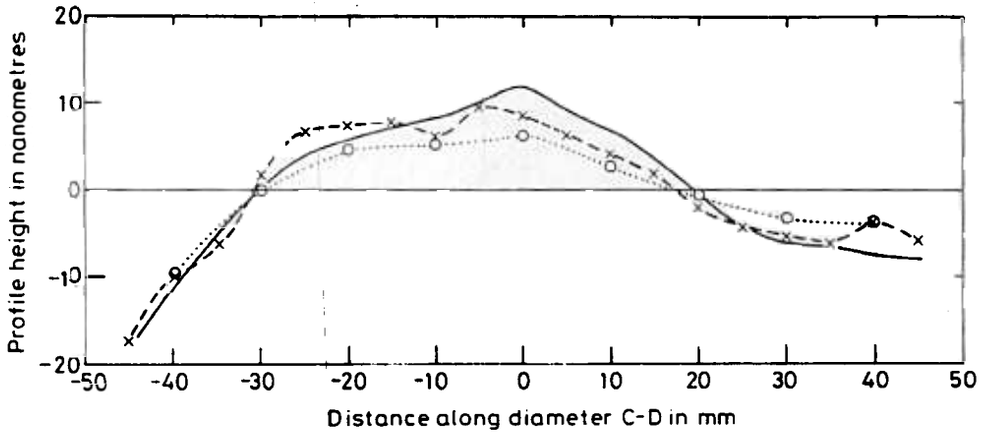


Figure 6(b). Intercomparison of flatness measurements along diameter C-D; ·····, Fizeau interferometer; - - - - -, Zygo interferometer; ——, laser profilometry.

Figure 7. Departure from flatness for a gold coated :e over 10 x 10 mm; step length is 0.5 mm; contour interval is 3 nm; - - - - -, contours indicate valleys.

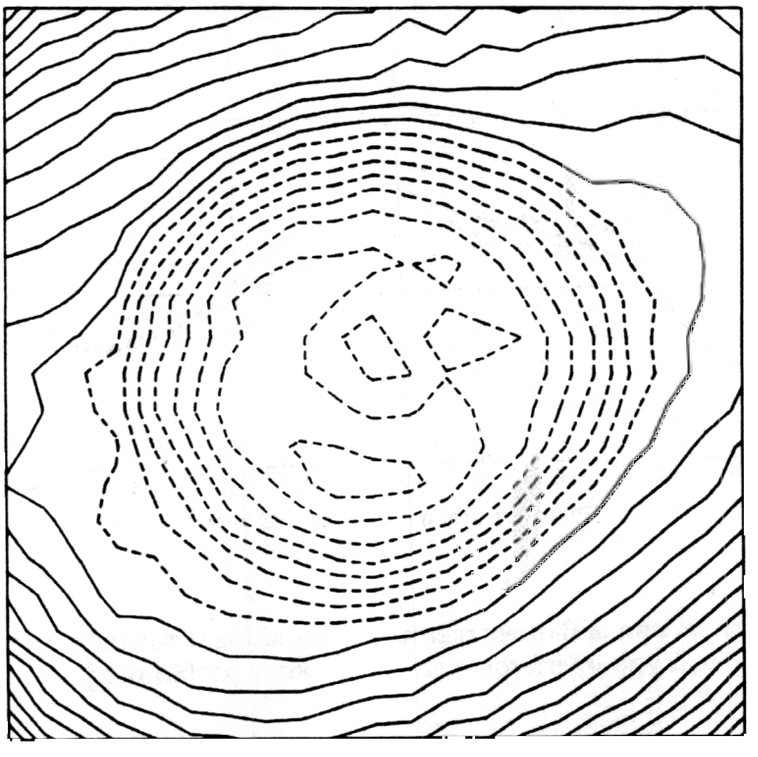


Figure [illegible] flatness measuremen fused-silica flat over 80 x 80 mm; step length is 4 mm; contour in[illegible] ndicate negative

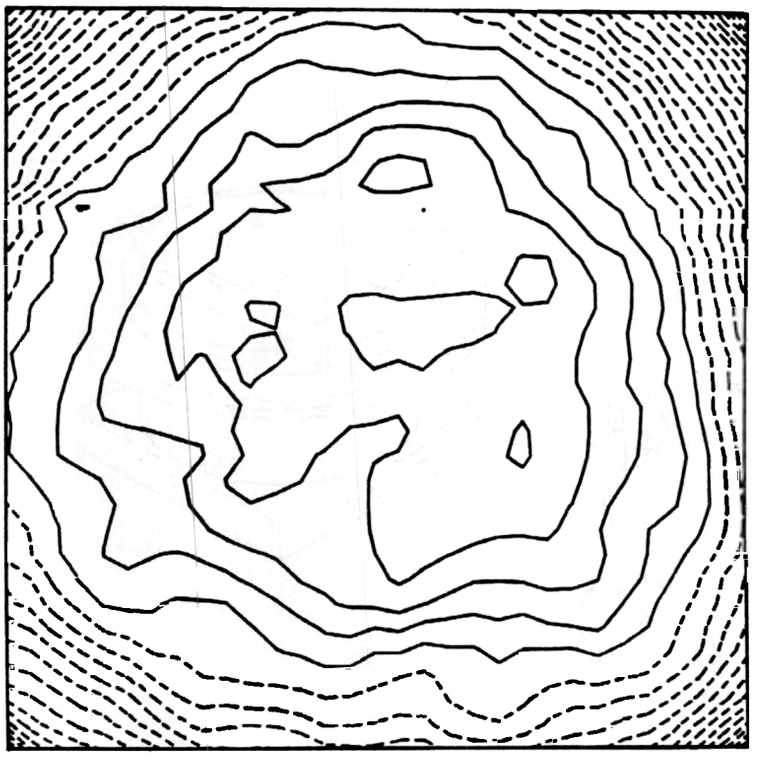


Figure 8.(b) Assessment of flatness over an extended area of 120 x 120 mm; step length is 4 mm; contour interval is 3 nm; - - - - -, indicate negative values.

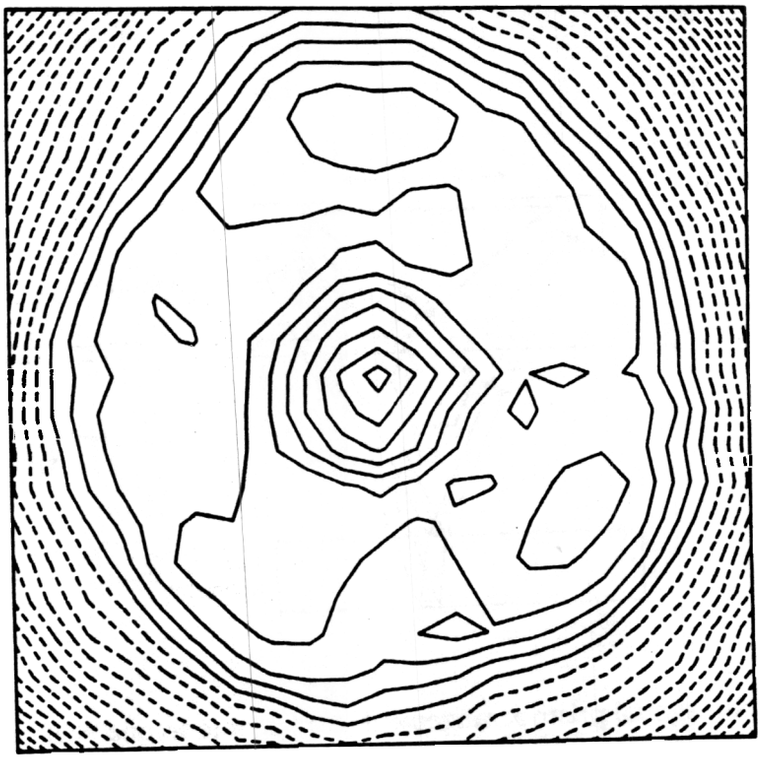


Figure 9. Flatness measurement for a Zerodur flat over 80 x 80 mm; step length is 4 mm; contour interval is 2 nm; - - - - -, indicate negative values.

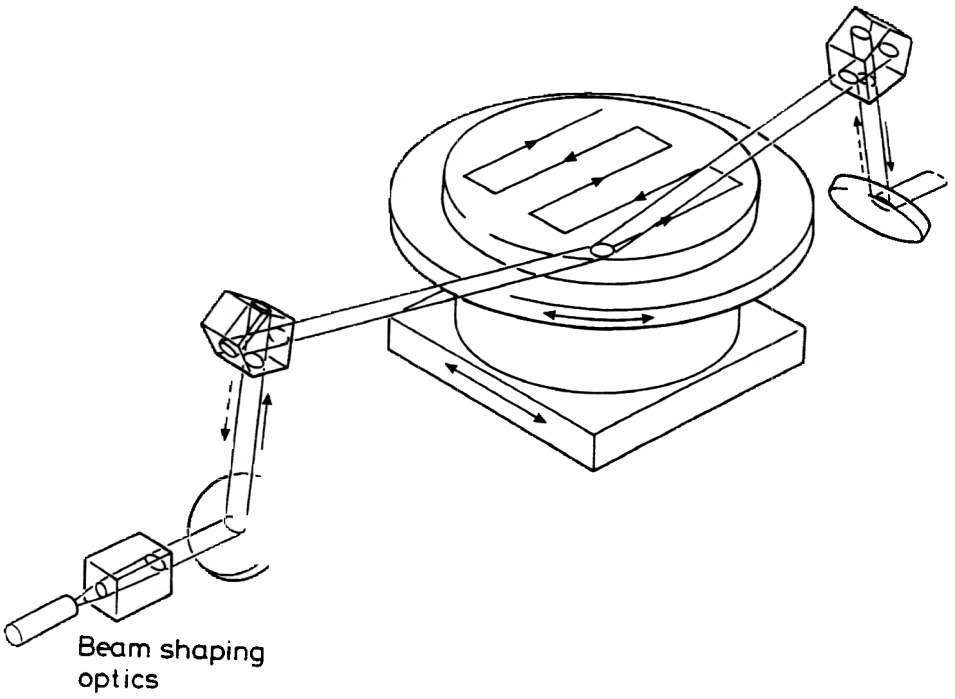


Figure 10. An oblique incidence profilometer to characterise large specular and non-specular surfaces.

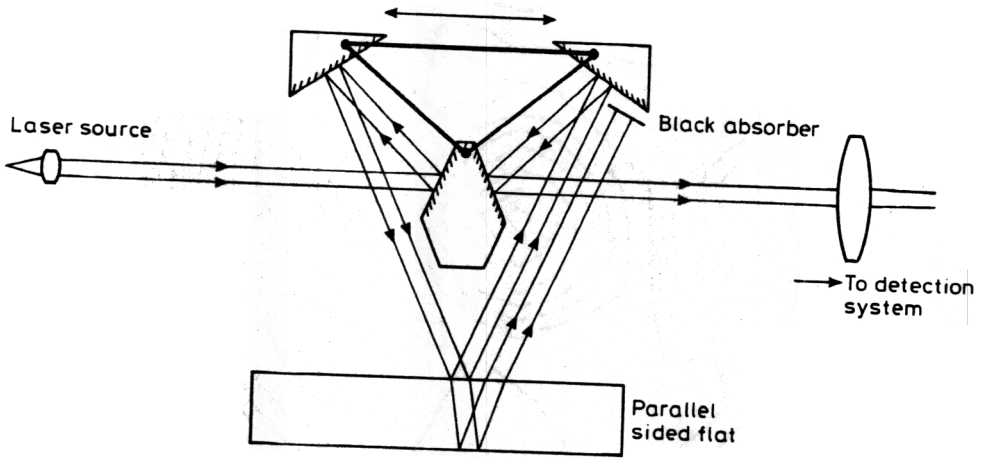


Figure 11. A new pentagonal prism arrangement to overcome second surface reflections for parallel-sided transparent surfaces.