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STRAY LIGHT IMPLICATIONS OF SCRATCH/DIG SPECIFICATIONS

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Stray Light Implications of Scratch/Dig Specifications*

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Abstract

The bidirectional transmittance distribution function (BTDF) of two sets of scratch/dig standard sets were measured. These sets were representative of the inspection standards used in the optical industry to characterize polished surface defects. Measurements were taken with a small (1 mm diameter) illumination beam to maximize signal. The increase in average BTDF that results from a single scratch or dig over the MIL-STD 20 mm diameter surface was then calculated to determine what overall impact a defect will have on system stray light above base surface scattering due to surface micro-roughness. A BTDF measurement was taken with the illumination beam centered on the defect, then with it centered on a smooth section of the reference sample to find the increase in scattering caused by the defect.

Results show that dig scattering, when normalized to account for the single dig per 20 mm MIL-STD inspection area criteria, did not catastrophically increase the 0.05 B_0 (B_0 is the BTDF at 0.57°) at 633 nm characteristic of a high quality optical surface. As intuitively expected, dig scattering was angularly symmetric. Scratches, however, scattered highly directionally. Normalized BTDF is substantially increased from a smooth surface's typical 0.05 B_0 perpendicular to the scratch axis, but is unaffected in other angles. On average, the scratches may not have increased net surface scattering.

Scattering from the defects on the surfaces below the 40-20 scratch/dig level was found to not cause a catastrophic increase in scattering over the level os a well-polished optic (typically 4Å rms roughness). Since comparisons with scratch/dig samples only serve to provide a measure of the localized defects, and fail to be useful in determining the low-level scattering from the surface microroughness, one should not assume that a "40-20" surface is necessarily a low-scattering optic.

Introduction

Sensor systems designers have always had to worry about overall performance margin in the presence of stray light. In order to achieve a signal to noise ratio, the amount of scattering from bright out-of-field radiation sources onto the focal plane (or film plane) must be controlled. In many systems, the scattering off the optical elements, which is a function of the optical surface quality or microroughness, is the limiting factor in out-of-field stray light transmission to the focal plane.

The best way to measure surface scatter is a direct test of the scattering, such as bidirectional reflectance distribution function (BRDF) or bidirectional transmittance distribution function (BTDF). The method preferred in the absense of scattering measurement capability is surface roughness data, which generally correlates well with BR/TDF. Unfortunately, the cost in capital equipment and time associated with both of these tests (especially the BR/TDF tests) is often prohibitive. Most optical houses cannot perform either test. The optical industry standard is the scratch/dig reference. The scattering from these standards is visually compared to the scattering of the optical surface in question. While this is a good technique for

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determining scatter from the prominent defects, it does not allow information on the average scattering over the entire surface.

Past work has been published about the confusion surrounding standard sets[1]. (Common scattering community perception is that quantitative BR/TDF can vary by up to a factor of ten between so called standards). While reference articles with attempts to malign the standard were readily available, no articles that characterize the scattering from the standards were found. No data was found relating the average scattering of a scratch or dig to an overall surface BRDF. This study was undertaken to quantify the typical amount of scattering from surface flaws and to find the resulting impact on average surface BR/TDF.

Experiment.

Two sets of scratch/dig standards were purchased from Beale Optical. Since the purpose of this project was to find typical scattering values of defects, variation between the two sets was not a concern. To the contrary, by inspecting 2 sets of reference marks, it was hoped some insight into the variation between "reference" standards could be gleaned. Our end goal was to determine how the surface quality specification of an optic purchased from the optical manufacturing community related to scattering from the entire surface.

The first step in the characterization of the two standard sets was a visual comparison with OCA's quality control standards, which were received from and have been annually recalibrated by the Frankfort Arsenal.[2] Apparent brightness was evaluated both in transmission and in reflection. Two evaluators compared the Beale sets to the OCA standard. One evaluator was a quality control inspector, familiar with the standard visual comparison through 15 years of optical QC experience; the other evaluator was the primary author of this paper. The second step in the characterization was scattering measurements

The general trend: the newer Beale standards of a particular flaw appear dimmer than reference flaws from the Frankfort Arsenal set. For example, one of the #80 scratches from the newer sets is visually equivalent to the #60 scratch from the Frankfort Arsenal reference set.

BTDF Measurements.

BTDF data was taken with an elliptical gaussian illumination beam, with 1/e points at ±0.23 mm vertical by ± 0.30 mm horizontal. Instrument profile of the scatterometer was performed for this beam diameter, and was saved for comparison.

The illumination spot was centered on the defect with centration search precision of 1/10 spot diameter.

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[1] Young, Matt. "The scratch standard is only a cosmetic standard", SPIE Vol. 1164 Surface Charaterization and Testing II (1989), pp. 185 - 189.

[2] Historically, scratched and digs were fabricated solely by and rated against a reference at the Frankfort Arsenal. Later, scratch/dig widths were given in MIL-O-13830A in an attempt create a universal reference that could be fabricated at remote facilities. This is generally considered to yield only marginally correct comparison flaws, with yearly Arsenal re-calibrations *de rigueur* procedure to ensure uniformity among scratch/dig QC sets.

Centering is determined by maximizing the observed scatter. Scattering from digs was found to be angularly invariant, so a single rotation position was measured for each sample. Scratches, however, scatter quite preferentially in the direction perpendicular to their axes. Scans are performed in this maximum scatter direction, and in the perpendicular direction. To determine how constant the stray light is along the scratch, measurements were taken at 2 points. Scratch alignment is performed visually by observing the scatter from the defect, rotating the sample first for maximum scattering in the horizontal scan axis, then for maximum scattering in the vertical axis. (The scatterometer always sweeps in the horizontal axis.) For reference of the sample scattering surface in the absence of the defect, the BTDF is scanned with the illumination spot centered on an area that is visually free of defects.

Data Analysis.

The goal of these experiments is to quantify the increase in scattering caused by a given defect level over a uniformly illuminated surface. Intuitively, it can be seen that the scattering of a surface under uniform illumination, I_o, is the sum of the scattering over smaller segments when each is illuminated with I_o. Figure 1 illustrates this principle.

BTDF is the energy scattered (per solid angle), divided by the energy impinging on a surface. Consider a surface broken into two sections, of areas A_1 and A_2, with a uniform illumination of total energy E impinging on the surface. The light scattered from A_1 at an angle q, $E_{s1}(q)$, is:

$$E_{s_1} = \frac{E \cdot A_1}{(A_1 + A_2)} \cdot BTDF_1\,(q) \qquad (1)$$

and the energy scattered from area A_2 is similarly:

$$E_{s_2} = \frac{A \cdot A_2}{(A_1 + A_2)} \cdot BTDF_2\,(q) \qquad (2)$$

The BTDF of the entire surface is $(E_{s1} + E_{s2}) / E$:

$$BTDF\,(q) = \frac{A_1 \cdot BTDF_1\,(q) + A_2 \cdot BTDF_2}{A_1 + A_2} \qquad (3)$$

Since scratches and digs occupy only a small area fraction of the optical surface, by definition of the cosmetic standard which limits the number of defects in any 20 mm observation diameter, the average BR/TDF over the entire surface cannot be significantly affected unless the scattering is quite high from the local defect.

The amount of light scattered from a defect is proportional to the light incident on the defect. The BR/TDF, equal to scattered light divided by total incident light, is proportional to the light incident on the defect divided by the total illumination spot diameter. In effect, larger measurement beams dilute the influence of the defect with average scattering from the nominal surface. To maximize the BTDF measurement from a defect, illumination should be done with the minimum reasonable beam diameter. This ensures that the fraction of scattered light divided by incident light is a maximum, increasing the local

BTDF measurement to hopefully higher than that of the average surface.

In the CASI-C2 scatterometer, the illumination beam is not a constant: it is a gaussian. This alters the previous equations (Eqs. 1 - 3). With the largest scratch nominally 8 μm wide, no concern exists that the illumination varies over the scattering width. Normalization is, however, required for the variations along the beam diameter over the length of a scratch, and for the higher flux density of the central beam portion over the diameter of a dig. At the larger dig diameters, up to 0.5 mm, the illumination density does vary across the defect, making interpretation of the results somewhat ambiguous: scattering from the center/edge of the dig will be based on varying illumination intensity.

Figure 2 illustrates the averaging of the effective scattering over a 20 mm diameter surface area from a BTDF measurement with a smaller gaussian illumination beam. Variance in illumination intensity is seen along the length of the scratch. Considering the definition of cosmetic finish, one 20 mm long scratch can exist within a 20 mm diameter clear aperture. If a scratch were illuminated with a flux density source, I_0 {W/cm^2}, the amount of light scattered into a particular viewing solid angle would be BTDF · I_0 · W · L, where W and L are the width and length of the scratch. This is the integral along the length of the scratch of:

$$E_s = \int_l \mathrm{BTDF} \cdot I_o \cdot W\, dl \qquad (4)$$

With gaussian illumination, I is a function of L, but not W as mentioned earlier. Note that the experimental beam was an elliptical gaussian, so vertical and horizontal scratch orientations must be treated separately. For beam 1/e radius w_0 in the direction of the scratch width, and 1/e radius of l_0 along the length of the defect, and a total energy of E_0, the beam illumination intensity function is given by:

$$I(w,l) = \frac{E_o}{P\, w_o l_o} \cdot e^{-\left\{\left(\frac{w^2}{w_o}\right) + \left(\frac{l}{l_o}\right)^2\right\}} \qquad (5)$$

Integrating along the length of the scratch over a 20 mm maximum length to find the average flux density on the scratch:

$$\frac{1}{WL} \cdot \int_{-w_s}^{w_s} \int_{-10\,mm}^{+10\,mm} I(w,l)\, dl\, dw$$

$$\frac{1}{P\, w_o\, l_o\, WL} \cdot E_o\, P\, w_o\, l_o \cdot \mathrm{erf}\left(\frac{w_s}{w_o}\right) \cdot \mathrm{erf}\left(\frac{10\ mm}{l_o}\right)$$

$$\frac{E_o}{WL} \cdot \mathrm{erf}\left(\frac{w_s}{w_o}\right) \cdot \mathrm{erf}\left(\frac{10\ mm}{l_o}\right)$$

$$@\frac{E_o}{WL} \cdot \mathrm{erf}\left(\frac{w_s}{w_o}\right) \qquad (6)$$

This simplification of erf { 10 mm/ l_0 } is possible for the small gaussian beam radii (l_0) used in our experiment.

The energy impinging on the defect is:

$$E_o \cdot \operatorname{erf}\left(\frac{W_s}{W_o}\right) \tag{7}$$

From Eqs. 1 - 3, recall that the total scattering from a surface is a function of the energy impinging on the surface. The scatterometer instrumentation registers the ratio of scattered light to total light incident on the measurement piece- not just the total light incident on the defect. The measured BTDF values must thus be multiplied by a correction factor that accounts for the ratio of energy on the defect to total illumination energy to find the true, or corrected, BTDF, before incorporation in equations 1, 2, and 3.

$$BTDF_{corrected} = \frac{BTDF_{meas}}{\operatorname{erf}\left(\frac{W_s}{W_o}\right)} \tag{8}$$

For a constant illumination intensity, I_s, the energy impinging on the scratch, E_{scr}, would be $I_s \cdot WL$, and the amount of scattered energy would be $E_{scr} \cdot BTDF_{corrected}$. The scattered energy from the normal surface finish over the 20 mm defect definition area is :

$$BTDF_{surf} \cdot I_s \cdot \pi/4 \cdot (20\ \text{mm})^2 \tag{9}$$

where BTDF is the BTDF of the base surface without defects. The percentage of increase in scattered light is:

$$\%\ \text{increase BTDF} = \frac{100 \cdot I_s \cdot BTDF_{meas} \cdot WL}{\operatorname{erf}\left(\frac{W_s}{W_o}\right) \cdot BTDF_{surf} \cdot I_s \cdot \frac{P}{4} \cdot (20\ \text{mm})^2}$$

$$= \frac{100 \cdot BTDF_{meas} \cdot WL}{BTDF_{surf} \cdot \operatorname{erf}\left(\frac{W_s}{W_o}\right) \cdot \frac{P}{4} \cdot (20\ \text{mm})^2} \tag{10}$$

Figure 3 shows the scattering from a #80 scratch perpendicular to the scratch axis. The width, W, of this defect is defined to be 8 μm, for a w_s of 4 μm. In the experimental set up, the gaussian beam half width is 230 μm vertically and is 300 μm horizontally. It can be seen from the figure that the BTDF slope is actually steeper than -2. This is characteristic of scratch measurements. A second example is given in figure 4. Digs tend to have BTDF slope shallower than -2, as shown in the examples of Figures 5 and 6. The ideal comparison (equation 10) would present impact on BRDF as function of angle. The data presentation in Table 1 summarizes the scattering by selecting a small, fixed range of angles, and extrapolating the BTDF value to the 0.57° scattering angle. This allows a single "$BTDF_{meas}$", reported as B_0 at 0.57°, to compress data. The value is a conservative fit (highest reasonable value) to scattering data in the 5° to 40° angle range.

For a well polished surface at the measurement wavelength of 633 nm, the B_0 value is generally taken as 0.05. Thus, the percentage scattering increase of the defect and base over a 20 mm dia. is the measured B_0 value of the scratch times 69. This is an increase of average surface scatter of up to 4200 percent (42X increase) for one of the #80 scratch references. Table 2 gives the corrected BTDF of each scratch, then the percentage of increase in scattering over a "high quality" 0.05 B_0 surface for one 20 mm long scratch per 20 mm dia. Note that data in Table 2 is given only for scattering perpendicular to the scratch axis. Measurements with a concentrated spot outside a few degrees from perpendicular showed no appreciable increase over the base surface scatter.

For digs, a different set of equations is needed to correlate the overall increase in surface scattering with measured BTDFs. Since the 2-axis gaussian test beam widths are very similar, the illumination function can be approximated by a symmetric gaussian with the average beam radius with little loss of precision. The illumination intensity is modeled by:

$$I(r) = \frac{E_o \cdot e^{-\left(\frac{r}{r_o}\right)^2}}{P\, r_o^2} \qquad (11)$$

(Variations between references have more impact than this illumination simplification. This allows simpler math.) The average illumination intensity over a dig is then:

$$I_{ave} = \frac{1}{P\, r_d^2} \cdot \int_o^{r_d} \int_o^{2P} 2P r\, I(r,q)\, dq\, dr \qquad (12)$$

The energy incident on the dig is $I_{ave} \cdot p\, r_d^2 = E_o \cdot \left\{1 - e^{-\left(\frac{r_d}{r_o}\right)^2}\right\}$

To correct BTDF, as with the scratch measurements, the measured values must be multiplied by the ratio of the total light incident on the test piece divided by the light incident on the defect. This yields:

$$BTDF_{corrected} = \frac{BTDF_{meas}}{1 - e^{-\left(\frac{r_d}{r_o}\right)^2}} \qquad (14)$$

The percentage of increase in scattered light for a dig defect over a 20 mm diameter area is:

$$\% \text{ increase BTDF} = \frac{100 \cdot I_s \cdot p\, r_d^2 \cdot BTDF_{meas}}{\left(1 - e^{-\left(\frac{r_d}{r_o}\right)^2}\right) \cdot BTDF_{surf} \cdot I_s \cdot \frac{p}{4} \cdot (20\ \text{mm})^2}$$

$$= \frac{400\, BTDF_{meas} \cdot r_d^2}{BTDF_{surf} \cdot \left(1 - e^{-\left(\frac{r_d}{r_o}\right)^2}\right) \cdot (20\ \text{mm})^2} \qquad (15)$$

As mentioned before, the illumination density varies substantially over the diameter of the larger digs. With the mean 1/e radius of the illumination equal to 260 μm, the illumination at the outer diameter of a

#50 dig is 40% of the intensity at the center of the dig. Under such circumstances, it would be desirable to know the empirical mechanism for scattering. Specifically, we would want to know how the edge's contribution compared to the center's. This might be done in the future by measuring a single dig with varying gaussian illumination profiles. Correlation between scattering and both average illumination density and illumination density at 250 µm radius can be done. These correlations were not made in this series of tests. In lieu of this, one could examine the variance between digs to determine whether scattering varies with the periphery of the dig and the illumination density at the dig diameter, or with the dig area and the average illumination over the dig. Equations 12 - 14 are developed based on average intensity over the dig area. If this approach is correct, one would expect the corrected BTDF to be relatively constant between dig samples. Table 3 shows the corrected BTDF (based on average illumination density over the dig area), and the percentage of average scatter increase compared to a "high quality" surface without defects. Note that $BTDF_{corrected}$, while not constant, has no readily apparent correlation with dig area.

Alternatively, the scattering can be correlated to the illumination density at the periphery and the length of the dig periphery. In such a case, the illumination density at the periphery:

$$I_{periphery} = \frac{E_o}{p\, r_d^2} \cdot e^{-\left(\frac{r_d}{r_o}\right)^2} \qquad (16)$$

and the corrected BTDF would be the scattered light divided by the total light incident on the dig if $I_{periphery}$ were the uniform illumination density over the dig:

$$BTDF_{corrected} = BTDF_{meas} \cdot \left(\frac{r_o}{r_d}\right)^2 \cdot e^{\left(\frac{r_d}{r_o}\right)^2} \qquad (17)$$

Table 4 lists $BTDF_{corrected}$ based on periphery illumination domination of scatter and the percentage of average scatter increase compared to a "high quality" surface without defects. Note that $BTDF_{corrected}$ varies quite similarly with the calculations on Table 3. Since this table's analysis assumes an edge function, the BTDF should not be expected to be constant for the various dig diameters, as would an area-scattering dig. The corrected BTDF would be expected to vary inversely with dig radius, since the BTDF definition is based on the total energy incident on the defect (varying with diameter^2) while scattering would actually be varying with periphery, which varies linearly with diameter.

Comparing the data correlation in Tables 3 and 4 for the methods of anticipating dig scatter, it is unclear that either of the two dig scattering assumptions is superior to the other. Apparently, scattering variation between the digs is quite large. Definitive empirical scattering mechanism studies would have to be done on a single dig, varying the average to edge illumination ratio. For now, it can be stated that either analytic assumption will yield equally acceptable results.

Conclusions.

The single #50 dig within a 20 mm diameter aperture will increase the overall scattering level of an otherwise 0.05 B_0 {ster^{-1}} smooth surface by approximately a factor of 2 to 3. A #40 dig induces an increase of 2X; a #20 dig 1X; a #10 dig 10%; and a #5 dig 2%. A single large dig in 20 mm diameter will noticeably increase the average scattering of an otherwise high quality surface. The smaller digs do not severely impact the scattering of an optical surface.

Scratches scatter directionally, perpendicular to the scratch axis. A single 20 mm long #80 scratch will increase overall "smooth" surface 0.05 B_0 by 20X to 40X in the maximum scattering direction. No noticeable increase is seen except within a few degrees of perpendicular to the scratch. A #60 scratch increases scatter by approximately 20X; a #40 by 10X; a #20 by 3X, and a #10 by 5X.

Whether the scratch scattering adversely affects system stray light suppression is unclear. While BTDF is certainly increased in one direction, the increase in total scattering may be a more significant measure of system impact, pending stray light propagation path geometry. A suggestion for future experiments would be to conduct TIS measurements with the scratches, and similarly over a "smooth" section of the reference surface, then normalize the effect over the 20 mm diameter inspection criteria as a lower bound for scattering impact.

Variations between reference standards are clearly evident, with the scattering from the #10 scratches actually measuring higher than from the #20 scratches.

Typical data presented in this paper does allow general conclusions about the area-averaged scattering impacts of cosmetic defects. Thus, the significance of a scatch/dig on overall scatter can now be made. On the other hand, comparisons of a surface with a scratch dig standard do not give microroughness data. Meeting a scratch/dig comparison only means that the surface may be as low as the scattering levels measured on the isolated defects (averaged over the surface), but could be much higher if the microroughness is large.

<u>Please note:</u> Since the raw data from the scratches/digs does not follow a $\{ \sin(\text{theta}) \}^{-2}$ mapping, simple comparisons with the "B_0" of a nominal low-scatter surface should ideally be adjusted for the scattering angle of greatest concern. To generate the summary tables in this paper, the scattering data in the 10° to 30° from specular region was extrapolated at a "-2"slope.[3]

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[3] "-2" refers to the exponent n in $\text{BTDF} = B_0 \cdot \{ [\sin(\text{theta}) - \sin(\text{theta}_0)] / 0.01 \}^n$

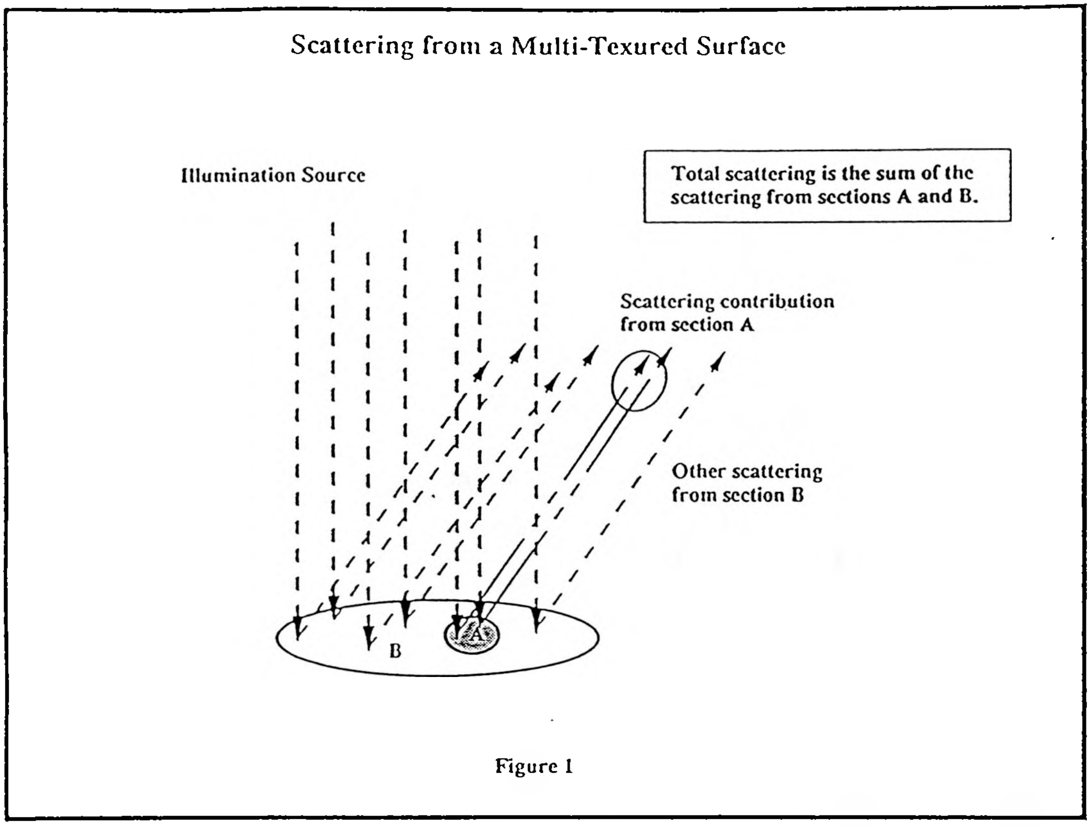


Figure 1

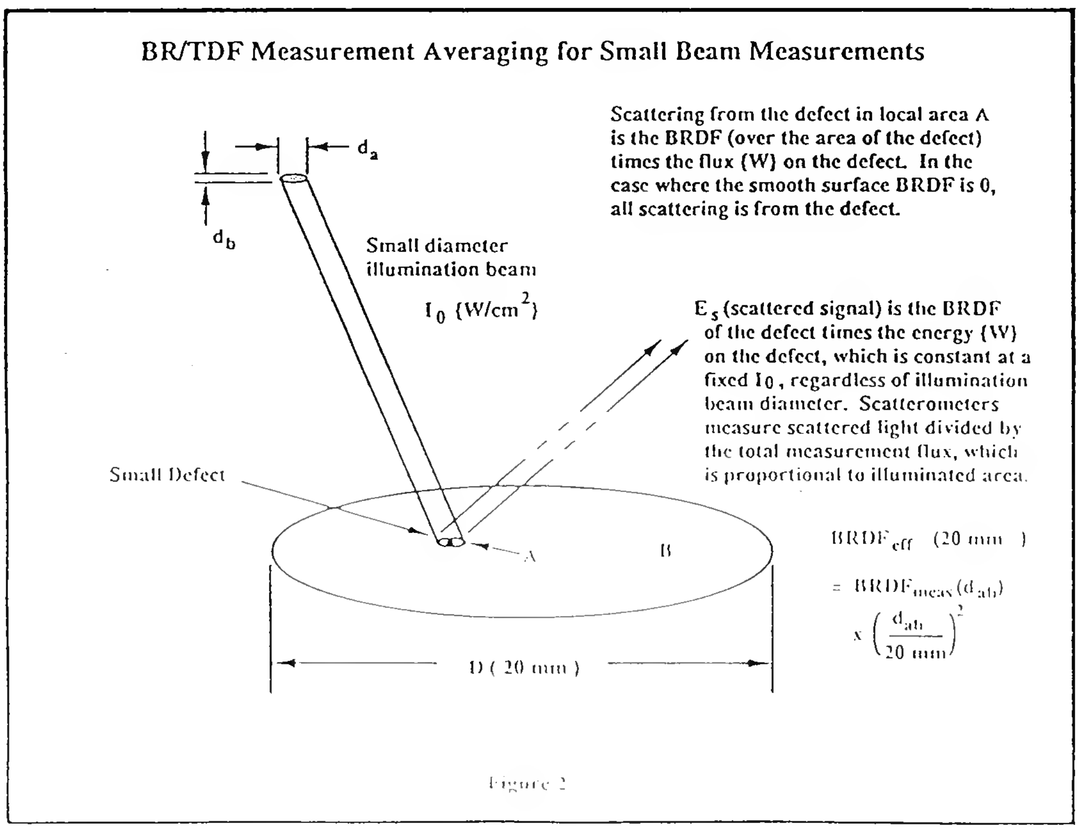


Figure 2

Forward Scattering Data from a #80 Scratch, Perpendicular to Axis

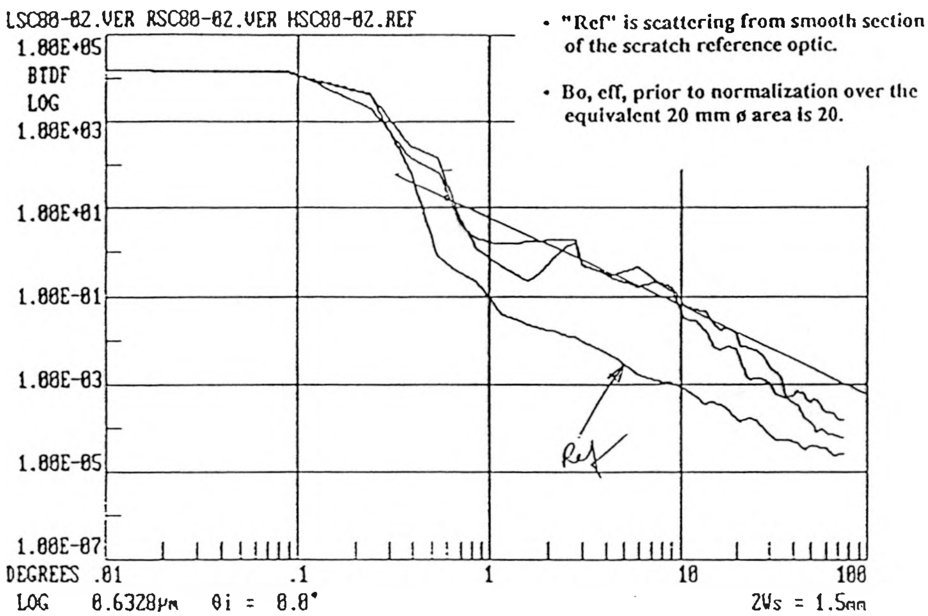


Figure 3

Forward Scattering Data from a #40 Scratch, Perpendicular to Axis

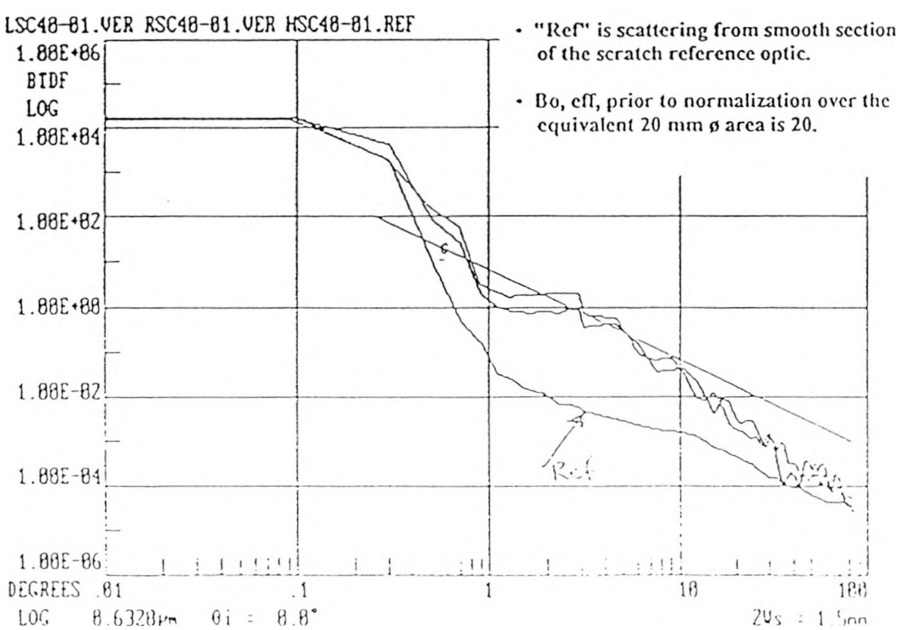
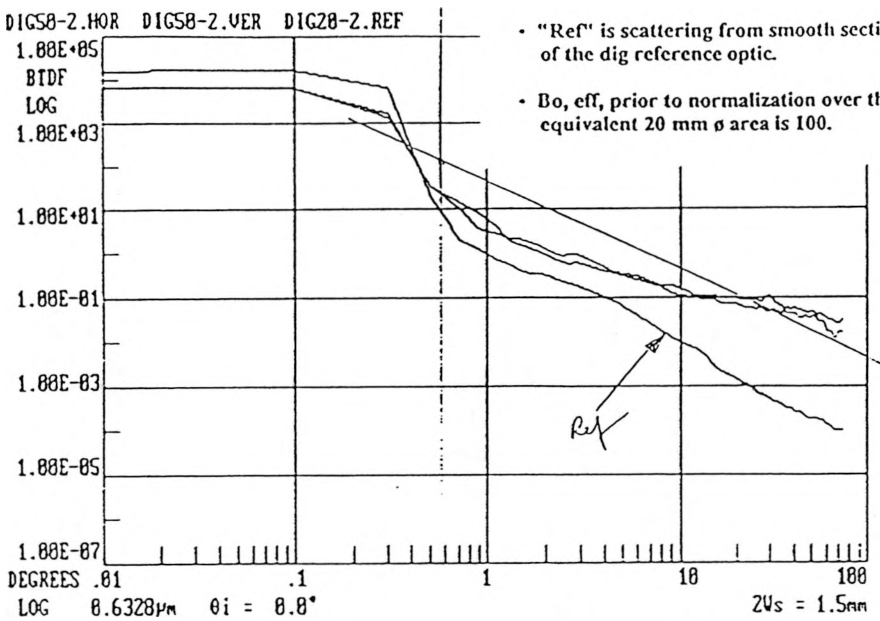


Figure 4

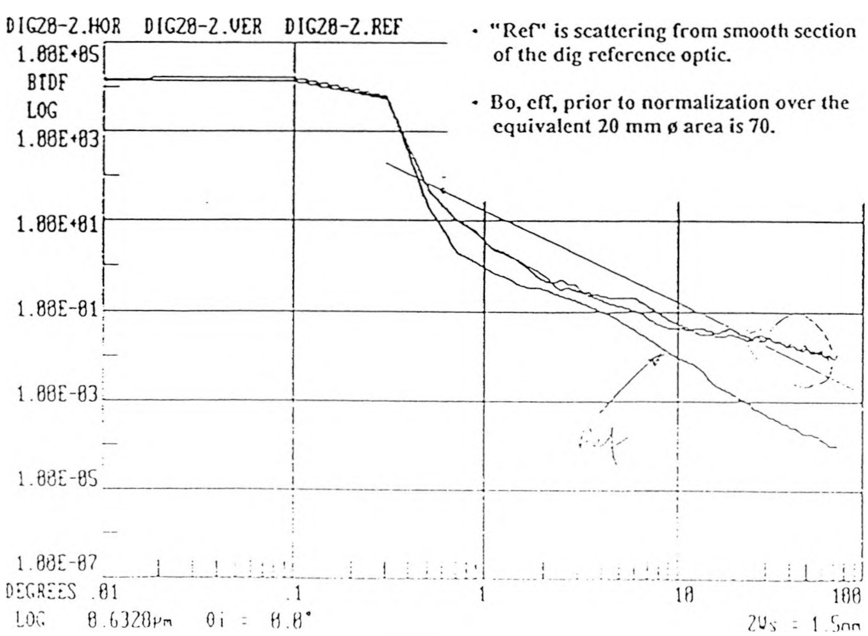
Forward Scattering Data from a #50 Dig



- "Ref" is scattering from smooth section of the dig reference optic.
- Bo, eff, prior to normalization over the equivalent 20 mm ø area is 100.

Figure 5

Forward Scattering Data from a #20 Dig



- "Ref" is scattering from smooth section of the dig reference optic.
- Bo, eff, prior to normalization over the equivalent 20 mm ø area is 70.

Figure 6

Table 1
Visual Inspection Matrix of the Scratch/Dig Sets

Beale Optical sets were compared to OCA's Frankfort Arsenal reference set. The left column (defects) are the stated values of the Beale sets. The data given in the columns is the Frankfort Arsenal reference mark that is visually equivalent. In some of the Beale scratches, variation was seen along the defect. In these instances, the minimum and the maximum are given. Defects were compared to the reference both in transmission and in reflection; transmissive/reflective differences are given only as noted.

Defect	Inspection	Set #1 Equivalent	Set #2 Equivalent
#50 Dig:	reflective (visual)	50	50
	transmissive (visual)	between 40 & 50	between 40 & 50
#40 Dig	reflective/transmissive	40	40
#20 Dig	reflectivetransmissive	20	20
#10 Dig	reflective/transmissive	between 5 & 10	10
#05 Dig	reflective/transmissive	5	<5 (barely visible)
#80 Scratch	reflective	between 60 & 80	60
	transmissive	between 40 & 80	60
#60 Scratch	reflective/transmissive	60	40
#40 Scratch	reflective/transmissive	40	40
#20 Scratch	reflective	10	20
	transmissive	10	between 10 & 20
#10 Scratch	reflective/transmissive	between 10 & 20	20

Table 2
BTDF of Scratches, Perpendicular to Scratch Axis

This table contains raw and corrected B_0 data for each scratch of 2 sets of standards. The first column, $BTDF_{meas}$, reports the B_0 as printed form the CASI scatterometer. The second column, $BTDF_{corrected}$, lists the BTDF that would have been measured if the scratch were exactly filled with constant illumination flux. The third column is the increase in BTDF over a 20 mm surface of nominal B_0 = 0.05 of the base surface (absent from defects) when a single 20 mm long scratch is located within the illuminated clear aperture.

Scratch	$BTDF_{meas}$	$BTDF_{corrected}$	% average B_0 increase
#80, set 1	60	4100	4200
#80, set 2	20	1400	1400
#60, set 1	30	2700	2100
#60, set 2	30	2700	2100
#40, set 1	20	2700	1400
#40, set 2	10	1400	700
#20, set 1	4	1100	280
#20, set 2	5	1400	350
#10, set 1	4	2200	280
#10, set 2	10	5500	700

Table 3
BTDF of Digs, Corrected for Area Scattering

This table contains raw and corrected B_0 data for each dig of 2 sets of standards. The first column, $BTDF_{meas}$, reports the B_0 as printed form the CASI scatterometer. The second column, $BTDF_{corrected}$, lists the BTDF that would have been measured if the scratch were exactly filled with constant illumination flux, assuming that the mechanism for scattering is functionally equivalent to scattering from the area of the dig. The third column is the increase in BTDF over a 20 mm surface of nominal $B_0 = 0.05$ of the base surface (absent from defects) when a single dig is located within the illuminated clear aperture.

Scratch	$BTDF_{meas}$	$BTDF_{corrected}$	% average B_0 increase
#50, set 1	60	100	130
#50, set 2	100	170	210
#40, set 1	100	230	180
#40, set 2	100	230	180
#20, set 1	70	520	100
#20, set 2	40	300	60
#10, set 1	5	140	7
#10, set 2	7	200	10
#5, set 1	2	220	2.8
#5, set 2	0.7	80	1.0

Table 4
BTDF of Digs, Corrected for Edge Scattering

This table contains raw and corrected B_0 data for each dig of 2 sets of standards. The first column, $BTDF_{meas}$, reports the B_0 as printed form the CASI scatterometer. The second column, $BTDF_{corrected}$, lists the BTDF that would have been measured if the scratch were exactly filled with constant illumination flux, assuming that the mechanism for scattering is functionally equivalent to scattering from the edge of the dig. The third column is the increase in BTDF over a 20 mm surface of nominal $B_0 = 0.05$ of the base surface (absent from defects) when a single dig is located within the illuminated clear aperture.

Scratch	$BTDF_{meas}$	$BTDF_{corrected}$	% average B_0 increase
#50, set 1	60	160	210
#50, set 2	100	270	340
#40, set 1	100	310	240
#40, set 2	100	310	240
#20, set 1	70	560	110
#20, set 2	40	320	65
#10, set 1	5	140	7
#10, set 2	7	200	10
#5, set 1	2	220	2.8
#5, set 2	0.7	80	1.0