Absolute Optical Testing: Computers, Interferometers Combine For More Accurate Optical Tests

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By combining a personal computer with an optical testing interferometer, it is possible to perform optical tests with better accuracy than the accuracy of the reference optics used in the interferometer. There are different techniques for performing absolute tests of flat surfaces, spherical surfaces and surface roughness.

The measurement of any quantity involves the comparison of the quantity with some reference. In interferometry, this reference is generally a flat or spherical mirror, but it might be a shifted version of the surface under test, as in lateral shearing interferometry, or a nonoptical surface, such as the air-bearing table used in the Sommargren profiler.[1] In any case, the surface is always measured relative to a reference.

Over the years, techniques have been developed for measuring surfaces in an absolute sense in that the effects of the reference surface are removed in the final results. The major problem with these techniques has been the amount of computation required to obtain the final results. Now that state-of-the-art interferometers are interfaced with personal computers, this major drawback has been eliminated, and the making of absolute measurements is common practice.

Spherical surfaces

Computer techniques make it possible to subtract interferometer errors from errors in a spherical mirror being tested if three measurements are performed.[2] Figure 1 shows the three measurements required. First, the mirror is tested at the center of curvature using common techniques. Next, the mirror is rotated 180°, and the measurement is repeated. Then either a flat mirror or the mirror under test is placed at the focus of the diverger lens. If W_{ref} is the error due to the reference arm of the interferometer, W_{div} is the error due to the diverger lens, and W_{surf} is the error due to the spherical mirror under test, the three measurements give:

$$W_{0°} = W_{surf} + W_{ref} + W_{div}$$

$$W_{180°} = \overline{W}_{surf} + W_{ref} + W_{div}$$

$$W_{focus} = W_{ref} + 1/2\,[W_{div} + \overline{W}_{div}]$$

The bar over the symbol means the quantity has been rotated 180°. The error due to only the mirror surface is obtained by combining these three measurements.

$$W_{surf} = 1/2\,[W_{0°} + \overline{W}_{180°} - W_{focus} - \overline{W}_{focus}]$$

Figure 2 shows typical results for removing interferometer errors from a spherical-mirror measurement.

Flat surfaces

Absolute measurements of flat surfaces are also available, although the most popular technique gives only profiles through the surface.[3] To obtain x and y profiles from an absolute

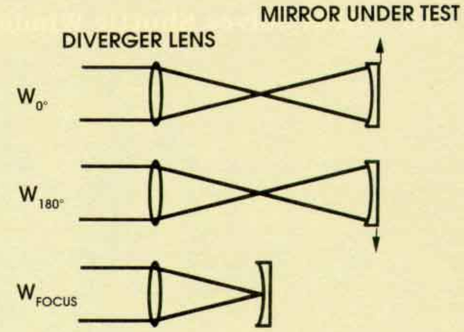

Figure 1. *Three measurements required for absolute testing of a spherical mirror.*

measurement of a flat surface, four measurements and three flats are required. Figure 3 shows the four measurements required of flats A, B and C.

If G(x,y) is a measurement, and f(x,y) is the surface error of a flat, the four measurements give:

$$G_{AB}(x,y) = f_A(x,y) + f_B(-x,y)$$

$$G_{AC}(x,y) = f_A(x,y) + f_C(-x,y)$$

$$G_{BC}(x,y) = f_B(x,y) + f_C(-x,y)$$

$$G_{BC'}(x,y) = f_B(-x,-y) + f_C(-x,y)$$

From these four equations it is possible to solve for both the x and y profiles of the three flats. For example, the x profile of the three flats is given by:

$$f_A(x,0) = \frac{G_{AB}(x,0) + G_{AC}(x,0) - G_{BC'}(x,0)}{2}$$

$$f_B(x,0) = \frac{G_{AB}(x,0) - G_{AC}(x,0) + G_{BC'}(x,0)}{2}$$

$$f_C(x,0) = \frac{-G_{AB}(x,0) + G_{AC}(x,0) + G_{BC'}(x,0)}{2}$$

Once the x profile is known for the reference flat, the reference flat can be used to find additional profiles for a test flat.

If the shape of the entire surface is desired, multiple profiles can be obtained by repeating the above process. If it is known that the surface errors can be described with Zernike polynomials, eight measurements using three flats with relative rotations of 45, 90, and 180° can be used to give the entire surface shape. The measured shape will be described in terms of Zernike polynomials.[4]

Surface roughness

Powerful computer techniques make it possible to measure interferometrically surfaces smoother than the reference surface in the interferometer. As described below, errors in the reference surface can be removed, enabling a person to measure subangstrom surface microstructure routinely, even with a much rougher reference surface.[5]

Each measurement made with an interferometric optical profiler yields the relative point-by-point distance between the reference and test surfaces. Assuming the test and reference surfaces are uncorrelated and independent of one another, the rms roughness σ_{meas} of the interferometric measurement is a combination of the two rms roughness values:

$$\sigma_{meas} = \sqrt{\sigma_{test}^2 + \sigma_{ref}^2}$$

where σ_{test} is the rms roughness of the surface under test and σ_{ref} is the rms roughness of the interferometer reference surface.

To subtract the effects of the reference surface in the interferometer, three different techniques can be implemented. A straightforward means of producing a reference-surface profile is to measure a super-smooth mirror with an rms roughness of less than 1 A. This information can be stored in the computer and subtracted from each measurement.

Another technique is to create a profile of the reference surface by averaging a number of measurements, N, of a smooth mirror. The mirror surface used to do the averaging does not need to be supersmooth, but the smoother it is, the fewer the measurements needed to be averaged. Between measurements, the mirror is moved by a distance greater than the correlation length of the surface.

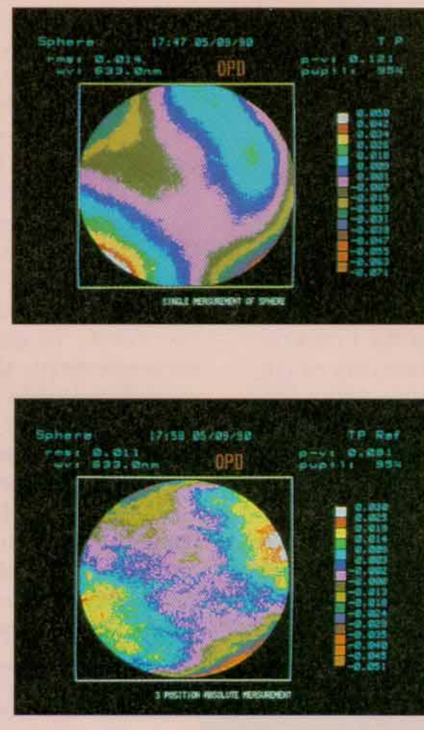

Figure 2. Measurement of spherical mirror. Interferometer aberrations: rms surface roughness is 0.014 λ, peak-to-valley difference is 0.121 λ, (a). After interferometer errors are removed, rms surface roughness is 0.011 λ, peak-to-valley difference is 0.081 λ, (b).

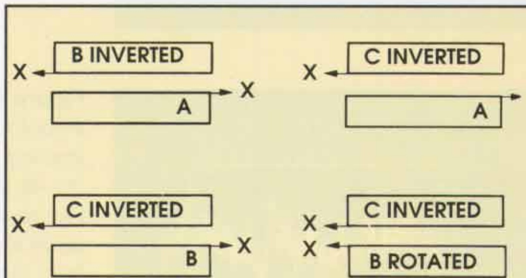

Figure 3. Four measurements required for three-flat test.

The roughness of the mirror being measured tends to cancel out, and the result obtained after averaging approximates the reference surface. The resulting rms roughness-measurement error is given by:

$$\sigma_{error} = \frac{\sigma_{mirror}}{\sqrt{n}}$$

where σ_{mirror} refers to the rms roughness of the mirror surface used to produce the generated reference profile. Thus, the error in the measurement of the test-surface rms roughness is reduced by using a smoother mirror to generate the reference and by increasing the number of measurements averaged to generate the reference. Once the reference-surface profile is generated, it can then be subtracted from subsequent measurements of test surfaces to measure the surface profile minus the reference surface. Using this procedure, supersmooth surfaces with rms roughness values of less than an angstrom can be measured.

A simple technique for obtaining the rms roughness of a supersmooth surface, but not the profile, is to use the so-called absolute rms roughness-measurement technique. For the absolute rms roughness measurement, two uncorrelated measurements of the test surface are made. To get an uncorrelated measurement, the test surface is moved between measurements a distance greater than the correlation length of the surface. Since the reference-surface effect on the measured profile should not change from the first to the second measurement, the effects of the reference-surface profile cancel out when the difference of these two measurements is taken. If we assume the two measurements, test 1 and test 2, are uncorrelated, the rms roughness of the difference profile can be written:

$$\sigma_{diff}^2 = \sigma_{test1}^2 + \sigma_{test2}^2$$

Because independent measurements of the test-surface profile should have similar statistics,

$$\sigma_{test1} = \sigma_{test2}$$

The rms roughness of the test surface is given by:

$$\sigma_{test} = \frac{\sigma_{diff}}{\sqrt{2}}$$

Thus, the rms roughness of the test surface can be easily determined by making two measurements of the surface. When these measurements are made, the effects of the reference surface cancel, and the surface statistics are derived. However, the calculated surface profile does not represent the actual test surface.

Figure 4 shows measurement results for a supersmooth mirror which was found to have an rms surface error of 0.071 nm. Measurements performed using the absolute rms technique gave a similar result of 0.070 nm.

The use of a computer with an optical testing interferometer creates a much more powerful system than the interferometer by itself. Being able to perform optical tests more accurately than the reference, can go a long way in improving the quality of the optical systems produced. □

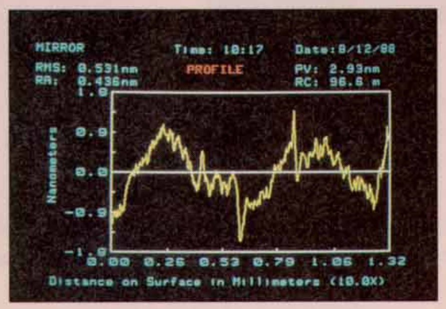

***Figure 4a.** Profile of the supersmooth mirror with the effects of errors in the reference surface remaining.*

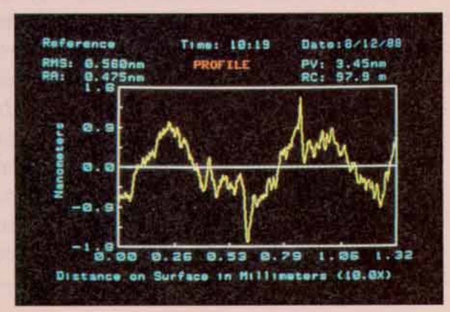

***Figure 4b.** Profile of the reference surface obtained by averaging 16 uncorrelated measurements of the supersmooth mirror.*

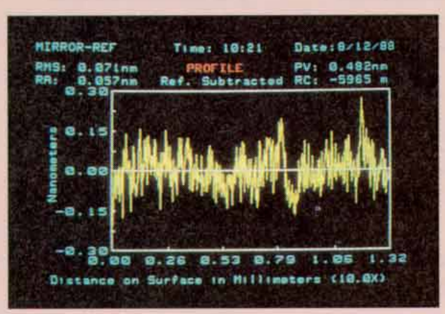

***Figure 4c.** Profile of the supersmooth surface obtained by subtracting the profile shown in Figure 4b from the profile shown in Figure 4a. Note that the vertical scale for Figure 4c is different from that of Figures 4a and 4b.*

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