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Standards for optical surface quality using total integrated scattering*

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Abstract

Standards for optical surface quality are suggested to address two distinct problems: (1) the cosmetic appearance of the optical component and (2) its functional performance in an optical system. For the first problem, a series of standard scratches with appropriately defined profiles is suggested, so that the visual appearance of the standard scratch matches the appearance of scratches produced by normal optical polishing. For the second problem, we suggest a measurement of total integrated scattering, which can be related quantitatively to the rms height of surface microirregularities. The scattering from scratches of different sizes can also be made quantitative. Angular scattering is too dependent on surface properties to permit it to be a useful standard. However, total integrated scattering is useful for approximately predicting the relative amounts of light scattered at a given angle by surfaces having different roughnesses.

Introduction

Optical surface quality affects not only the image-forming properties of a system but also the energy throughput and the amount of scattered light in the system. In many cases these latter quantities are more important than the geometrical image-forming properties of the system. When one is concerned with the performance of a component in an optical system, one should have standards of surface quality that measure such performance. On the other hand, there are some purchasers of optics who look only at visible surface defects and do not seem to care about how the component performs. They are, of course, violating one of the major precepts in optics - that optics are to be looked through, not at. For these people, however, one needs so-called cosmetic standards, i.e., standards for which surface defects are specified in a manner closely related to how they appear by visual inspection. In this paper we will discuss both types of standards and outline the important features of each.

Cosmetic Standards

Historically, the so-called Scratch/Dig Standard, which is part of MIL-13830A, was set up to satisfy the need for a cosmetic standard that would assist the optical inspector in accepting or rejecting optical components. The standard scratches were graded from a #10, which was barely detectable, to a #80 that looked like a deep gouge. The widths of the scratches varied in proportion to their scratch numbers. In the current revision to MIL-13830A the widths of the scratches measured in micrometers are equal to one tenth of their scratch numbers. For example, a #10 scratch is 1-μm wide, a #20 scratch is 2-μm wide, etc. The digs, which are isolated circular pits, have long been defined in the specification by their diameters. In this case, a #10 dig has a diameter of 100 μm (or 0.1 mm), a #20 dig has a diameter of 200 μm (0.2 mm), etc. Currently, no other properties of the scratches or digs have been made quantitative, although there has been discussion about defining the slopes of the sides of the scratch, whether or not it should have a flat bottom, etc. Even the width of a scratch is not easy to measure unambiguously since the width as perceived by the eye may not be equal to the total width of the disturbed area on the surface. Until recently, it has not been possible to directly measure the actual profile of a scratch, and hence discussions about scratch geometry have been largely academic. However, with the advent of surface profiling instruments that have very sharp diamond styluses, it is now possible to directly measure scratch profiles. Figure 1 shows two such profiles - a #20 scratch and a #60 scratch - drawn to scale. These scratches do not look very impressive. The #60 scratch, in particular, has an irregular bottom and slight bumps on the outer edges where material from the bottom of the scratch has been displaced upward. The angles of the sides of the scratch are smaller for the #20 scratch than for the #60 scratch. In order to see the profiles more clearly, they have been replotted in Figure 2 with the vertical scale equal to ten times the horizontal scale. The slope angles of the scratch sides are now distorted, but the scratch features are much clearer. We immediately see problems which will arise when one attempts to define the geometrical width and depth of a scratch. Is the width set equal to the maximum width of the disturbed area on the surface, or is it defined as related to the width which the scratch would appear to have if viewed at normal incidence under a low power microscope objective. The scratch widths indicated on Figures

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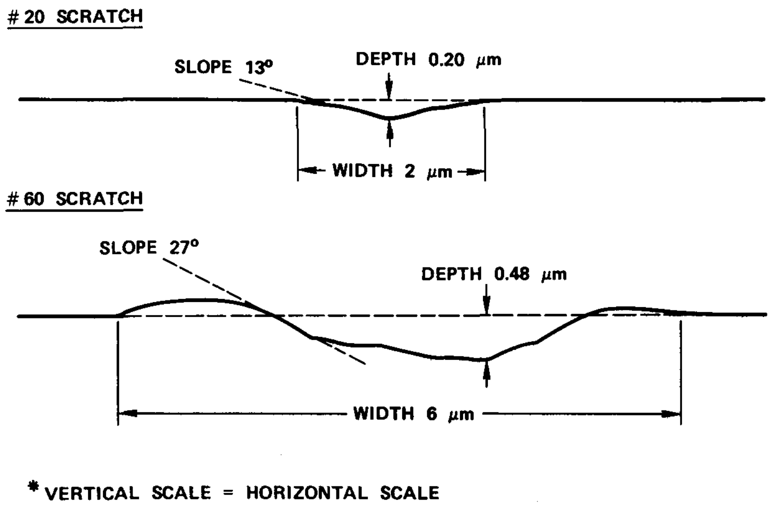

Fig. 1. Profiles of standard scratches as measured with a profilometer having a 1-µm-radius conical diamond stylus.

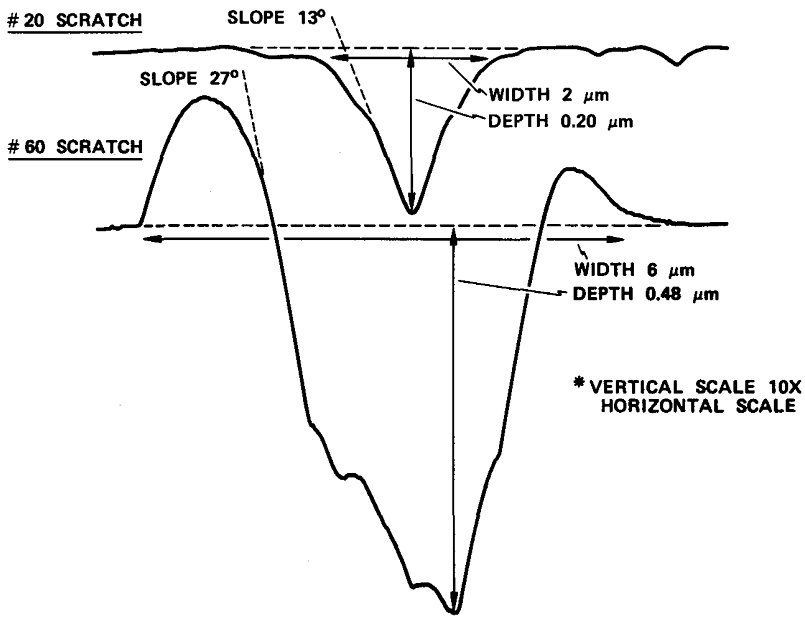

Fig. 2. Same as Figure 1 with vertical scale 10X horizontal scale.

1 and 2 are attempts to follow this latter definition. The widths measured for these scratches by personnel at Frankford Arsenal, from where the scratches came, are 2.6 µm for the #20 scratch and 5.4 µm for the #60 scratch,(1) in good agreement with the widths shown in Figures 1 and 2. Likewise, the scratch depth is ambiguous. Is it measured relative to the undisturbed surface level, or is it the maximum distance from the highest to the lowest point? Here we have used the former definition. Still unanswered is the most important question: How is the visual appearance of a scratch related to its geometry? We may get a clue to the answer by examining the ratio of the scratch depth to its width for these two scratches. The ratios are 10% and 8% for the #20 and #60 scratches, respectively. If the widths or depths were defined differently, the ratios would change only slightly. A possible conclusion to draw from these examples is that, even though the slopes of the sides of

the scratches are quite different in the two cases, the depth-to-width ratio is surprisingly constant. Perhaps this information could be included in a future definition of the scratch profile.

We should briefly mention the method used to obtain the scratch profiles shown in Figures 1 and 2. A surface profiling instrument, shown schematically in Figure 3, was used.[2] It had a conical diamond stylus with approximately 90° included angle and ~ 1-μm radius, as determined from a measurement of a scanning electron micrograph.[3] The loading on the stylus was light enough that no permanent mark was left on the surface.[3] The noise level of the instrument using the 1-μm-radius stylus was equivalent to a surface roughness of 1 - 2 Å rms. In order to determine how much error is made by the stylus not reaching the bottom of the scratch, one can assume that the true scratch profile is in the form of a "V", with sides having the slope angles indicated. Then the distance between the bottom of the stylus and the bottom of the V can be easily determined from a scale drawing of the scratch and stylus profiles. The distances determined in this manner are approximately 250 Å for the #20 scratch and approximately 1000 Å for the #60 scratch. Thus, the error made in measuring the scratch depths is about 12 - 21%. Since a worst case was assumed, the actual error may be less.

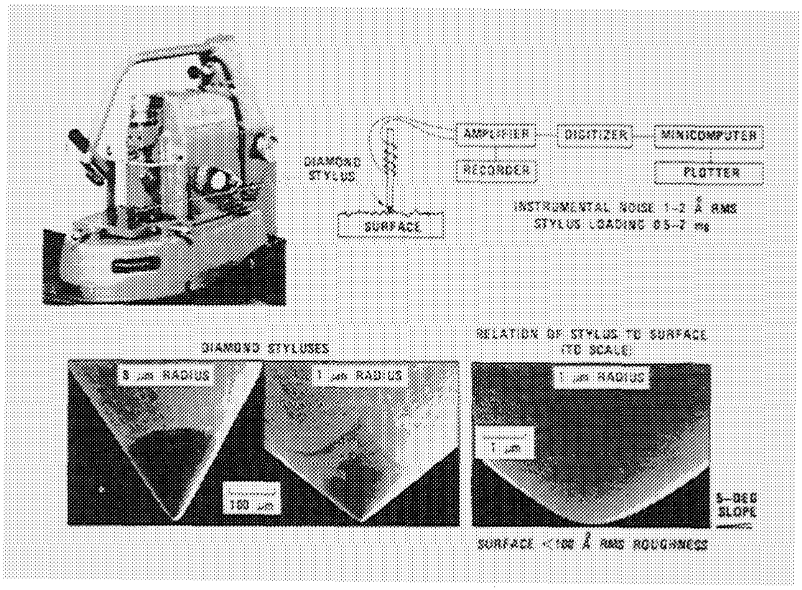

Fig. 3. Schematic of surface profile measuring system used to obtain scratch profiles, and electron micrographs of stylus used.

By taking a series of profiles at equally spaced intervals along the scratch, one can generate a three-dimensional representation of the scratch, as shown in Figure 4. In this representation, the x- and y-coordinates give the position on the surface, and the scratch profile is shown inverted in the z-direction. Note that the horizontal and vertical scales are much different, although they are the same for the two scratches, to show the relative proportions. Bear in mind that the scratch widths are a few micrometers, and the scratch depths are approximately one tenth of the scratch widths.

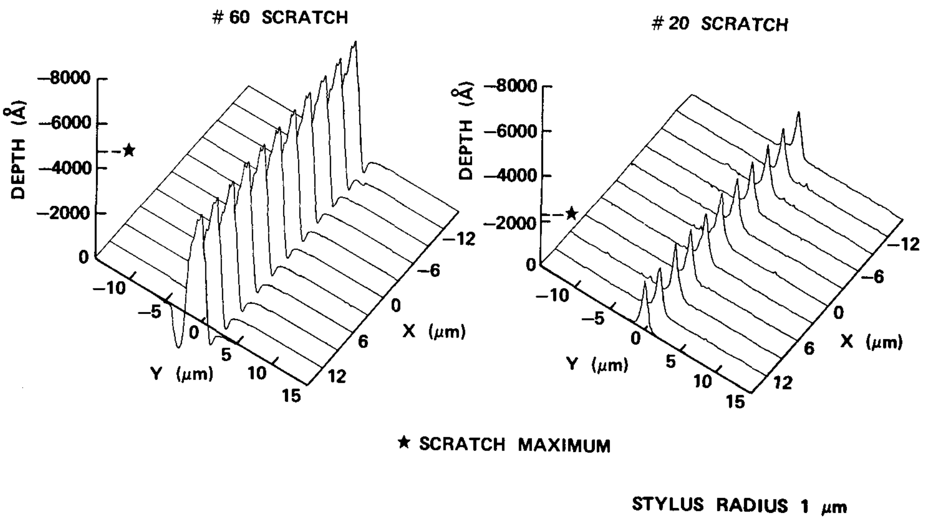

Fig. 4. Three-dimensional representations of scratch standards based on a series of equally spaced profiles. Profiles are shown inverted with exaggerated vertical scales.

Functional Standards

In the preceding section we were concerned with the scratch geometry for its own sake, but did not relate the geometry to the scattering properties of the scratch. Since the eye is not an integrating sphere, the visual appearance of a scratch is related to its angular scattering properties. However, the effect of a scratch on the performance of an optical system may be more directly related to the total integrated scattering (TIS) of the scratch into a hemisphere. In order to determine the relation between the scratch numbers and their TIS, we have measured the TIS of the #20 and #60 scratches ruled on glass surfaces. The instrument used was the Optical Evaluation Facility, which has been described previously,(4) although a simpler version, the Optical Functional Tester,(5,6) would also be adequate. The area of the surface illuminated in each of these instruments is a circular spot approximately 1 mm in diameter.

Figures 5 - 7 show three-dimensional plots of backscattering for the #20 and #60 scratches. In these figures the x- and y-axes give the positions on the surface and the z-axis is the measured scattering intensity. Since the spacing of the measurements was ~ 0.25 mm, the scratch is seen in about four adjacent measurements. The stars on the z-axis indicate the maximum scattering level from the scratch, while the triangles are the average scattering level from the surrounding background. The scratch widths are visually measured values, as explained earlier. An important point to notice in all the graphs is that the #60 scratch contributes an amount of scattering which is several times that of the background, even though the width of the scratch is only about 0.6% of the diameter of the laser beam illuminating the surface. In the case of the #20 scratch, the maximum scattering level is only about twice that of the rest of the surface (see also Table 1). On well-polished surfaces there should not be any scratches as large as a #60, although #10 and #20 scratches may be present. A common practice to disguise the smaller scratches is to make the substrate on which the scratch is ruled rougher so the presence of small scratches is not so evident.(7) Unfortunately, this practice has the effect of increasing the total scattering level of the system even though it may make the particular piece pass the quality control inspector.

TABLE 1. Backscattering levels from a #20 and a #60 standard scratch and the substrates on which they are ruled.

Background	#60 Scratch	Background	#20 Scratch
	6471 Å		
1.4×10^{-3}	5.5×10^{-3}	1.8×10^{-4}	3.6×10^{-4}
	3.39 μm		
7.9×10^{-5}	1.4×10^{-4}	---	---

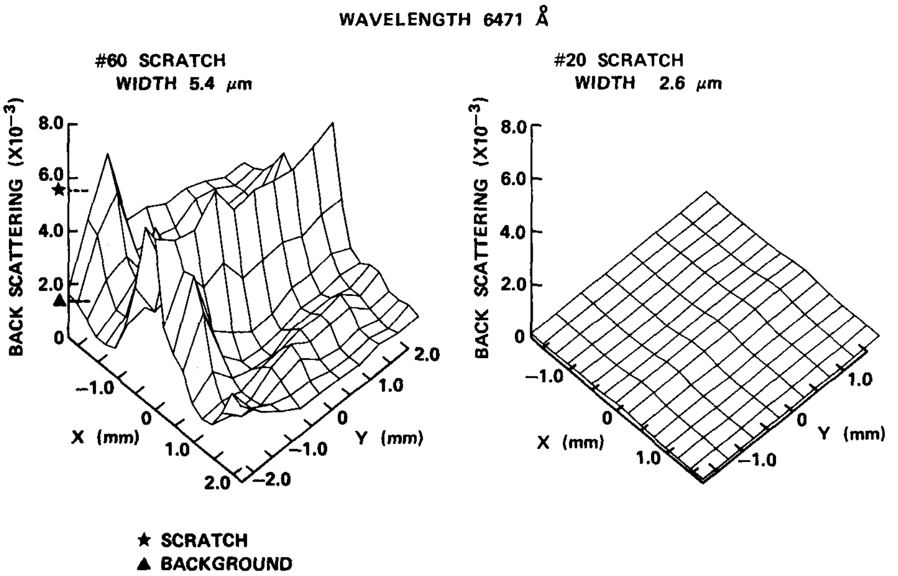

Fig. 5. Three-dimensional plots of backscattering from uncoated #60 and #20 scratch standards measured at a wavelength of 6471 Å. Both plots are to the same vertical scale.

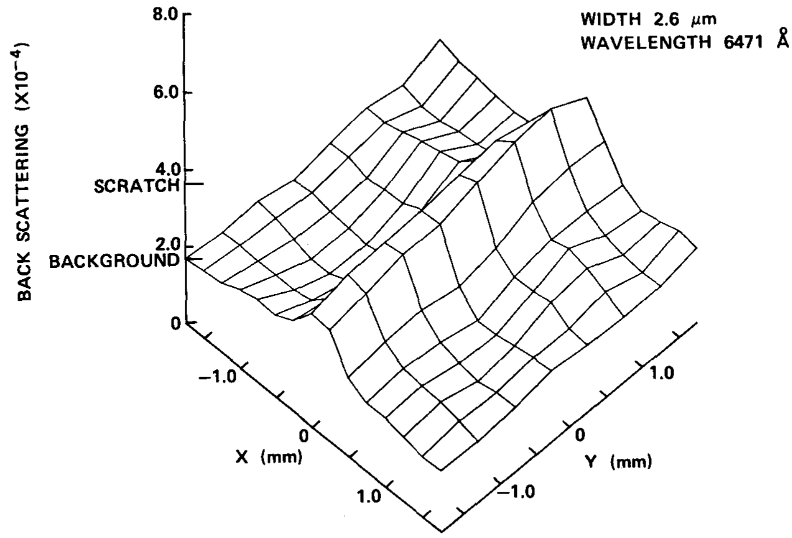

Fig. 6. Expanded version of plot for #20 scratch standard shown in Figure 5.

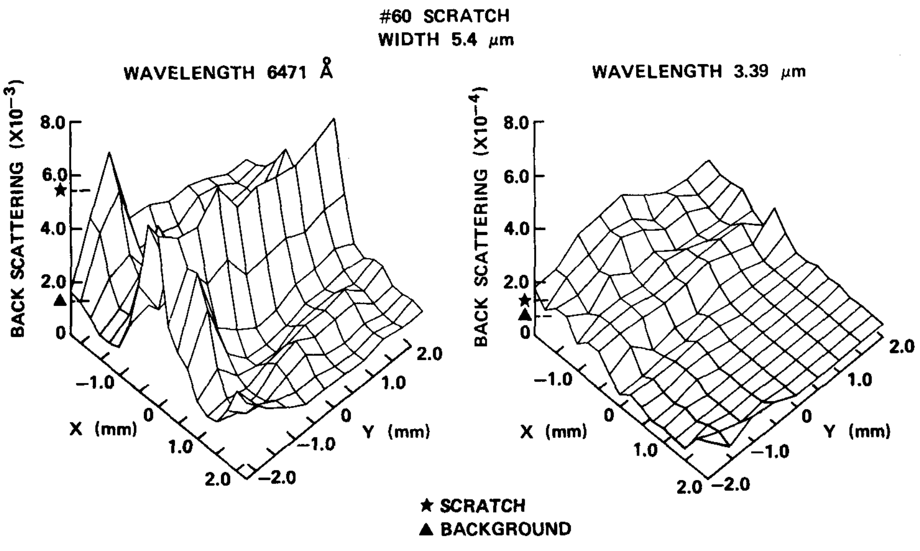

Fig. 7. Three-dimensional plots for comparing backscattering from a #60 scratch standard measured at wavelengths of 6471 Å and 3.39 μm. Vertical scale factor of 3.39 μm plot is 10X that for the 6471 Å plot.

In comparing the magnitudes of the scattering from the scratches in Figures 5 - 7 (values are also listed in Table 1), it is evident in Figures 5 and 6 that the maximum backscattering from the #60 scratch is about 15 times that from the #20 scratch at the visible 6471 Å red krypton laser line. In Figure 7 we see that the backscattering from the #60 scratch is comparable to that of the background in the infrared (3.39 μm). This is because the total scattering level for the substrate is down by about a factor of 20 from its value in the visible, and the residual scattering is caused mainly by particulates – dust, etc. – rather than by microirregularities. This result is important if one is concerned with scattering from infrared optics.

So far we have been primarily concerned with scattering from standard scratches ruled on optical surfaces. However, a well-polished piece of optics rarely has large scratches on its surface, and only a few smaller scratches. Thus, most of the scattering from the component will be scattering from the correlated surface microroughness, i.e., the residual surface finish left by the polishing process. The theory of backscattering from correlated microirregularities is well understood, and there exists a relation between the TIS and the rms height δ of the surface microirregularities:(7,8)

$$\mathrm{TIS} = (4\pi\delta/\lambda)^2 \quad , \tag{1}$$

where λ is the wavelength. Equation (1) holds when the roughness is small compared to the wavelength, and the distribution of the heights of the surface microirregularities is Gaussian. Both of these conditions are met for polished glass and quartz optical surfaces, and for many other types of materials.(9) Polished alkali halide surfaces are frequently exceptions, since their height distributions are not Gaussian.(9) The subject of microirregularity scattering has been discussed in detail elsewhere.(2,7,10)

Angular Scattering

Surface standards are also often requested for angular scattering, or BRDF.(11) This is a much more difficult requirement because angular scattering depends not only on the heights of surface irregularities but also on their separations, or autocovariance lengths.(2) Vector scattering theories are available which predict the angular scattering from surface microirregularities;(10) one of these has been adapted to use measured surface autocovariance functions in the calculation.(2) The agreement between calculated and measured angular scattering curves is encouraging, but not sufficiently quantitative to use as a specification of angular scattering. Experimental angular scattering curves show extreme sensitivity to surface contamination and have, in fact, been used to measure surface cleanliness.(12) Also, the curves are sensitive to the angle of incidence of the illuminating beam, the polarization of the incident beam, and the polarization and plane of the scattered light. Some of these effects are illustrated in Figures 8 and 9. Figure 8 shows the angular scattering in the p- and s-planes for normal incidence illumination of a very smooth aluminized polished fused quartz surface. (The p- (s-) scattering plane is the plane parallel (perpendicular) to the direction of the incident beam polarization.) Even for this isotropic surface illuminated at normal incidence, the planes of polarization of the illuminating and scattered beams are important if one is concerned with measuring scattering at angles greater than about 20° from the specular direction. Figure 9 shows the effect of particulates embedded in the surface of a multilayer dielectric reflector. For a scattering measurement in the s-plane, not only is the magnitude of the scattering increased by a contaminated surface, but also the shape of the curve is different (more structure is present). The instrument used to make these measurements had a well-collimated He-Ne 6328 Å laser source, a 1-meter distance between the sample and collecting optics, a variable circular aperture on the collecting optics that could collect scattered light with an angular acceptance of 0.1 to 1°, and an extremely low system scattered light level. This last feature makes it possible to measure angular scattering from extremely smooth surfaces.

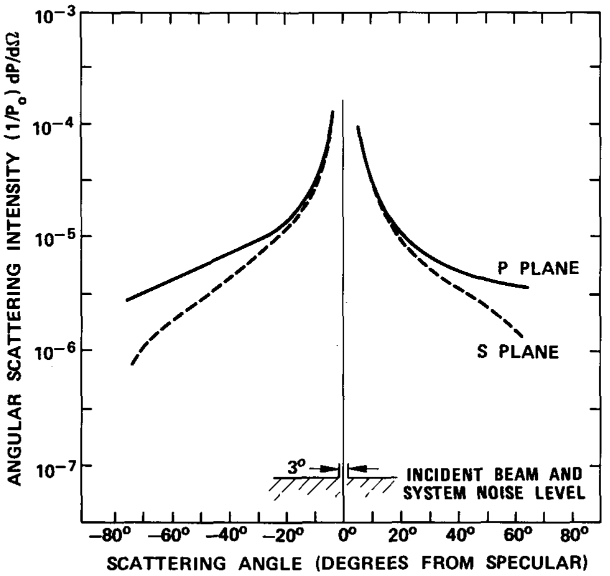

Fig. 8. Angular scattering in the p- and s-planes for normal incidence illumination of a very smooth aluminized polished fused quartz surface measured at a wavelength of 6328 Å.

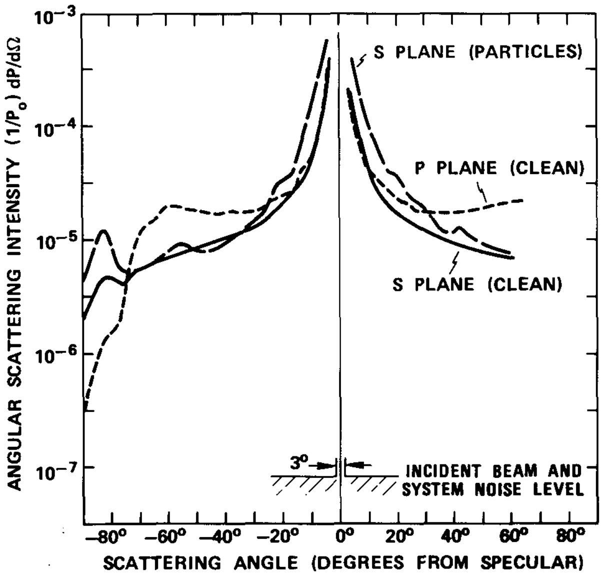

Fig. 9. Effect of particulates on the angular scattering from a multilayer dielectric reflector measured at a wavelength of 6328 Å.

TIS Surface Quality Standard

Since angular scattering is so sensitive to surface properties such as the autocovariance length, a more reasonable reproducible functional standard of optical surface quality would be a standard of TIS. Total integrated backscattering, as mentioned previously, is sensitive only to the heights of surface microirregularities and not their autocovariance properties (slopes, autocovariance lengths, etc.). This type of standard would have the advantages that (1) relatively inexpensive instrumentation can be built to measure TIS,[5,6] (2) TIS is less sensitive to surface contamination than is angular scattering, (3) the theory relating TIS to the heights of surface microirregularities is well established, and (4) the effect of scratches and other isolated surface defects can also be quantified.[7] Prototype instruments for production-type TIS measurements have already been built.[5,6]

One objection that is frequently raised in connection with TIS measurements is that a "large amount" of energy is lost because one cannot collect the scattered light at angles very close to the specular beam. Since the angular scattering curves rise so steeply as the specular direction is approached, it is "clear" that large errors in TIS will be made by limiting the collection angle to, for example, 4 or 5° from the specular direction. Church,[13] in fact, predicts that the TIS measured outside of an angle of 2.29° from the specular direction will be only 0.2% of the correct value, taking into account all angles from 0° to 90° for surfaces having a Gaussian autocovariance function, a correlation length of 10 μm, and a wavelength of 0.5 μm. Fortunately, this calculation does not apply to real surfaces, which do not have Gaussian autocovariance functions and which have correlation lengths closer to 1 or 2 μm. Figures 10 and 11 show plots of experimentally measured values of cumulative scattered light integrated from minimum measured angles of 0.5° and 4°, respectively, from the specular direction. These measurements were made with the instrument described in the previous section. Although the surfaces are different, both are extremely low scatter ones having short autocovariance lengths. In Figure 10 the detector collected light falling into a tenth of a degree width, while there was a 1° collection angle for the data in Figure 11. From Figure 10 we see that the fraction of the scattered light falling into angles from 0.5 to 4° is 66% of the total amount scattered into angles of 0.5 to 10°. While this value may seem high, one should keep in mind the magnitude of the scattering into an entire hemisphere, as shown in Figure 11. In this figure the fractions of the total scattering in the 4 to 10°, 10 to 60°, and 60 to 90° ranges are 18%, 72%, and 10%, respectively, of the light scattered into the 4 to 90° range. (We have extrapolated the measured curve from 78 to 90°, but no appreciable error is made because the measured scattering falls off rapidly in this region.) An important conclusion to be drawn from the above data is that the major amount of the TIS falls between the angles of 10 and 60°. This result is caused primarily by the large increase in solid angle as the angle from the specular direction increases. The large increase in solid angle more than

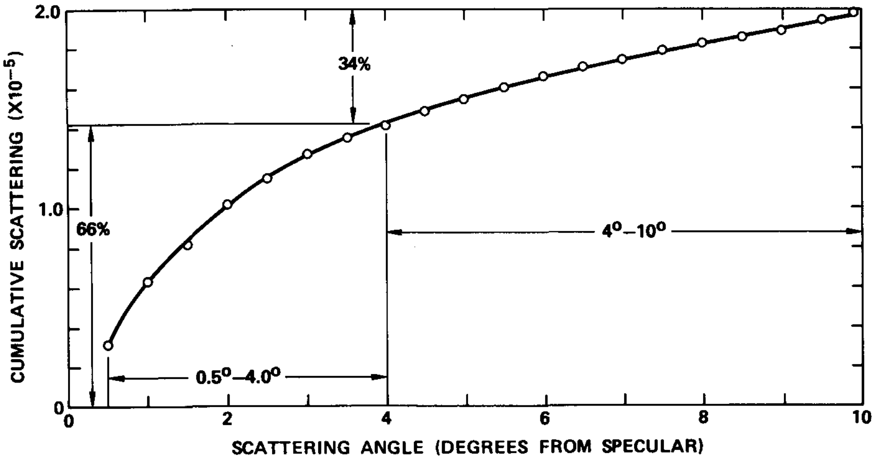

Fig. 10. Cumulative scattering from a multilayer dielectric reflector measured at 6328 Å and normal incidence. Values were integrated from measurements made at 0.1° intervals from 0.5 to 9.9° with a 0.1°-wide collection angle; not all data points are shown. The multilayer is a commercial, state-of-the-art, laser gyro mirror with approximately 20 layers of TiO_2 and SiO_2.

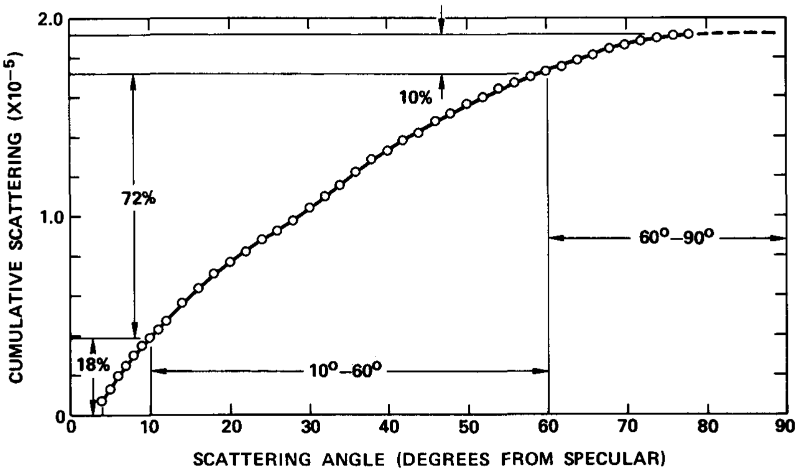

Fig. 11. Cumulative scattering from a very low scatter, aluminized fused quartz surface measured at 6328 Å and normal incidence. Values were integrated from measurements made at 1 or 2° intervals from 4 to 78° with a 1.0° collection angle.

compensates for the decrease in scattering level with increasing angle. If we combine data from the two graphs, no more than 26% can be at angles between 0.5 and 4°. Experimentally, it is very difficult to measure the contribution to the scattered light for angles less than a few tenths of a degree from the specular direction because one cannot distinguish between the specular beam and the scattered light. However, it would be extremely unlikely if scattering in this region dominated the scattering in the remaining solid angles. Even Church's equations(13) for the contribution to the scattering from angles of 0.5 to 90° for surfaces having an exponential (Gaussian) autocovariance function, a correlation length of 2 μm, and a wavelength of 0.5 μm, indicate that the ratio is 79.4% (89.6%) of the true value, taking into account scattering from 0 to 90°. At infrared wavelengths these percentages will be even higher.

Conclusions

We have shown that two types of standards of optical surface quality are desirable: (1) one that addresses the problem of the cosmetic appearance of an optical component and (2) one that considers the functional performance of the component. For the former type, standard scratches are needed that have carefully defined profiles so that their visual appearance closely matches the appearance of scratches produced by optical polishing. A corollary to this definition is that the substrates on which the scratches are ruled should be extremely smooth so that the finer scratches are not masked by background microirregularities. For the latter type of standard, we suggest a measurement of TIS, forward scattering for transmitting optics, and backscattering for reflecting optics. TIS will measure the effect of scratches, digs, and other isolated surface defects, but, more importantly, will measure the contribution of microirregularity scattering which is not now covered by existing standards. We do not recommend a standard for angular scattering because of the extreme dependence of this quantity on surface properties. However, a standard for TIS, since it measures the total light scattered by a surface, will also give a measure of the relative amounts of scattering to be expected at a particular angle or range of angles from surfaces of different roughness.

References

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Question 1: Were the Frankford Arsenal scratches shown on the slide matched visually to the master scratch standards?

Question 2: Is not the #20 out of specification to Rev. J of the Army drawing for scratches? (You showed it to be 2.6 u wide, but I believe the specification is 2.0±0.2u.)

Reply to Questions 1 & 2: The standard scratches reported on here were received from Nate Scott of Frankford Arsenal several years ago. He selected some which approximately met the suggested width specification, so that we could measure their TIS. They were not specifically made to the new revision's specifications, so they may well be outside the current width tolerance. It is our understanding that they did visually match the master scratch standards.

Question 3: The width listed in Rev. J of the Army drawing is for a manufacturer of the standard only. In use the scratch must still be visually compared to the standard.

Question 3 requires no reply.