NBSIR 73-219

Eight Techniques for the Optical Measurement of Surface Roughness

Russell D. Young

Institute for Basic Standards
National Bureau of Standards
Washington, D.C. 20234

May 25, 1973

Interim Report

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

NBSIR 73-219

EIGHT TECHNIQUES FOR THE OPTICAL MEASUREMENT OF SURFACE ROUGHNESS

PRELIMINARY

Russell D. Young

Institute for Basic Standards
National Bureau of Standards
Washington, D.C. 20234

May 25, 1973

Interim Report

U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

Eight Techniques for the Optical Measurement of Surface Roughness

by

Russell D. Young

Abstract

The need for a fast, on line, non-destructive technique for measuring surface roughness has recently accelerated the decade long development of optical methods. It is anticipated that these new techniques will add a new dimension to the surface roughness measurement system which may require an appropriate NBS response. In order to formulate this response, the eight optical techniques which have been identified are briefly described and are summarized and compared in Table 1.

It is concluded that model deficiencies, questionable theoretical bases, as well as physical and analytical limitations cast serious doubt on the present accuracy of these techniques for absolute measurements. Optical techniques seem more suitable for comparison measurements, i.e. measurement after appropriate calibration using surfaces which have been measured using other techniques. Thus, it is concluded that the most appropriate NBS response to the increased use of optical techniques is to concentrate our limited resources on developing much improved instruments such as the Topografiner and traditional stylus instruments so that highly refined optical

	Light Scattering (Specular)	Laser Speckle	White Light Speckle	Holographic Interferometry	Interferometric fringe contrast	Multiple Beam (Tolansky)	FECO Interference Scan	Nomarski Polarized Beam Interfere[illegible]
1. Approximate Roughness Range (μ")	2 - 50	1 - 10	16 - 250	4 - 20	0.04 - 5	0.1 - 20	0.04 - 10	very sens[illegible] qualita[illegible]
2. Cost (Complexity)	moderate to high	medium	low	medium	high	low	extremely high	low
3. Light Source	laser or spectrometer	laser	white	laser	laser	white filtered	white	white
4. Accuracy	good 5%	?	depend on calibration	moderate	good 3%	fair	high	----
5. Measurement Time	Short	long (densitometer)	10 min	long (densitometer)	long (densitometer)	10 min	long	----
6. Operator Skill	moderate	high	low	high	high	moderate	high	moderate
7. Data Record	meter	film	meter	film	film	film	meter or film	film
8. Horizontal Resolution	fair	?	?	?	?	poor	fair	good
9. Specimen Coating Required	no	no	no	no	no	yes	yes	no
10. NBS Capability	no	no	no	no	no	yes	no	yes

TABLE I. COMPARISON OF OPTICAL TECHNIQUES FOR MEASURING SURFACE ROUGHNESS

surfaces can be measured and their surface parameters determined accurately.

Introduction

The need for a fast on line, non-destructive technique for measuring surface roughness has recently accelerated the decade long development of optical methods. It is of particular concern to NBS that certain high technology industries are rapidly developing proprietary and perhaps patentable optical instruments for measuring roughness. Our concern is that we may soon be called upon to mediate calibration disagreements arising from model dependent measurements which result from pairs or groups of instruments which have different theoretical bases. Of still greater concern is the immediate need for accurate measurements of the extremely smooth surfaces which are typically investigated by optical techniques. The following brief evaluation is an attempt to predict the impact of these optical techniques on the surface roughness measurement system.

The eight distinct optical techniques which have been evaluated to date are briefly described in the following pages, together with a table comparing their performance, cost, operation skill, and other parameters. The techniques are then evaluated, the potential impacts on NBS identified and a response proposed.

I. Specular and Diffuse Light Scattering.

During the last decade a number of investigators, particularly Bennett et al,[1-5] have studied the relationship between light reflection and surface roughness in order to measure the surface finish of optical components. Experimentally, the specular and/or diffuse reflectance of the specimen surface is measured as a function of another parameter, for example angle of incidence, angle of reflection, acceptance angle of detector, wavelength, reflectance per unit solid angle, etc. Assuming that the surface roughness height and roughness periodicity along the surface are Gaussian, one or more of the above measurements can be related to the rms surface roughness height and the autocovariance length of the surface roughness.

Theory: Scalar and Vector Theories of Specular and Scattered Reflectance.

In the scalar theory,[6-8] the incident radiation is assumed to be modulated in phase by the height variations along the surface so that, at a certain point above the surface, the resultant intensity is derived from a complex diffraction pattern. It is further assumed that (1) the roughness height is Gaussian with an rms roughness of δ, (2) the autocovariance function is Gaussian with a standard deviation a, (3) the surface is perfectly conducting and would have a specular reflectance of unity if perfectly smooth. With these assumptions, the relative reflectance of the surface

when light is normally incident is[2]

$$\frac{R}{R_o} = e^{-\left(\frac{4\pi\delta}{\lambda}\right)^2} + \left[1-e^{-\left(\frac{4\pi\delta}{\lambda}\right)^2}\right]\left[1-e^{-\left(\frac{\pi\alpha a}{\lambda}\right)^2}\right] \qquad (1)$$

where R is the reflectance into a cone of half angle α about the specular direction, R_o is the total reflectance of the sample, and λ is the wavelength of the incident light. The first term is the well-known specular reflectance of the surface. The second term gives the fraction of scattered light which falls within a half angle α of the specular direction. It is assumed in the derivation that $\delta << \lambda$.

The scalar scattering theory is energy conserving in the sense that all incident light lost from the specular beam should appear in the scattered beam. The reflectance of the material can be taken into account in equation 1 by calculating the reflectance relative to the reflectance of an ideally smooth surface of the same material. However, this does not account for losses or extra emission due to surface currents (called plasmons). It was also assumed in deriving equation 1 that the autocovariance length a is of the order of or greater than λ.

In the vector theory,[7,9-18] the polarization and the wave vector components are used both to match boundary conditions at the surface and to determine the intensity of the radiation after reflection. For example, a plane wave incident upon a flat surface

sets up currents having the same component of wave vector in the surface as the incident wave in order to match the boundary conditions on the electric and magnetic fields. Thus, radiation is only found in the specular direction. Rough surfaces cause currents with normal as well as tangential wave vectors which are modulated by the roughness height.

In the case where plasmon excitation does not make an important contribution, the reflectance distribution per solid angle for normal incidence is given by[2, 10]

$$\frac{8\pi^3 \delta^2 a^2 \cos^2\alpha}{\lambda^4}(1-\sqrt{\epsilon})\left\{\left|\frac{\sqrt{\epsilon-\sin^2\alpha}}{\sqrt{\epsilon-\sin^2\alpha}+\cos\alpha}\right|^2+\left|\frac{1}{\sqrt{\epsilon-\sin^2\alpha}+\cos\alpha}\right|^2\right\}e^{-\frac{\pi a^2\sin^2\alpha}{\lambda^2}} \tag{2}$$

where α is the angle between the specular direction and the scattering direction and ϵ is the dielectric constant of the reflecting surface. The first term in curly brackets represents p polarized light (light polarized in the plane of incidence), the second is a polarized scattered light (light polarized perpendicular to the plane of incidence).

Near the specular direction where α is small, the reflectance distribution is simply:[2]

$$\frac{16\pi^3 \delta^2 a^2}{\lambda^4}\; e^{-\left(\frac{\pi\alpha a}{\lambda}\right)^2}, \tag{3}$$

which does not result in strong forward scattering near the specular direction. In addition to a thorough textbook treatment of the

of the subject, there are several recent theoretical treatments of scattering.[9-18]

In general, the scalar theory of scattering is used when theory is compared with experiment because the complicated vector theory makes the determination of the roughness very difficult. Typically, a measurement is made of the specular reflectance and the rms roughness is determined by using the first term of equation 1. Then the reflectance is measured for the case where α is appreciable and both terms of equation 1 are used to obtain the autocovariance length.

<u>Experiment</u>.

In order to test equation 1 Bennett and Porteus first measured the wavelength dependence of the relative reflectance of a finely ground glass surface (see fig. 1).

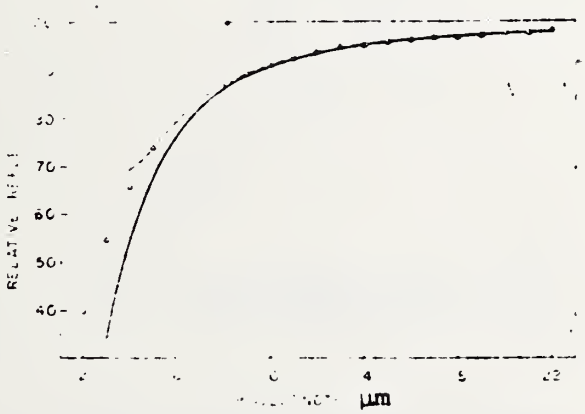

Fig. 1. Relative reflectance of a finely ground glass surface. Circles indicate experimental points - the solid curve is from eq. 1 and the dotted curve includes a correction for near specular scattering.

At the lower end of the curve in figure 1, the requirement that $\delta << \lambda$ is violated. It is noted that at wavelengths greater than 8 micrometers the agreement is very good without correction for scattering near the specular angle. Experimental results indicated that accurate measurements would be expected below $\delta = 100 - 200$ Å for $\lambda = 1$ micrometer.

Birkebak[19] compared the results obtained by a number of investigators[20-25] using long wavelength specular reflection measurements interpreted according to the first term in equation 1 as shown in figure 2.

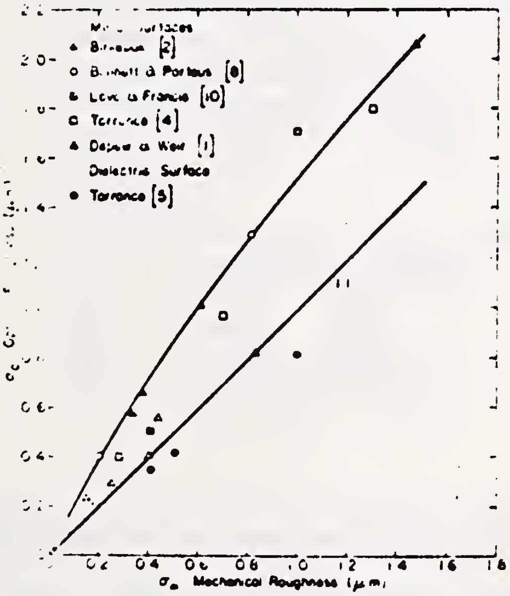

Fig. 2. Optical vs Mechanical Roughness. Birkebak,[19] Torrance[25] and Bennett[1] used a stylus of 12.5μm radius. Depew and Weir[24] used a 2.54μm stylus and Torrance[23,25] used a 1.25 μm stylus. The figure suggests that smaller styli result in much improved agreement between stylus and light scattering measurements.

In another approach, the acceptance angle of the optical system is varied and the relationship between relative intensity and acceptance angle is used to determine both δ and mean slope of the surface roughness m.[26] (Note: It can be shown[1] that m, δ and a are related by the expression $a = \sqrt{2}\ \delta/m$). Table 2 shows the rms roughness and slopes of polished fused silica samples measured interferometrically (in brackets) and with the acceptance angle technique.[26] A number of other scattering measurements have been reported.[27-29,49]

Table 2 RMS roughness and slope of polished fused silica

(Interferometric values in brackets)

Final polishing time (min)	σ (nm)	$m \times 10^3$ rad
15	0·97 (0·76)	1·25 (0·32)
45	0·73	1·12
75	0·68	0·78
120	0·56	0·59
330	0·23 (0·24)	0·38 (0·21)

Despite the success of the scattering technique, there are several studies which suggest that a healthy skepticism should be exercised. Bennett et. al. found that in the case of a silver surface, there was no difference between the infrared reflectance of rough and smooth samples up to 45 Å rms, in disagreement with the theory.[30] This observation is attributed to the anomalous skin effect. It is also

important to avoid wavelengths where plasma resonances are likely to occur, as these may cause greatly enhanced scattering in the presence of surface roughness.[10,31,32] Furthermore, it must be noted that scattering experiments are typically carried out with surfaces produced through random abrasion of many particles, and that machined surfaces with deterministic roughness are avoided.

The most telling criticism of the light scattering technique is due to R. P. Edwin of NPL.[33] He performed a careful measurement of angular dependence of scattering from highly polished surfaces using the apparatus shown in figure 3.

Fig. 3. Special apparatus for measuring the angular dependence of light scattering.

The results of the measurement are shown in figure 4.

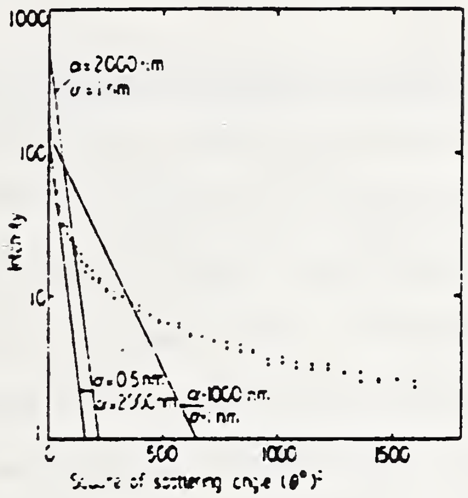

Fig. 4. The variation with angle of the scattered light intensity for Lapmaster polished Spectrosil B (dots). The straight lines were obtained form theory assuming values for α and σ indicated.

The author attributes the rather gross discrepancy to either the rather small ratio of roughness to wavelength ($\delta/\lambda = 0.002$) or more probably to the fact that the surface structure is not well described by Gaussian statistics. The presence of pits in the surface, even though small in number, may well dominate over roughness scattering. It is important to note that freshly cleaved mica which should not be pitted, gave a similar curve. The author then points out that fringe contrast and speckle contrast techniques have been proposed but no experimental results have been obtained. The Topografiner[1]

1. Instrument developed at NBS for high resolution topographic mapping. See article in RSI Vol. 43, No. 7, July '72 by Young, Ward, and Scire.

is particularly mentioned as having superior resolution.

Sprague also reported that his specular reflectance measurements only applied to certain types of finishes and that correlation for a more general category of surfaces was not sufficient to ensure accurate measurement.[38]

II. Laser Speckle Method of Measuring Surface Roughness.

It has been proposed that laser speckle may be used to measure the roughness of surfaces[35-36] although this has not been experimentally verified. Speckle patterns result when spatially coherent light waves are reflected from a rough surface. The average size of the speckles is determined by the aperture function of the illuminating source, while the fine structural details of the speckle is due to the roughness of the reflecting surface. By determining the autocorrelation and spectral density information from film records of the speckle pattern, it should be possible to extract surface roughness information. Goldfischer[37] carried out the first detailed solution of speckle patterns and Crane[35] then calculated the characteristics of speckle resulting from random (Gaussian) surface roughness.

The complex formulas resulting from the theoretical solutions of this problem limit the potential usefulness of the technique. While it might well be used as a quality control technique by comparing the speckle from similar surfaces, it is doubtful that values for roughness height and autocovariance length can be extracted from

speckle photographs without considerable difficulty. The usefulness of the technique will be determined by future developments.

III. Surface Roughness Measurement with White Light Speckle (see Sprague, ref. 38).

We noted above that when a rough surface is illuminated with coherent light using an optical system with a finite aperture, speckle is produced. Light at each image point originates from a small area on the object because of resolution limitations. If the height on the object surface varies appreciably across the width of the point spread function, speckle will result from interference effects. The size of the speckle depends on the system aperture; the contrast of the speckle depends on the surface roughness. Two conditions are necessary for high contrast speckle: (1) the interfering waves must have phase difference of at least $\lambda/2$ to give complete destructive interference at points in the pattern, (2) the interfering waves must be temporally coherent. For the first reason, the speckle contrast is low for smooth surfaces. The second condition presents an opportunity to measure surface roughness since speckle contrast is related to the relative values of the roughness and the coherence length.[38] Thus, if roughness and coherence length are comparable, speckle contrast will be reduced. Coherence length can be defined as the pathlength difference in a Michelson interferometer where the fringe contrast goes essentially to zero, and, for a square spectral distribution, is equal to the velocity of light divided by the frequency bandwidth.

Sprague points out[38] that there is an opportunity in speckle measurements to introduce a parameter which is similar to the roughness width cutoff--the greatest spacing of surface structure to be included in the measurement. An exact equivalent cannot be attained because the optical image is the Fourier transform of the object. However, a similar effect can be created by moving the detector somewhat ahead of the image plane, causing the point spread function to increase in width. When projected back in object space onto the rough surface, this width can be set to the roughness width cutoff.

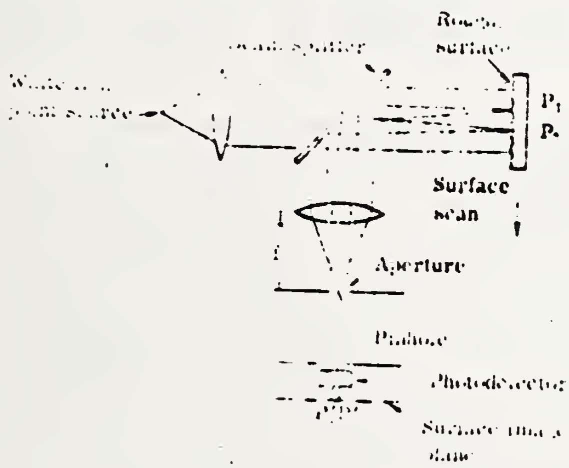

Fig. 5. Apparatus used to measure speckle contrast by scanning speckle pattern past a point detector.

The experimental apparatus is shown in figure 5. The rough surface is translated perpendicular to its axes so that the speckle pattern is scanned across the pinhole. The aperture must be small enough

so the speckle size is larger than the pinhole. The maximum separation of surface points contributing light to the same spot in the image plane is set equal to the roughness width cutoff by moving the pinhole ahead of the image plane. The light source is a tungsten-zirconium arc, yielding a coherence length of 1.5 μm with no filters. This coherence length can be increased to 30 μm by inserting a filter in the beam.

The instrument shown in figure 5 was tested by measuring the arithmetic average absolute deviation of the speckle intensity from its mean value for a series of metal roughness standards. The results are shown in figure 6. As expected the contrast drops close

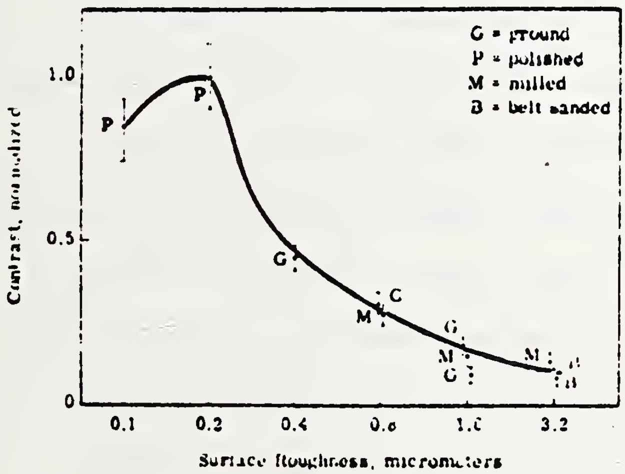

Fig. 6. Speckle contrast vs surface roughness as measured with a Profilometer. The contrast is seen to become small when the roughness is comparable in magnitude with the coherence length of illumination (1.5 μm) and when the roughness is less than a quarter of the mean wavelength of illumination (λ=0.5μm).

to zero when twice the roughness is about equal to the coherence length of the illumination, and also drops when the sample is so smooth that the surface roughness is smaller than the mean wavelength. It is particularly significant that the relationship between contrast and roughness is independent of the surface finishing technique.

The above technique has certain limitations. The necessarily small pinhole results in very low signal levels. Image points are measured serially; only a small part of the signal is used at a time, requiring long measurement times. Furthermore, only a small part of the surface is sampled. These limitations can be avoided by measuring the whole image with nonlinear photoconductors as detectors. Nonlinear photoconductive cells are used for detecting maximum image contrast in automatic focus detectors. By splitting the beam in front of the detector and adding a diffuser (to eliminate speckle) and a second detector, it is possible to measure the ratio of the resistances of the two photoconductors and thus measure the contrast in the speckle pattern. In practice a variable neutral density filter is adjusted for each sample to give a standard reading on the reference detector, and the resistance difference is used to determine the speckle contrast. The results of measurements with the modified apparatus is shown in figure 7. Unfortunately, the nonlinear detectors have a high temperature sensitivity which limits the accuracy of measurements.

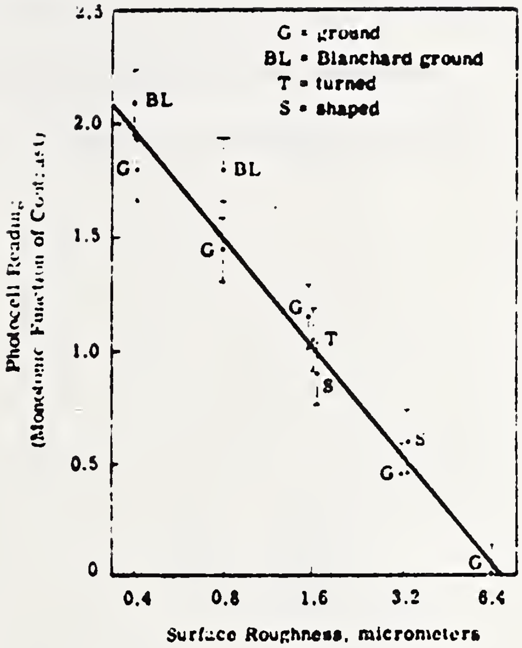

Fig. 7. Photocell difference reading vs surface roughness as measured with a profilometer. The coherence length of illumination was approximately 8.5 μm, with a mean wavelength of 0.75 μm. The apparent linearity of response is due to the combination of nonlinear photocell response with a nonlinear contrast curve.

The white light speckle technique, after instrument calibration, is particularly useful for measuring rough surfaces and as a quality control device. Its usefulness would be enhanced by a firmer theoretical base.

IV. <u>Surface Roughness Measurement by Holographic Interferometry (Ribbens)</u>.

Holographic techniques are particularly attractive for roughness measurements since they permit an optical comparison of a given surface

with a slightly displaced version of itself while maintaining the phase associated with the reflection from each element of the surface.[39] This process is most easily understood by reference to figure 8. The light from the laser is split into two beams. Beam u_o illuminates

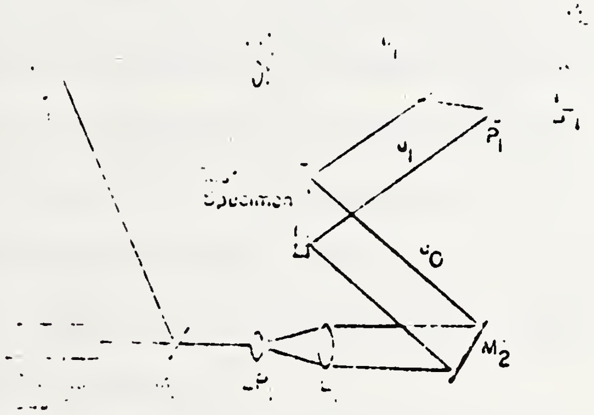

Fig. 8. Instrumentation for holographic interferometric surface roughness measurement.

the object and u_r serves as a reference beam for holographically recording the light amplitude u_1 reflected from the test specimen. M_1 is a partially reflecting mirror, M_2 and M_3 are totally reflecting ultraflat mirrors, LP_1 and LP_2 are lens-pinhole spatial filters and L_1 is a collimating lens. If the hologram formed at P_1 is photographically recorded, and the holographic plate placed at P_1, when the hologram is illuminated by the reference beam u_r a portion of u_r is diffracted, this being denoted u_2. If, in addition, the plate

is illuminated by beam u_1 from the test surface, an interference pattern is formed between u_1 and u_2. The interference pattern is a consequence of the imperfect registration of the hologram plate when it is returned to P_1. The misalignment is controlled by means of micropositioning screws which position the plate.

The contrast ratio of these fringes is a measure of the cross correlation between the light amplitude components u_1 and u_2, which in turn depends on the spatial and temporal coherence of the incident light beam and by the roughness of the test specimen. If the beam is sufficiently coherent and if the specimen is flat compared to the light wavelength, then the contrast ratio is uniquely determined by the surface roughness of the test specimen. The interference contrast is measured in plane P_2.

Theory -- While the vector theory (see scattering theory) is necessary to interpret the interference contrast properly, the scalar theory offers valuable insight and agrees well with experiment. Assuming a Gaussian distribution of roughness with an rms value of σ, the contrast ratio R is given by:

$$R = \left\{ \frac{P + \exp\ [(-k^2\sigma^2/2]}{P - \exp\ [-k^2\sigma^2/2]} \right\}^2 , \qquad (4)$$

where $k = 2\pi/\lambda$, P is the ratio of the amplitude of u_1 and u_2 as determined by the reference beam and hologram efficiency.

An experimental investigation of the technique was conducted by

measuring the contrast ratio of a number of finished steel specimens using a wavelength of 6328 Å. The fringe intensity distribution was measured with a scanning photocell whose aperture was small compared to the fringe spacing. The contrast ratio is obtained from the maxima and minima of the photocell output. The results of these measurements are shown in Figure 9.

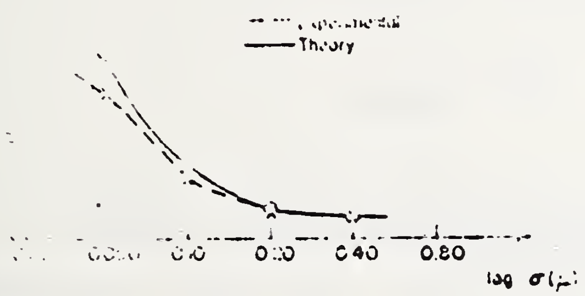

Fig. 9. Comparison of theory and experiment.

The correlation between theory and experiment is quite good between roughness values of 0.050 μm and 0.40 μm (2-16 μ"). The poor agreement below 0.05 μm is a consequence of finite laser coherence. A contrast ratio of about 9 is the maximum that can be obtained for this configuration.

V. <u>Interferometric Fringe Contrast Method of Measuring Surface Roughness (Ribbens).</u>[40]

In addition to the holographic technique discussed above, Ribbens

has also proposed that fringe contrast interferometry be applied to roughness measurement.[40] The accuracy of this technique improves with the smoothness of the surface. A schematic drawing of the instrument is shown in figure 10. The instrument is an interferometer whose

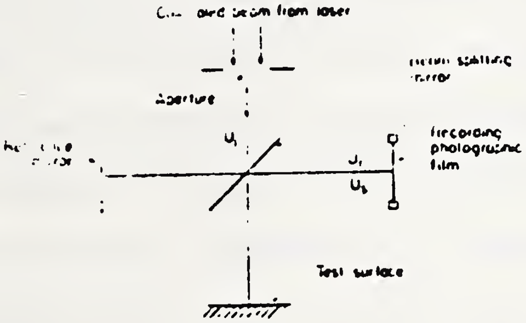

Fig. 10. Schematic drawing of instrumentation used in roughness measurement.

reflecting surfaces are under study. The fringe contrast of the instrument is determined by the mutual coherence of the wavefronts from the two reflecting surfaces which in turn is determined by the roughness of the two reflecting surfaces. If the reference mirror is sufficiently smooth and flat, fringe contrast will be determined by the test flat only. It is then necessary to determine the relationship between fringe contrast and surface roughness in order to determine the roughness of the test surface.

<u>Theory</u> -- It is assumed that light is normally incident on the test surface, that the Fraunhofer approximation applies and that the surface is smooth enough so that shadowing does not occur. Under these

circumstances, it can be shown[40] that the rms surface roughness is given by:

$$\sigma = \frac{\lambda}{4\pi} \ln\left(\frac{(R+1)^{1/2}}{P(R-1)^{1/2}}\right) \tag{5}$$

where R is the contrast ratio and P is the ratio of the reflectivities of the reference and test surfaces. The lower roughness limit is determined by the roughness of the reference mirror, which may be as low as 10 Å, and the coherence of the laser, which may provide contrast ratios as great as 10^5 or 10^6, again implying a 10 Å roughness limit. The validity of the maximum roughness limit rests on the assumptions used in the theory and is best determined experimentally.

Figure 11 shows the relative error for stylus instrument and fringe contrast measurements between 0.1 and 10 μin. measured with

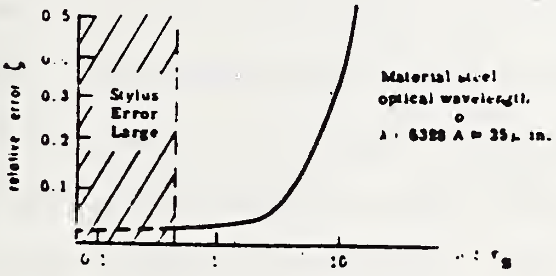

Fig. 11. Relative error vs rms roughness.

a number of steel surfaces. It is evident that the theory is not applicable beyond a few microinches although a calibrated fringe contrast instrument might extend to much higher roughness values. The upper limit can be extended by employing longer wavelength light.

Thus, the range of validity is nominally 10 Å to λ/5 Å.

Munnerlyn and Latta[41] have proposed the use of a Twyman Green interferometer, CO_2 laser and a liquid crystal detector in a similar experiment. They derive a somewhat different relationship between fringe contrast and roughness.

VI. Multiple Beam Interference (Tolansky) Measurement of Surface Roughness.

While interference microscopes[43] have long been used to estimate surface quality, the low cost, elegance and sensitivity of the multiple beam interference microscope, mostly due to Tolansky,[44] has brought it to the forefront in surface roughness measurement in the range where the peak to valley distance is less than λ/2 (10 micro-inches). The optical components of such an instrument are shown in figure 12.[44]

In the multiple beam interferometer, the lower surface of the flat glass plate (Fizeau plate) is coated with a layer of silver which may be up to 97% reflecting. The light reflects between the Fizeau plate and the test specimen (usually coated with an opaque layer of silver) many times, perhaps 50 - 100 times, before passing through the Fizeau plate again and into the eyepiece. Since there is a very small wedge between the Fizeau and the test specimen, the light tends to move laterally after many reflections ("walk off"), typically as much as 5 wavelengths. This tends to limit the lateral resolution to 2.5 μm. While commercial instrument makers quote a vertical

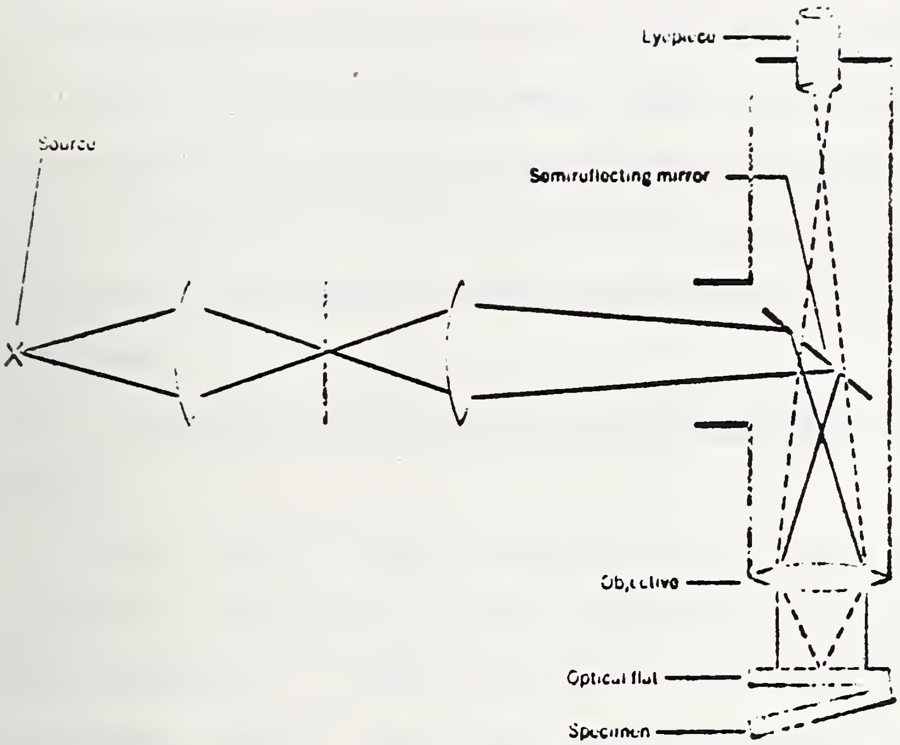

Fig. 12. Multiple-beam interference microscope. Monochromatic light from the source illuminates a slit focused at the back focal point of the objective. Parallel light is transmitted through the silver film on the lower surface of the optical flat to the specimen surface. After repeated reflection a fraction of this light returns through the objective to the eyepiece. The resulting fringes can be pictured as arising from the intersection of the surface and a set of parallel lines spaced a half wavelength apart. (From reference 44).

resolution of about 25 Å, Tolansky claims that, by careful work, the vertical resolution may be extended to 5 Å.

Surface roughness is determined by drawing a straight mean line through an interference fringe and plotting the line profile. The amplitude is determined by the knowledge of the fringe spacing (of

known half wavelength) and the ratio of the fringe deviation to this distance. As commerical instruments become more readily available, this technique is gaining in popularity where roughness is less than 10 microinches. A more sophisticated data acquisition system, similar to the FECO instrument, is equally applicable to the multiple beam instrument.

VII. Surface Roughness Measurement with FECO (Fringes of Equal Chromatic Order).

Bennett and co-workers have exploited the unusual properties associated with fringes of equal chromatic order in measuring surface roughness.[2,42] Figure 13 shows the most recent version of their measurement system. A white light source Z illuminates the interferometer I through beam splitter B. One element of the interferometer is the highly reflecting (coated) specimen surface to be measured. Slit S serves to define a narrow (1 mm x 3 μm) region on the specimen surface. The light then passes through spectrometer p and an image is formed in front of the slow scan TV as shown in the inset. The resulting fringes (see fig. 14) all come from the same region on the specimen. The fringes to the right in figure 14 come from the red part of the spectrum with order of interference 7, while the fringes to the left have order 8 and are in the blue green spectral region.

The image of the fringes and reference spectral lines is detected by a slow scan TV camera employing an image dissector tube with 500 scan lines. A single line is scanned repetitively with the output

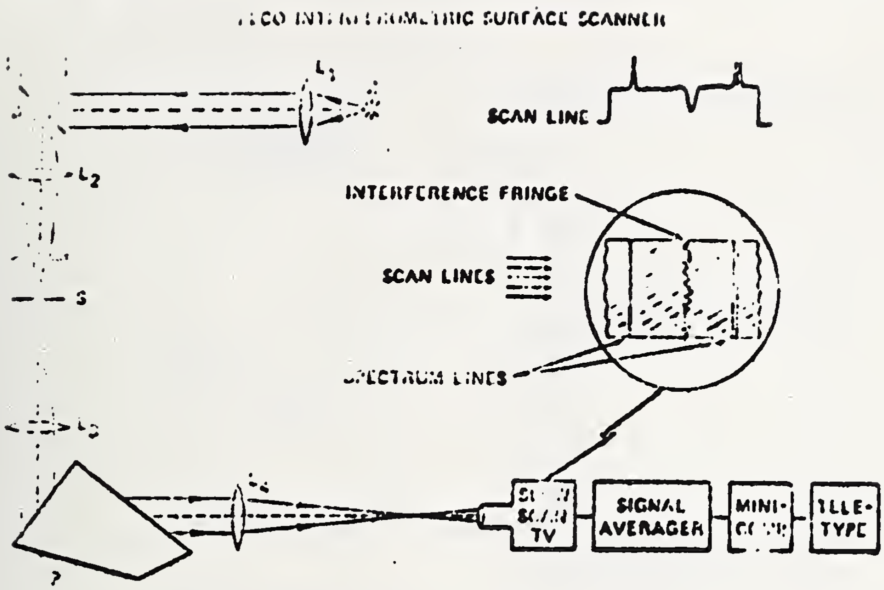

Fig. 13. Schematic diagram of FECO Interferometric Surface Scanner used to measure surface roughness of plane samples. The image detected by the slow scan TV is shown at right center and a single scan line is shown above it.

going to a signal averager until the signal to noise level is adequate and the contour appears as in the upper part of figure 13. Then the information on the scan line is digitized and fed to a minicomputer which calculates and stores the wavelength of the segment of the interference fringe contained in the scan line. The camera now shifts to the next scan and repeats the process until a 500 point wavelength (spacing) profile is obtained. These data can then be used to obtain the usual surface parameters (rms roughness, height distribution, autocovariance fcn, etc.). The system, when fully

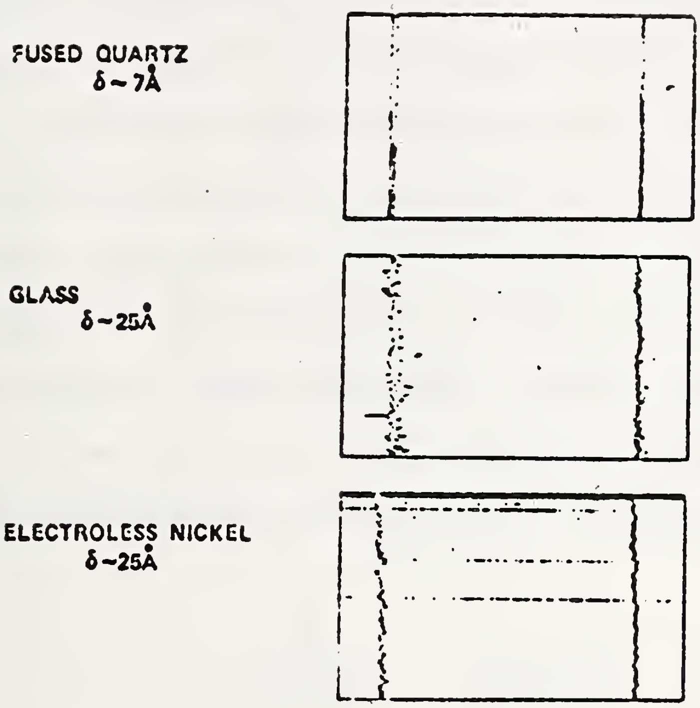

Fig. 14. FECO fringes obtained from (a) a superpolished fused quartz optical flat, (b) a good quality polished glass surface, and (c) a very smooth polished metal surface. The reference surface in all cases was a superpolished fused quartz optical flat.

completed, should be able to detect irregularities under 10 Å peak-to-valley provided that the lateral scale of roughness is greater than the three micron lateral resolution limit of the optical system.

The FECO system requires critical adjustment of the interferometer as well as extremely costly electronics, computer and spectrometer. For this reason, it is unlikely that more than one or two

such instruments will be constructed.

VIII. Nomarski Differential Interference Contrast Technique for Measuring Roughness.

The Nomarski technique[46,47] is an excellent qualitative method for observing the fine detail of surfece roughness at high resolution. In effect, two images of the surfece, displaced by less than the resolution of the microscope, are made to interfere destructively (interference contrast). Only where there is a difference in altitude of adjacent regions is the image illuminated. However, the system is sufficiently sensitive so that, when properly edjusted, the full microdeteil of the surface is seen in high contrast. The essential elements of the instrument are shown in figure 15. The polarized

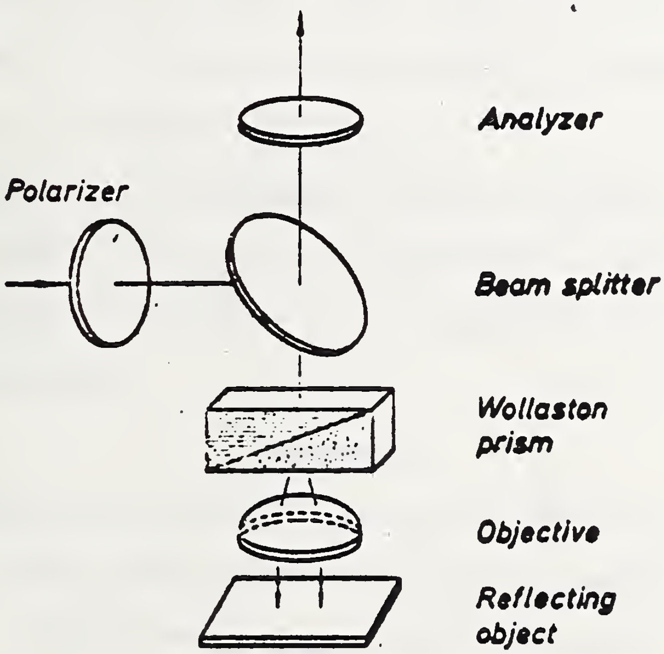

Fig. 15. Schematic diagram of a reflected-light system for differential interference-contrast microscopy. (Separation between the two wavefronts is exaggerated.)

light source from the left is reflected along the optical axis of the instrument by the beam splitter. The polarized beam is angularly split by the Wollaston prism into two mutually coherent beams which arrive at the specimen displaced by about 1 μm, the approximate resolution of the microscope objective. After reflection, the beams are recombined at the Wollaston prism and then pass through second polarizer which is crossed with the first. If the path difference for adjacent rays of the two beams is zero, a dark field results. Any displacement of the rays at tilted areas of the specimen leads to their return through a non-symmetrical path in the optical system. The field therefore has a dark appearance, with tilted features appearing bright on the dark background. Since white light is used, the contrast in the image is also seen as color variations which exploit the high sensitivity of the human eye to color.

The differential interference contrast technique suffers mainly from the limitation that it is not quantitative. Bennett suggests that autocovariance function can be obtained by scanning superimposed Nomarski micrographs.

Conclusions

An examination of the eight techniques, which are intercompared in Table 1, reveals some common limitations for certain subgroups of the eight. The light scattering, white light speckle, laser speckle, holographic interferometry and interference contrast techniques presume a Gaussian model for surface roughness which is probably characteristic

of only a limited number of surface finishes. The concept of the cut off length, used to separate roughness from waviness, is very difficult to implement optically. All of these techniques involve a trade off in that their inherent averaging property precludes examining a single defect, say a pit or scratch, in isolation. Some of these techniques require the use of infrared (invisible) radiation.

One clear advantage of using a light scattering technique in evaluating optical surfaces is that it often measures precisely the needed parameter, the light scattering properties of the optical element, without introducing the intervening parameter, surface roughness. However, when used to obtain a quantitative measurement of surface roughness, the strong model dependence together with the questionable theoretical base, limit severely the reliability of these measurements.

The second group of optical techniques includes multiple beam interference, FECO, and Nomarski. The first two techniques employ a rather simple model and yield surface profiles of rather limited horizontal resolution. The user is immediately faced with the task of extracting roughness parameters from an optical representation of a profile. The necessity of coating the surface renders this a destructive test in cases where the metallic coating cannot be safely removed. In addition, there is risk of damage when the Fizeau plate contacts the specimen surface. The Normarski technique is not quantitative. Thus, this last group of techniques has model integrity but

suffers from physical and analytical limitations. The multiple beam technique seems to have the least severe limitations, particularly cost and ease of interpretation, and is finding increased use, particlarly in conjunction with replicating techniques.

There is little doubt that the surge in popularity of optical techniques will disturb the surface roughness measurement system, perhaps severely. The above review suggests that optical techniques will become more popular because of their inherent attractiveness for on line, non contacting measurements rather than because of increased accuracy in measuring surface roughness parameters. In other words optical techniques seem more suitable for comparative measurements, i.e. measurements after appropriate calibration using surfaces which have been measured by other techniques.

Thus, it is concluded that the most appropriate NBS response to the increasing use of optical techniques is to concentrate our limited resources on developing much improved instruments, such as the Topografiner[48] and traditional stylus instruments, so that extremely smooth optical surfaces can be measured and parameterized accurately. These measurements could then be utilized, through appropriate transfer artifacts, to characterize and calibrate optical instruments used in surface roughness measurement.

References

[1] Bennett, H. E., Porteus, J. O., "Relation Between Surface Roughness and Specular Reflectance at Normal Incidence" J. Opt. Soc. Amer. 51 123 Feb 1961.

[2] Bennett, H. E., Bennett, J. M., Stanford, J. L., "Surface Irregularities and Scattering," Proc. of The Infrared Information Symposium, Huntsville, Ala. Jan 16, 1973.

[3] Bennett, H. E., Porteus, J. O., Bennett, J. M., and Stanford, J. L. "Surface Evaluation for High Energy Laser Windows" High Energy Laser Window Conference Hyannis Mass. Oct 30 - Nov 1, 1972.

[4] Bennett, H. E., Bennett, J. M., and Ashley, E. J., "Infrared Reflectance of Evaporated Aluminum Films" J. of Opt. Soc. Amer. 52 1245, Nov 1962.

[5] Bennett, H. E., and Koehler, W. F., "Precision Measurement of Absolute Specular Reflectance with Minimized Systematic Errors," J. of Opt. Soc. Amer. 50 1, Jan. 1960.

[6] Davis, H., "The Reflection of Electromagnetic Waves from a Rough Surface" Proc. Inst. Elec. Engrs. 101 209 1954.

[7] Beckmann, P. and Spizzichino, A., "The Scattering of Electromagnetic Waves from Rough Surfaces" McMillan, N. Y. 1963.

[8] Morathay, A.S., Heiko, L. and Zuckerman, J. L., "Study of Rough Surfaces by Light Scattering" App. Optics 9 2470, Nov 1970.

[9] Kröger, E. and Kretschman, E., Physik 237, 1 (1970).

[10] Hunderi, O. and Beaglehole, D., Phys. Rev. B2 321 (1970).

[11] Elson, J. M. and Ritchie, R. H., Phys. Rev. B4 4129 (1971).

[12] Hagfors, T. "Relationship of Geometric Optics and Autocorrelation Approaches to the Analysis of Lunar and Planetary Radar", J. of Geophysical Research 71 379 Jan. 15, 1966.

[13] Barrick, D. E., "Rough Surface Scattering Based on the Specular Point Theory", IEE Trans on Antennas and Propagation, AP-16 449 July 1968.

[14] Kröger, E, and Kretschmann, E. "Scattering of Light by Slightly Rough Surfaces or Thin Films including Plasma Resonance Emission," Z. Physik 237 1 1970.

[15] Leader, J. C., "Bidirectional Scattering of Electromagnetic Waves from Rough Surfaces", J. of App. Phys. 42 4808 Nov, 1971.

[16] Aas, J. A., "Reconstruction of Surface Profiles from Their Diffraction Spectra", App. Optics 11 1579 July 1972.

[17] Azzam, R. M. and Bashara, N. M., "Polarization Characteristics of Scattered Radiation from a Diffraction Grating by Ellipsometry with Application to Surface Roughness", Phys. Rev. B 5 4721 June 15, 1972.

[18] Barrick, D. E., "Relationship Between Slope Probability Density Function and the Physical Optics Integral in Rough Surface Scattering", Proc IEEE (Lett) 56 1728 Oct 1968. See also correction in 57 256, Feb 1969.

[19] Birkebak, R. C., "Optical and Mechanical RMS Surface Roughness Comparison," App. Optics 10 1970, Aug 1971.

[20] Birkebak, R. C., "Monchromatic Directional Distribution of Reflected Thermal Radiation from Roughened Surfaces", Ph. D. Dissertation - U. of Minn (1962).

[21] Birkebak, R. C. and Eckert, E. R., Trans. ASME, Ser. C 87, 85 1965.

[22] Love, T. J. and Francis, R. E., Prog. Astronautics Aeronautics 20 115 1967.

[23] Torrance, K. E., "Off Specular Peaks and Angular Distribution of Reflected Thermal Radiation", Ph. D. Dissertation, U. of Minn. 1966.

[24] Depew, C. A., and Weir, R. D., "Surface Roughness Determination by the Measurement of Reflectance", App. Optics 10 969 April 1971.

[25] Torrance, K. E., "Monochromatic Directional Distribution of Reflected Thermal Radiation from Roughened Dielectric Surfaces," M. S. Thesis, U. of Minn. 1964.

[26] Hodgkinson, I. J., "A Simple Scatter Method for Optical Surface Roughness and Slope Measurements". J. of Phys E 3 341 May 1970.

[27] Greenwood and Edward Powers, "Determination of Surface Height Power Spectral Density from a Laser Scattering Method" J. Optical Society Amer. 61 1589 (Abstract) 1971.

[28] Corey, H. S., "Optical Surface Finish Measurement" Oak Ridge Report # Y1826, March 27, 1972.

[29] Hasunuma H., and Nara, J., "On the Sheen Gloss" J. Phys. Soc. Japan 11 69 Jan '56.

[30] Bennett, H., Bennett, J., Ashley, E., and Motyka, R., "Verification of the Anomalous - Skin - Effect Theory for Silver

in The Infrared", Physical Review 165 755, 15 Jan. 1968.

[31] Hunderi, O. and Beaglehole, D., "On the Reflectivity of Rough Metal Surfaces", Physics Letters 29A 335 2 June 1969.

[32] Kretschmann, E., "The Angular Dependence and the Polarization of Light Emitted by Surface Plasmons on Metals Due to Roughness," Optics Communications 5 331 August 1972.

[33] Edwin, R. P., "Light Scattering as a Technique for Measuring the Roughness of Optical Surfaces," J of Phys. E 60 1973.

[34] Grabe, M., "Nonstationary Surface Roughness Measurement by Scattered Light (Theory) Proc. of IEEE 60 339, March 1972.

[35] Crane, R. "Use of Laser-Produced Speckle Pattern to Determine Surface Roughness," J. Opt. Soc. Amer. 60 1658, Dec. 1970.

[36] Arsenault, H. "Roughness Determination with Laser Speckle" J. Opt. Soc. Amer. 61 1426 Oct. 1971.

[37] Goldfischer, L., "Autocorrelation Function and Power Spectral Density of Laser-Produced Speckle Patterns", J. Opt. Soc. Amer 55 247 March 1965.

[38] Sprague, R., "Surface Roughness Measurement Using White Light Speckle; Applied Optics 11 2811 Dec 1972.

[39] Ribbens, W. B., "Surface Roughness Measurement by Holographic Interferometry", Applied Optics 11 807 April 1972.

[40] Ribbens, W. B., "Interferometric Surface Roughness Measurement" Applied Optics 8 2173 Nov. 1969.

[41] Munnerlyn, C. R. and Latta, Milton, "Rough Surface Interferometry Using a CO_2 Laser Source" Applied Optics (Letter) 7 1858 Sept 1968.

[42] Bennett, H. and Bennett, J., "Precision Measurement in Thin Film Optics", in Physics of Thin Films, Vol 4, Ed. G. Hass and R. Thun, Academic Press, N.Y. 1967.

[43] Francon, M. "Progress in Microscopy," Pergammon, Oxford (1961).

[44] Tolansky, S., "Multiple-Beam Interference Microscopy of Metals", Academic Press, New York (1970).

[46] Normarski, G. and Weill, A., Soc. Franc. Miner. Crist 77 840 (1954); R. Allen, G. David and G. Nomarski, Z. Wiss Mikroskopie und Micro Tech 69 193 1969 (an excellent paper - in English).

[47] Gifkins, R. C., "Optical Microscopy of Metals" American Elsenier, N. Y. 1970.

[48] Young, Russell, Ward, John and Scire, Fredric, "The Topografiner: An Instrument for Measuring Surface Microtopography", The Rev. of Sci. Instr. Vol 43 No 7 July 1972.

[49] Westberg, John, "Assessing the Quality of Very Fine Surfaces - A Coming Breakthrough for Lightreflection Photo-electrical Methods?" Proceedings of the International Conference on Surface Technology, May 1 - 3, 1973.