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Redefining the Scratch Standards

Matt Young
Eric G. Johnson, Jr.

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The scratch standard (MIL-O-13830A) is a cosmetic standard that is effected by a visual comparison with a set of submasters that are in turn evaluated by comparison with a set of master standards. Both manufacture and certification of the submasters are somewhat unreliable. In this paper, we show that the submasters can be classified according to the relative power scattered at a relatively small angle. We have designed etched gratings with which to replace the submasters; these gratings have the appearance of scratches but diffract light into a broad peak between 5 and 10 degrees off the axis of the incident beam. We have classified some prototypes both by comparison with the master standards and by a photoelectric measurement; agreement between the two methods is good. We suggest that such gratings be used as the submasters and possibly that they be classified by a photoelectric rather than visual measurement.

Key words: cosmetic standard; diffraction; MIL standard; optical quality; optical-surface quality; scattering; scratch and dig standard; standards; surface quality; surfaces

1. Introduction and Objective

The Scratch and Dig Standard [1] is the most important descriptor of optical-surface quality used in the United States. The dig standard is well understood because the designation of a dig on a surface is related to the diameter of the dig. The scratch standard is less well understood and less well controlled; therefore, we take a few moments to discuss its current status.

To begin, the scratch standard is in most applications purely a cosmetic standard. Although scratches on a surface are very visible, in general they contribute only a small fraction of the total light scattered by the surface. Thus, unless a surface is located in or near an image or object plane, the presence of a scratch is likely to be irrelevant to the performance of an instrument. (Scratches have, however, been implicated in damage to high-power laser components, and the scratch width is suspected to be a factor [2]. For such components, possibly a standard of measured width needs to be developed; the scratch standard as it exists today is unfortunately not appropriate.)

The designation (S-10, -20, -40, -60, or -80) of a scratch on a specimen is determined by a visual comparison with a submaster. Typically, the submaster and the specimen are held at roughly the shortest distance of distinct vision (about 25 cm) and viewed in transmission, with no intervening optics. The inspector classifies scratches on the specimen by comparing the peak scattered intensity with that of the set of submasters. The numerical designation of the submaster or of a scratch on the specimen has no direct relationship to the width of the scratch. This is also true of a newly developed method of measuring the relative visibility of a scratch [3].

The submasters themselves are classified by a visual comparison with a set of master scratches. This leads to significant error and, hence, scratches with a relatively wide range of scattering parameters may be given the same designation. In addition, trained inspectors often reject a high proportion of the submasters they examine; part of the purpose of our investigation was therefore to find ways to improve manufacturing and thereby reduce costs.

(In the past, it was believed that the designation of a scratch on a submaster was equal to about 10 times the scratch width in micrometers. We have no way of verifying this contention; however, today the scratches are certainly less than that width [4]. This has led some of our colleagues in the industry to suggest that the primary standards may have healed with time and that the current standard is therefore substantially more stringent than when it was introduced. Again, we have no means to verify this claim.)

A careful literature search revealed few objective measurements besides some integrated scatter scans that were reported several years ago [5]. We have therefore undertaken a comprehensive program to (1) provide quantitative measurements of the light scattered by the scratches, (2) develop a body of theory to relate the properties of the scratches to the pattern of scattered light, (3) correlate the measurements with the assessment made by the eye [6,7], and (4) develop a set of artifacts that can be manufactured reliably and serve as the submasters [6-8].

One purpose of this program was to attack the measurement and characterization problem. To this end, we have developed photoelectric measurement techniques and theory, and used them to characterize existing sets of submasters. These are scribed scratches as well as artifacts produced by other methods (such as etching).

In the body of this Technical Note, we report the results of our investigations and further propose that the submasters be replaced by etched gratings manufactured by high-resolution electron-beam lithography. The gratings are designed to scatter maximum intensity into the range between 5 and 10° off the axis of the illuminating beam; we report preliminary measurements on such gratings. If the gratings can be manufactured reliably, the artifact standards can be retired.

2. Elementary Diffraction Theory

In this section we apply the Fraunhofer-Kirchhoff diffraction theory to diffraction by a one-dimensional phase object [6]. The results are useful for design purposes and are accurate for grooves that are wider than a few wavelengths and shallow enough that we may assume single scattering. Likewise, the scattering angles must be sufficiently small that single scattering applies.

We begin by calculating the diffraction pattern of a groove whose depth is so small that the groove affects only the phase of the beam. The width of the groove is b and the width of the illuminating beam is B. The phase change across the groove is Δ. The equation for the diffraction pattern in the far field is

$$E(\theta) = \int_{-B/2}^{B/2} A(s)\, e^{-i(k \sin\theta)s}\, ds, \qquad (1)$$

where E is electric field strength, k is $2\pi/\lambda$, and where multiplicative constants have been ignored [6]. A(s) is the amplitude of the electric field at any point s between -B/2 and B/2 and, for uniform and collimated illumination, is equal to $A_0e^{i\Delta}$ at the location of the groove and A_0 elsewhere. If the index of refraction of the glass is n and the depth of the scratch is t, $\Delta = k(n - 1)t$.

The integral, Eq. (1), may be evaluated by separating it into an integral corresponding to the diffraction pattern of an aperture with width B and a second integral corresponding to the diffraction pattern of a slit with width b but with a relative strength dependent on the phase shift Δ. The result is the sum of two terms,

$$E(\theta) \propto \operatorname{sinc} \Phi + \frac{2i\ b}{B} e^{i\Delta/2} \sin (\Delta/2) \operatorname{sinc} \phi, \tag{2}$$

where $\operatorname{sinc} x = (\sin x)/x$, $\Phi = (\pi/\lambda)\ B \sin\theta$ and $\phi = (\pi/\lambda)\ b \sin\theta$. The first term describes the unscattered or zero-order light. The second term describes the scattered light and is the diffraction pattern of the groove; it is weaker by $(2b/B) \sin (\Delta/2)$ than the first term. It also has angular spread B/b times the first; therefore, the first term dominates around $\theta = 0$, whereas the second term dominates elsewhere.

A system capable of measuring the entire scattered-radiation pattern must be capable of measuring both the scattered and unscattered light. The relative intensity, just off specular transmission, is given by

$$I_s(0)/I_o(0) = 4(b/B)^2 \sin^2(\Delta/2), \tag{3}$$

where subscripts stand for scattered and incident intensity. The scattered intensity is a maximum when $\sin^2(\Delta/2) = 1$, or when $t = \lambda/2(n - 1)$; for the case $n = 1.5$, the condition $t = \lambda$ (or some odd multiple of λ) results in maximum scattered intensity. Many scratches are much shallower than one wavelength. Thus, Eq. (3) shows that, if the detection system is limited to a range of six orders of magnitude or so, the width B of the illuminating beam must be no greater than several hundred times the width b of the scratch. This is a comparatively stringent requirement and requires the design of a unique optical system [6].

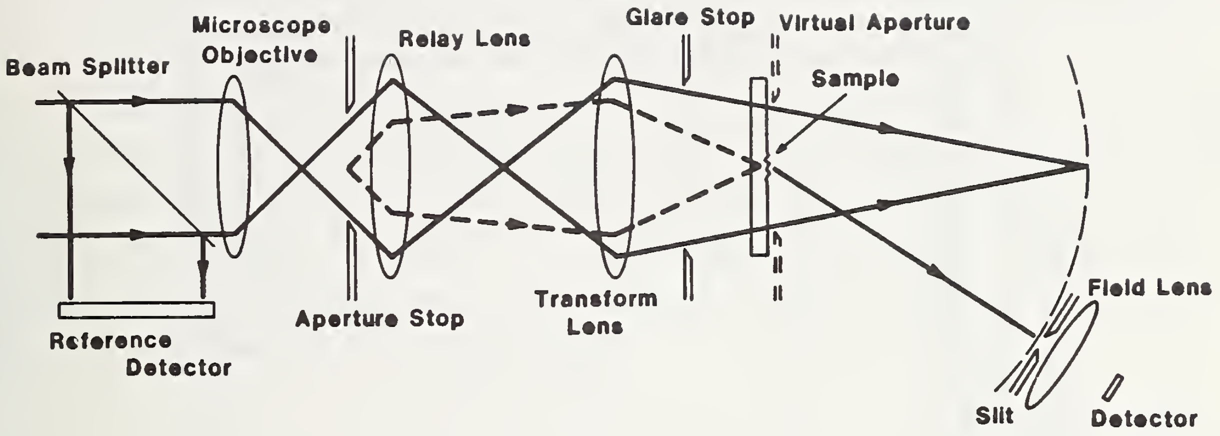

Figure 1. Experimental apparatus. Dashed lines show how image of aperture stop is projected into plane of sample. After reference 6.

3. Instrumentation

The optical system for measuring the scattered light as a function of angle is shown in Fig. 1 [6]. A detector assembly is located on the circumference of a circle centered about the sample position. The transform lens focuses the HeNe-laser beam to a point on that circle; the intensity at points along the circle is the Fraunhofer or far-field diffraction pattern of the sample.

The limiting aperture is a small rectangular opening located in a novel position: to the left of a relay lens. The function of the relay lens is to project an image of that aperture through the transform lens and into the plane of the scratch. (The transform lens has to be located at least one focal length to the left of the sample.) This is necessary because space problems prohibit placing the aperture in contact with the scratch, and even a few centimeters' separation results in a Fresnel-diffraction pattern. The intensity variation resulting from this diffraction pattern may be 20 percent or so in the plane of the scratch. For studies of scattering by overall surface roughness, this may not be an important factor. For studies of scattering by an isolated defect, however, an error will arise, depending upon the precise positioning of the defect in the peaks or valleys of the diffraction

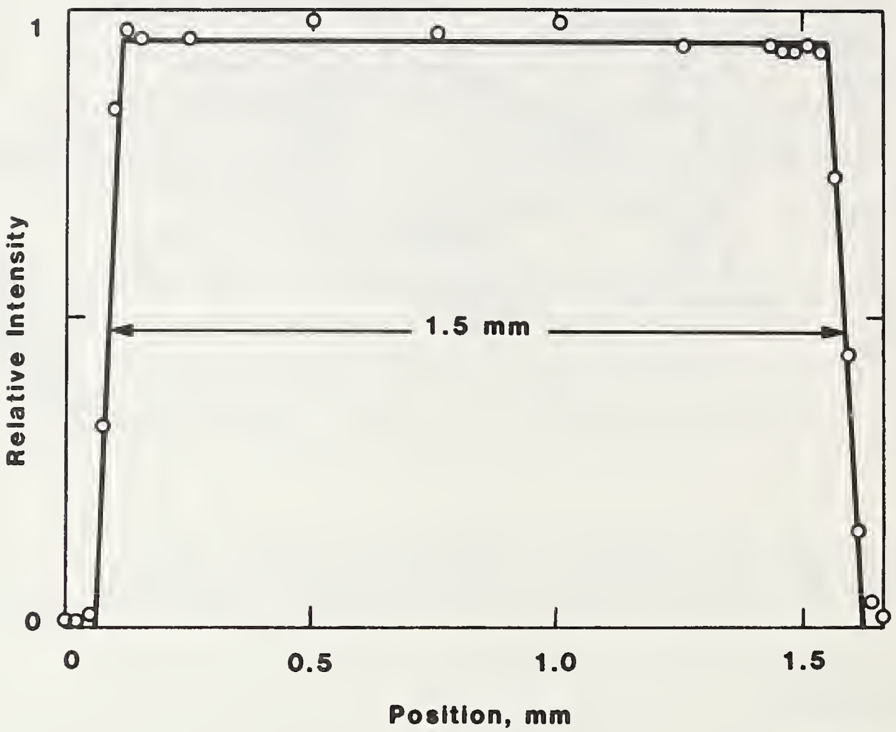

Figure 2. Intensity as function of position in plane of sample. Resolution limit is 25 μm.

pattern. Using the relay lens to image the aperture stop in the plane of the sample eliminates this error by locating a pupil, or a virtual aperture, precisely in that plane. The principle is identical to that of imaging pupils in a telescope.

We determined the uniformity of the illumination by scanning the sample plane with a 25-μm slit oriented perpendicularly to the plane of incidence. Figure 2 is the result of one such scan; the beam is uniform to about 2 percent.

The impulse response of the system is the profile of the light diffracted or scattered by the transform lens. At angles of 10 or 20° off axis, this may amount to 10^{-6} or so of the power measured at 0° and may be comparable to the power scattered at those angles by a weak scratch. Hence, we inserted a glare stop to the right of the transform lens to cut off a line of sight from the lens to the detector, except very near the axis. The glare stop ensures that the impulse response will be very nearly zero beyond a few degrees off axis.

A slit precedes the detector; it is 2.5 mm wide and 1 cm high. The width of the slit determines the angular-resolution limit as well as the total scattered power that falls onto the detector at any angle; it is chosen so that the resolution limit is about 0.3°. The height of the slit is sufficient to capture light scattered out of the detector plane in case the scratch is not precisely perpendicular to that plane.

The detector is a silicon photodiode with a built-in operational amplifier. The photodiode is a 2.5-mm disk. We therefore require a field lens to project onto the detector all the light that passes through the centimeter-high slit. This is accomplished by choosing the lens so that it images the scratch onto the plane of the detector. The entire assembly is enclosed in a box with a red glass filter (not shown) to reduce stray light. A mechanical chopper modulates the incident beam for detection of the scattered light with a lock-in amplifier.

The entire experiment is computer controlled. The computer drives a stepping motor, which revolves the detector about the axis of the sample, acquires data from the detector and the reference detector, and ultimately processes and plots the data and records a paper copy of the graphics. In addition, the computer automatically changes the range of detection by switching a precision feedback resistor in the detector circuitry. There are six such feedback resistors, each about ten times the resistance of the last; counting an order of magnitude or so for the lock-in amplifier, this yields a range of seven or eight orders of magnitude in total.

We checked the linearity of the system by measuring the transmittance of a filter on each of the ranges of the detector; the intensity was reduced each time by attenuating the beam by approximately a factor of 10. The measured transmittance of the filter was plotted against the nominal optical density of the attenuating filters. The result should be a line with a slope equal to zero, so we calculated the slope and standard deviation of the slope with a linear least-squares fit. The data shown in Fig. 3 yielded a slope of -1.0×10^{-3} and a standard deviation of the slope of 0.8×10^{-3}. The slope is

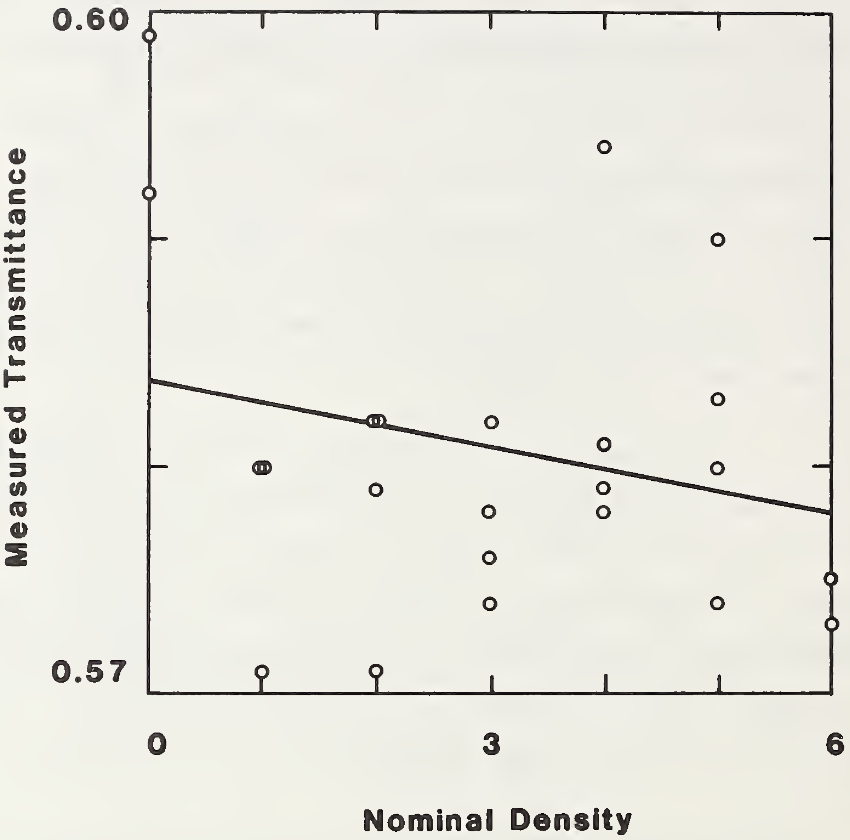

Figure 3. Measured transmittance of a filter at various intensities. Horizontal scale is the nominal optical density of filters used to attenuate the beam. Solid line is a line of best fit and shows slope of ~0.1 percent per decade.

therefore practically zero but gives rise to an error of 0.1 to 0.2 percent per decade, as the intensity is decreased. In addition, we estimate an error of less than one percent per decade owing to uncertainty in the feedback resistors, with an additional error of about three percent on the most-sensitive scale, where the precision resistor is not so well characterized.

After checking detector linearity we tested the system by measuring the diffraction patterns of some precision slits. Figure 4 shows two such scans. The first graph is a plot of the measured diffraction pattern of a nominally 50-μm slit. The black dots are the calculated values of the maxima relative to the intensity of the principal maximum; they are calculated using 51 μm, which fit the data better than the nominal value. The minima are not zero

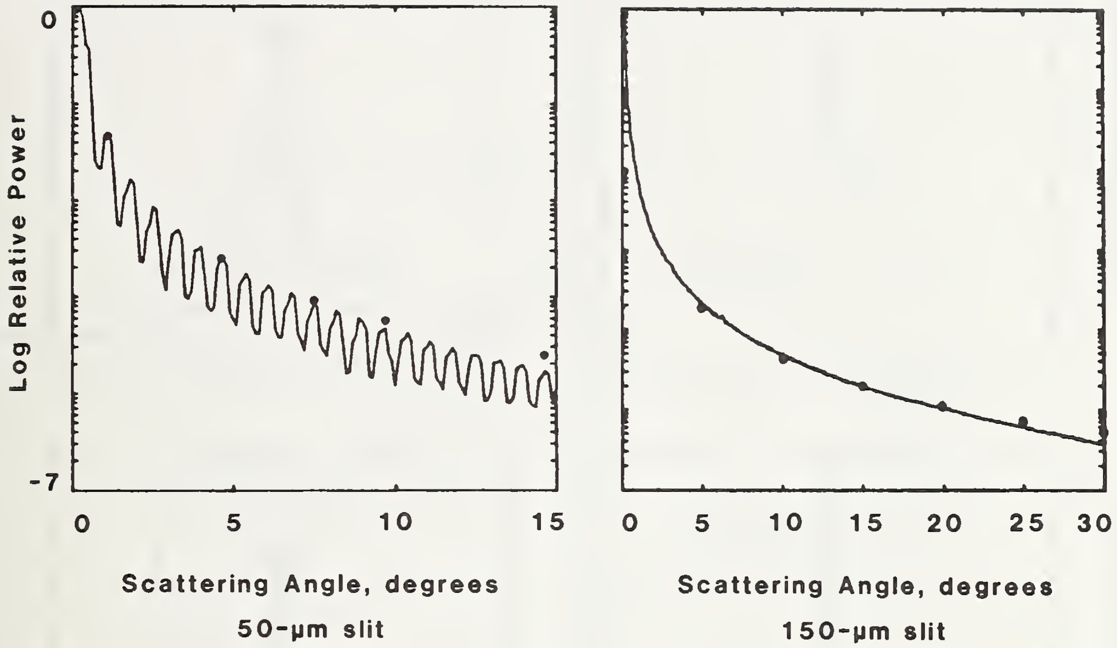

Figure 4. Diffraction patterns of 50-µm slit (left) and 150-µm slit (right). Black circles are calculated values using 51 µm and 150-µm widths.

because of the finite size of the scanning aperture (which is only three or four times smaller than the width of the sidelobes). Beyond 10° or so, phase errors resulting from slit irregularities cause slight deviations of theory from experiment.

The second graph in Fig. 4 is the diffraction pattern of a 150-µm slit. Here the system does not resolve the sidelobes because the detector width is about equal to the sidelobe width. The four black dots are calculated values, which include a correction factor to account for the detector width.

4. Measurements on Existing Standards

We have run polar scans of the intensity scattered by several sets of scratches that had previously been classified by visual comparison with the master standards housed at Picatinny Arsenal [6]. Scans of a set designated number 1 are shown in Fig. 5. The structure seen in the 1-60 and -80 scans is typical of some of the wider scratches and results from the use of coherent

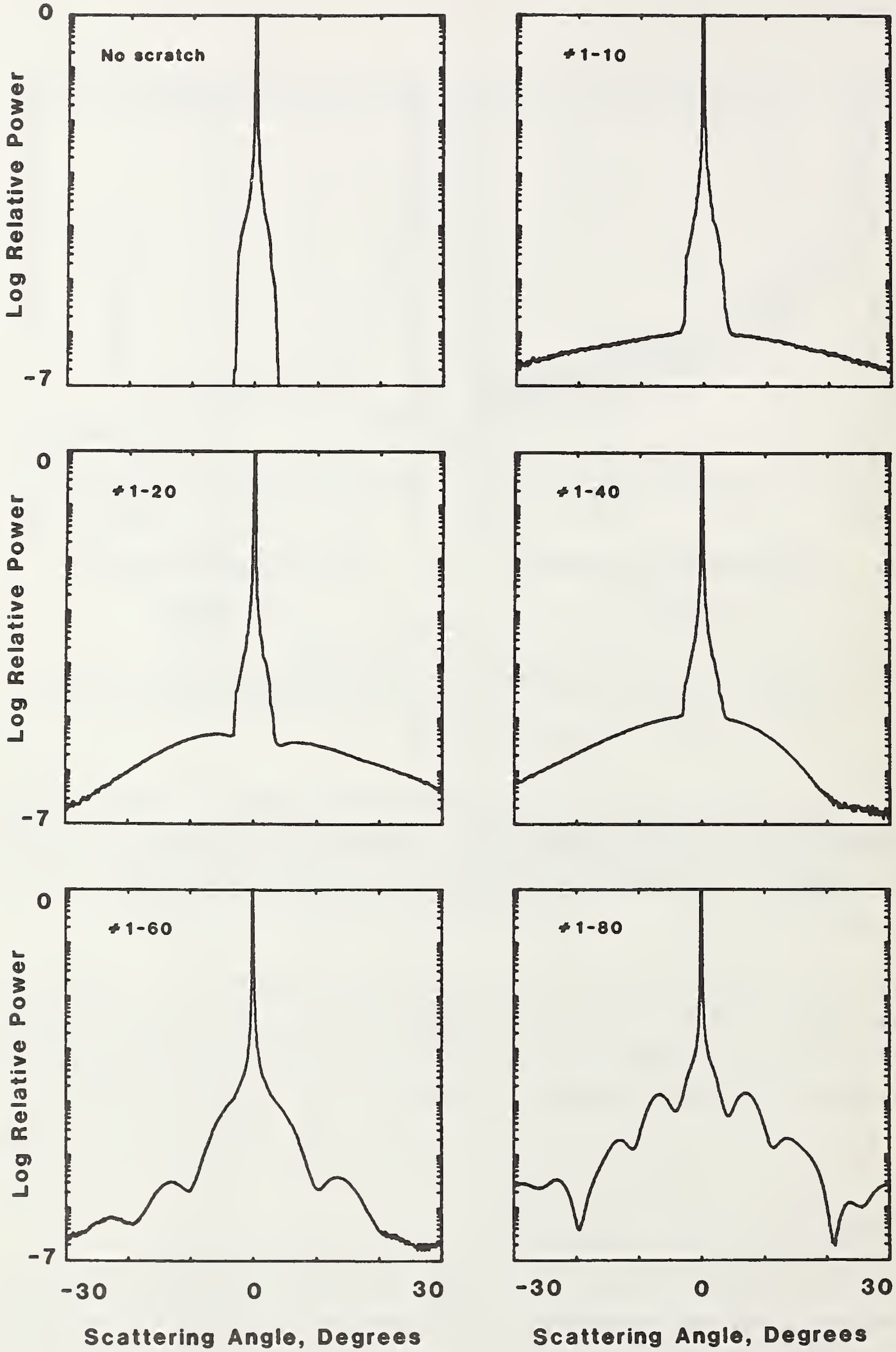

Figure 5. Power scattered as function of angle for set of scratches designated number 1. Curve labeled "No scratch" shows beam with no sample present. From reference 6.

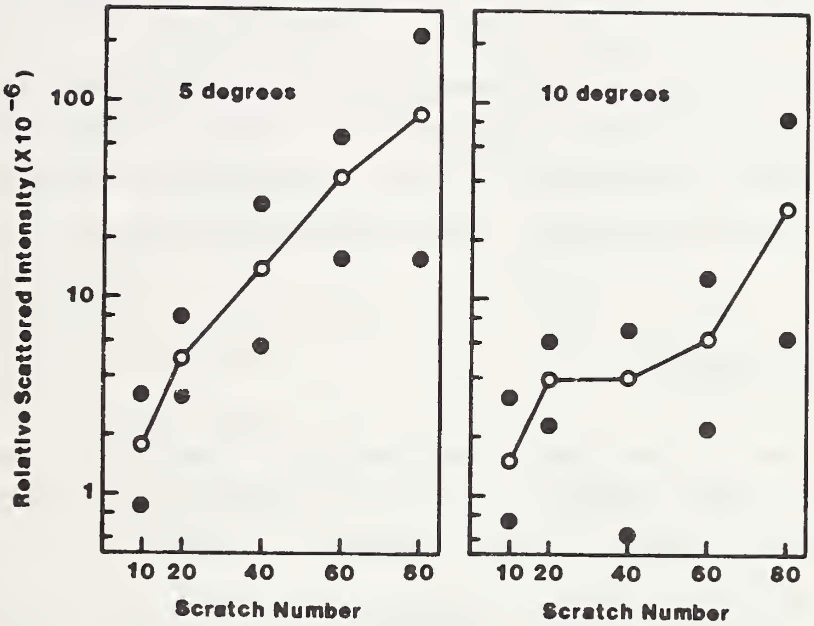

Figure 6. Power scattered at ±5 and ±10° as a function of scratch number. Open circles are averages of five artifacts (ten points); closed circles are extrema. From reference 6.

Table 1. Relative power detected at ±5° and ±10°.*

Scratch designation	±5°			±10°		
	Lo	Av ± 1 σ	Hi	Lo	Av ± 1 σ	Hi
10	0.89	1.8 ± 1.0	3.2	0.75	1.5 ± 0.9	3.2
20	3.2	4.9 ± 1.6	8.1	2.3	3.9 ± 1.2	6.1
40	5.7	14 ± 10	30	0.63	4.0 ± 2.2	7.0
60	16	41 ± 19	66	2.2	6.3 ± 3.8	13
80	16	85 ± 76	220	6.4	29 ± 26	84

*Units of 10^{-6}. Average of four sets, or eight measurements per designation. σ = standard deviation.

light; with a somewhat extended, broadband source such as those used for visual observations, the curves would be substantially smoother.

Table 1 is a compilation showing the relative power scattered by different samples at angles of 5 and 10° off axis; it lists the lowest, highest, and average values for four sets of scratches. When plotted on a semi-logarithmic scale (Fig. 6), the average 5° data are nearly linear with designation. Still, the data show a fairly large spread, only some of which results from the accidental minima that result from the use of coherent light. The data points overlap in such a way that a given designation could not always be distinguished from its nearest neighbor by a single photoelectric measurement.

5. Proposed New Standards

The data shown in Fig. 6 become very uncertain beyond 10° or so. Near zero, the specular beam interferes with the observation. We therefore restrict our consideration to the range between 5 and 10°.

We wish to design an artifact standard that can be manufactured by photolithography or electron-beam lithography. We suggest that the scattering pattern should approximately match our experimental 5° data and peak between 5 and 10°. An etched grating may be manufactured to meet these criteria.

This grating must be narrow enough that the eye cannot resolve it at the shortest distance of distinct vision, d_v [9]. If the eye were diffraction limited, this would imply that

$$w \lesssim \lambda d_v/D, \tag{4}$$

where w is the overall width of the grating and D is the diameter of the pupil of the eye. If we assume that $d_v = 25$ cm and $D = 5$ mm, we find that w must be less than 27.5 μm for visible light whose average wavelength is about 550 nm. (In reality, w can be somewhat larger than this value because the eye is not diffraction limited when D = 5 mm.)

To be useful as an artifact standard, a grating must imitate the visual appearance of a true scratch; a single sharp diffraction maximum will not suffice. Therefore, we, in essence, generate grating ghosts by specifying a grating whose spatial frequency is not a constant but varies symmetrically with distance from the center of the grating [10]. (If the grating is not symmetrical about its center, the radiation pattern will be skewed to one side.) A grating designed in this way will display a scattering pattern that is broad rather than sharp.

To design the gratings, we have developed a scalar diffraction theory; it has been reported earlier and is too lengthy to discuss here [10]. We have used the theory to calculate the intensity scattered by gratings composed of rectangular grooves, with modulated spatial frequency as just described.

For simplicity, we make all the grooves the same width. The intensity scattered (that is, diffracted) by a set of identical grooves is equal to the appropriate interference pattern multiplied by the diffraction pattern of a single groove [9]. Thus, the groove width determines the location of the first diffraction minimum, which we require to be beyond 15°, in agreement with our decision to design for uniform scattering between 5 and 10°. Equation (2) shows that the first minimum appears at the angle λ/b, where sinc $\phi = 0$; each groove must therefore be less than 8 μm wide.

Equation (2) also shows that the scattered intensity varies with the depth t of the groove. Because of the $\sin^2$ variation of scattered intensity with depth, the scattered intensity is least sensitive to depth error when the grooves are one wavelength deep. If the grooves are less than this depth, the scattered intensity is reduced by the factor $\sin^2 (\pi t/2\lambda)$, but the overall pattern is not changed. Therefore, we may calculate the scattered intensity for any convenient depth and use this factor to scale to other depths.

By varying the depth and number of grooves in each grating, we are able to simulate the scattering pattern of any scratch.

We performed calculations on frequency-modulated gratings shown in Fig. 7. For simplicity, we impressed a linear modulation term onto the spatial frequency of the grating. For the case of an odd number of grooves, the position x_m of the ±mth groove with respect to the grating center is given by

$$x_m = mx_1[1 + r(m - 1)], \tag{5a}$$

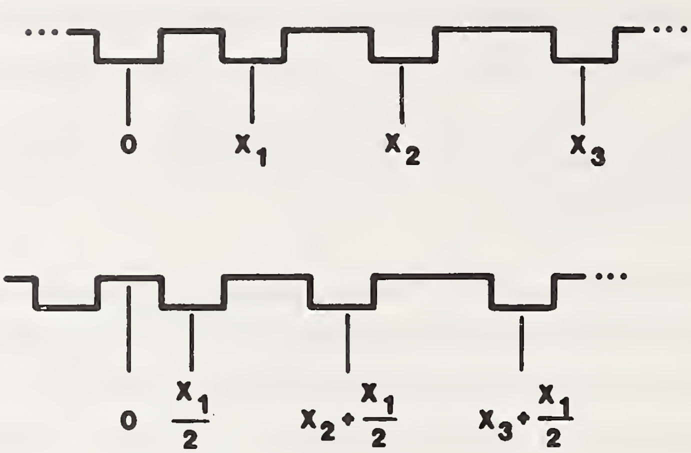

Figure 7. Proposed frequency-modulated gratings. Sketch shows positions x_m of grooves with respect to center 0. Upper sketch: odd number of grooves. Lower sketch: even number of grooves.

where m is an integer, $0 \leqslant m \leqslant (N - 1)/2$; r is a number of the order of 0.1; and x_1 is the location of the first groove from the center. If r were zero, the grating would have uniform spacing x_1. [In the terms of Ref. 10, $x_1 = \lambda_0(\alpha + \beta)$ and $r = \beta/(\alpha + \beta)$.]

The case where the number of grooves is even is shown in the lower part of Fig. 7; the position x_m may in this case be given by the expression,

$$x_m = (2m - 1)x_1[1 + r(m - 1)], \tag{5b}$$

where $1 \leqslant m \leqslant N/2$. [In the terms of Ref. 10, $x_1 = (\lambda_0/2)(\alpha + \beta/2)$ and $r = \beta/(\alpha + \beta/2)$.] In this notation, the two centermost grooves are separated by $2x_1$, center to center.

Figure 8 shows calculated scattering patterns of gratings with various parameters. In all cases, the wavelength is 0.55 μm and the width of the grooves is b = 1.1 μm. The latter value has been chosen to ensure that the first minimum of the diffraction pattern of a single groove is well beyond 10°. By adjusting b, x_1, and r, we may approximately match any data within a restricted range of angles. Scattering is small outside that range. Likewise, by adjusting the depth of the grooves, we can match any intensity. Thus, we have a means for simulating the scratch standards by an etching technique.

After consulting with the sponsor and his consultant, we decided to design the artifacts for peak intensity at 7.5°. The number of grooves, the groove width, and the groove depth are to be chosen so that the peak scattered intensity roughly follows the 5° data of Fig. 6; that is, a semi-logarithmic plot of the peak scattered intensity should be approximately linear and have an overall range on the vertical axis of just less than two orders of magnitude.

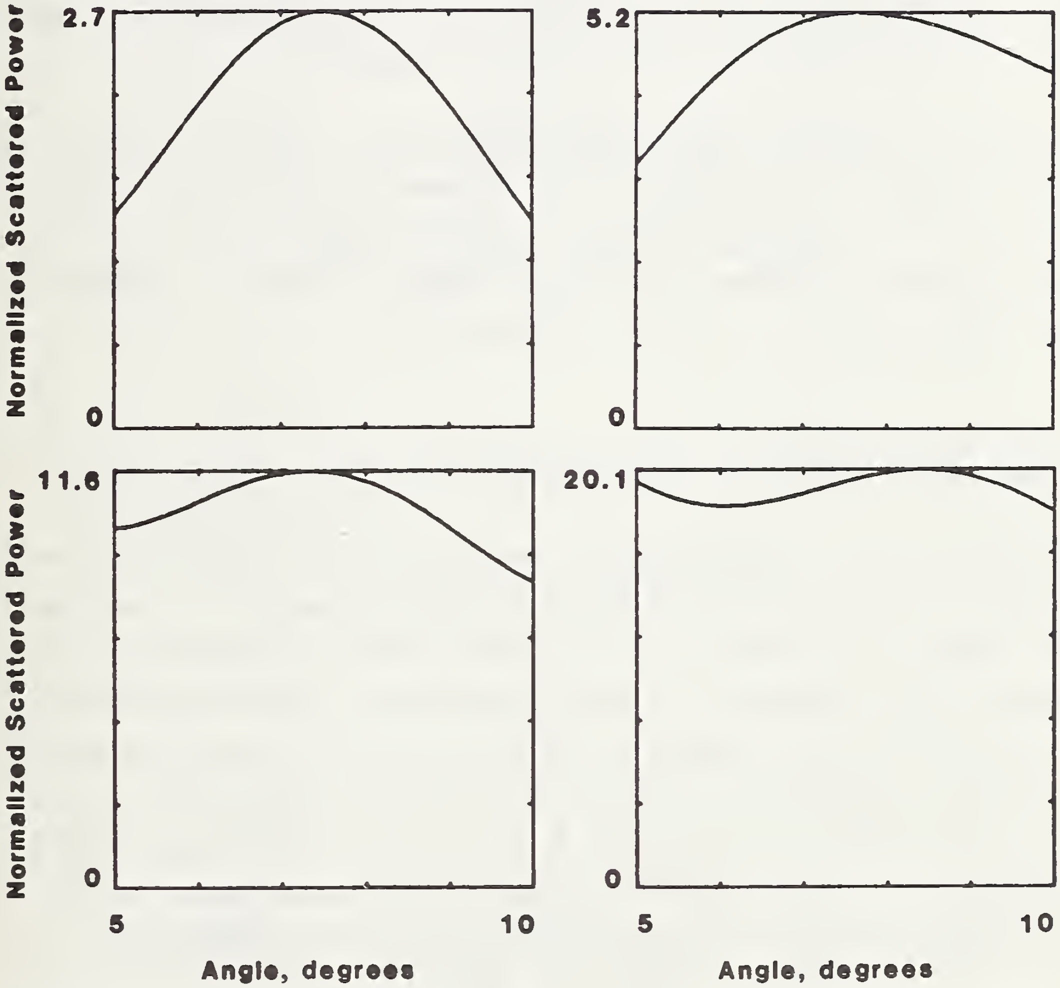

Figure 8. Four calibrated curves whose peak intensities span about one order of magnitude and are roughly linear when plotted logarithmically. Intensities are normalized to intensity calculated for single groove at 5°, actual values depend on depth.
Upper left: $x_1 = 4.1$ μm, $t = 4.07$ μm, $r = 0.1$, $N = 2$;
Upper right: $x_1 = 4.2$ μm, $t = 4.235$ μm, $r = 0.09$, $N = 5$;
Lower left: $x_1 = 2.5$ μm, $t = 2.475$ μm, $r = 0.1$, $N = 12$;
Lower right: $x_1 = 1.9$ μm, $t = 1.925$ μm, $r = 0.7$, $N = 18$;
In all cases, $b = 1.1$ μm.

Figure 8 shows theoretical curves for four gratings that could be used to simulate the existing standards. All the grooves have the same width $b = 1.1$ μm. The depth is arbitrary in that the vertical scale is in each case normalized to the power scattered at 5° by a single 1.1-μm groove. The other parameters are as noted in the caption.

The power scattered by these four gratings has a range of a factor of 7.5. Their peak powers are roughly linear on a semi-logarithmic plot like Fig. 6. Unfortunately, the four gratings do not all have the same depth, so they could not be manufactured on a single substrate.

Figure 6 shows that the overall dynamic range must be a factor of 50, and more if an S-120 or -160 scratch is to be added. Equation (4) prohibits an arbitrarily large number of grooves. However, several sets of gratings such as these four may be etched to different depths to extend the dynamic range to several factors of 7.5.

6. Experimental Results

We have received several sets of artifacts etched into white crown glass. One of these artifacts was a single groove, approximately 0.55 μm (one wavelength) deep and 1 μm wide. A scan of the intensity scattered by that groove is shown in Fig. 9, where it is also compared with the prediction of Eq. (2). The curves differ by a constant factor of 2; this may be attributed to the fact that the actual cross section of the groove is not perfectly rectangular and that the width is not precisely 1 μm. In particular, any rounding of the groove will give rise to enhanced scattering; the experimental result is therefore expected to be greater than the theoretical prediction.

Comparison with Fig. 6 shows that the single groove corresponds very nearly to the average S-20 scratch. This piece of information, along with the scaling rules and the theoretical curves such as those in Fig. 8, allows the designer to specify a grating for virtually any scattered intensity.

We chose for further examination some single grooves and 10-groove gratings. The latter were tuned to exhibit a diffraction peak near 8°. They had a "chirp factor" r of about 0.1; the spacing $2x_1$ between the centermost

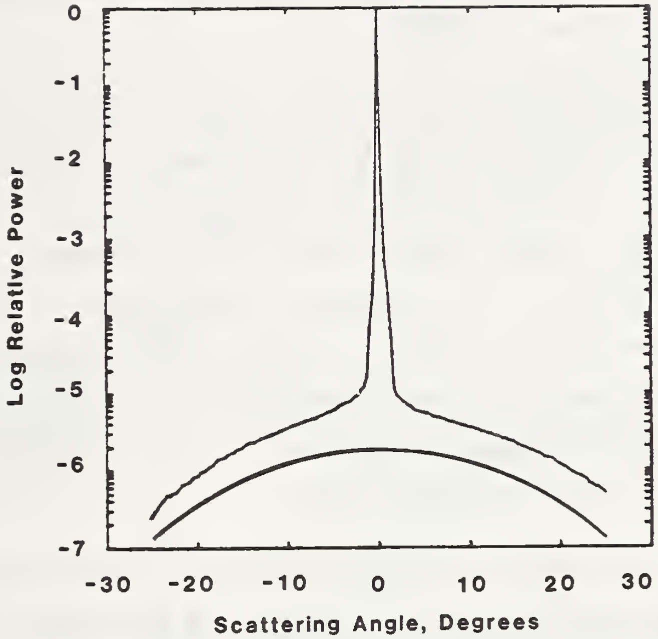

Figure 9. Power scattered by single, etched groove, nominally 1.0 µm wide and 0.55 µm deep. Lower curve is calculated for rectangular groove with those dimensions.

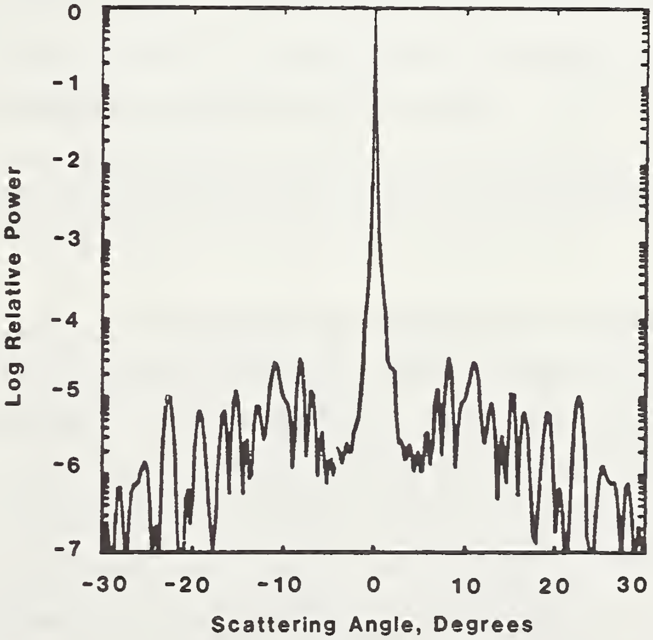

Figure 10. Power scattered as function of angle by 10-groove artifact that has been classified S-40 by trained observers.

grooves was about 2.88 μm. The groove width was between 1 and 1.5 μm, depending on the etching process. The depth of the grooves depends on processing and is unknown at the time of writing.

The artifacts had the appearance of a visual scratch. Some were sent to Picatinny Arsenal for classification by their standard visual comparison with the primary standards. They were then forwarded to NBS for our polar scan. Figure 10 shows a polar scan of one of the 10-line gratings. The peaks and valleys are the result of using a coherent source, which has nearly zero beam divergence. The peaks typically have angular subtense of about 1° (full angular width at half maximum). Visual observations are performed with an incoherent source that subtends several degrees; as a result, observers do not see the fine structure in the diffracted beam.

To compare the photoelectric measurements with the visual assessments, we averaged the highest peak with its nearest trough (in almost all cases this was the same as dividing the peak value by 2). This procedure has nearly the same effect as increasing the angular subtense of the source. For the single grooves, we used the intensity scattered at 5°.

Figure 11 shows the results, plotted as in Fig. 6 [8]. The solid line connects the average values, as in Fig. 6. The points are the new data: An x represents a single, chemically etched groove; a plus sign represents a 10-line, chemically etched grating; and a triangle represents a 10-line, ion-beam-etched grating. Each point is labeled according to its classification by trained observers. H means the artifact was judged to be on the high side and L, on the low side.

The data for the multiple-groove gratings at 5° fall agreeably (to us!) close to the solid line, whereas the single-groove data show a variance comparable to the ordinary submasters. We attribute this to the fact that the gratings were designed to exhibit an off-specular peak, which forces the observer to look at a specific angle. The way testing is performed today, we cannot know at what angle the observer views the single grooves, and this can affect the results. In addition, the isolated grooves simulated S-10 and -20 scratches; these are comparatively difficult to see, and we expect some uncertainty.

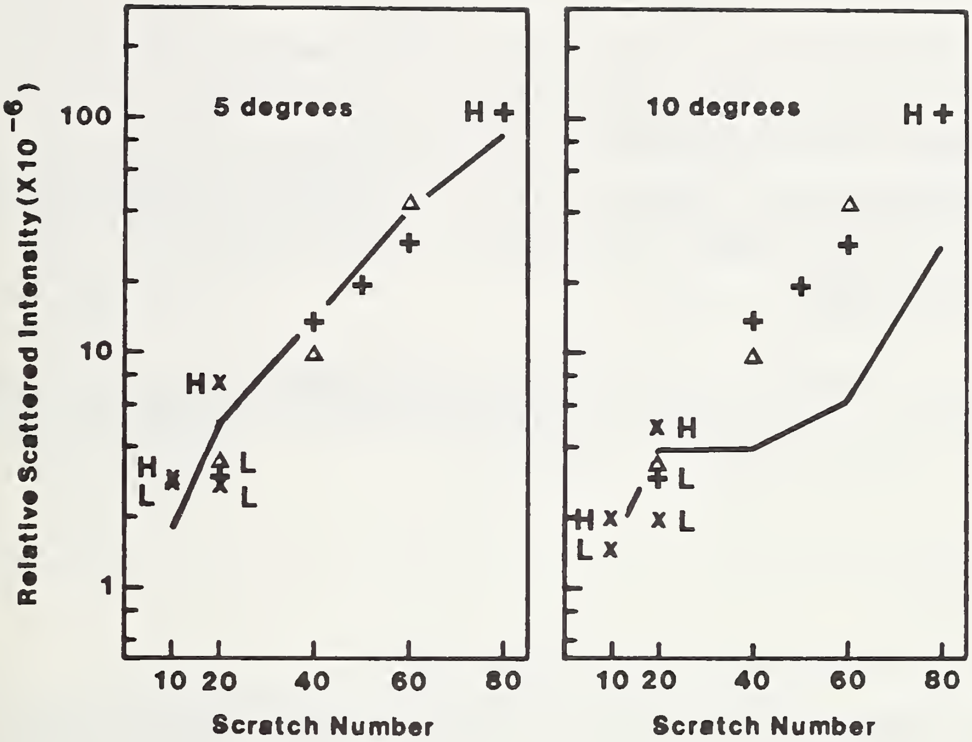

Figure 11. Power scattered by etched artifacts at ±5° and ±10°, as function of visual classification, as in figure 6. Solid line is the solid line in Fig. 6. "H" and "L" stand for "High" and "Low" in appearance.

7. Conclusions and Recommendations for Future Work

Further analysis of the prototypes is still under way; standards can be manufactured after perhaps one or two more experiments.

We recommend that, where possible, the artifacts be made of multiple-line gratings, which we have found to be more accurately evaluated by eye. We have further suggested that the sponsor consider manufacturing S-120 or -160 scratches as well as the existing set. Finally, we have noted that the S-20 scratch is quite close to the S-40 and should perhaps be dropped.

As long as the manufacturing process is sufficiently well controlled, a simple photoelectric device should be adequate to test the artifacts objectively. We recommend that (at least for testing the submasters) such a device be designed and built to replace the present visual system.

Matt Young performed the experimental work, and Eric Johnson conceived and carried out the chirped-grating theory. We are indebted to John Salerno for his support and encouragement, and for supplying the scratch samples; to Richard Goldgraben for a yeomanly effort in providing the etched-grating samples; and to Edie DeWeese for preparing the manuscript in her usual excellent and cheerful fashion.

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11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

The scratch standard (MIL-O-13830A) is a cosmetic standard that is effected by a visual comparison with a set of submasters that are in turn evaluated by comparison with a set of master standards. Both manufacture and certification of the submasters are somewhat unreliable. In this paper, we show that the submasters can be classified according to the relative power scattered at a relatively small angle. We have designed etched gratings with which to replace the submasters; these gratings have the appearance of scratches but diffract a broad peak between 5 and 10 degrees off the axis of the incident beam. We have classified some prototypes both by comparison with the master standards and by a photoelectric measurement; agreement between the two methods is good. We suggest that such gratings be used as the submasters and possibly that they be classified by a photoelectric rather than visual measurement.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*
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